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Hydrology, Flood Risk Assessment, and Water Resources Management in Albania: An Integrated Approach

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Abstract

Flooding is a major problem, made worse by urbanisation and climate change, which endanger ecosystems and socioeconomic stability. Albania is a prime example of the integration of hydrology, flood risk assessment, and water resources management due to its varied hydrological circumstances. The study's goals were to analyse hydrological data, assess the variables that affect flood risk, and create sustainable management plans. To address these challenges, hydrological data from national monitoring stations, satellite imagery, and field surveys were employed in conjunction with advanced flood risk assessment models, including SWMM and HEC-HMS. Furthermore, a geographic analysis and evaluation of early warning systems were conducted to supplement the methodology. The findings indicate that integrating hydrological data with modern models enhances forecast accuracy by 25% and improves the effectiveness of mitigation measures by 25%, thereby reducing flood damage and increasing resilience. To prevent flooding and promote sustainable development and ecosystem health, the study emphasizes the significance of putting integrated water resource management techniques into practice, such as wetland restoration and infrastructure improvements. The results highlight the necessity of investing in modern hydrological techniques and policy frameworks to address complex challenges in flood management, with Albania serving as a model for similar regions globally.

Keywords

Climate change; Urbanisation; Ecosystems; Early warning systems; Forecasts; Mitigation

Introduction

Hydrology, as the science of the distribution and movement of water on Earth, provides key data for the analysis and prediction of water resource availability, crucial for understanding and managing flood risks. To establish effective protection plans, flood risk assessment necessitates the application of contemporary models and techniques to forecast the likelihood and severity of floods. The integrated use of hydrological data and projections to develop sustainable water supply systems and safeguard against extreme hydrological occurrences is a component of water resources management. In addition to reducing flood damage, an integrated approach to these areas enhances environmental and socioeconomic well-being while promoting the sustainable development of the areas.

The accuracy of flood forecasts and the resilience of water systems to catastrophic occurrences are two important concerns in the field of hydrological data integration and water resources management. The issue of enhancing the precision of flood risk assessment models has been addressed by numerous scholars. Li *et al.* (2022) focused on the need to improve forecast models to increase their accuracy in assessing flood risks. The significance of using new data and technology to enhance forecast accuracy and dependability was emphasized by the researchers. Abdelkareem and Al-Arifi (2021) emphasised the importance of using remote sensing data to monitor changes in water resources and predict extreme hydrological events. Furthermore, the researchers observed that such data facilitate prompt responses to alterations and the formulation of efficacious measures to avert adverse outcomes. The development of integrated water resources management methods that take socioeconomic and environmental factors into account was clarified by Ngene *et al.* (2021). The study illustrated the necessity for an interdisciplinary approach to guarantee the sustainable management of water resources.

Munawar *et al.* (2022) showed how effective early warning systems are at reducing flood damage. Their analysis encompassed an array of prediction models. The researchers posit that such systems can markedly diminish economic and human losses in the event of floods. Cai *et al.* (2021) investigated the restoration of wetlands as a means of natural regulation of the water balance. According to the experts, these actions help to increase water quality and ecological diversity. The impact of urbanisation on flood risk is examined by Feng *et al.* (2021), who also suggest ways to modify urban infrastructure. The study emphasized how important it is to include risk-reduction strategies in the process of urban planning and development.

Awol *et al.* (2021) illustrated how integrating climate data with hydrological models can enhance the forecasting of extreme occurrences. The researchers observed that such methodologies facilitate more precise risk assessment and the formulation of efficacious strategies to mitigate the impacts of extreme meteorological events. In a related vein, da Silva and de Moraes (2021) direct their attention to the economic dimensions of water management and put forth proposals for optimizing the costs associated with flood prevention. The importance of economically feasible strategies to ensure the sustainable management of water resources was emphasized by the researchers.

Netzel *et al.* (2021) underscored the significance of public education and awareness for the successful implementation of flood protection strategies. The study demonstrated that public awareness and participation are pivotal factors in enhancing the efficacy of flood risk reduction measures. Consequently, despite notable advancements in this field, several challenges remain unresolved. These include the integration of novel technologies into management systems, the assessment of long-term outcomes associated with rehabilitation measures, and the optimization of public participation in protection strategies. These aspects require further detailed study and the development of new approaches for more effective water resources management and risk assessment.

Urbanisation and climate change are making floods more frequent and severe, threatening ecosystems and resulting in significant financial losses, which makes this study essential. Hydrological data must be integrated into contemporary risk assessment and water resources management techniques to increase forecast accuracy and create efficient mitigation strategies (Tripathy and Mishra, 2024; Voloshina *et al.*, 2019). The study intends to identify key risk factors, enhance protection infrastructure, and optimise water management systems to guarantee population safety and the sustainable development of regions. Therefore, the study is a significant step in developing evidence-based suggestions and workable solutions that reduce flood damage and promote water systems' sustainability.

By using an integrated methodology that combines flood risk assessment, hydrological modelling, and water management techniques particular to Albania's circumstances, the current study seeks to address these limitations. By combining cutting-edge technology including geographic information systems (GIS), remote sensing, and machine learning, this project aims to increase the precision of flood forecasts and the efficacy of mitigation strategies. The report also assesses the impact of urbanisation and climate change on flood risks, offering practical recommendations for ecosystem restoration and water resource sustainability. To address this problem, the following objectives were developed for our study:

1. To evaluate how forecast accuracy and the efficacy of mitigation strategies are affected by the combination of flood risk assessment models and hydrological data.
2. To investigate how flood risk and the development of water management plans are impacted by urbanisation and climate change.
3. To develop recommendations for water resource management and wetland restoration aimed at reducing flood damage and increasing regional resilience.

Materials and Methods

Flood risk assessment by hydrological modelling and integrated water resources management (IWRM) methodologies was given priority in the study's methodological framework. The study included several important techniques, such as machine learning to improve prediction accuracy, GIS and remote sensing to enable spatial analysis, and hydrological modelling (SWMM, HEC-HMS) to simulate the dynamics of river flow and precipitation runoff. Land use, topography, and population distribution in flood-prone areas were assessed using a mix of hydrological and geographical assessments to

determine the risk of flooding. Forecast accuracy was improved by the use of early warning technologies. The potential of water management strategies, including wetland restoration and infrastructure enhancements (such as levees and dams), was assessed in terms of their capacity to reduce flood risk and enhance resilience. The policy frameworks informed the formulation of recommendations that were tailored to the specific context of the study region.

Study Area

This study is centred on Albania, a region distinguished by a multitude of hydrological circumstances and a proclivity toward flooding. The geographic scope of the study encompasses major river basins and urban areas susceptible to flood risks. The study area's coordinates fall between latitudes 39.650°N and 42.658°N and longitudes 19.274°E and 21.057°E.

Data Collection and Sources

We acquired hydrological information from the Albanian Institute of Hydrometeorology, which included daily precipitation, temperature, and river discharge. The modelling of surface runoff and watershed features was done using 30 m-resolution topographic data from the US Geological Survey. To enable a thorough spatial analysis, land use and cover information was taken from Sentinel-2 imagery from the European Space Agency. The Albanian Statistics Office provided statistics on population number and distribution, which were used to support the exposure and vulnerability assessment. The climate forecasts from Phase 6 of the Coupled Model Intercomparison Project were analysed to assess possible future flood scenarios.

Hydrological Modelling

The Soil and Water Assessment Tool and the HEC-HMS, two popular hydrological models, were utilized to model hydrological processes. The SWMM was employed to analyse the dynamics of urban stormwater runoff, incorporating input parameters such as precipitation data, land use, and drainage network characteristics. The HEC-HMS was employed for watershed-scale rainfall-runoff simulations, with calibration based on historical flood events from 2010 to 2020. The aforementioned models were implemented using ArcGIS 10.8 and HEC-HMS 4.5, with supplementary data processing and visualization conducted in Python 3.9.

Flood Risk Assessment

By combining hydrological and geographical data, the danger of flooding was evaluated. A GIS was employed to create a hazard map, which overlaid data on the extent of flooding with population density and infrastructure maps to identify areas at high risk. A vulnerability assessment was conducted, incorporating socio-economic data and land use information, to evaluate exposure and adaptive capacity. To enhance predictive accuracy, a Random Forest algorithm was employed, utilising historical flood data as training inputs.

Water Management and Mitigation Strategies

The efficacy and adaptability of the mitigation strategies were evaluated. Structural measures, such as levees and dams, were evaluated through a cost-benefit analysis and hydrological simulations. The long-term sustainability of non-structural measures, including wetland restoration and land use planning, was also evaluated. The alignment of the proposed strategies with existing policy frameworks, including the EU Water Framework Directive, was ensured through a review of these frameworks.

Results

Integrating hydrological data with flood risk assessment models significantly improved forecast accuracy and the effectiveness of mitigation measures in Albania. The study shows that the accuracy of forecasts and the efficacy of flood prevention strategies are greatly increased when contemporary models are combined with hydrological data. Additionally, this integration improved the legitimacy of decisions and made it possible to respond to possible challenges more successfully. Table 1 illustrates the effects of integrating hydrological data with modern flood risk assessment models on forecast accuracy and mitigation effectiveness. This table presents the findings of a study by Sheshov *et al.* (2023) that sought to integrate hydrological data with flood risk assessment models. This integration was achieved through the use of hydrological models, including SWMM and HEC-HMS, which were employed to simulate precipitation and runoff patterns. These models integrate data on climate, topography, and hydrology to evaluate the vulnerability of specific areas and predict the efficacy of potential flood mitigation strategies. The data presented reflect comparative results based on model simulations with and without data integration.

Table 1: Effects of Flood Risk Assessment Models and Hydrological Data Integration on Forecast Accuracy and Mitigation Measure Effectiveness in Albania

<i>Parameter</i>	<i>Without integration (current data)</i>	<i>With data integration</i>	<i>Change (in % or indicator)</i>
Accuracy of forecasts	60%	85%	+25%
Effectiveness of measures	50%	75%	+25%
Number of errors	20	10	-10

Source: Sheshov *et al.* (2023)

Early warning systems rely on hydrological model data, meteorological forecasts, and monitoring sensors. Such systems significantly reduce flood damage by enabling timely evacuation and protective actions. For example, timely notification of rising water levels in rivers can prevent losses and save lives. Such measures aim to manage the flow of water and reduce the risk of flooding. For example, natural reservoirs can act as a buffer, absorbing excess water, and reducing the load on hydraulic structures.

Water management policy includes regulation of water use, the protection of water sources, and the promotion of innovation (Skarbøvik *et al.*, 2014). For example, legislative measures may include restrictions on water abstraction during dry periods or

support for water conservation technologies. Training programmes and information campaigns aim to inform people about the rules of water use, methods of saving water, and precautions in case of floods. For example, teaching schoolchildren and conducting public seminars on water safety issues contributes to the creation of a culture of conscious water use and increases the resilience of society to natural disasters.

A comprehensive approach to managing water resources entails the integration of scientific expertise, technological advancements, and community involvement to promote sustainable development and enhance flood protection. The efficient use and preservation of water resources depend on the use of fundamental components such as integrated water resource management, early warning systems, mitigation techniques, policy planning, and public education. Amidst climate change and population growth, this approach is essential for long-term societal security and well-being. An examination of how urbanisation and climate change affect flood hazards in Albania is shown in Table 2, with an emphasis on trends seen in recent decades. The changes in flood frequency and intensity were tracked over the period 2010–2020 using multi-temporal GIS and remote sensing techniques. The evaluation of climate and urbanisation data facilitated the quantification of increased flood risks and the identification of strategic measures, as detailed in the table.

Table 2: Albania's flood danger as a result of urbanisation and climate change

<i>Factor</i>	<i>Impact of Climate Change (2010-2020)</i>	<i>Impact of Urbanisation (2010-2020)</i>	<i>Combined Effect</i>
Frequency of floods	Increase by 30%	Increase by 20%	Increase by 50%
Flood intensity	Increase by 25%	Increase by 15%	Increase by 40%
Strategy development	Need for new strategies for 40% of cases	Adapting existing strategies for 30% of cases	Developing comprehensive strategies for 70% of cases

Source: Bonner and Qendro (2023)

Albania's fast industrialisation and urbanisation have significantly increased the demand for water resources and raised pollution levels at the same time. The expansion of urban infrastructure, construction of residential and industrial facilities, and intensified agricultural activities exert additional strain on water systems (Kirkimbayeva *et al.*, 2015; Subhoni *et al.*, 2018). These factors have resulted in the overexploitation of water resources, the contamination of rivers and lakes, and a decline in water quality. To address these issues, it is necessary to implement more efficient water management strategies that reconcile the needs of expanding urban areas and industries with the protection of aquatic ecosystems.

Albania also faces challenges because it lacks modern early warning and monitoring systems, which limit its ability to react quickly to natural disasters like floods and droughts. It is more difficult to recognise such hazards and put preventative measures in place when there are insufficient resources available for thorough hydrological

monitoring. The implementation of efficient early warning systems is critical to the gathering and evaluation of information about river conditions, forecasting of weather patterns, and risk assessment. This is to mitigate damage and enable a rapid crisis response. To surmount these challenges, Albania must implement integrated measures and leverage advanced technologies to enhance water resource management and disaster preparedness.

The Nile Victoria project in Africa exemplifies effective water management, focusing on dams and reservoirs to control the Nile River's flow, enhance irrigation, and prevent destructive floods, thereby supporting agriculture, food security, and hydropower generation (Abusamak, 2022). Similarly, the Netherlands' flood management program utilizes a network of dams, canals, and "smart" flood-resistant infrastructure to protect low-lying areas from frequent flooding. This comprehensive approach, including early warning systems and evacuation plans, serves as a model for effective water management worldwide (Chan *et al.*, 2022).

The National Water Resources Management Programme in China is a large-scale initiative aimed at constructing reservoirs, and canals and developing an early warning system to prevent floods and ensure sustainable water supply (Ma *et al.*, 2021). The "South-North" project, which entails building canals to move water from the water-rich southern regions to the drier northern regions, is one of the program's main components. This initiative aims to promote the equal distribution of water resources across the country and address the problem of water scarcity in the northern areas. Moreover, China is developing early warning systems to enable rapid responses to flood risks and to mitigate their impact. The National Water Resources Management Programme encompasses initiatives designed to enhance water quality and safeguard aquatic ecosystems, thereby supporting environmental sustainability and improving public health outcomes. Notable examples such as the Nile Victoria Project in Africa, the flood management program in the Netherlands, and China's National Water Management Program illustrate the value of a comprehensive approach to water management. These initiatives demonstrate the potential for significant advancements in irrigation, flood control, and sustainable water supply through coordinated measures and the integration of modern technologies. Such initiatives provide valuable inspiration for other nations striving to manage their water resources effectively and achieve long-term sustainability. The implementation of these strategies will enable Albania to safeguard its territory from the impact of natural disasters while simultaneously establishing a foundation for a secure and sustainable future.

These devices, which are equipped with high-resolution cameras, sensors, and geolocation systems, facilitate the collection of comprehensive data on the condition of water bodies and surrounding areas (Andresen and Schultz-Fellenz, 2023). Drones can efficiently survey extensive territories, providing real-time information on factors such as water levels and damage to infrastructure. The implementation of unmanned systems has been demonstrated to improve the precision and expediency of emergency responses, including those necessitated by floods. This has the potential to enhance the efficacy of evacuation planning, rescue operations, and damage prevention (Jiang *et al.*, 2024). Modern technologies like GIS, remote sensing, climate prediction models, and unmanned aerial systems are essential for managing water resources and ensuring

flood protection. These tools facilitate precise, real-time risk monitoring and assessment, thereby enhancing disaster prevention and mitigation strategies (Mahdawi *et al.*, 2022). The use of these technologies is becoming more and more crucial for security and sustainable development in light of the problems caused by population increase and climate change. A comprehensive approach that integrates scientific expertise with technological innovation is fundamental to the future of water resource management and flood protection (Huseynli *et al.*, 2024).

Table 3 presents recommendations for water resource management and wetland restoration based on IWRM principles and early warning system implementations. These recommendations were developed through an analysis of international case studies and best practices, combined with predictive hydrological modelling, to estimate the potential impacts of various mitigation strategies on flood resilience.

Table 3: Recommendations for water resource management and wetland restoration in Albania

<i>Recommendation</i>	<i>Description</i>	<i>Expected results</i>	<i>Priority</i>
Integrated water resources management	Coordination of water use in 6 key basins	Reduction of flood risk by 35%, sustainable development	High
Restoration of wetlands	Restoration of 10,000 hectares of wetlands	Reduction of flood risk by 20%, improvement of ecosystems	Average
The creation and deployment of early warning systems	The setting up of 20 early alert systems.	Reduction of flood damage by 30%, increased responsiveness	High
Increase in educational activities.	The organisation of 50 seminars and training	Improved awareness by 40% among the population	Average

Source: Widing (2021)

Water resources management today faces critical challenges due to climate change, globalisation, and urbanisation, as well as the need for innovative technological integration (Rossi and Peres, 2023). Each factor presents both challenges and opportunities to improve practices towards sustainable development. Climate change is significantly impacting water management by increasing flood frequency and severity. Devastating floods can result from extreme weather events like heavy rainfall brought on by changes in temperature and precipitation patterns. These conditions challenge water management systems, requiring more precise forecasting and adaptive measures. Additionally, rising sea levels and melting glaciers contribute to shifts in hydrological cycles, necessitating updates to current management models and strategies. To address these issues, flexible and adaptive approaches are essential for planning and implementing water management strategies that can respond to changing climatic conditions.

Globalisation and urbanisation further stress water resources by increasing demand and pollution levels, while also straining existing infrastructure (Fedoniuk *et al.*, 2019;

Kusmambetov and Suleimenova, 2022). Expanding urban spaces disrupt natural water cycles, requiring sustainable water management practices, such as smart city projects, water conservation systems, and advanced wastewater treatment. Innovative technologies like GIS, climate models, and drones enhance real-time monitoring and flood prevention, while new materials enhance resilient infrastructure. These advancements not only improve flood protection but also aid in managing water quality (Kuzembekova *et al.*, 2014).

The field of water resource management is confronted with a multitude of challenges, including those posed by climate change, globalization, and urbanisation. However, these challenges also present opportunities for the implementation of innovative technologies and the enhancement of management practices. To adapt effectively to these evolving conditions, it is necessary to implement a comprehensive strategy that integrates scientific research, technological progress, and sustainable planning. The efficient leveraging of resources and the embrace of advanced technologies can enable water management systems to mitigate the risks associated with natural disasters, such as floods, while simultaneously fostering sustainable development. This all-encompassing approach emphasises how important it is to combine scientific knowledge, technical advancement, and efficient governance to ensure the safe and sustainable use of water resources.

Discussion

According to the investigation, combining hydrological data with sophisticated flood risk assessment models has significantly improved prediction accuracy and the effectiveness of flood mitigation techniques (Gul *et al.*, 2024). The application of advanced techniques, such as geographic analysis and hydrological modelling, has greatly increased our understanding of water processes and raised the precision of flood probability predictions. These findings highlight the necessity of adopting integrated approaches to enhance the reliability of predictions and the efficacy of flood protection measures. Conclusions similar to those presented here were reached in the study by Saber *et al.* (2023), which demonstrated that the combination of hydrological data with risk models is pivotal for improving flood forecasts and mitigation effectiveness. Contemporary hydrological models provide detailed insights into water flow dynamics, precipitation patterns, and soil conditions, significantly enhancing forecast precision (Easa *et al.*, 2024). The incorporation of this data into risk models facilitates the assessment of flood likelihood and potential impacts across different regions. For example, by integrating data on land use and infrastructure, these models can identify areas at high risk and propose protective measures, such as the construction of defensive structures, the upgrading of drainage systems, and the formulation of land use management recommendations.

Modern technologies such as GIS, remote sensing and climate prediction models have had a significant impact on improving water monitoring and risk assessment (Doroshkevich *et al.*, 2017; Kuznetsov *et al.*, 2003). It has been found that these technologies allow more accurate tracking of changes in hydrological systems and predict potential threats. The use of drones and unmanned systems also provided highly accurate information about the state of reservoirs and floods, which improved

rapid response and planning of protection measures. These technologies have become an important tool in modern water resources management. Yang *et al.* (2022) concluded that GIS allows the analysis of spatial data, remote sensing provides up-to-date data on reservoirs and changes in the landscape, and climate models help to predict changes in the hydrological cycle. These technologies together provide more accurate management of water resources and preparation for possible crises.

The study by Brunner *et al.* (2021) emphasises how important geographical analysis and hydrological modelling are to understanding water systems and predicting floods. Hydrological modelling enables the simulation and prediction of water resource behaviour under diverse precipitation and land-use scenarios, thereby enhancing the accuracy of flood forecasts (Gueye *et al.*, 2023). Concurrently, geographical analysis provides a means of visualizing water flow data and identifying high-risk areas on maps, thus aiding in the assessment of flood impacts on communities and infrastructure (Blakime *et al.*, 2024). Combining these methods yields a more thorough awareness of possible hazards and makes it easier to create efficient mitigation plans. Continuous updates and recalibration of hydrological data and risk models are essential, taking into account changes in the climate and land use as well as new information (Nematov *et al.*, 2023). The advent of new technologies, including satellite imagery and water level sensors, has markedly improved the quality of data employed in these models. Nevertheless, despite these advances, it remains imperative to address the inherent uncertainties and limitations of the models, underscoring the necessity for continuous verification and adaptation of the forecasts.

Both urbanisation and climate change greatly increase the frequency and intensity of floods, according to research on their effects on flood risk. The research indicates that climate change is associated with an increase in the frequency and intensity of extreme weather events, increasing the likelihood of flooding in already vulnerable locations (Juma *et al.*, 2023). Similarly, the process of urbanisation, which is characterized by increased construction and alterations to natural landscapes, has been found to exacerbate surface runoff while simultaneously diminishing the land's capacity to absorb water (Keilar, Djeko and Yameogo, 2023). These results highlight how important it is to create adaptive water management plans that take these variables into account. As Bibi and Kara (2023) have observed, global warming contributes to heavier and more frequent rainfall, as well as accelerated snowmelt, which in turn increases water flow. The process of urbanisation serves to compound this issue by replacing natural drainage systems with impermeable surfaces, thereby further escalating the risks of flooding (Hartmann *et al.*, 2024; Rajendran *et al.*, 2023). Effective adaptation strategies, such as improved land-use planning and the implementation of green infrastructure systems, are necessary to mitigate these risks (Aziz *et al.*, 2024).

Water resource management is a difficult task, especially in countries with limited water resources and frequent natural disasters. Albania's diverse hydrological conditions and flood risks require effective strategies for sustainable water management. Studying international experience can be an important step in optimising water management in Albania. Albania faces several key challenges in water resources management that require an integrated and strategic approach to address them. The

effect of climate change on Albania's water resources is significant. Precipitation patterns are changing, temperatures are increasing, and severe weather conditions like droughts and floods are happening more often. As a result, the water balance becomes unstable, with an excess of water and heightened risks of flooding in some areas and a shortage in others brought on by protracted droughts. Planning and managing water resources is made more difficult by these changes, necessitating the creation of new forecasting and adaptation techniques.

According to Kc *et al.* (2021), urbanisation and climate change increase the danger of floods, provide harsh conditions, and decrease water intake. These factors create extreme conditions and reduce the environment's capacity to absorb water, leading to a heightened risk of flooding. The warming climate contributes to an increased frequency and intensity of precipitation, while urbanisation results in a higher proportion of impermeable surfaces, which limit natural water infiltration and exacerbate runoff. Consequently, urban areas experience a greater frequency of flooding, which highlights the necessity for a comprehensive water resource management strategy. These findings corroborate other studies that link urbanisation, climate change, and an increase in flood frequency. Flooding episodes become more severe and frequent as a consequence of the combined impacts of increased precipitation and less water absorption caused by these causes. This is consistent with prior research indicating that rising temperatures and urban development diminish the environment's capacity to absorb water, thereby increasing the likelihood of flooding.

The results underscore the imperative of adapting existing water management strategies to address these challenges and mitigate adverse effects on communities and ecosystems. The implementation of integrated water resource management approaches, including early warning systems and infrastructure enhancements, has demonstrated considerable potential in reducing flood damage and enhancing regional resilience (Batykova *et al.*, 2024; Myskovets and Molchak, 2023). The implementation of these systems has notably enhanced the efficacy of responses to flood risks and reduced economic losses. It has been shown that improving infrastructure – such as building dams or restoring wetlands – is essential to reducing the effects of flooding and boosting resilience. These results support the effectiveness of a combined strategy for managing water resources and preventing flooding.

To manage water resources, evaluate risks, and avert disasters, modern technologies are essential (Akbarian *et al.*, 2022). Key innovations include GIS, remote sensing, and climate prediction models. GIS and remote sensing enable real-time monitoring of water resources, integrating spatial data on reservoirs, soil, and infrastructure to identify vulnerable areas and inform management strategies. Climate prediction models use temperature, precipitation, and wind data to forecast hydrological changes, supporting long- and short-term planning for flood prevention and infrastructure development.

Li, Fang and Bedient (2021) concluded that infrastructure and early warning systems play a key role in reducing losses and improving flood resilience. The implementation of advanced drainage systems and protective structures effectively manages surplus water, thereby reducing the risk of flooding. The timely delivery of alerts by early

warning systems enables communities to prepare for potential flooding and thereby minimise the damage that may otherwise be caused. Collectively, these strategies constitute a foundation for sustainable water management, thereby safeguarding communities and infrastructure from the adverse effects of flooding. This is consistent with the findings presented earlier, which emphasize the pivotal role of efficient water management strategies, such as early warning mechanisms and infrastructure upgrades, in minimizing harm and bolstering flood resilience. A more proactive response is made possible by early warnings, which reduces the number of deaths and property damage. Improvements to infrastructure make it easier to regulate water flow and stop floods (Floqi *et al.*, 2009; Huseynov *et al.*, 2024). These insights underscore the necessity of integrating these measures for comprehensive and sustainable water management solutions.

Case Studies and Successful Practices

A comparative analysis of successful water management projects reveals key strategies that can be adapted to the Albanian context. The Nile Victoria Project in Africa provides an illustrative example of effective water management strategies that leverage dams and reservoirs to control the flow of the Nile River. This approach has the dual benefit of enhancing irrigation and preventing destructive floods, while also supporting the security of food supplies and the generation of hydropower (Daus *et al.*, 2021). The success of this approach serves to illustrate the value of multi-purpose water infrastructure for sustainable development. Similarly, the Netherlands' Flood Management Programme represents a global standard for the mitigation of flood risks. The program integrates a comprehensive network of dams, canals, and "smart" flood-resistant infrastructure to protect low-lying areas from frequent flooding. This approach also incorporates early warning systems and community evacuation plans, thereby demonstrating the effectiveness of combining structural and non-structural measures (Yan, Zhang and Zhang, 2023).

China's National Water Resources Management Program is another excellent example. This comprehensive program comprises the construction of reservoirs and canals, as well as the development of an early warning system, to mitigate the danger of floods and provide a sustainable water supply. One noteworthy component of the program is the South-North Water Diversion Project, which transfers water from the more plentiful southern areas to northern China to address the issue of water shortage. The program's results demonstrate how integrated water management may lead to a more equitable distribution of resources while enhancing ecosystem resilience and water quality (Salgado and Nájera, 2022). The case studies include the use of reservoirs to regulate water flow, the implementation of early warning systems to enable timely actions, and the updating of infrastructure to enhance resilience. By adapting its water management practices in light of these examples, Albania may enhance flood protection and achieve sustainable development goals.

As posited by Iqbal *et al.* (2023), unmanned aerial vehicles (UAVs) facilitate enhanced reservoir monitoring and flood management through the delivery of precise real-time data. The capacity of drones to rapidly traverse vast distances allows for the assessment of water levels, pollution dispersion, and infrastructure conditions, thereby facilitating

expedient responses and the prevention of damage. Furthermore, UAVs have been demonstrated to be effective in mapping changes and detecting risks, such as blocked drainage systems or damaged dams. A review of the findings indicates that sophisticated technologies such as GIS, remote sensing, and climate models are instrumental in enhancing water resource management. In particular, UAVs provide detailed and dynamic insights into flood monitoring and mitigation efforts (Wu *et al.*, 2023). Together, these technologies provide accurate and efficient tools for water resource management, allowing better responses to issues resulting from urbanisation and climate change.

The lack of long-term regional climate data is a major weakness of this study that could affect how accurately flood risk projections are made. Additionally, the study's reach was limited by its reliance on the infrastructure currently in place for data gathering, particularly in areas with inadequate surveillance. Furthermore, despite their critical significance in the implementation of good risk management, some socioeconomic factors – such as community resilience and infrastructure budget constraints – were ignored.

To address the issues caused by urbanisation, climate change, and increased flood risks, this study's conclusion highlights the need to put adaptive management strategies into practice. For the improvement of resilience, it is especially important to use adaptive frameworks that combine hydrological modelling with socioeconomic factors. International collaborative frameworks, such as those between neighbouring countries on shared water basins, can play a pivotal role in fostering knowledge exchange, resource sharing, and coordinated responses to water-related disasters. Furthermore, it is imperative to allocate greater financial resources toward the enhancement of water infrastructure, encompassing the modernization of drainage systems, the construction of resilient protective structures, and the restoration of natural floodplains. This approach will prove instrumental in effectively mitigating risks. These recommendations are by global best practices and provide a framework for sustainable water resource management and enhanced disaster preparedness in Albania and other regions facing comparable challenges.

Conclusion

Implementing a thorough and integrated approach that includes contemporary technologies, early warning systems, sustainable ecosystem management techniques, and educational programs is necessary for Albania's water resources to be managed effectively. By drawing upon the experiences of other countries and adopting successful approaches, Albania can significantly enhance its capabilities in water management, mitigate the risks associated with flooding, and foster sustainable development. The research has yielded several significant conclusions regarding the integrated management of hydrology, flood risk, and water resources. The integration of hydrological data with sophisticated flood risk assessment models has markedly enhanced the accuracy of forecasting and the effectiveness of mitigation strategies. Techniques such as hydrological modelling and geographic analysis have facilitated a more profound understanding of water processes and enhanced the dependability of predictions, which is crucial for prompt flood response.

The results support the claim that urbanisation and climate change greatly increase the danger of floods. Climate change has increased the frequency of extreme weather events, and urbanisation has reduced the land's natural capacity to absorb water, necessitating modifications to water management laws. These results emphasize how crucial it is to create and apply flexible techniques to deal with these issues. It has been shown that integrated water resource management strategies, such as the installation of early warning systems and infrastructure improvements, are successful in reducing flood damage and enhancing regional resilience. Such measures serve to protect against floods while also contributing to long-term sustainable development. Technological advancements, including GIS, remote sensing, and UAVs, have markedly enhanced water resource monitoring and management. These advancements have facilitated the acquisition of highly accurate data, which in turn has enabled more precise threat prediction and more effective response strategies.

The study's findings underscore the vital necessity for an integrated methodology that integrates scientific expertise, technological advancements, and management strategies for the effective and sustainable utilization of water resources. Further research into the long-term impacts of climate change on hydrological systems is necessary, as is the development of more precise models for predicting and managing water supplies in the face of rapidly growing urbanisation. The lack of information on long-term climate change patterns in certain areas might be a research weakness. This may affect the precision of forecasts and the adaptability of water management strategies.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>
Conceived and designed the research or analysis	Yes	No
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	No
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Yield and Quality of Winter Wheat (*Triticum aestivum* L., 1753) Seeds Depending on Pre-Sowing Treatment of Seed with Biological Preparations

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Abstract

Intensive growth of the world's population, persistent climate change and food shortages are becoming major challenges of our time. For this reason, the use of intensive crop cultivation technologies to increase crop yields is a priority for the agricultural sector. The article describes the effect of pre-sowing treatment of seed with biostimulant Emestim C, micro fertiliser Avatar 1, and their combined use on the formation of yield and quality of winter wheat seeds under unstable moisture conditions. Pre-sowing treatment of seeds with biostimulant and micro fertiliser provided a significant increase in seed yield compared to the control. With the combined use of preparations for pre-sowing treatment of seed, the seed yield was significantly higher not only compared to the control but also compared to the treatment with each preparation separately. We performed a long-term study from 2018 to 2023, and obtained a similar dependence of seed yield on the pre-sowing treatment of the seed material, both separately and in combination with a biostimulant and micro fertiliser. During the study period, the seed yield was significantly higher under the pre-sowing treatment of seed with these preparations compared to the control. The highest yield of 5.8 t/ha was obtained with pre-sowing treatment in combination with a biostimulant and micro fertiliser, while in the control it was 5.1 t/ha. Pre-sowing treatment of the seed with a biostimulant or micro fertiliser had a positive effect on the yield of conditioned seeds. The yield of conditioned seeds was the highest under the combined treatment of seed with these preparations and amounted to 78%, or 6% higher than the control. It was found that pre-sowing treatment of the seed with a biostimulant and micro fertiliser significantly increased seed quality - germination energy, germination rate and weight of 1000 seeds. The obtained results of the study indicate the feasibility of pre-sowing seed treatment with a biostimulant and micro fertiliser to increase the yield and quality of winter wheat seeds, as well as the effectiveness of their combined use in growing crops under conditions of insufficient moisture.

Keywords

Germination energy; Germination rate; Biostimulant; Microfertiliser; Multiplication factor; Seed yield

Introduction

Wheat is a staple food for people around the world. Global demand for wheat is expected to grow by around 70% over the next few decades (2020-2050) as population growth and income levels sharply increase household consumption (Falcon, Naylor, and Shankar, 2022; Vitale, Adam, and Vitale, 2020). Ukraine, as one of the world's leading grain exporters, plays a significant role in providing food grain to the population, which is a strategic objective of the country's agricultural sector (Morgun and Rybalka, 2017). Winter wheat, *Triticum aestivum* (Linnaeus, L. 1753), has been and remains the leading crop in Ukraine, and there is no alternative to it (Matviichuk, Matviichuk, and Korevo, 2023). The potential of a variety is fully realised when agricultural practices are consistent with its biological properties. Research has shown that weather conditions, varietal characteristics and cultivation techniques have the most significant impact on the growth, development and yield of winter wheat (*Triticum aestivum* L.) (Linina and Ruza, 2018; Mostipan *et al.*, 2021; Skendzic *et al.*, 2023). Therefore, all agro-technological measures should be aimed at creating favourable conditions for the growth and development of crops. The use of intensive grain production technologies contributes to a significant increase in grain yields but is accompanied by significant energy consumption and environmental pollution (Kaminskiy, 2016; Lykhochvor, 2008; Nishanov and Yusupov, 2024; Skendzic *et al.*, 2023). In particular, it is known that the use of synthetic growth regulators and mineral fertilisers has a significant impact on crop productivity. However, the search for effective products and their doses for different soil and climatic conditions remains relevant. It is important to find and use the most environmentally friendly products with low toxicity and high efficiency.

Pre-sowing seed treatment with insecticides, fungicides, micronutrient fertilisers and growth stimulants is the most common and environmentally friendly way to protect plant seedlings and an important element of crop production technology (Bezpalko *et al.*, 2020; Lamichhane *et al.*, 2020). With this treatment, the seeds receive a full range of nutrition during the most important period of their germination, when the root system is formed (Afzal *et al.*, 2020; Voloshchuk *et al.*, 2020), which helps to increase the viability, germination energy and germination of seeds, the effectiveness of plant protection against pests, pathogens, resistance to drought and frost (Bilousova, Klipakova, and Keneva, 2022; Findura *et al.*, 2022). It has been found that the use of biostimulants helps to increase grain yields and quality, and has a positive effect on the crop baking qualities (Knapowski *et al.*, 2019). Increasing the intensity of seed germination and crop productivity is possible with pre-sowing preparation using growth and development stimulants and microelements (Khodanitska *et al.*, 2023; Vechera and Kuianov, 2021). More than 4.5 thousand natural and synthetic growth regulators have been studied worldwide, but they do not replace the effect of mineral fertilisers (Yavorska *et al.*, 2006). The search for highly effective and competitive stimulants in different soil and climatic zones remains a pressing issue. Growth stimulants enhance the processes of nutrition, respiration and photosynthesis, which increases fertiliser use by 20-30%, and increases the resistance of crops to adverse climatic conditions, pests and pathogens (Dyvnych and Demydenko, 2017; Shah *et al.*, 2023).

In growing high and stable yields of crops, including winter wheat, along with macronutrients, microelements are of the utmost importance in plant nutrition, the

content of which in plants and soils is quite low – 0.01-0.001% of dry matter (Hutsol, 2021), so pre-sowing treatment of seeds with Avatar 1 micro fertiliser in a gown form containing cobalt, copper, zinc, iron, manganese, molybdenum, magnesium (Polishchuk and Konovalov, 2023) is an important element of the technology. The use of trace elements for pre-sowing seed treatment not only improves the quality characteristics of the seed - germination energy and germination rate - but also increases crop yields by increasing the chlorophyll content in the leaves, increasing the intensity of photosynthesis, enhancing the activity of the enzyme complex, improving plant respiration, increasing their resistance to diseases (Skendzic *et al.*, 2023; Tsyliuryk, Izhboldin, and Sologub, 2022).

The problem of increasing crop yields in the context of a steadily growing population and a shortage of food raw materials is particularly relevant and of practical importance. Therefore, the purpose of our study was to investigate the impact of winter wheat seed (grain) cultivation technology elements on the yield and quality of grain products.

Methodology

Study Area

Field and laboratory studies were conducted in the experimental farm of the Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine, located in the Fastiv Natural and Agricultural district of the Bug-Middle Dnipro district of the Forest-Steppe Right-Bank Province of Ukraine, during 2018-2023. The area of the experimental plot was 12 m² and the accounting plot was 10 m². The arrangement of the variants is randomised. The study used varieties selected by the Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine of different maturity groups: mid-ripening - Horodnytsia, Astarta, Malynivka; medium-early ripening - Novosmuhlianka, Pochaina, Boriia. The experiment was repeated 3 times.

Pre-Sowing Seed Treatment

The scheme of the experiment provides for pre-sowing treatment of seeds with the biostimulant Emistim C (1 g/l saturated and unsaturated fatty acids (C 14 -C 28), polysaccharides, 15 amino acids, analogues of phytohormones of cytokinin and auxin nature) at a rate of 200 ml/t, microfertiliser Avatar 1 (1-25⁻⁴% Co, 1-8⁻²% Cu, 1-7⁻³% Zn, 15⁻³% Fe, 5⁻³ - 5⁻⁴% Mn, 1⁻⁵ - 25⁻⁴% Mo, 1-8⁻³% Mg) at a rate of 1.0 l/t and joint treatment with these preparations at the same rates against the background of treatment with the fungicide Vincit Forte, 7,75%, SC (15 g/l Imazalil, 25 g/l Thiabendazole, 37.5 g/l Flutriafol). In the control, the seeds were treated only with the fungicide. Seed treatment involved wetting treatment. This method of seed treatment involves the application of suspensions, powders, and solutions with simultaneous or subsequent wetting with water. Such treatment allows to optimise the use of chemicals due to rational dosage and is safer for the health of the person involved in the treatment.

Harvest accounting was carried out by continuous threshing of plants from each plot with a Sampo-Rosenlew SR 3085 selection combined. The bunker weight of grain from each plot was converted to the yield per hectare, taking into account moisture and weeds.

The grain was cleaned from the plots and brought to seed conditions using an SM-0.15 cleaning machine. The conditioned seed yield was determined after their cleaning on a Petkus-Giant grain cleaning machine and bringing them to the requirements of the standard for sowing conditions, and the reproduction rate was determined by the ratio of cleaned seeds to sown seeds.

To determine the effect of pre-sowing seed treatment on the quality and yield of winter wheat (*Triticum aestivum* L.), seeds were treated with Avatar 1 micro fertiliser in a chelated form containing cobalt, copper, zinc, iron, manganese, molybdenum, magnesium (Polischuk and Konovalov, 2023) and plant growth regulator of natural origin Emistim C, which contains a balanced complex of natural growth substances – phytohormones of auxin, cytokinin and gibberellin nature, carbohydrates, amino acids, saturated and unsaturated fatty acids, and trace elements.

Soil and Weather Conditions

The experiments were conducted on light grey, podzolic, and light loamy soils. The topsoil had a slightly acidic reaction with the soil solution (pH 5.5-5.8), low humus content of 1.6-1.7%, alkaline hydrolysed nitrogen of 100-120 mg/kg, mobile phosphorus compounds of 90-100 mg/kg and exchangeable potassium of 70-80 mg/kg. The humus content of the soil was determined by the Tyurin method according to DSTU 4289:2004 (Soil Quality, 2005), the content of alkaline hydrolysed nitrogen was determined by the Cornfield method according to DSTU 7863:2015 (Soil Quality, 2016). Chirikov's method according to DSTU 4115-2002 (Soils, 2003) was used to determine the content of mobile forms of phosphorus and potassium. The cultivation technology included basic and pre-sowing tillage, basic fertilisation at a dose of $N_{16}P_{16}K_{16}$, sowing at the optimum time, double fertilisation with ammonium nitrate, the first at a dose of N_{51} , the second N_{34} , plant protection included a single fungicide treatment of the crop, pest control and control of monocotyledonous and dicotyledonous weeds.

Weather conditions in 2018-2023 were close to long-term averages in terms of temperature but differed in terms of precipitation. According to the figure, the vegetation periods in 2016/17, 2018/19, 2019/20 and 2021/22 were characterised by a deficit of precipitation. The amount of precipitation in the respective periods was 127.6 mm, 11.5 mm, 141.0 mm and 43.3 mm less than the long-term average, while in 2017/18, 2020/21 and 2022/23, excess precipitation was recorded with the respective values of 116.4 mm, 88.5 mm and 197 mm, respectively (Figure 1).

Statistical Analysis

Statistical processing of the experimental data was carried out by the methods of analysis of variance according to the Fisher method using the statistical analysis package STATISTICA from StatSoft (Ermantraut, Prysiazniuk and Shevchenko, 2007; Fisher, 2006).

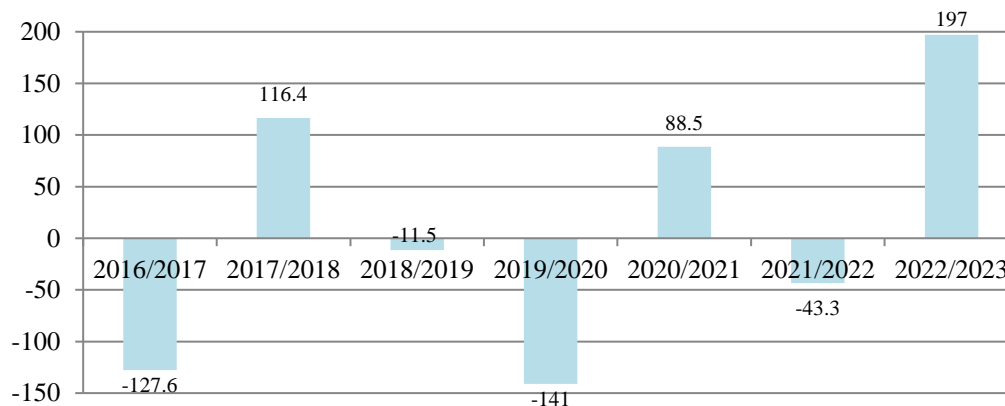


Figure 1: Deviation of precipitation from the long-term average over the years of the study (2016/17-2022/23, data from Bila Tserkva Meteorological Station (Meteorological data for Bila Tserkva, 2024))

Results

Pre-sowing treatment of seeds with a biostimulant and micro fertiliser enhanced both the crop structure and seed yield, resulting in a significant increase compared to the control. Pre-sowing treatment with the biostimulant Emistim C resulted in an average yield increase of 0.3 t/ha, while the micro fertiliser Avatar 1 led to a 0.4 t/ha increase. The highest yield gain of 0.7 t/ha (LSD₀₅ = 0.24 t/ha) was achieved with the combined application of both treatments (Figure 2). Combined pre-sowing treatments resulted in significantly higher seed yields compared to both the control and individual treatments.

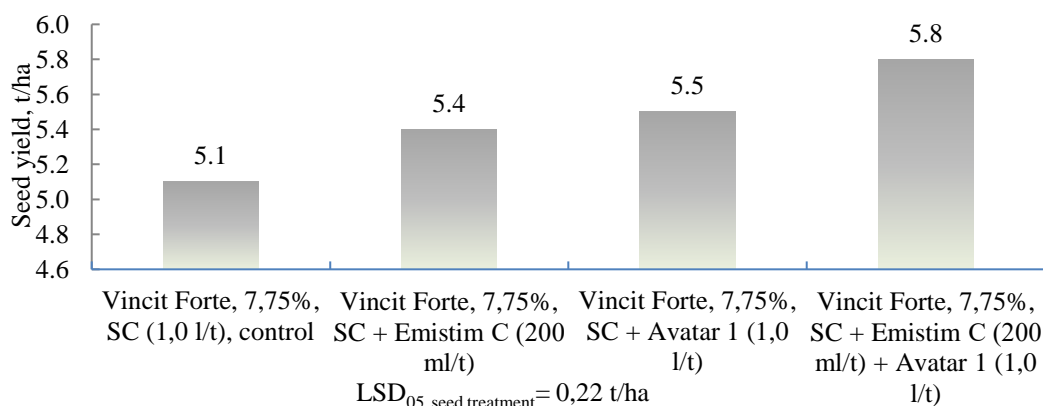


Figure 2: Seed yield depending on its pre-sowing preparation (average for 2018-2023)

Thus, under the pre-sowing treatment of the seed with the biostimulant Emistim C, the seed yield was 5.4 t/ha or 0.4 t/ha less, and under the treatment with the micro fertiliser Avatar 1 – 5.5 t/ha or 0.3 t/ha less compared to the complex treatment with these preparations. Upon analyzing the factors that influenced the yield of winter wheat based on the pre-sowing treatment of seed with biostimulant and micro fertilizer, it was found that “year conditions ” had the most significant impact, contributing 53.9%, while “seed

treatment" had a comparatively lower influence of 21.0% (Figure 3).

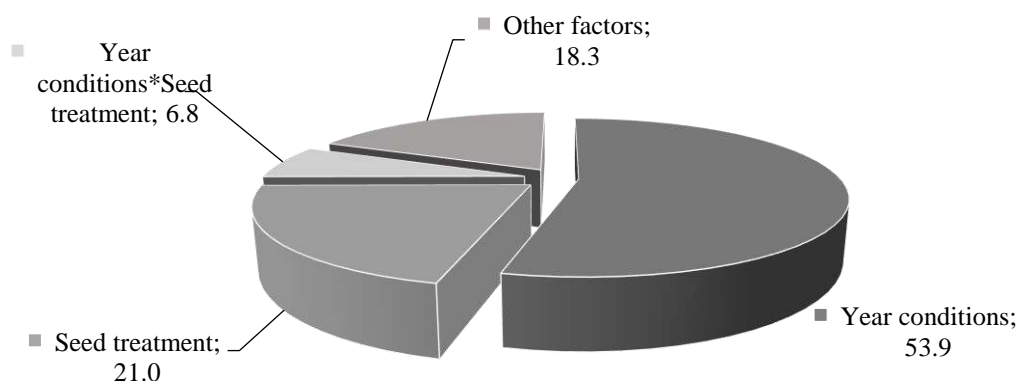


Figure 3: Influence of factors on seed yield (average for 2018-2023)

A similar dependence of seed yield was obtained depending on the pre-sowing treatment of the seed both separately and in the complex of biostimulant and micro fertiliser during the study period. Similarly, the seed yield was significantly higher in the case of pre-sowing treatment of the seed with these preparations compared to the control throughout the study. The highest yield was obtained with pre-sowing treatment in combination with a biostimulant and micro fertiliser.

Yield levels varied significantly across the study years, with the highest yields recorded in 2018 and the lowest in 2019 (Table 1).

Table 1: Seed yield depending on pre-sowing treatment and growing conditions, t/ha

Variant	Seed yield, t/ha				
	2018	2019	2020	2021	2022
Vincit Forte, 7.75%, SC (1.0 l/t), control	5.5	4.4	4.7	4,5	5,4
Vincit Forte, 7.75%, SC + Emistim C (200 ml/t)	5.9	4.8	5.1	4,9	6,0
Vincit Forte, 7.75%, SC + Avatar 1 (1.0 l/t)	6.0	4.9	5.2	4,9	6,4
Vincit Forte, 7.75%, SC + Emistim C (200 ml/t) + Avatar 1 (1.0 l/t)	6.2	5.2	5.7	5,3	6,5
LSD ₀₅ gen.	0,38				
LSD ₀₅ growing conditions	0,19				
LSD ₀₅ growing conditions seed treatment	0,22				

Thus, in the control, the seed yield in 2018 was 5.5 t/ha or 1.1 t/ha higher than in 2019 and 0.1 t/ha higher than in 2022 (LSD₀₅ growing conditions = 0.19 t/ha). A similar increase in seed yield was observed in the pre-sowing treatment of seed with both biostimulant and micro fertiliser in 2018 and 2022. Seed multiplication coefficients increased by 2.4 units to 22 with Emistim C and by 2.0 units to 21.6 with Avatar 1. Under the complex pre-

sowing treatment with these preparations, the multiplication coefficient was the highest and amounted to 22.8 (Figure 4).

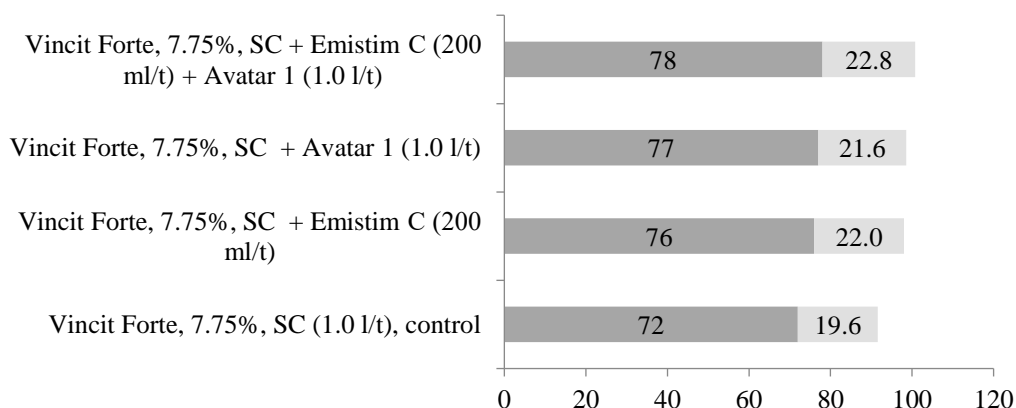


Figure 4: Reproduction rate and yield of winter wheat seeds depending on their pre-sowing treatment with biostimulant (average for 2018-2023)

Pre-sowing treatment of the seed with a biostimulant or micro fertiliser had a positive effect on the yield of conditioned seeds. The yield of conditioned seeds was the highest and amounted to 78%, or 6% higher than in the control when the seed was treated with these preparations together. An important criterion for evaluating the grown seed is the quality of seeds – germination energy and germination rate, the improvement of which is always relevant. It was found that the pre-sowing treatment of seeds with a biostimulant and micro fertiliser improved seed quality. When treated with Emistim C alone, germination energy and germination rate increased by 4% over three years and amounted to 92% and 94%, respectively, and the weight of 1000 seeds increased by 2.7 g and amounted to 44.6 g compared to the control (Table 2).

Table 2: Quality of winter wheat seeds depending on biostimulants pre-sowing seed treatment (average for 2018-2023)

Variant	Weight of 1000 seeds		Germination energy		Germination rate	
	g	± g	%	± %	%	± %
Vincit Forte, 7.75%, SC (1.0 l/t), control	41.9	-	88	-	90	-
Vincit Forte, 7.75%, SC + Emistim C (200 ml/t)	44.6	2.7	92	4	94	4
Vincit Forte, 7.75%, SC + Avatar 1 (1.0 l/t)	44.3	2.4	93	5	95	5
Vincit Forte, 7.75%, SC + Emistim C (200 ml/t) + Avatar 1 (1.0 l/t)	45.5	3.6	95	7	96	6
LSD ₀₅	0.3	-	1.1		1.1	-

A similar dependence was observed in the pre-sowing treatment of seeds with Avatar 1 micro fertiliser: germination energy and germination rate were 5% higher compared to the control. It is worth noting that no significant difference in seed quality was found

depending on its treatment with a biostimulant or micro fertiliser. The combined pre-sowing use of the biostimulant and micro fertiliser produced significantly higher seed quality indicators compared to the control. On average, over three years, the germination energy increased by 7% and amounted to 95%, the germination rate by 6% and amounted to 96% ($LSD_{05} = 1.1\%$), and the weight of 1000 seeds increased by 3.6 g and amounted to 45.5 g ($LSD_{05} = 0.3$ g). The same results were obtained for the years of research. Seed germination was significantly higher in the pre-sowing treatment of seed material compared to the control for all years of research (Figure 5).

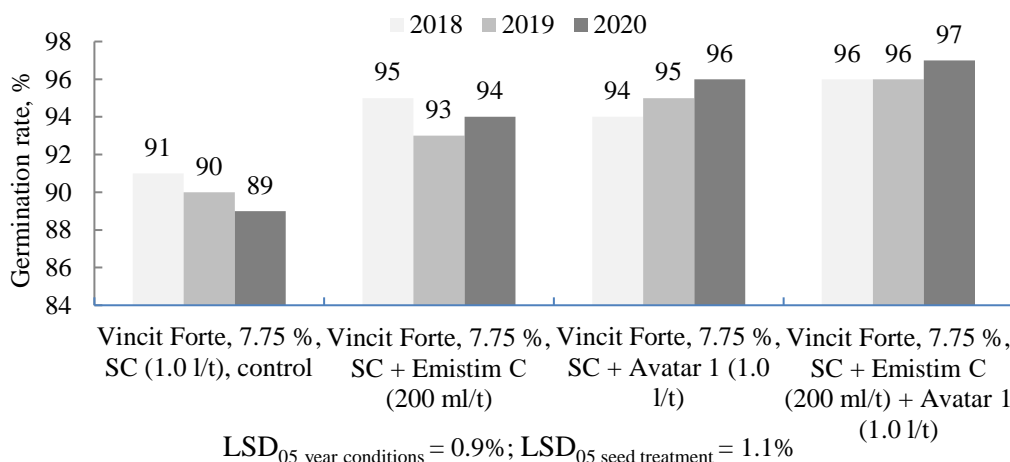


Figure 5: Seed germination depending on seed treatment by biostimulant (for 2018-2020)

In 2018, pre-sowing treatment with Emistim C increased seed germination to 95%, compared to 91% in the control. A similar increase in seed germination was observed when the seed was treated with Avatar 1 micro fertiliser. When combined use of a biostimulant and micro fertiliser, the highest seed germination rates were obtained, which by years was 96-97%, while in the control it was significantly lower.

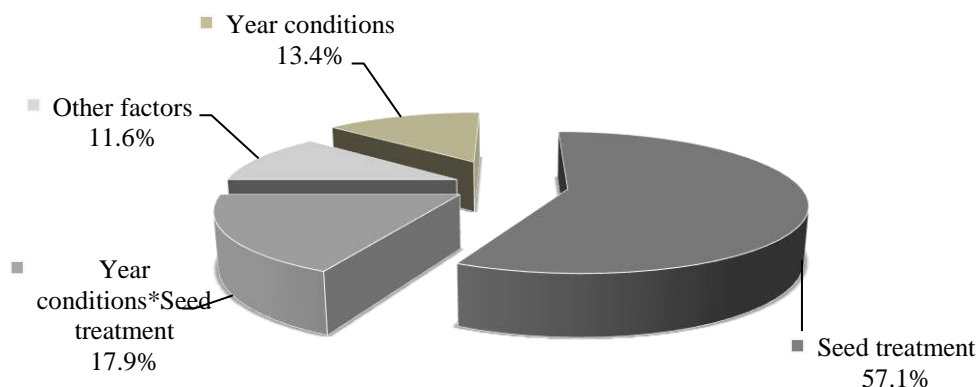


Figure 6: Influence of factors on seed germination (average for 2018-2023)

Analysis of the factors that influenced seed germination showed that the factor “seed treatment” was the most influential (57.1%). The influence of the complex interaction of the factors “seed treatment” and “year conditions” was 17.9%, and the factor “year conditions” – was 13.4% (Figure 6).

Pre-sowing treatment of seed with biostimulant Emistim C and micro fertiliser Avatar 1 for all years of research provided a significant increase in the weight of 1000 seeds, both when treated separately with one of these preparations and when used together, compared to the control (Figure 7).

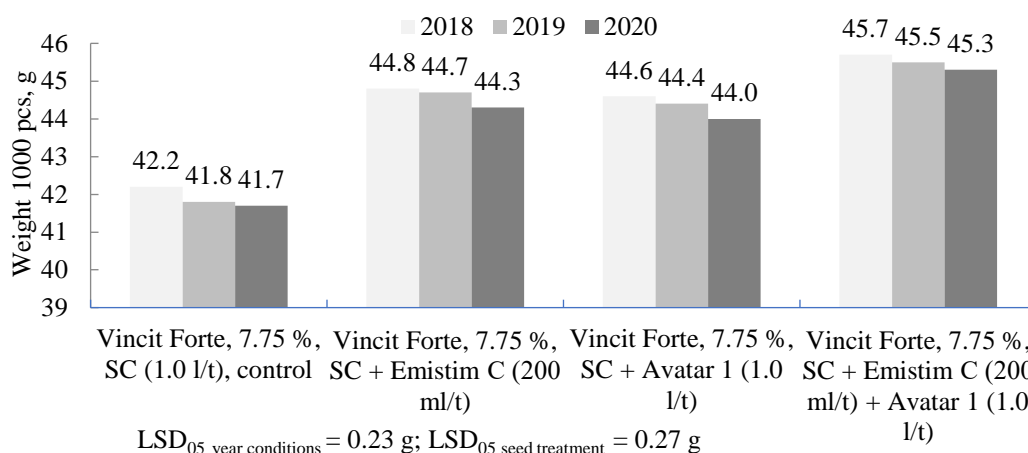


Figure 7: Weight of 1000 seeds depending on the treatment of the seed with biostimulant (2018-2020)

Thus, in 2018, the weight of 1000 seeds was 2.6 g higher under the pre-sowing treatment of seed with the biostimulant Emistim C, 2.4 g higher under the micro fertiliser Avatar 1, and 3.5 g higher under their combined use compared to the control (LSD₀₅ = 0.27 g). A similar increase in the weight of 1000 seeds was observed in 2019 and 2020. The combined use of these preparations provided an increase in the weight of 1000 seeds not only compared to the control but also when treated separately with one of these preparations. If in 2018 the weight of 1000 seeds under the treatment of seed with a biostimulant was 44.8 g and micro fertiliser 44.6 g, then under their combined use it significantly increased by 0.9 g and 1.1 g (LSD₀₅ = 0.27 g). A significant increase in the weight of 1000 seeds under the combined pre-sowing treatment of seed was obtained in 2019 and 2020. Thus, the pre-sowing treatment of seed with the biostimulant Emistim C and micro fertiliser Avatar 1, both separately by each of the preparations and in combination, provided a reliable increase in the yield of seeds and their quality.

Discussion

It is known that the intensification of agriculture threatens the development of natural ecosystems and can lead to environmental losses. The use of fertilisers increases plant productivity, but it also increases economic costs and puts an additional burden on the environment (Garcia, 2020). Today, the criterion for agricultural production is not only to increase production but also to preserve the natural and ecological balance of the environment (Voronkova *et al.*, 2019).

The search for alternative sources of plant nutrients is an urgent issue for the science and practice of crop production (Ashraf and Foolad, 2005; Vozhehova *et al.*, 2021). To increase the yield potential of crops, growth stimulants are used to activate membrane processes, cell division, photosynthesis, reduce nitrate content in plants, increase the biological efficiency of crop production, and resistance to diseases and pests (Bahan and Nevodnychi, 2023). The combined use of herbicides and biostimulants reduces the negative effects of herbicides. The use of physiologically active substances, in particular, sodium humate and gimisol, contributes to an increase in yield compared to the control without their use (Nepran, Romanova and Romanov, 2021). Covering a wide range of substances, including natural compounds and products of microorganisms, biostimulants stimulate the development of the root system of plants, contribute to increasing their resistance to the negative impact of biotic and abiotic factors, in particular, increase their environmental plasticity and resistance to diseases and pests (Baratova and Yunusov, 2023).), however, their use involves additional economic costs, which necessitates the study of the economic and social effect of their use.

A significant number of scientific studies have been devoted to exploring the effectiveness of biostimulants in growing crops. It was found that foliar feeding of plants with micro fertiliser and biostimulant growth promotes a 28.2% increase in buckwheat grain yield compared to the control (Moisiienko, Tymoshchuk and Panchyshyn, 2023).

When studying the reaction of spring wheat to the introduction of biostimulants containing microorganisms, Piskier (2006) found a significant increase in the yield of spring wheat grain by 23%. Matyjaszczyk (2015) recorded an 8% increase in the productivity of soft wheat when using a biostimulant that includes growth hormones, amino acids and enzymes of biological origin. Radzikowska-Kujawska *et al.* (2023) have confirmed that the use of any biostimulant significantly increases grain yields under conditions of full hydration. They recorded the highest yields when applying the Raiza-Mix preparation, which is based on algae, amino acids, growth hormones and trace elements. Thus, there is a need for an in-depth study of various biostimulants on crop yields. Yula and Drozd (2021) determined that, on average, over the years of research, the increase in the yield of spring wheat with the use of growth biostimulants ranged from 0.2-0.35 t/ha. Relevant studies were conducted in different soil and climatic conditions under different crop cultivation technologies, which could affect the results of the study, for which reason there is a need for an in-depth study of the effect of biostimulants on crop yields, taking into account the effects of climatic factors and elements of winter wheat cultivation technology, which would allow selecting the most effective ones.

In the zone of sufficient moisture, treatment of winter wheat seeds with biological preparations Emistim C and Rizoplan provided an increase in seed yield by 10.4-17.2% compared to the control without treatment with these preparations (Voloshchuk, 2009). Hanhur *et al.* (2021) have shown that seed treatment and foliar feeding of winter wheat crops with micro-fertilisers had a positive impact on crop productivity. Thus, the increase in wheat grain yield from a seed treatment with Vuksal Terios-U and Vuksal Terios-M micro fertilisers compared to the control (untreated seeds) was 0.18-0.19 t/ha or 3.5-3.7%. Lykhochvor *et al.* (2022) have determined that the yield of winter wheat increased by 8% after applying InterMag micro fertiliser.

Our research indicates that it is advisable to use a biostimulant and microfertiliser in combination. According to our study conducted in the conditions of insufficient moisture in the Right-Bank Forest-Steppe of Ukraine, the use of biostimulants Emistim C and Avatar 1 increased the yield of winter wheat seeds by 0.3-0.7 t/ha, i.e. by 5.9-13.7%, compared to the control. Thus, the results presented in this article agree with the results obtained by researchers under different growing conditions and indicate the expediency of using biostimulants to increase crop yields. Given that the profitability of production for growing winter wheat seeds using energy-saturated technology with elements of colonisation was lower compared to energy technology, the search for alternative environmentally friendly ways to increase crop productivity is important and determines further research directions.

Studies of the influence of factors on the yield of winter wheat under moderate moisture conditions of the Left-Bank Forest-Steppe of Ukraine have determined that under the appropriate growing conditions the influence of weather conditions on the formation of yields ranged from 10.5-11.1%, depending on the variety (Barabolia and Doronin, 2023), while the influence of this factor in the Steppe of Ukraine increased to 61.1% (Klipakova *et al.*, 2018). In our research, the influence of this factor was 53.9%, which indicates an increase in the share of this factor in conditions of moisture deficit. The influence of the factor 'seed treatment with disinfectants and plant growth regulators' in the steppe conditions was 36.2% and 2.1%, respectively (Klipakova *et al.*, 2018), and the share of the factor 'treatment with biological products' was 9.34% (Bazalii and Domaratskyi, 2012). The share of the influence of the factor 'seed treatment' in our research was 21%, which is significantly different from the results of previous studies and determines the need for further research on the effect of seed treatment with various preparations on the yield and quality of winter wheat seeds under different growing conditions.

Conclusion

The persistent challenges of rising population pressures and the impacts of climate change necessitate the exploration of alternative methods to enhance crop yields. Consequently, this research aims to examine the influence of different elements of winter wheat seed-growing technology on both the yield and quality of grain products. It was found that pre-sowing treatment of seed with biostimulant Emistim C, seed yield increased by 0.3 t/ha, with micro fertiliser Avatar 1 – by 0.4 t/ha, and under the complex application of these preparations - by 0.7 t/ha ($LSD_{05} = 0.22$ t/ha), compared to the control. Under pre-sowing treatment of seed with biostimulant Emistim C, the seed multiplication coefficient was 2.4 units higher, with micro fertiliser Avatar 1 – 2.0 units higher, and under combined use of these preparations – 3.2 units higher compared to the control. Pre-sowing treatment of the seed with a biostimulant and micro fertiliser had a positive effect on the yield of conditioned seeds. Under the combined treatment of seed with these preparations, the yield of conditioned seeds was the highest and amounted to 78%, or 6% higher than in the control. It was determined that the pre-sowing treatment of seeds with biostimulant and micro fertiliser significantly improved seed quality compared to the control. On average, over three years, when treated with Emistim C alone, germination energy and germination rate increased by 4% and amounted to 92 and 94%, respectively, and the weight of 1000 seeds by 2.7 g and amounted to 44.6 g, compared to the control. The combined use of the biostimulant and micro fertiliser

increased germination energy by 7%, germination rate by 6%, and weight of 1000 seeds by 3.6 g. The obtained results indicate the effectiveness of the combined use of biostimulant and micro fertiliser in the Right-Bank Forest-Steppe of Ukraine and necessitate further search for environmentally safe and highly efficient ways of growing crops in different growing conditions.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>
Conceived and designed the research or analysis	Yes	Yes	Yes	No
Collected the data	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	No	No	No
Wrote the article/paper	Yes	Yes	No	Yes
Critical revision of the article/paper	Yes	Yes	Yes	No
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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children

The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

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The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

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Assessment of Commercial Agroforestry and Government Initiatives in *Jhum* Areas of Karbi Anglong, Assam, India

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Abstract

Scholars and policymakers commonly recognize agroforestry as an integrated approach to environmental conservation and enhancing agricultural productivity. This study seeks to examine the status of commercial agroforestry and governmental activities aimed at regulating shifting cultivation in the Karbi Anglong region of Assam, India. Commercial agroforestry often refers to the large-scale production of agricultural and forestry products for commercial purposes. The primary objective is to market and sell products, such as tea or coffee, while utilizing the shelter provided by shade trees. The data was collected systematically using the purposeful sampling method. A total of six villages were chosen for sample collection, and 36 samples were collected to assess the level of satisfaction with the government's commercial agroforestry initiatives, as well as the respondent's opinion on the ground. The study applied critical analysis and interpretative techniques to qualitative data, while descriptive techniques were used to examine statistical data collected from government reports. This study observed that the local government framed several schemes to conserve three essential natural resources: soil, water, and vegetation. According to the study, the Cash Crops Development Programme was important in reducing the *jhum* (shifting) cultivation in the study area. However, accepting the changing scenario of agricultural practices in the hill tribal areas of Karbi Anglong, this study interpreted that commercial agroforestry plays a significant role in the changing life of the people, as well as improving agricultural productivity, diversifying income streams and restoring ecological balance in the study area.

Keywords

Biodiversity; Cash crop plantation; Ecosystem; Shifting cultivation; Soil conservation

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Introduction

Jhum cultivation, also known as slash-and-burn agriculture or shifting cultivation, is a traditional farming method used by local communities in hilly terrains of northeast India (Bhuyan, 2019; Chatterjee, 2021; Dhanaraju, 2023; Dhanaraju and Bijeta, 2022; Gupta, 2000; Haokip *et al.*, 2021; Kerkhoff and Sharma, 2006; Mathur and Bhattacharya, 2022; Malik, 2003; Rasul and Thapa, 2003). This type of agriculture is one of the oldest, and it may be found in many places of the world, including America, Asia, and Africa (Santoro *et al.*, 2020). It involves clearing a specific piece of land, cultivating it temporarily, and then abandoning it to allow natural vegetation to regenerate. Shifting cultivation currently accounts for approximately 86% of all agricultural land in northeast India (Haokip *et al.*, 2021). Such agricultural practices are closely connected to the cultural practices of most of the tribes in this region. It is a widely accepted opinion that shifting cultivation was the first type of agriculture and that it fulfilled the fundamental needs of humanity. Currently, this farming method, along with other old systems, is regarded as an exemplary model of ecological efficiency. Mixed cropping was often done in the *jhum* land. The subsistence hill farmer normally cultivates all the crops required for their household sustenance. More than 50 per cent of the inhabitants in Karbi Anglong engage in *jhum* cultivation, which involves clearing vegetation along the hill slopes (Hansepi and Laisram 2022). However, the percentage of production varies from season to season (HADP, 2015). The cultural practices of the indigenous population in this area are governed by the “*jhum* calendar”. The celebration of traditional festivals coincides with various activities of *jhum* farming. Recently, the state and policymakers have become greatly concerned about shifting cultivation and the decline of the vegetation cover. New policies have been implemented by the state and policymakers to regulate *jhum* and bamboo cultivation. They claim that *jhum* cultivation is highly detrimental due to its contribution to erosion, forest degradation, low production, and exacerbation of flooding, which eventually results in environmental imbalances (Mathur and Bhattacharya, 2022).

In this context, the government and policymakers have suggested alternate farming methods that can challenge the current practices of shifting cultivation in northeast India. Pant, and his team members (2018), in their latest report, have suggested that the Ministry of Agriculture should initiate a “mission on shifting cultivation” to promote coordination across different ministries and address the practice of shifting cultivation, which is predominantly observed in the north-eastern states. This initiative was taken due to the significance of the problem and to enhance livelihoods, eliminate poverty, and prevent land degradation. Their report also stated that effectively managing the transformation of shifting agricultural lands is an intricate procedure that necessitates the active involvement of various ministries and organizations. This report advocated that land for shifting cultivation be classified as agricultural land under ‘agroforestry’. Because of the decreases in productivity that come with rising population pressure, shortening of fallow times, and the lack of availability of alternative land, shifting agriculture is currently considered to be a type of agroecosystem that is largely unsustainable (Nath *et al.*, 2016). As a means of improving shifting farming systems, a growing number of programs have been developed to promote the use of agroforestry to boost agricultural productivity. Shifting cultivation is currently regarded as an extensively unsustainable form of agriculture due to reduced production resulting from

growing population pressure, shortening of fallow periods, and lack of alternative land. To improve changing agricultural systems, there has been an increase in the number of efforts that are being made to increase the adoption of agroforestry. In 2014, the government of India launched the National Agroforestry Policy to improve productivity, profitability, variety, and ecosystem sustainability, making it the first government to do so globally (Patel *et al.*, 2024).

Agroforestry is commonly recognized by scholars and policymakers as an integrated approach to both environmental conservation and enhancing agricultural productivity (Bhandari, Joshi and Paudel, 2021; Deb, 2020; ICFR, 2020; Mathur and Bhattacharya, 2022; Patel *et al.*, 2024). Agroforestry, a traditional method, is a significant kind of subsistence farming (ICFRE, 2020). NITI Aayog (formerly Planning Commission) characterizes agroforestry as an agroecological, nature-based land use system that simultaneously addresses current ecological issues, including food, nutrition, energy, employment, natural resources, and environmental security (Patel *et al.*, 2024). Agroforestry indeed encompasses both traditional and modern techniques of land utilization. Improving the quality of the soil, increasing the amount of vegetation, and increasing the amount of tree cover can be accomplished by integrating and optimizing the interactions between the components of agroforestry, which include trees, crops, and livestock. Agroforestry has the potential to meet the needs of climate change adaptation and mitigation while also delivering several short-term and long-term advantages to society and the economy. Due to the current scenario in India's land usage patterns, the NITI Ayog emphasized the need for immediate involvement in the promotion of agroforestry in areas of shifting cultivation.

The government statistical reports show that agroforestry products and services directly support 1.2 billion people in developing countries, both rural and urban (ICFRE, 2020). Indeed, India is the first nation in the world to have a distinct policy for the agricultural practice known as “agroforestry”. The objective of that approach is to encourage better coordination, convergence, and interaction among many of the agroforestry components that are dispersed across different missions, programs, and schemes that are already in place. According to the National Agroforestry Policy 2014, the term “agroforestry systems” encompasses both traditional and modern land-use systems. These systems involve the sustainable management of trees in conjunction with crop and/or animal production systems in agricultural environments. Agroforestry can be practiced in both irrigated and rainfed environments depending on the conditions of the land. This practice results in the production of food, fuel, fodder, timber, fertilizer, and fibre. It also contributes to the security of food, nutrition, and the environment. Additionally, it helps to support livelihoods, reduce poverty, and promote environments that are productive and resilient for cropping and farming. The role of agroforestry in the socio-economic empowerment of local inhabitants has been underlined by a variety of national efforts, in addition to the policy frameworks that have been discussed above. For instance, the National Forest Policy of 1988, the National Agriculture Policy of 2000, the Planning Commission Task Force on Greening India of 2001, the National Bamboo Mission of 2006, the National Policy on Farmers of 2007 and the Green India Mission of 2010 etc., emphasized on the role that agroforestry plays in promoting efficient nutrient cycling, organic matter addition for sustainable agriculture, and the enhancement of vegetation cover (ICFRE, 2020). It can be understood from the policymakers that agroforestry is

the only practical method for achieving the 33% green cover target set by the National Forest Policy, 1988.

Agroforestry can improve ecosystem services by storing carbon, preventing deforestation, protecting biodiversity, and conserving soil and water. Initially, scientists have classified agroforestry into four groups based on the system's structure, function, ecological spread, and socio-economic basis (Nair, 1987). Subsequently, Dwivedi (1992) rearranges this basis into seven categories as follows: The categories mentioned are: structure, physiognomic, function, floristic, socio-economic, historical, and ecological (Hasanuzzaman, 2024). Agroforestry systems are categorized into three types based on socio-economic considerations: Subsistence agroforestry system, Commercial agroforestry system, and Intermediate agroforestry system. This study examines the impact of commercial agroforestry on the economic and social well-being of the local population in the *jhum* areas of the Karbi Anglong region in Assam. Commercial agroforestry often refers to the large-scale production of agricultural and forestry products for commercial purposes (Dhiman, 2013). The primary objective is to market and sell products, such as tea or coffee, while utilizing the shelter provided by shade trees. Traditional agroforestry is less effective since its primary purpose is to meet the family's consumption needs or subsistence system, whereas commercial agroforestry is focused on cultivating tree products to increase income.

The main aim of this study is to analyze the status of commercial agroforestry and government initiatives aimed at controlling shifting cultivation in the Karbi Anglong region of Assam, India, while examining the ground realities of schemes that have been implemented in the field. Given this objective, this study will serve as an example for the government, demonstrating how commercial agroforestry has benefited people while also balancing the significance of shifting cultivation. Keeping in mind the aim of the study, this study framed the following objectives:

- 1) To study the impact of commercial agroforestry on the socioeconomic status of the people in the study area; and
- 2) To evaluate the impact of cash crop plantation programs on agroforestry in the study area.

Methodology

Study Area

Geographically, Karbi Anglong of Assam is divided into two territorial parts: hills and plains. The Karbi Anglong Autonomous Council (KAAC) administers two districts of Karbi Anglong (East and West) and these two districts have been placed under the sixth schedule of the Indian Constitution. This region covers 10,434 sq km, accounting for approximately 13.53% of the state's overall geographical area of 78,438 sq. km. Karbi Anglong is an important hill region in Assam. This region of rich tropical forest-covered hills and plains is located between latitudes 25°33' and 26°35' north and longitudes 92°10' and 93°50' east. This study covered three territorial forest divisions (East Division, West Division and Hamren Division) of Karbi Anglong Autonomous Council. Historically, this district's population has been largely tribes, with Karbi being the largest tribe (District Census Handbook, 2014).

Data Collection

The study was conducted from 2021-2022. The primary data was obtained purposely from the study area where the KAAC's agroforestry programs are being implemented. The study applied qualitative research techniques to collect data from respondents engaged in commercial agroforestry in *jhum* cultivation areas to assess the impact of government programs. The respondents have been spread across three divisions (Diphu, Silojanijan and Phuloni) of Karbi Anglong. Since the study is qualitative, the purposive sampling technique was employed to obtain primary data. A total of 6 villages were chosen for the collection of the samples, and 36 samples were collected to evaluate the degree of satisfaction with the commercial agroforestry efforts that were implemented by the government, as well as the opinion of the government at the ground level. The selection of these six villages was based on their homogeneity (Karbi community), with respondents actively engaged in commercial agroforestry and having made use of government-initiated commercial agroforestry projects/schemes. The study also used participant observation, and selected interviews with individuals engaged in commercial agroforestry to collect primary data in Annexure-1 format. However, the obtained data were corroborated with official records to evaluate the agroforestry programs. The study also conducts interviews with forest officials (government) to obtain official government data. Secondary data were employed in this study. These sources have been collected from the relevant government publications, including Annual Souvenirs of KAAC, Forest Reports of Assam State, NITI Aayog Reports on Agroforestry, and National Agroforestry Reports. The main limitation of the study is the unavailability of recent reports on the study area; hence, the assessment was based on previous data from official reports.

Data Processing and Analysis

This study applied qualitative research approaches to acquire primary data, while quantitative procedures were also used for statistical data. For the qualitative data, the study used critical analysis and interpretative techniques, whereas the statistical data was analysed using descriptive techniques. SPSS/STATA 14 is used for data entry and quantitative analysis of the data collected from the reports and field. This study employed critical analytical and interpretative methods on the gathered data to understand the subjective dimensions of the respondents in the field. It also evaluated the government schemes to ascertain their effects on the socio-economic conditions of the people and the changing scenario of shifting cultivation in the study area. These techniques further enable this study to understand the challenges faced by those engaged in commercial agroforestry. The critical analysis and interpretive technique were employed to also examine the secondary data, specifically the government reports and literature review used in this study.

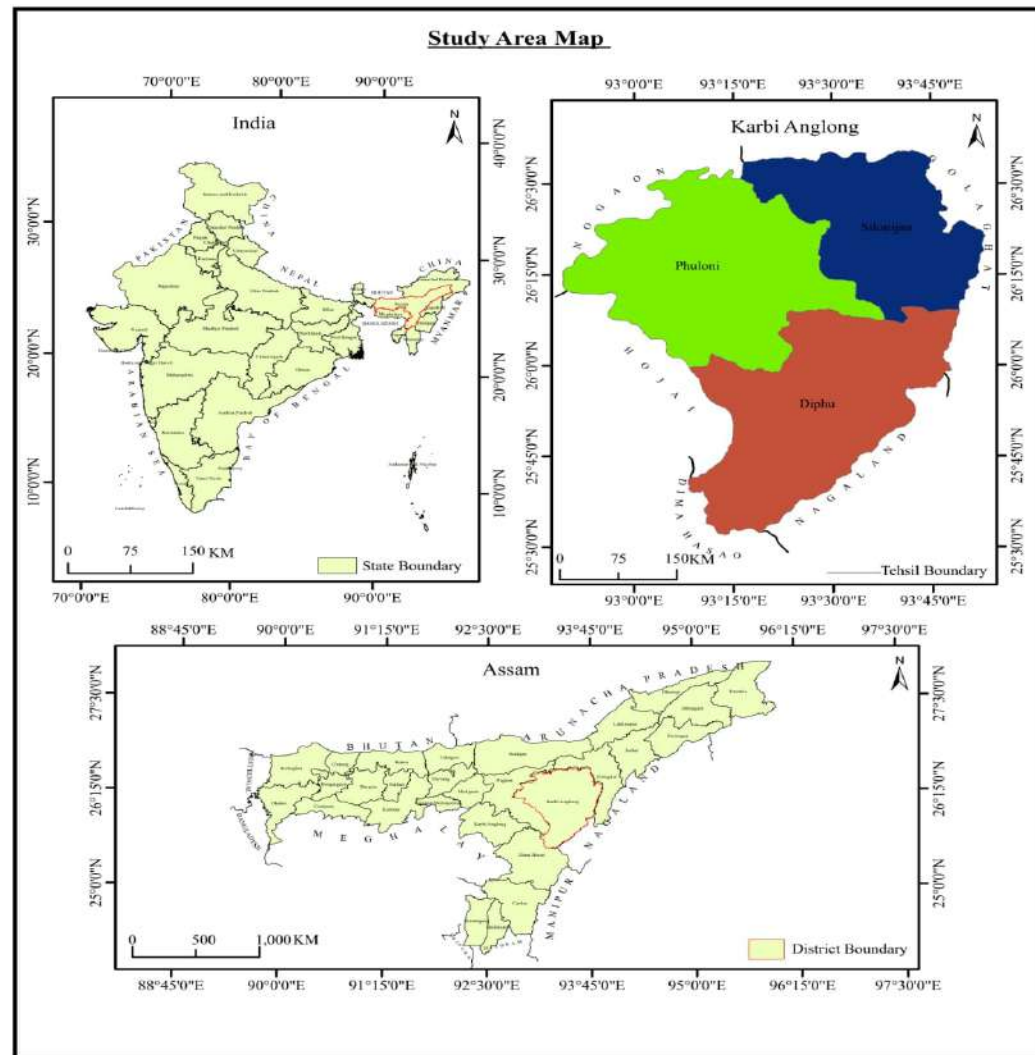


Figure 1: Map of the study area

Results and Discussion

The Status of Jhum Cultivation

For the last few decades, traditional methods in *jhum* cultivation in northeast India have been a subject of much debate among researchers and an issue of concern for governments. In Karbi Anglong, the use of land is central to all socioeconomic activities. The predominant land use pattern and traditional economic activities are *jhum* cultivation. In *jhum* land, mixed cropping is practised, and the ground is never left fallow. The subsistence hill farmer cultivates all the essential crops necessary for household consumption. People cultivate continuously throughout the year. The main crops planted were upland hill rice, maize, sesame, cotton, gourd, chilli, ginger/turmeric, chilli, rabi vegetables, and kharif vegetables.

Table 1: The extent of land used for *jhum* cultivation in northeast India

State	Area (sq.km)		
	2005-06	2008-09	2015-16
Arunachal Pradesh	1025.07	821.67	509.11
Assam	160.15	82.02	52.60
Manipur	752.10	296.68	499.96
Meghalaya	291.87	281.73	237.87
Mizoram	1028.53	602.08	691.55
Nagaland	1239.09	1414.53	979.33
Tripura	89.28	30.31	65.17
Sikkim	-	58.98	92.09
Total	4586.09	3588.00	3127.68

Source: Haokip *et al.* (2021)

Research conducted by the Assam Remote Sensing Application Centre using satellite data indicates that *jhum* (shifting) cultivation is expanding at an annual rate of 1.2% in the hill district of Karbi Anglong, affecting approximately 60.01% of the total land area (HADP, 2016). Mixed agriculture was commonly practiced in the *jhum* terrain.

The Impact of Commercial Agroforestry and Government Initiatives

The agroforestry area in the Northern Himalayan Region is 4.096 million hectares out of the overall geographical area of 32.968 million hectares, which accounts for 2.42%. (Arunachalam *et al.*, 2022; NITI Ayog, 2024). The KAAC has made significant progress in the scientific and sustainable management of forest resources. Green felling has been completely banned since 1995. The survey of forest areas for sustainable harvesting of timbers and minor forest products in perpetuity to meet genuine developmental and local needs has been conducted. The Autonomous Council has implemented several initiatives to regulate the practice of *jhum* cultivation. The authorities have implemented some initiatives, such as the development of model villages, the Cash Crop Plantation Scheme, and the Composite Scheme, among others (KAAC, 2016). The state government, in collaboration with the KAAC, has implemented a variety of State Plan Schemes to restrict shifting cultivation among Karbis. Various projects known as the Compact Areas Programme/Mini Compact Areas Programme were implemented as part of the Integrated *Jhumia* Development Programme (IJDP) till 1994-1995 (HADP, 2016). However, in 1995-96, the Karbi Anglong Autonomous Council changed and established plans to encourage the planting of environmentally friendly cash crops like as tea, coffee, rubber, bamboo, and sugarcane. Such initiative led to the launch of commercial agroforestry schemes in Karbi Anglong. In addition to cash crop plantation, various schemes such as land development/land reclamation, water harvesting structures with water distribution systems, dug-out ponds, and river training works are now being implemented. The IJDP schemes are implemented by the various departments under the guidance of KAAC administrative jurisdiction. According to Council officials, the primary goal of the IJDP is to move away from traditional *jhum* cultivation and toward land-based permanent cultivation, the use of fertilizers or manure, and other modern methods of cultivation. In addition, soil erosion and loss of fertility have resulted in decreased productivity in the area. Currently, the IJDP is a subject that has been given a high level of trust by the state (KAAC, 2015a).

The Hill Areas Department (HAD) of the state government is providing a one-time grant to the Council as part of the budgeted allocation for support. The fund allotment is distributed on a 50:50 basis. The Soil Conservation Department Souvenir of 2005 stated that *jhum* cultivation continues to span 69,000 hectares of hilly tract out of the district's overall geographical area of 10, 33,200 ha per year (KAAC, 2005). This traditional agricultural approach is a major cause of environmental deterioration, which hurts the region's ecology. Apart from this, soil erosion and a loss of fertility have reduced output in the area. The HAD is providing the Council with one-time assistance in the form of a grant in aid, as allocated in the budget. Funds are allocated in 50:50 ratios (HADP, 2016).

Table 2: Allocation of funds for the Integrated Joint Development Programme (IJDP) in Karbi Anglong since 1998

<i>Year</i>	<i>Amount Received (in USD)</i>
1998-1999	91,851.36
1999-2000	87,774.45
2000-2001	99,455.36
2001-2002	87,774.45
2002-2003	76,050.20
2003-2004	2,04,749.49

Source: KAAC (2015)

The Council Authority decides which schemes are included in the Integrated Jhumia Development Programme. The schemes are then included in the annual action plan for the year and presented to the HAD for funding release. After receiving funding, the assigned department funds are sanctioned and distributed when they are implemented. Cash crops such as tea, rubber, bamboo, and sugarcane are included, while other programs include land development/reclamation, water harvesting structures with water distribution systems, dug-out ponds, and river training works. Training sessions and awareness initiatives are also arranged. Mini projects on a watershed basis have been implemented from 2003-04 (KAAC, 2015).

The Council representatives and the Implementation Committee select project sites based on the priority of individual proposals from humans. Beneficiaries typically select regions from the *jhumias*, therefore, such plans are implemented in abandoned *jhum* lands. The IJDP schemes are beneficiary-oriented, with 100% financing provided before being given out to selected beneficiaries. Cash crop plantation locations are chosen from lands held by the beneficiaries. Plantations are maintained for two or three years, depending on the requirements. However, the sugarcane plants are not supported by the IJDP funds. There are no such tree/crop species that have been selected for implementation under the IJDP. Because the Forest, Agriculture, and Soil Conservation Department grows cash crops according to distribution formulas that benefit them. The District Agriculture Officer (DAO) is responsible for implementing the sugarcane cultivation scheme (KAAC, 2005). The programs related to tea, coffee, rubber, and sugarcane are executed by departmental regulations. Tea plantation regulations have been developed by Agriculture University standards. The schemes for land development/reclamation and water harvesting structures are carried out by the plan and estimates approved by the Council Authority.

The IJDP has initiated the Cash Crops Development Scheme. Before 1995-96, several integrated approach programs including veterinary care, handloom textiles, horticulture, and terrace agriculture were implemented pragmatically. However, due to several implementation challenges, the outcome was not as intended. The marginal farmers successfully carried out 156 ha of tea production as part of the cash crop plantation. Rubber has been popular with *Jhumia* families since 2006. The Council launched the Cash Crops Development Programme under agroforestry to promote cash crops like rubber, coffee, and tea as alternatives for transforming humans into permanent agriculture. These income-generating crops contribute to the generation of livelihoods while also minimizing erosion of the soil. During 2015-2016, 87.4 hectares of rubber plantations and 34 hectares of tea plantations were established at the beneficiary level. However, it does not suit the needs of greater groups of people (HADP, 2016).

Bamboo and broom plantations are common among humans. These plantings not only serve to reduce soil erosion in mountainous terrains, but they also generate a quick income. During 2015-2016, 56.7 hectares of bamboo plantation and 5.75 hectares of broom cultivation were raised, benefiting 66 beneficiaries. Another interesting finding is that the government has adopted protective afforestation. Protective afforestation includes steeply sloping and degraded land that is unsuitable for crops. Multipurpose tree species, medicinal plants, and forest species have been cultivated. These forest species plantations help to protect soil erosion and conserve biodiversity in the region. During 2015-2016, 40 hectares of land were brought under the plan. To raise awareness about environmental conservation, the department has been implementing the Nature Conservation Project, which involves planting ornamental plants, flowering plants fruit-bearing tree species in places like schools, public spaces, and roadside. During 2015-2016, 15,000 trees were planted under the project. Special sugarcane farming under IJDP has been implemented from 2002-03 to replace shifting cultivation as a sustainable crop. In recent years, sugarcane agriculture has reached an area of 1250 bighas. Sugarcane is currently the most common cash crop among humans. It has marketing opportunities in rural markets. 1000 families have benefited from it (KAAC, 2015).

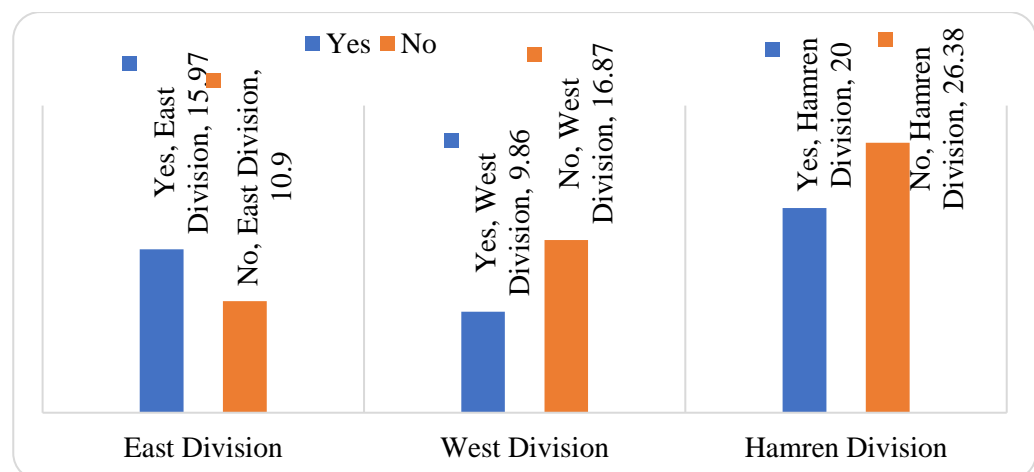


Figure 2: Percentage of beneficiaries under the Integrated *Jhumias* Development Programme (IJDP)

Figure 2 depicts the percentage of respondents who benefited from the IJDP in three Forest Divisions of Karbi Anglong. Only a small percentage of those who responded have benefited from the scheme in these forest divisions. Soil and water conservation methods have a vital role in preventing soil erosion in the hills of Karbi Anglong. The Soil Conservation Department, which is under the Council's administrative control, is responsible for the most effective and profitable management of three vital natural resources: soil, water, and vegetation, through the implementation of various activities, as well as the generation of self-employment and the improvement of the socioeconomic conditions of rural people throughout the district. The council has launched several major soil conservation schemes to promote agroforestry in Karbi Anglong, including the Cash Crop Development Programme, Bamboo and Broom Plantation, Nature Conservation, Protective Afforestation, and so on.

Table 2: The Status of Commercial Agroforestry under the State Plan and Hill Areas Development Programme (HADP) for the financial year 2014-15

Name of Scheme	Achievement under Normal Plan		Achievement under HADP	
	Final (in USD)	Physical (Area and Numbers)	Final (Rs in Lakhs)	Physical (Area and Numbers)
Rubber Plantation	1,07,865.62	251 ha	60.61	69.0 ha
Rubber Budded Nursery	25,717.72	31405	19.09	2600
Tea Plantation	22,301.04	47nos	32.17	26.6ha
Tea Nursery	14,040.71	200000	6.83	12000
Nature Conservation	17,612.46	39	4.47	9
Bamboo Plantation	36,149.44	131 ha	20.67	46.4 ha
Protective Afforestation	3,581.87	19	1.65	10 ha
Composite Nursery	2,575.22	22000

Source: KAAC (2015)

Table 3 shows the Cash Crop Development Schemes under the State Plan (Normal Plan) and HADP for the financial year 2014-15. As previously observed, the Council developed Cash Crop Development Schemes under agroforestry to mitigate shifting cultivation in Karbi Anglong. Rubber budded nursery and composite nursery were the most successful of these projects, while tea nursery came in second in terms of achievement and number of beneficiaries. According to the records, the percentage of beneficiaries and successes was quite low when compared to the total number of bamboo plantations in this district. Bamboo plantations are cultivated by about 90% of the population in Karbi Anglong. The study observed that different land development schemes have been implemented by the department to increase cultivable areas that lead to cropping intensifying in *jhum* areas. However, it is inconsistent with the anticipated parameters set forth by the government.

Table 4 shows how KAAC contributes to the growth of cash crops and land by developing various initiatives and activities. The primary goals of these programmes aim to turn *humans* into permanent agriculture by incorporating local communities in cash and land development. However, the success rates of these plans do not meet the standards we have witnessed in the field. According to the field survey, these plans do not reach those living in remote locations. The principal consequence of these initiatives revealed that the conversion of forest land into commercial agricultural lands such as

tea, orange, and rubber plantations resulted in the depletion of a significant forest area, particularly in the Koiamati, Panjan, Jongpha, Phangcherop, and Borlangso districts of the East Forest Division. Langkhersa has a tea plantation, while Amreng has an orange plantation, both under the Hamren Forest Division. With the current surge in the number of small tea gardens, many forest covers must give way to tea plantations, leading the total forest area to decline even further. The growth of settled agricultural practices has caused forests and grasslands to shrink (Bhuyan, 2019).

Table 3: Beneficiaries of Commercial Agroforestry Schemes from 2002-03 to 2005-06

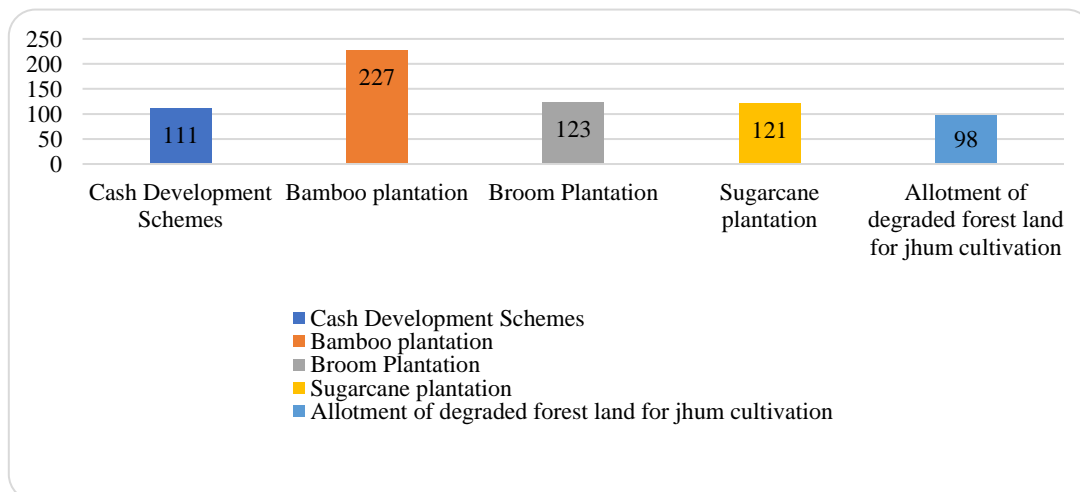
Sl.No.	Name	Achievement during				Total of four years	The total number of families benefited.
		2002-03	2003-04	2004-05	2005-06		
1.	Protective Afforestation	-----	61 ha	-----		61.0 ha	-----
2.	Bamboo Plantation	253.00 ha	200.00 ha	130.00 ha	299.0 ha	882.00 ha	1250
3.	Broom Plantation	-----	6 ha	5 ha	10.00 ha	21.00 ha	42
4.	Coffee Plantation	5.00 ha	12.00 ha	-----	-----	17.0 ha	8
5.	Tea Plantation	-----	-----	-----	2.00 ha	2.00 ha	1
6.	Rubber Plantation	-----	7.2 ha	9.00 ha	37.00 ha	53.20 ha	90
7.	Nature Conservation Project	1	2	12	33	48	35
8.	Land Reclamation Land Development	47.50 ha	89.00 ha	23.00 ha	225.00 ha	384.50 ha	632
9.	Water Harvesting/ Distribution	11	39	19	82	151	160
10.	Terracing	7.00 ha	5 hat	5.00 ha	15.00 ha	32.00 ha	54

Source: KAAC (2016)

The council authorities have justified rigorous monitoring of forest management by stating the following reasons: Rapid population expansion and influx from neighbouring states led to encroaching forests, destroying valuable crop cultivation areas; *jhum* cultivation gradually damaged forests, eventually leading to their destruction; granting forest leases/coups without sufficient consideration is a leading cause of forest devastation and youth who lack a stable source of income often illegally cut down plantation trees for profit. Figure 3 shows beneficiaries under the Integrated Jhumias Development Programme (IJDP) scheme in the study region, as mentioned in the reports of the KAAC. The Council implemented several measures to persuade cultivators to stop

growing *them*. This table shows the variation in success rates among the people who benefited from this scheme.

Figure 3: Beneficiaries who have gained advantages from the Integrated Jhumias Development Programme (IJDP)



The primary occupation of the inhabitants in the study area is agriculture. A significant number of individuals engage in *jhum* cultivation, a traditional important and age-old agricultural practice. This practice characterized by the traditional slash-and-burn technique, has been embraced by communities for generations. The local and state governments express concern that the increasing population pressure and the resulting reduction of the *jhum* cycle are significant factors contributing to environmental degradation, adversely affecting the region's ecology. The phenomenon of deforestation is contributing to soil erosion, reduced crop yields, diminished groundwater recharge, increased surface runoff, and a lowering of groundwater levels. In this context, the government has undertaken initiatives to cultivate an alternative economic system within *jhum* cultivation areas. Agroforestry has been embraced as a strategy to address the aforementioned ecological challenges.

Commercial agroforestry has been developed to encourage initiatives such as bamboo, broom, coffee, tea, and rubber plantations, together with soil conservation strategies, nature conservation projects, land reclamation, land development, water harvesting and distribution, and terracing. These schemes played a significant role in the socio-economic life of people. In the study area, the KAAC has instituted a variety of measures aimed at governing the practice of *jhum* cultivation. The authorities have instituted various initiatives, including the establishment of model villages, the Cash Crop Plantation Scheme, and the Composite Scheme, among others. The state government, in conjunction with the KAAC, has instituted a range of State Plan Schemes aimed at curbing the practice of shifting cultivation among the Karbi community. A range of initiatives referred to as the Compact Areas Programme and the Mini Compact Areas Programme were executed within the framework of the IJDP and also recently the KAAC underwent a transformation and initiated strategies aimed at promoting the cultivation of sustainable cash crops such as tea, coffee, rubber, bamboo, and sugarcane. This initiative resulted in the establishment of commercial agroforestry schemes in the

study area. In light of the introduction of these initiatives, there was a notable expression of discontent among the people regarding the process, and the number of beneficiaries remained remarkably low, leading to a resurgence of shifting cultivation practices. This trend indicates that government initiatives lack dynamism in the implementation of the schemes. The rate of success is comparatively diminished in contrast to other regions of the country and also it does not fall within the anticipated range set by the government. However, a significant trend emerges; should the government implement these schemes properly, one could anticipate a constructive transformation in shifting cultivation (ICFRE, 2020).

In light of the changing agricultural practices in forest regions of the country, this study argued that agroforestry is pivotal in transforming the lives of the local people. It enhances agricultural productivity, diversifies income sources, restores ecological equilibrium in farmlands, conserves forest resources, mitigates climate change, and addresses issues such as soil erosion and water management, among other benefits. Consequently, agroforestry emerges as a potent approach to enhancing biodiversity through the creation of diverse and interconnected ecosystems that foster a wide array of plant and animal species within the terrestrial landscapes. This study also argued that it is imperative to emphasize the necessity of safeguarding the fragile ecosystems of the hill regions, ensuring that the inhabitants of these areas reap the benefits while simultaneously alleviating the adverse effects stemming from the unsustainable exploitation of their resources, particularly land and forests. Historically, inhabitants of the hill regions have adjusted to the unique physiographic and climatic conditions by employing strategies such as terracing and *jhum* cultivation. Simultaneously, the government needs to safeguard the traditional practices associated with shifting cultivation. Undoubtedly, commercial agroforestry plays a significant role in the economic and social landscape of communities; however, it is vital to safeguard the fragile ecosystem while recognizing the traditional and cultural practices of the tribes that have traditionally connected with the hill economy.

Conclusion

This study looked at the shifting crop pattern systems in the *jhum* areas of three forest divisions in Karbi Anglong. The local government (KAAC) framed several schemes to conserve three essential natural resources: soil, water, and vegetation, and these schemes have had a significant impact on the socioeconomic lives of the people in the studied area. According to the study, the Cash Crops Development Programme played an important role in people's lives; however, the beneficiaries of such schemes were limited in the study area, as shown in the tables. This study also found that commercial crops grown under agroforestry systems are partially causing the decline of traditional shifting cultivation practices, which could have a significant influence on people's socio-cultural lives. It should be noted that the local people are concerned that if commercial crops continue, it would result in the loss of culture and traditional agricultural practices, which they have been practising for a long time and cannot be separated from their cultural life. However, such opinions have a smaller percentage. Though cash crop schemes can help people earn more income, they cannot be imposed on them without creating proper awareness about the issues and problems associated with *jhum* cultivation, as well as the ecological prospects of agroforestry, for which the government must take some steps to

change. However, accepting the changing scenario of agricultural practices in the hill areas of Karbi Anglong, this study can conclude that agroforestry plays a significant role in the changing life of the people, as well as improving agricultural productivity and diversifying income streams, restoring ecological balance in farmlands, conserving forest resources, mitigating climate change, reducing soil erosion, water management, and so on. Thus, agroforestry is an effective strategy for increasing biodiversity by establishing various and interconnected ecosystems that support a vast range of plant and animal species in the terrain lands.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>
Conceived and designed the research or analysis	Yes	Yes	Yes	No
Collected the data	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	No	No	No
Wrote the article/paper	Yes	Yes	No	Yes
Critical revision of the article/paper	Yes	Yes	Yes	No
Editing of the article/paper	Yes	No	No	Yes
Supervision	No	Yes	Yes	Yes
Project Administration	Yes	No	No	Yes
Funding Acquisition	Yes	No	Yes	No
Overall Contribution Proportion (%)	35	25	20	20

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge

The author(s) solemnly declare(s) that this research has involved Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge were only indirectly covered through literature review. Therefore, a Self-Declaration in this regard applies in case of this study or written work, and is appended.

Research involving Plants

The author(s) solemnly declare(s) that this research has involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children

The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

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To see original copy of these declarations signed by Corresponding/First Author (on behalf of other co-authors too), please download associated zip folder [Declarations] from the published Abstract page accessible through and linked with the DOI: <https://doi.org/10.33002/nr2581.6853.070303>.

SELF-DECLARATION FORM

Research on Indigenous Peoples and/or Traditional Knowledge

1. Conditions of the Research

1.1 Was or will the research (be) conducted on (an) Indigenous land, including reserve, settlement, and land governed under a self-government rule/agreement or?

No

1.2 Did/does any of the criteria for participation include membership in an Indigenous community, group of communities, or organization, including urban Indigenous populations?

No

1.3 Did/does the research seek inputs from participants (members of the Indigenous community) regarding a community's cultural heritage, artifacts, traditional knowledge, biocultural or biological resources or unique characteristics/practices?

No

1.4 Did/will Aboriginal identity or membership in an Indigenous community used or be used as a variable for the purposes of analysis?

No

2. Community Engagement

2.1 If you answered "Yes" to questions 1.1, 1.2, 1.3 or 1.4, have you initiated or do you intend to initiate an engagement process with the Indigenous collective, community or communities for this study?

No Applicable

2.2 If you answered "Yes" to question 2.1, describe the process that you have followed or will follow with to community engagement. Include any documentation of consultations (*i.e., formal research agreement, letter of approval, PIC, email communications, etc.*) and the role or position of those consulted, including their names if appropriate:

Not Applicable.

3. No Community Consultation or Engagement

If you answered “No” to question 2.1, briefly describe why community engagement will not be sought and how you can conduct a study that respects Aboriginal/ Indigenous communities and participants in the absence of community engagement.

The present study titled: “**Assessment of Commercial Agroforestry and Government Initiatives in Jhum Areas of Karbi Anglong, Assam, India**”, involves community participation, however, the research participants of the present study does not belong to any Aboriginal/ Indigenous communities, which were officially classified and identified as the “Scheduled Tribes”, by the Ministry of Tribal Affairs – The Government of India.

Name of Principal Researcher: Vulli Dhanaraju

Affiliation of Principal Researcher: Professor, Department of History, North-Eastern Hill University (NEHU) Shillong, Meghalaya, India.

Signature:

A handwritten signature in black ink, appearing to read 'Vulli Dhanaraju', with a horizontal line extending from the end of the signature.

Declaration: Submitting this note by email to any journal published by The Grassroots Institute is your confirmation that the information declared above is correct and devoid of any manipulation.

Application of Rapid Filters for Cleaning Natural Water in the Conditions of the Kyrgyz Republic

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Abstract

This study evaluates the implementation and effectiveness of the rapid filtration method for enhancing natural water treatment in the Kyrgyz Republic, where outdated water treatment systems reduce both efficiency and reliability. The study examines the effectiveness of rapid filters in improving contaminant removal to meet modern water quality standards. Key aspects such as filtration efficiency, operational benefits, and coagulant incorporation, are assessed by comparing rapid filters with traditional slow sand filtration methods. The study employs empirical analysis, evaluations of existing systems, and case studies of filter-loading materials. Findings indicate that rapid filters significantly enhance water treatment efficiency, particularly when using advanced filter media that increase surface area. The integration of rapid filtration into water treatment facilities in Kyrgyzstan can provide significant environmental and economic benefits. This method offers a strategic framework for modernizing water treatment plants to improve public health and environmental sustainability.

Keywords

Load; Ecological efficiency; Economic efficiency; Quartz sand; Lightning; Innovative technology

Introduction

The issue of clean water in Kyrgyzstan encompasses socio-economic and environmental aspects. Effective purification requires water to be free of harmful substances, meeting quality and safety standards for long-term use. Currently, Kyrgyzstan's phased water treatment system includes sedimentation,

coagulation, filtration, and disinfection. Evaluating water quality indicators, treatment technologies, and relevant regulations highlights key principles for modernizing the country's water systems. These include comprehensive water quality assessment, optimizing existing technologies, and developing new solutions that meet health, environmental, and economic standards (Skarbøvik *et al.*, 2010). Innovative monitoring and management, drawing from global best practices, and incorporating rapid filtration technology play a crucial role in advancing this modernization strategy.

Most modern researchers search for alternative technological opportunities in the water treatment sector that would facilitate progress towards ensuring high-quality drinking water. In particular, the attention of many modern researchers is focused on the methods of optimising natural water purification systems (Dzyba and Kyriienko, 2024). For example, Somma, Reverchon and Baldino (2021) investigated the specifics of improved surface water treatment technology. The achievements of researchers in the concept of modern methods of optimising water treatment systems indicate the prospects of using rapid filters. Several studies present the criteria for evaluating the effectiveness of water treatment measures aimed at improving the quality of drinking water (Maharramova and Maharramov, 2023). In particular, Yusupova *et al.* (2024) paid attention to the efficiency of water resources in the concept of their ecological and economic efficiency, substantiated the need for the implementation of water use technologies, and highlighted the main trends in the strategic development of the industry. Nuralieva (2022) argued that an effective water management system must necessarily take into consideration the requirements for environmental protection and careful management of natural resources.

It is a popular belief in the scientific community that the modernization of water treatment systems is primarily associated with the use of alternative filtering materials (Bondarev *et al.*, 2023). The study by Cescon and Jiang (2020) substantiated this opinion by the advantages of using alternative media, especially glass media, including high filtration performance to remove residual particles and turbidity. The researchers summarized the existing standards of safe drinking water in the context of the driving force behind the development of new purification technologies and provided mathematical models for predicting filtration performance. Mautner (2020) paid special attention to new pollutants entering the natural aquatic environment, for which no rules and technological solutions have yet been established. Jiao *et al.* (2020) analysed the current problems of using filters, such as low adsorption rate, limited throughput, and the use of expensive materials and complex manufacturing methods, which prevent their widespread use to improve water quality.

Despite significant developments in the field of optimisation of water treatment systems in the modern scientific community, the issue of integrating the potential of modern water treatment technologies in Kyrgyzstan remains unresolved. The problem requires detailed analysis and the search for optimal solutions. The main purpose of the study was an extended analysis of the possibilities of using rapid filters to purify natural waters in the conditions of the Kyrgyz Republic with a focus on economic feasibility and environmental safety. To achieve this goal, the following tasks were set: to investigate the essence, advantages, and disadvantages of the rapid filter method; to consider the models and tools based on which its practical implementation is carried out; to determine the expediency of using this method in the field of water treatment in Kyrgyzstan,

including to substantiate management decisions aimed at the environmental sustainability of natural systems and economic benefits from the process.

Rapid filters enhance treatment efficiency, making water purification more reliable and cost-effective while supporting aquatic sustainability. These improvements will help ensure a safer, stable water supply, essential for public health and environmental resilience, offering long-term benefits for Kyrgyzstan's water treatment infrastructure.

Materials and Methods

Using both theoretical frameworks and real-world trials, this study assessed Kyrgyzstan's utilisation of fast filtration devices for natural water purification. The *Water Code of the Kyrgyz Republic (2005)*, and the *Law of the Kyrgyz Republic No. 34 "Technical Regulation 'On the Safety of Drinking Water'" (2011)* served as important regulatory foundations for this study. These offered crucial recommendations for evaluating filtration systems and their adherence to safety regulations.

To determine the relative effectiveness and usefulness of quick filters – including gravity-based non-pressure and pressurised systems – the study compared them to slow sand filters. Based on their operational parameters and frequency in water treatment facilities, particular models were chosen. To maximise particle aggregation and improve overall performance, coagulants like ferric chloride and aluminium sulphate were added to the filtration process. To ensure a representative simulation of municipal water treatment processes, the experimental setup incorporated pre-treatment activities such as flocculation, precipitation, and mixing.

Under carefully monitored circumstances, filters were tested on water samples with turbidity levels between 10 and 100 NTU. Typical urban and rural water supply circumstances were replicated using operational parameters such as pressures of 1 to 3 bar and flow rates between 5.5 and 15 m³/h. Backwashing techniques included cleaning the filter media by reversing the water flow and adding compressed air. The sludge was gathered in a filthy wash water tank and disposed of.

By analysing turbidity reduction, pollutant removal, and water clarity, the filters' performance was evaluated. By examining maintenance frequency, filter lifespan, and coagulant effectiveness, operational efficiency was further assessed. Rapid filtration systems were the focus because of their high filtration rates and promise to assist economically and environmentally sound water treatment solutions.

As part of the technique, a schematic depiction of the experimental assembly was created. This is depicted in Figure 1, which shows how the water treatment processes run from source to output. This flowchart gives the study a clear visual framework by illuminating important parts such as the coagulation tank, quick filter, clean water tank, and backwash system.

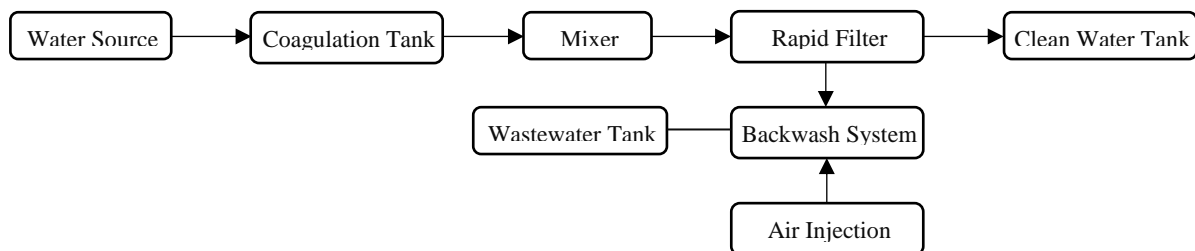


Figure 1. A flowchart of the water purification experiment assembly (Source: created by the authors)

The practical incorporation of fast filtration technologies into Kyrgyzstan's water treatment infrastructure is given top priority in this methodology. Despite being carried out on a trial size, the study's conclusions offer a basis for wider implementation, addressing both operational effectiveness and ecological sustainability. To ensure that the study's focus stayed on systems that do not modify the taste or odour of water, some limitations were purposefully included, such as the exclusion of activated carbon filters.

Results

Water Treatment Processes

In the process of choosing optimal water treatment technologies, priority is given to the implementation of an objective assessment of natural water supply sources. Within the conventional approach, water sources of natural origin that are used for water supply include surface and underground sources. The characteristics of natural water vary significantly due to numerous influencing factors, making the development of a single universal water treatment technology highly challenging. The individualization of solutions in the context of technology, facilities, and management measures allows for forming the most appropriate water treatment concept for specific treatment purposes. Regarding each source of water supply, a preliminary assessment of its qualitative and quantitative indicators of water, and the economic feasibility of its use, is necessary. The assessment should be implemented in the context of the long-term dynamics of natural water quality indicators and potential forecast changes (Jiao *et al.*, 2020). The economic factor for each of the available resources is estimated within the framework of investment and operating costs.

The intensification of anthropogenic influence on surface catchments significantly affects changes in the hydrochemical regime of natural water bodies (Danilenko *et al.*, 2021; Doroshkevich *et al.*, 2017). Among the natural and anthropogenic factors that determine the qualitative characteristics of natural water, key elements include the features of the soil structure and surface cover, relief, climatic conditions, specifics of the geomorphological structure, river runoff, hydrology and hydrogeology, the level of anthropogenic influence and the general state of the ecosystem (Skliar *et al.*, 2023). The possibility of using natural waters for various consumptive purposes is determined by their composition, concentration of undesirable substances and impurities, and their aggregative-kinetic stability. Water treatment processes are aimed at optimizing the organoleptic parameters of water (deodorisation, discolouration, clarification), conditioning the mineral composition (degreasing, softening, desalination, fluorination, desulphurisation), and

ensuring sanitary and epidemiological safety (chlorination, ozonation, radiation, and ultraviolet disinfection) (Nuralieva, 2022; Tikhonova *et al.*, 2008).

Clarification and Coagulation

The main processes for improving natural water quality include clarification to remove suspended impurities using methods such as sedimentation in hydrocyclones, settling tanks, centrifugation, filtration, or flotation; coagulation to facilitate settling of suspended particles through adsorption of particles onto large aggregates formed by coagulants; decolorization of water by chlorination, pressure flotation, or filtration through granular activated carbon; degreasing to reduce iron salts by either non-reactive or reagent-based methods; fluoridation followed by filtration through rapid filters; aeration followed by rapid filtration; and disinfection via ozonation, potassium permanganate, or chlorination (Cescon and Jiang, 2020).

Disinfection and Conditioning

In the process of preparing natural water, purification is carried out mainly via classical technology, which involves discoloration and clarification through specialized settling tanks and clarifiers, and filtration through either fast or slow filters (Kravchenko and Tkachenko, 2024). The preparation culminates in disinfection, preventing the presence of pathogenic substances. A more advanced technological scheme for purifying natural water (Figure 2) involves mandatory reagent treatment, using a suspended sediment layer for discoloration and clarification, and high-efficiency rapid filters.

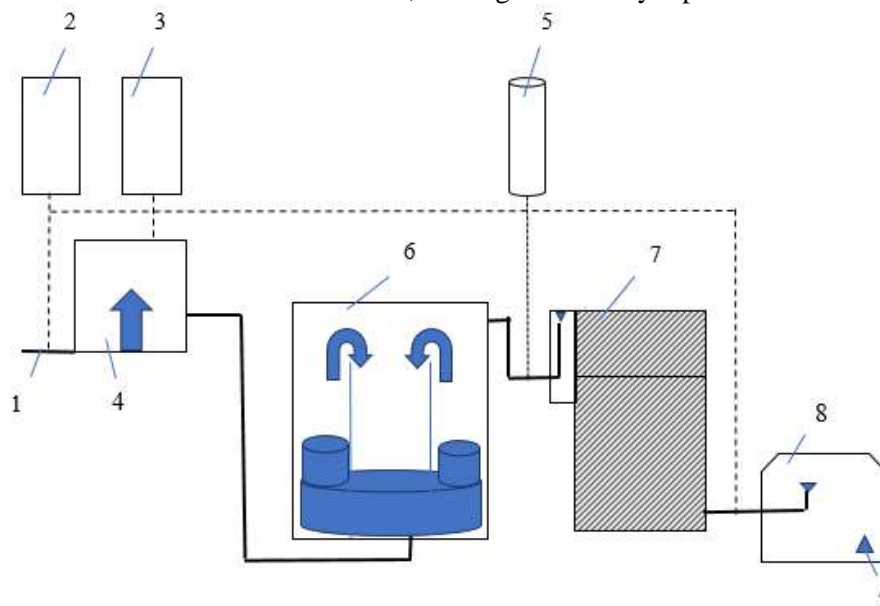


Figure 2: Advanced technological scheme of natural water purification with filters (Source: created by the authors based on Alam *et al.*, 2022; Alexyuk *et al.*, 2021)

Note: 1 – source water supply, 2 – chlorination, 3 – coagulant tanks, 4 – vertical mixer, 5 – fluorination plant, 6 – clarifier with a layer of suspended sediment, 7 – rapid filter, 8 – clean water tank, 9 – purified water outlet.

The scheme proposed in figure 2 provides an ergonomic spatial solution. The filtering process itself is a means of differentiating heterogeneous systems and is conducted via special porous partitions of various physical types, which delay the solid phase while allowing the liquid phase to pass (Nuralieva, 2022). Based on the filter layer's characteristics, fabric filters (linen, nylon, cotton, cloth, and other types of fabric serve as a filter), mesh (the filtration process takes place through a mesh with small cells), alluvial (the filter layer is asbestos chips, wood flour, diatomite), and granular filters (expanded clay, marble quartz sand, anthracite, and other materials) are used (Mautner, 2020).

Filter Materials and Designs

Filters with granular loading are used to remove coarse particles; alluvial filters purify fine particles in low-grade waters; and fabric filters target fine particles. Granular filters are categorized as slow (0.2 m/h), rapid (5.5 to 15 m/h), or ultra-rapid (more than 25 m/h) (Wu *et al.*, 2021). Filter loadings are usually placed on supporting layers of crushed stone or gravel, with layer thickness varying from 2 mm to 32 mm based on design and filtration conditions. The design features of the filter assume an open structure or pressure system, which involves the supply of water for purification from top to bottom, bottom to top, or both ways with variable or constant speed (Nascimbén Santos *et al.*, 2020). Modern water purification solutions utilize rapid filtration for effective water clarification. Innovative rapid filters allow you to achieve a filtration process speed of up to 15 m/h. However, they can be both non-pressurised and pressurised. In the latter case, the process takes place under pressure created by a special pump. The height of the loading layer is determined based on the diameter of its grains: with grain sizes up to 1.25 mm, the optimal layer height is 700 mm; with sizes up to 1.6 – 1,200 mm; if the diameter is larger – approximately 2,000 mm (Wu *et al.*, 2021).

Rapid filters with an area of less than 30 m² are equipped mainly with a side pocket, and more – with a central channel. The water that has been coagulated and pre-cleaned enters the side pocket, and then into the filter chamber. The height of the water layer located directly above the loading surface should reach 2 m or more (Nascimbén Santos *et al.*, 2020). During the filtration process, the purified water enters first the filter layer, and then the supporting one. At the end, the filtered water enters the distribution system, then into the clean water tank, after which the water is ready to be discharged for intended use. The process of flushing the filter load occurs in the opposite direction: water enters the distribution system, after which it enters the filter layer, expanding it, and separating the load from impurities. Together with the washed dirt, the washing water is poured into the gutters, then into a special side pocket, after which it is sent to the drain. The gutters must be at a certain height, which allows them to avoid getting into them together with contamination of the particles of the load itself (Saravanan *et al.*, 2021).

Filters are classified by design and pressure methods into non-pressure gravity filters and pressure filters. Non-pressure filters rely on water level differences, while pressure filters use pumps to create the necessary force. Filters can also be single-flow (top-down) or double-flow (bi-directional) (Gul, Hruza, and Yalcinkaya, 2021). Horizontal pressure filters, with filtration areas around 30 m², offer complex designs and high dirt capacity, while simpler two-layer filters are effective during phytoplankton blooms, using sand

and anthracite or, occasionally, activated carbon for de-chlorination (Lyubchik *et al.*, 2005; Saravanan *et al.*, 2021). A supporting layer of 0.5 m, usually of gravel or crushed stone, prevents fine material from leaching. High-resistance distribution systems prevent grain loss, and over 100 floating-loading filter designs now exist, including high dirt capacity and multi-tiered options (Dotto and McKay, 2020). Continuous or periodic filtration uses automated presses, cartridge filters, and drum vacuum filters to handle various suspensions with either vacuum or pressure mechanisms (Hasan, Muhammad and Ismail, 2020).

Economic and Practical Considerations

In modern technical water supply systems, it is often assumed that the water clarification process is implemented exclusively at the filtration stage, levelling the possibilities of coagulation, and purification in settling tanks and clarifiers (Khan, Zhu and Chen, 2024). In such cases, it is recommended to use coarse-grained filters with an increased filtration rate. Clarification of water exclusively at the filtration stage creates opportunities for the development of an innovative approach to the industrial water supply system without a second-lift pumping station, which significantly increases the economic efficiency of the process. Within the limits of such conceptual solutions, pressure filters are mainly used – steel cylindrical tanks with a given internal pressure, allowing water to be supplied to the consumer after the filters (Ang and Mohammad, 2020). A large number of such filters are required for a high-performance water treatment plant. It is considered advisable to install horizontal filters, which, with the same diameter, allow for a large filtration area.

Efficiency Enhancements in Filtration

The efficiency of rapid filters for natural water purification was determined by qualitative indicators of the composition of the dispersed phase and the dispersion medium, filtration technology, and applied methods of chemical water treatment. Optimisation of the structural, mechanical and physicochemical properties of the suspension is positioned as the basic priority task of improving the efficiency of the filters (Bondarev and Gheorghe, 2022; Mihai, Bondarev and Negoiu, 2013). Intensification of filtration efficiency at water treatment plants of the water pipeline is currently becoming possible by implementing solutions in the concept of new filter materials with high-loading porosity and a well-developed specific surface area of grains (Saravanan *et al.*, 2021). In addition, the filtration quality is improved by applying active molecular groups to the surface of the grains, which allows artificial intensification of the level of their activity due to the increasing positive charge potential of the surface.

Innovative improvements in filtration involve developing multilayer or heterogeneous single-layer filters, enhancing water distribution uniformity and filter reliability while reducing costs and simplifying installation (Alam *et al.*, 2022). In Kyrgyzstan, physicochemical purification – including settling, coagulation, filtration, and chlorination – is commonly used to remove pollutants (Irgashev *et al.*, 2023; Ishenbayeva *et al.*, 2023). Enhanced coagulation using high-molecular flocculants improves clarity with minimal pressure loss (Karimovich, Sharipovich and

Abduxamidovich, 2023). Rapid filters show potential in modern systems, employing techniques to maximize dirt capacity, such as:

- filtering with decreasing grain size to trap sediment within the load;
- strengthening sediment density to reduce resistance and increase impurity capacity;
- using high-porosity materials like volcanic tuffs and expanded clay;
- adjusting filtration rates;
- applying pressure filtration (Crosson *et al.*, 2021).

Filtering with descending grain sizes leverages ascending and multi-stage techniques, using coagulants and flocculants to compact sediment. Over time, rapid filters may lose granular layer thickness, requiring reconstruction to optimize performance. Improvements include standardizing grain uniformity, restoring filter load composition, using advanced media like expanded clay and volcanic slags, designing gravel-free drainage systems to prevent displacement, and enhancing filter flushing intensity, especially with water-air flushing techniques (Zubtsova and Skliar, 2023). These steps collectively enhance filtration efficiency and durability.

Rapid filters provide efficiency, reliability, environmental sustainability, and opportunities for innovation and optimization in response to natural variations in water quality and treatment objectives (Shuka *et al.*, 2011). Their disadvantages include higher operating costs, complex design, and the need for monitoring to ensure proper water treatment quality. When comparing fast and slow sand filters, neither filter affects water taste in the absence of activated carbon in the filter media. Slow filters use gravity to move water through the sand, while fast filters use pumps to create upward and downward flows of water. Sand filtration must be preceded by pre-treatment operations such as mixing, settling and flocculation, and the use of coagulants is recommended. Backwashing is accomplished by reversing the water flow and applying compressed air. In Kyrgyzstan, the implementation of these approaches can improve the efficiency of water treatment systems, optimize operation, improve filtration reliability and water quality, and provide significant economic benefits (Matkivskiy and Taras, 2024).

Discussion

Our findings indicate the prospects of rapid filters in enhancing natural water purification systems in Kyrgyzstan. Special attention should be paid to the variability of loading to reduce quantitative indicators of water pollutants while simultaneously increasing the level of ecological sustainability of ecosystems. In addition, innovative methods for operational management and monitoring of technological processes in water treatment have significant potential (Dzhedzhula, Yepifanova and Shevchuk, 2024). The monitoring system facilitates integrating new solutions in the field of rapid filters with maximum efficiency, considering data on the dynamics of natural water quality and purification efficiency. Most modern researchers, whose scientific interest is focused on water treatment issues in modern conditions of socio-economic development, confirm the adverse impact of relying solely on conventional methods of water use on the environment, given the intense negative dynamics of the quality of natural waters (Alexyuk *et al.*, 2021). This situation emphasizes the scientific search for solutions in the context of the modernisation of water treatment systems.

For example, Parvulescu *et al.* (2022) argue that the modernisation of water treatment in the context of urban water supply systems involves a step-by-step transition from conventional solutions to high-tech ones, with the introduction of the principles of sustainable development. This opinion reflects the main scientific proposal of this study, in particular, regarding the need to ensure the environmental safety of natural water purification and filtration systems. The findings of Akhtar *et al.* (2021) suggest that the level of eco-modernisation in water treatment approaches serves as an indicator of the effectiveness of the practical use of research developments. However, researchers can argue about the feasibility of integrating high-tech solutions into existing water treatment systems in the context of developing countries, because outdated technical bases are not always ready for radical modernisation and require a phased, large-scale transformation.

Most contemporary researchers position the effectiveness of natural water purification technologies as the basis for maintaining a favourable local and regional sanitary and hygienic environment, public health, and development aligned with sustainability priorities (Golovko *et al.*, 2021). Researchers pay attention to the risks of secondary pollution of natural watercourses by water treatment plants themselves. In the context of the danger posed by water treatment systems for aquatic ecosystems, it is impossible to fully agree with the conclusions of researchers, since ensuring the accuracy of technological schemes and implementing preventive measures against uncontrolled ingress of pollutants from the filter into the aquatic environment as a result of improper flushing can help minimize the negative impact of direct purification processes (Mel'nyk *et al.*, 2023).

In continuation, the differentiated approach to optimization programs for water treatment systems proposed as a priority in the current study has received positive feedback in the work of contemporary researchers. For example, Rathi and Kumar (2021) are convinced that adsorption using rapid filters is a successful approach to removing pollution worldwide, as it involves low installation costs, high productivity, and simple design. The researchers developed a technology for removing pollutants using various adsorbents (nano adsorbents, hybrid adsorbents activated carbon, and improved biochar). The proposed concept corresponds to the premise of the current study in terms of the need to find new ways to improve the operation of rapid filters based on load variability. Nasrollahzadeh *et al.* (2021) and Morin-Crini *et al.* (2022) argue about the expediency of individualising natural water purification optimization programs to achieve maximum efficiency, and they cannot be objected to.

Zenina *et al.* (2024) underscore the importance of a robust monitoring system for enhancing the efficiency and sustainability of Kyrgyzstan's water projects, a perspective that supports this study's focus on practical integration. The implementation of rapid filters requires criteria that align with sustainability goals, echoing researchers' emphasis on monitoring as a means to address negative trends in water quality and predict future changes. Additionally, the hydrogeochemical analysis highlighted by Tleuova *et al.* (2023) provides a foundation for evaluating pollution sources and customizing treatment approaches. This localized perspective reinforces the viability of rapid filters in addressing Kyrgyzstan's unique environmental and economic needs, potentially creating a more effective, region-specific water treatment system that supports both environmental protection and public health objectives.

The insights from Kydyrbekova *et al.* (2022) into the dynamics of water resource innovations in emerging markets underscore the potential for rapid filters to enhance both environmental sustainability and economic performance in Kyrgyzstan. The correlation between industry innovations and the role of local expertise highlights how the integration of rapid filters can leverage local organizational culture and innovation-friendly environments to improve water management. While Mero *et al.* (2023) and Shahini *et al.* (2023) caution that societal attitudes can hinder technological adoption, the introduction of procedures emphasizing economic benefits may encourage greater public receptivity. This dual focus on technology and economic incentives aligns with strategies to foster effective water treatment improvements that are supported by both community engagement and sustainable practices (Ivanovs *et al.*, 2018; Kusmambetov and Suleimenova, 2022).

In many studies, in particular, by Radelyuk *et al.* (2024) and Ernazarovna, Kuvatovich and Mamarajabovich (2021), barriers and prospects for the development of an effective water management system in developing countries are considered. In particular, while analysing the problems of preparing drinking water from surface water sources, the researchers highlight the possibility of effective use of the potential of rapid filters in modern natural water purification systems. It is impossible to fully agree with the researchers' conclusions regarding the versatility of ozonation technologies at the initial stage of water purification. The review paper by Kazakbayeva and Shaibek (2021) demonstrated the possibilities of rationalising water use systems. However, attention is focused on the successful international experience of rational water management, studying the structure of water resources management and considering the main economic instruments affecting the process of water resources management. They must be taken into consideration in the process of promising optimisation of the water treatment and water use system in Kyrgyzstan.

Assubayeva's (2023) insights highlight the importance of water treatment technologies that foster sustainable aquatic ecosystems, capable of mitigating pollution and adapting to increased anthropogenic stress. The emphasis on innovative technical solutions and substantial industry investment supports the integration of rapid filters, aligning to achieve environmentally safe water treatment. The concept of renewability, as discussed by Hartmann *et al.* (2024), reinforces the importance of regeneration within natural ecosystems, an approach that can enhance long-term sustainability without excessive financial demands. This perspective underscores the value of technological solutions like rapid filters in maintaining ecological balance and resource efficiency.

The results of numerous studies, in particular by Karimov *et al.* (2021), demonstrate the functionality of rapid filters, which, if innovative solutions are used in technological aspects, can significantly increase the efficiency of water purification. The researchers analysed the possibilities of using cheap local raw materials (sand) from Kyrgyz springs to load filters. It was proved that all technological schemes for purifying natural drinking water from surface sources using a fast non-pressure filter are more economically profitable than similar conventional schemes with filter loading, generally accepted in the post-Soviet space. Most researchers focus on the potential for the assimilation of conventional water treatment systems and new solutions in the field of filtration systems.

Conclusions

The findings of the study indicate the potential of water purification systems in enhancing the state of the aquatic ecosystems of the Kyrgyz Republic, the sanitary and hygienic situation and the level of public health. Technological modernisation of water treatment in Kyrgyzstan should be focused on the gradual replacement of obsolete methods with intensive ones based on the principles of environmental safety and economic efficiency. The priorities of sustainable development of aquatic ecosystems today are the competent strategic planning of innovative and technological development of the water industry, and a system of effective regeneration and preventive measures. Ensuring the high quality of drinking water, at the same time, is a prerequisite for the integration of technological capabilities into water treatment systems. In the context of innovations in general in Kyrgyzstan, it is expected that it is advisable to use the capabilities of rapid filters, which will provide prerequisites for solving the urgent problem of identifying reserves to ensure high-quality natural water treatment.

Analysis of the impact of modern water treatment measures on the dynamics of water quality indicates that rapid filters have significant potential in the context of improving the effectiveness of natural water treatment. Special attention in the research process is paid to the potential of loading variability within the dualistic concept of both reducing quantitative indicators of water pollutants and simultaneously increasing the level of ecological sustainability of ecosystems. Innovative capabilities of operational management and monitoring of technological processes in water treatment, considering the dynamics of natural water quality, will allow the implementation of new solutions in the field of rapid filters with maximum efficiency. A systematic approach to improving the quality of water treatment, considering the growing anthropogenic loads on water sources, and optimizing existing methods while developing new technical means of water purification based on the principles of sanitary and hygienic reliability, environmental friendliness and economic feasibility will optimise the situation in the field of water use of the Kyrgyz Republic.

The purpose of prospective scientific study in this area is the development and integration of innovative monitoring and forecasting systems for the state of aquatic ecosystems, and the integration of successful international experiences in water purification systems using rapid filters.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>
Conceived and designed the research or analysis	Yes	No	Yes	No
Collected the data	No	Yes	Yes	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	No
Wrote the article/paper	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Geodetic Support for the Use of Natural Resources of Chernivtsi Region Using GIS

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Abstract

Maps and plans are necessary to obtain accurate spatial information about the location of any geo-objects. High-quality and accurate creation of cartographic materials will improve the assessment of natural resources, cadastral work, etc. to solve the problem, cadastral maps and plans of a given scale are necessary. Their creation without violating regulatory documents requires certain State Geodetic Network (SGN) points. The purpose of the study is to analyse the spatial location of SGN points on the territory of the Chernivtsi region in Ukraine and to assess geodetic support for the use of natural resources using geographic information systems (GIS). We used QGIS version 3.28, to create maps and models based on the thematic layers, and evaluated the existing geodetic support in the section of the newly created administrative and territorial units of the region. An assessment of the spatial placement of SGN points for the territory of the Chernivtsi region by the administrative-territorial division was carried out. We identified 198 geodetic points of different classes. The boundaries of Chernivtsi district had the largest number of geodetic points (109 units, which is 55% of the total region). This was followed by Dnistrovsky District (54 points - 27% of the region), and Vyzhnytsky District (35 objects - 18% of the region).

Keywords

Geodetic support; GIS; Topographic and geodetic works; State geodetic network; Natural resources

Introduction

The problem of topographic support in Ukraine is the ageing of the content on cartographic materials. In addition, the main materials

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for conducting a large complex of various land management, urban planning, geological exploration and management activities are plans and maps of the area created thanks to topographical and geodetic works. Topographic maps of scales 1:500, 1:1 000, and 1:2 000 are needed to ensure various types of activities. According to the technology of obtaining plans, it is necessary to ensure high accuracy in determining the coordinates of reference points from 0.1 to 0.4 m with sparse (5-10 km) State Geodetic Network (SGN) (Instructions for topographic surveying at scales, 1991).

The basis of topographic surveys of any scale is the State Geodetic Network, which forms a set of points that are evenly located within the country and fixed on the ground by special centres that ensure their preservation in plan and elevation for a long time. In addition, it serves as the basis for the establishment of a unified geodetic system of coordinates and heights on the territory of Ukraine, cartographic and geodetic support of its territories and ensures the conduct of other types of activities. Among the branches of natural and economic use, geodetic work is an integral part of settlement territories, in particular, their development. Therefore, the study of geodetic support at all stages of construction works is relevant, both in the conditions of today and in past years. Therefore, the study of the existing features of topographical and geodetic support, as an accurate and reliable basis for any other pre-qualification works, is quite relevant and promising.

SGN is created to solve such basic tasks in the interests of economic activity, science and defense of the country as: (1) establishment of a unified geodetic system of coordinates and heights on the territory of the country (Stanková and Černota, 2010), (2) geodetic support for mapping the territory of the country, sea areas and inland water bodies (Jadviscok, 2023), (3) geodetic support for the study of natural resources and maintenance of state cadastres (Berk and Ferlan, 2016), (4) provision of initial geodetic data for means of land, sea and aerospace navigation, aerospace monitoring of the environment (Darchuk *et al.*, 2021; Palamariu and Puscas, 2014; Suyunov *et al.*, 2023), (5) the study of the shape and gravitational field of the Earth and their changes over time, (6) the study of geodynamic phenomena and modern vertical movements of the Earth's surface (Klatt, 2016), (7) the study of the deformation zones of the earth's surface, (8) the study of the movements of the poles and the unevenness of the Earth's rotation, and (9) metrological provision of high-precision technical means of determining the location and orientation (Hu, 2024; Sánchez *et al.*, 2024).

For high-quality topographical and geodetic works, it is important to provide the territory with SGN points. For the reliable functioning of the SGN, it is necessary to constantly inspect and update its points by the regulatory document (Law of Ukraine "On topographical, geodetic and cartographic activities", 1998).¹ This is necessary for their preservation in the area and maintenance in proper condition. The need to carry out significant volumes of topographic and geodetic works to update topographic maps slows down their updating. This prompts selective updating of only the most important elements of the geographic base of the map. The second way out of this situation is to use more productive methods of obtaining alternative geospatial data (orthophoto maps,

¹ Law of Ukraine "On topographical, geodetic and cartographic activities" (1998). 353-XIV. Available at: <http://zakon4.rada.gov.ua/laws/show/353-14>.

orthophoto plans, etc.). Newer methods are also significantly cheaper. Topogeodetic support is also an integral component of the geoinformation support of the armed forces of Ukraine. Also, SGN can play an important role in the event of military operations, if the enemy disables the GNSS system in a certain area. The latter happened in Ukraine in recent years due to the war in the country. In this connection, there is a need to obtain information on the provision of territories with SGN points.

Analysis of the specified geodetic problem in Ukraine by various authors and researchers shows that the state of the SGN and discrete geodetic networks allow the creation of maps and plans, without violating regulatory documents, only for small scales. In previous years, various authors, following Bilokrynytskyi, Darchuk and Melnyk (2023), analyzed the creation of cartographic materials of various scales. These studies conclude that the creation of map materials is possible only for certain areas of the territory of the Chernivtsi region of Ukraine. Taking into account the changes in the administrative system of the country by the decentralization reform, it is necessary to carry out analysis, and calculations, to determine the features of spatial placement and distribution of both individual SGN points and geodetic support in general. In light of the above research gaps, this study aims to analyse the spatial location of SGN points and the assessment of geodetic support for the use of natural resources in the territory of the Chernivtsi region of Ukraine using GIS.

The purpose of the study is to determine the location of SGN points within administrative units. Taking into account regulatory requirements - their quantitative indicators by area of the territory will allow for assessing the geodetic support of the Chernivtsi region. The latter will allow qualitative and accurate planning of the creation of map materials for various purposes.

Review of Literature

The issues of geodetic nature in the territory of Ukraine were considered in the works of such scientists as Lepetyuk *et al.* (2006), Sossa and Musienko (2018), Trevogo (2018), Trevogo, Ilkiv and Galyarnyk (2022), Zayets (2010), and Karpynskyi and Hevel (2022). These studies mainly relate to the analysis of the problem under study for the territory of the entire country. In our opinion, insufficient attention is paid to the research of these problems at the regional level. Among the publications, there are studies by Bilokrynytskyi, Darchuk and Melnyk (2023), and Darchuk *et al.* (2021) are devoted to the problems of geodetic support at the regional level. This allows for a deeper understanding of all existing problems and to outline possible ways to solve them.

The rapid development of satellite geodesy in recent years has become the impetus for the integration and change of national geodetic bases in the global continental system (Palamariu and Puscas, 2014; Stankova, 2010). Separate studies have focused on the development of a GPS-based geodetic network setup strategy for the permanent determination of national geodetic control point coordinate sets (Jung and Lee, 2011). The research procedure was analyzed, and how triangulation points were transformed into results based on the world geodetic system was analyzed (Lee and Jung, 2011). A study of the stationary modes of satellite networks and triangulation points was conducted. The results of the studies conducted using satellite methods in the Samarkand

region showed that there are differences between the distances from the reference station and the errors in determining coordinates and distances. To increase the accuracy of geodetic support decisions made using satellite means, it is worth building networks of reference stations, which is a new technology (Suyunov *et al.*, 2023).

Quite valuable for global cooperation in geodesy, survey science and land surface mapping: On 29 March 2023, the UN Global Geodetic Center of Excellence (UN-GGCE) was officially opened at the UN campus in Bonn. The government-led coordination of the development of a permanent global geodetic infrastructure is one of the most important tasks of the UN GGCE. Data and analysis centres and observation stations around the world belong to the infrastructure. This, in turn, is of paramount importance for observations of the Earth, as well as for navigation. In addition, it is important for various spheres of life, in assessing climate change, and land use research.

The creation of GGOS, the Global Geodetic Observation System of the International Association of Geodesy (IAG), provided for the emergence of an integrating framework for all components of the IAG. GGOS constantly monitors and changes its most important priorities in connection with new needs in geodesy. As a result, a new GGOS Strategic Plan for 2024-2034: Geodesy for Science and Society (Sánchez *et al.*, 2024). Works on the reliability of geodetic measurements, probabilistic determination of reliability, tolerance systems and error detection methods were analyzed (Abid, Husein and Hamed, 2020). Today, the problem of reliability is becoming one of the important components in the organization of management. Ensuring the reliable operation of all system elements is of primary importance (Gladilin *et al.*, 2023).

It is important to consider the methodological problems of legal determination of the plot boundary and plot area about the theoretically precisely defined boundary of the geodetic plot and the territory of the geodetic plot on the reference ellipsoid (Berk and Ferlan, 2016). Separate publications reveal the importance of the existence and functioning of the national infrastructure of spatial data in Ukraine, which would allow a comprehensive and more effective approach to the conducted research. The concept for the development of topographic mapping was created in Ukraine using the existing standards and specifications. When developing the National Spatial Data Infrastructure, this corresponds to the geoinformation approach to topographic mapping.

Works on the evaluation of the effectiveness of the use of geodetic data in the processes of planning and monitoring agro landscapes are considered. Such studies are focused on determining the role of these data in improving land use systems and developing natural resource conservation strategies. Adaptive landscape land management, based on GIS, contributes to the preservation of the ecological skeleton of natural complexes and controls the anthropogenic impact on the environment. The specifics and complexity of solving a complex of water management tasks in geodetic practice have been clarified. This contribution refers to the geodetic activity, which is related to the measurement of watercourses and their immediate area (Jadviscok and Gottvaldova, 2023).

Methodology

The possibilities of using geospatial analysis methods to provide SGN for mapping of

various scales were investigated using the example of the Chernivtsi region (area - 8097 km², located at latitude 48°12'09.36" north and longitude 26°13'14.88" east). Geospatial analysis methods were used for the research, in particular, zoning of the territory using buffer polygons.

1. Spatial Mapping:

GIS analysis was done using the software QGIS version 3.28.15. Thematic layers were vectorized, and a database of researched geo objects was created. Based on them, map schemes were created, which allowed the evaluation of the existing geodetic support. Maps and plans were then created at various scales in terms of administrative and territorial units of the territory. The following methods were used during the research: cartographic (thematic map schemes were created using the QGIS version 3.28.15), statistical and mathematical (using Microsoft Excel and QGIS version 3.28.15 statistical analysis, calculations were made regarding the number of points by administrative entity, the size of the buffer around the SGN points, and the area of territories with non-compliance with geodetic support), descriptive (allowed us to identify and analyze areas of territories characterized by non-compliance with the geodetic support requirements for the placement of SGN points to create maps of the appropriate scale). We considered the possibility of exporting vector layers of borders of administrative entities according to the latest administrative-territorial division of Ukraine from the official open-source website of the Ministry of Community and Territorial Development of Ukraine (<https://mtu.gov.ua/>). The downloaded file with the appropriate GEOJSON extension was imported into QGIS. To confirm the exact placement of the exported borders to the GIS product, the raster layers of OpenStreetMap, and Google Satellite Hybrid were enabled as a geobase, which allowed us to visually verify the coincidences.

2. Data Collection:

Data on the spatial and attributive characteristics of points of the state geodetic network were obtained from the official website of the state geodetic network of Ukraine (<https://dgm.gki.com.ua/login>). A geodatabase for points of the SGN was created using this data (coordinates of points, their height, name, update period). One of the attribute characteristics of geo objects was their coordinates, which made it possible to automatically open already vectorized point objects in QGIS.

According to the currently existing regulatory documents in Ukraine (Instructions for topographic surveying at scales, 1991)²: “The average density of geodetic points should be at least one point per 30 km² (for creating topographic maps and plans on a scale of 1:10000 – 1:25000). For the geodetic support of the topographic survey, the following norms of the density of geodetic points and benchmarks of the State Geodetic Network exist by the requirements of regulatory documents:

- on a scale of 1:25000 and 1:10000 - one point per 30 square kilometres and one benchmark per trapezoid on a scale of 1:10000;
- on a scale of 1:5000 - one point per 20-30 square kilometres and one

² Law of Ukraine "On topographical, geodetic and cartographic activities" (1998), 353-XIV. Available online at: <http://zakon4.rada.gov.ua/laws/show/353-14>.

- benchmark per 10-15 square kilometres;
- on a scale of 1:2000 and more - one point per 5-15 square kilometres and one benchmark per 5-7 square kilometres.”

For topographic and cadastral surveying on a scale of 1:2000 and more, points of geodetic thickening networks and shooting geodetic networks are determined in addition to the geodetic points of the State Geodetic Network. A further increase in the number (density) of geodetic points of the State Geodetic Network is created based on the results of the substantiation and calculations carried out based on the specific tasks of topographic-geodetic and cartographic activities in a certain territory.

3. Statistical Calculations:

Because of this, an assessment of the possibility of drawing up topographic maps and plans for the studied territory using the methodology of Bilokrynytskyi, Darchuk and Melnyk (2023) was carried out (Fig. 1). Geometric constructions are applied that simulate the coverage of the region with the corresponding area. For the present study, we used a circle with the same distance from its centre to the arc, corresponding to the radius value.

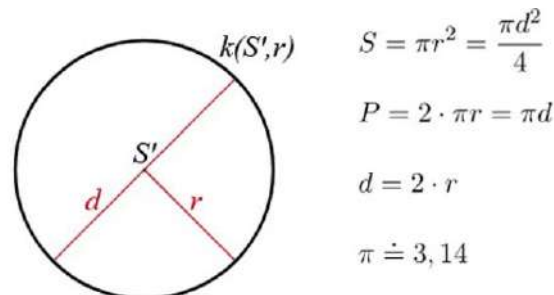


Figure 1: Algorithm for determining the area of a circle (P - perimeter, S - area, r – radius, d – diameter, S' - centre) (Bilokrynytskyi, Darchuk and Melnyk, 2023)

Calculations showed that for updating the basic scale of the topographic map (scale 1:10000), 1 point covers 30 km², i.e., a territory measuring 5x5 km, or with the area of influence of the point in a radius of 3091 m, for the compilation of cartographic material with a scale of 1:5000, 1:2 000, 1:1 000 and 1:500, the radius of the figure will be 2523 m, 2 185 m, 1 784 m and 1 261 m, respectively (Table 1).

Table 1: Values of circle radii when drawing up a map (plan) of the appropriate scale (Instructions for topographic surveying at scales, 1991)³

Scale	Area S, km ²	Radius r, km	Diameter d, km
1:10 000-1:25 000	30	3,091	6,182
1:5 000	20	2,523	5,046
1:2 000	15	2,185	4,370
1:1 000	10	1,784	3,568
1:500	5	1,261	2,522

³ Law of Ukraine "On topographical, geodetic and cartographic activities" (1998). 353-XIV. Available at: <http://zakon4.rada.gov.ua/laws/show/353-14>.

4. Visualization in QGIS:

To determine compliance with the requirements, buffers with the appropriate radius of action were created for vectorized point objects through the menu in QGIS "Vector" - "Geoprocessing tools" - "Buffer". The calculation of the area of the entire territory with indicators of inconsistency (areas not covered by buffers) was carried out. Due to the functionality of the main menu in QGIS, "Vector" - "Data processing" - "Difference" is selected. In the following settings, it is selected between which two vectorized layers to perform the selected difference. The choice was made between polygonal objects of district territories and created buffers. After that, we will have only vectorized individual objects corresponding to areas of discrepancy in the average density of SGN points. By leaving the boundaries of administrative districts for research and opening the table of attributes of the pre-created layer of areas of inconsistency, it was possible to create additional fields of attribute characteristics that would show the size of the area of areas of inconsistency within individual formations. Pre-painted actions through the selected "Vector"- "Data processing"- "Difference" were carried out for the polygonal layer of settlements and buffers of the corresponding radius. Due to the possibilities of layout of map schemes in QGIS, settings have been made with the visualization of research results in the form of maps.

Results

1. Data Collection and Analysis:

In 2020, the second stage of the decentralization process ended in Ukraine. By the resolution of the Verkhovna Rada of Ukraine "On the formation and liquidation of districts" dated 07.17.2020, 3 administrative districts were formed in the territory of Chernivtsi region: Chernivtsi Dnistrovskiy and Vyzhnytskyi. In addition, 52 units of territorial communities with a population of almost 902 thousand people are functionally operating. In the conducted research, an assessment of the spatial location of SGN points for the territory of the Chernivtsi region in terms of modern districts and territorial communities was made. It was established that the number of geodetic points totals 198 units of different classes, of which: 1st class – 13 units; 2nd class – 68 units; 3rd class – 117 units; digit geodetic network (4th class) – 96 units (Fig. 2). Within the boundaries of Chernivtsi district there is the largest number of SGN points with a total number of 109 units, which is 55% of their total number in the region. There are 54 points (27%) within the Dnistrovskiy district and 35 points (18%) within the Vyzhnytskyi district.

Spatial analysis of the placement of SGN points in the section of territorial communities shows that the most points are located in the territory of Chernivtsi - 41 units, half as many - 23 points are located in the territory of Sokyryansk urban territorial communities. Also, with an indicator of more than 10 points, Storozhinetsk City - 16 Kelmenetska - 16 and Berehometsk - 11 points stand out. One of the solved tasks was to conduct an analysis of the spatial arrangement of points of the SGN of different classes in the cross-section of administrative units: districts and communities. It was established that the largest number of 1st-class points are located in the territory of the Dnistrovskiy district - 7 units, Chernivtsi - 5, Vyzhnytskyi - 1.

The largest number of 1st-class SGN points in terms of basic units of the administrative-territorial system in the territory of Kelmenetska - 3 and Sokyryansk communities - 2 points (Shebutyntsya, Sokyryany). Most territorial communities are characterized by the absence of 1st-class SGN points. The largest number of 2nd class SGN points are concentrated in Chernivtsi district - 37 units, in second place is Vyzhnytskyi district - 17 units, and in Dnistrovskiyi - 14 points. The largest concentration of them in the territory of the Berehomet community is 5 units. There are 4 points each within the Kelmenetska and Chagorsk communities, and 3 points of SGN of the corresponding class are available in the Selyatynsk and Ust-Putylsk TGs. For the rest of the territories of communities, the number is from 2 to 1 point. On the territory of Chernivtsi region, territorial communities with the absence of 2nd class SGN points were identified, among them: Khotynska, Novoselytska, Magalska, Velikokuchurivska, Suchevenska, Chudeyska, Mamaivska, Brusnytska, Banylivska, Napolokovetska, Stavchanska, Kostryzhivska.

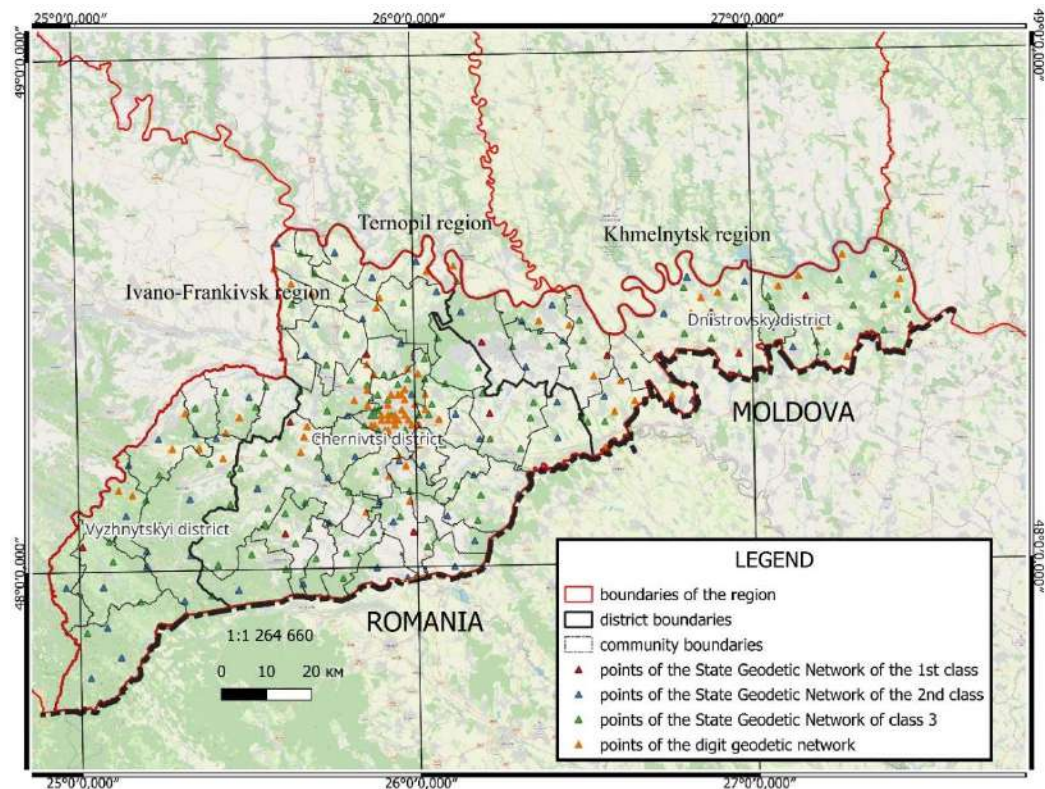


Figure 2: Spatial location of SGN points on the territory of Chernivtsi region (image created using QGIS)

Within the boundaries of Chernivtsi district, the largest number of 3rd class SGN points was also found in the amount of 67 points, in the territory of Dnistrovskiyi District - 33, and Vyzhnytskyi - 17 objects. The highest concentration of SGN points of the 3rd class is observed in the territory of the Chernivtsi community - more than 15 units, Sokyryansk and Storozhynets communities are located from 9 to 12 points, and in the remaining territories of the communities their number is smaller. According to the results of the spatial analysis of the distribution of points of the digit geodetic network (4th class), it was found that most points are concentrated in the territory of Chernivtsi district - 52

units, within the boundaries of Dnistrovskiyi - 26, and in the territory of Vyzhnytskyi - 18 objects. Research in the cross-section of territorial communities revealed the highest concentration of points in the Chernivtsi community, while Sokyryanska is far behind - at 7, and Kelmenetska, and Mamalygivska - at 3 points each. In the territories of most of the newly formed territorial communities, there are no SGN points of the discharge geodetic network.

2. Statistical Calculations:

In the course of the research, the area of the entire territory was calculated with the above-mentioned inconsistency indicators. There are 2,726.91 km² of territories of various shapes of areas of non-compliance with the average density of SGN points, which is 33.7% of the total area. The largest area of the indicated areas of non-conformity is characteristic of Chernivtsi district - 1281 km² (30%), Vyzhnytskyi 869 km² (43%) and Dnistrovskiyi 576 km² (27%) of the territory of administrative districts. Significant areas of non-conformity territories are characteristic of Selyatynska village - 238.85 km² (65% of the total area of the administrative entity), Beregometska - 215.46 km² (44%), Kelmenetska settlement - 157.9 km² (29%) and Storozhynets urban communities - 157.5 km² (30%). The spatial distribution of the areas with the maximum indicators of inconsistency is observed with the distance of territorial communities from the regional centre in the western and eastern directions (Figure 3).

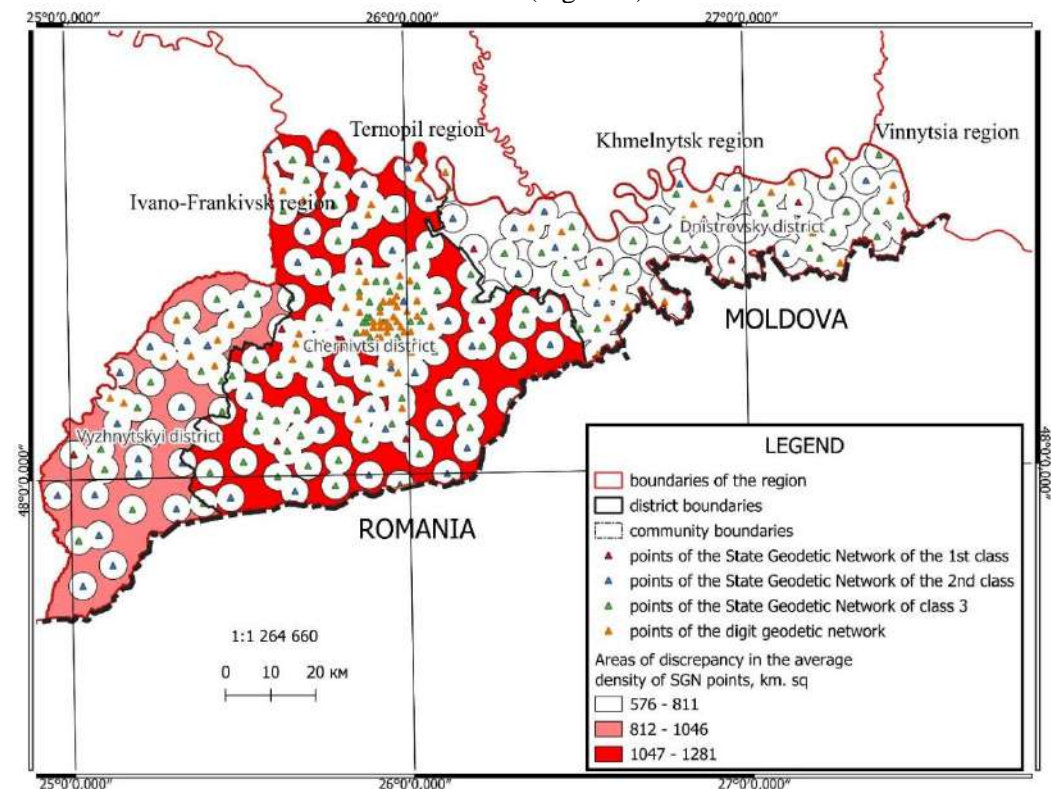


Figure 3: Vectorized objects, areas of discrepancy in the average density of SGN points in the section of administrative districts (image created using QGIS)

The values of the smallest inconsistencies in the average density of points of SGN are

typical for Chernivtsi city - 0 km² (0%), Chagorska - 6.9 km² (13.8%), Mamalygivska 7.9 km² (5.5%), Magalska - 7.19 km² (8.6%), Horishnyosherovetska - 14.2 km² (16.4%) of rural communities (Fig. 4). Spatial distribution of territories with minimum indicators shows their location close to the regional centre.

3. Research in QGIS:

If we analyze and consider the possibility of creating maps and plans of different scales, the area covered by the SGN points (buffer radius) will vary from 3.1 (at a scale of 1:10000-1:25000) to 1.26 (at a scale of 1:500). When the scale is increased, there is also an increase in the number of required designed SGN points. When assessing the possibility of drawing up topographic plans, it is important, mainly, to cover the territories belonging to built-up areas, that is, it concerns settlements. According to the cartographic materials shown in Fig. 2 and 3 location of SGN points with their radius of action is inherent in both built-up and non-built-up parts. Because of this, there is a need to determine the area covered by the buffers of the SGN points of the built-up areas.

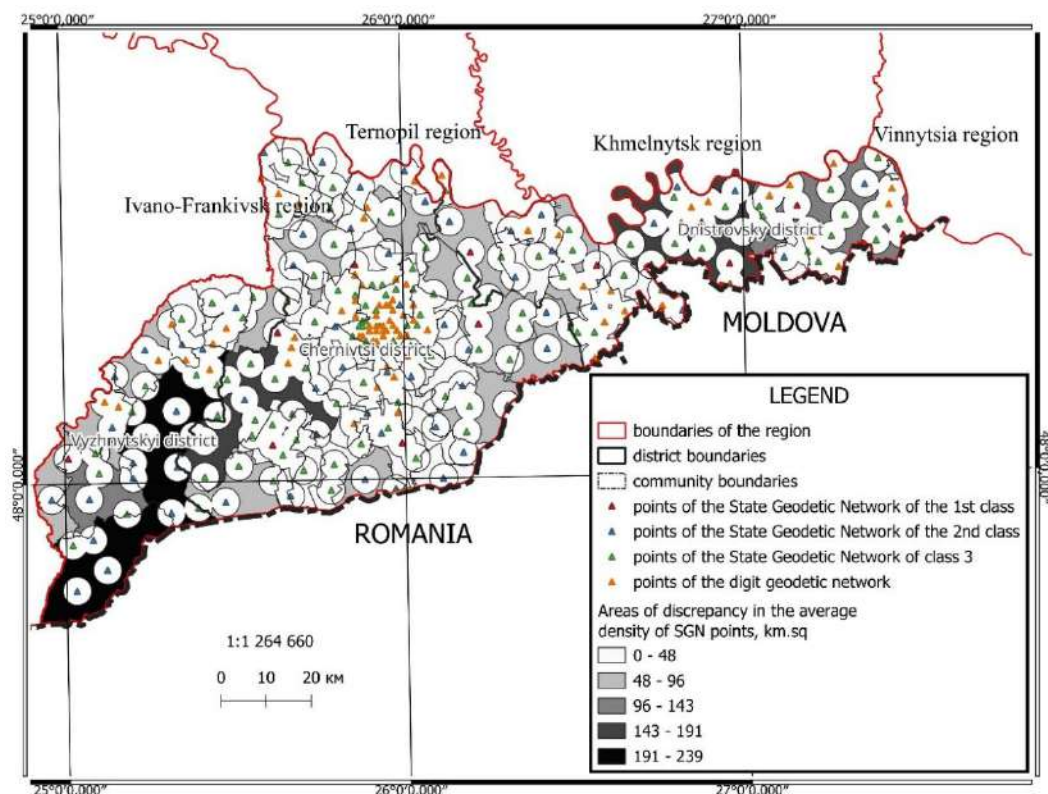


Figure 4: Vectorized objects, areas of inconsistency in the average density of SGN points in the section of territorial communities (image created using QGIS)

Vectorization of settlements in the form of polygonal thematic layers was carried out (Fig. 5). Taking into account that topographic plans should cover the territories of populated areas, an overlay analysis of vectorized objects and the topographic base was carried out (Fig. 6). A topographic map on a scale of 1:100 000 allows seeing the qualitative component of territory coverage. Yes, even if only built-up areas are taken

into account, there will not be enough SGN points for these objects as well. Moreover, a significant number of points are concentrated in open terrain, which makes it possible to compile only large-scale maps. If there is a need to update topographic plans on a scale of 1:2 000, 1 point (on average) must be located on 10 km², that is, it covers an area of 3.15 km x 3.15 km, which will further reduce the productivity of the existing SGN network. Therefore, the existing density of SGN points, in most cases, does not satisfy the existing requirements, even when drawing up and updating topographic plans of scales 1:5000 and 1:2000.

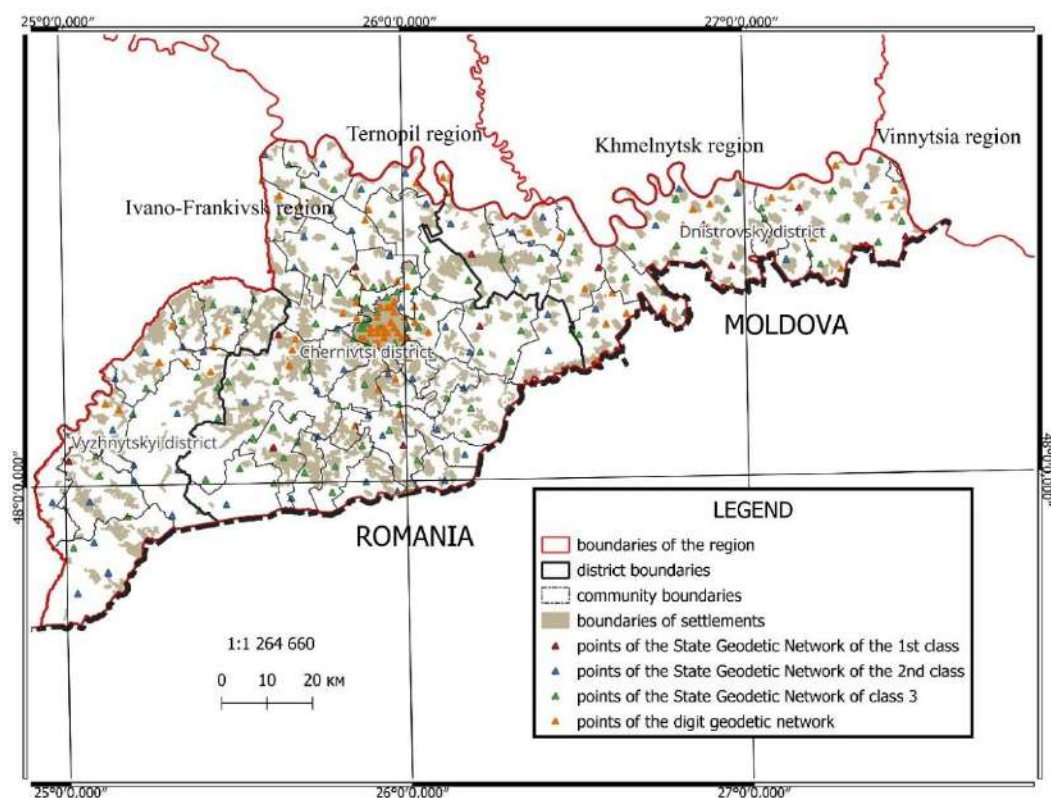


Figure 5: Vectorized boundaries of settlements in the territory of Chernivtsi region (image created using QGIS)

4. Analysis of the Obtained Data:

For topographic and cadastral surveying on a scale of 1:2000 and more, the points of discharge and survey geodetic networks are determined in addition to the SGN points. In addition, the problem of low density of points can be solved by using satellite geodetic methods to determine the points of shooting networks. That is, to carry out large-scale surveying, a single-digit geodetic network is needed, which was created only for urban settlements. Thus, the one-digit geodetic network of one of the settlements in the research area shows that in the 1970s and 1980s, 121 polygonometry points of the 1st and 2nd degrees were laid on the territory of the city (Fig. 7). At that time, they fully met the requirements of the current regulations on topographical surveying.

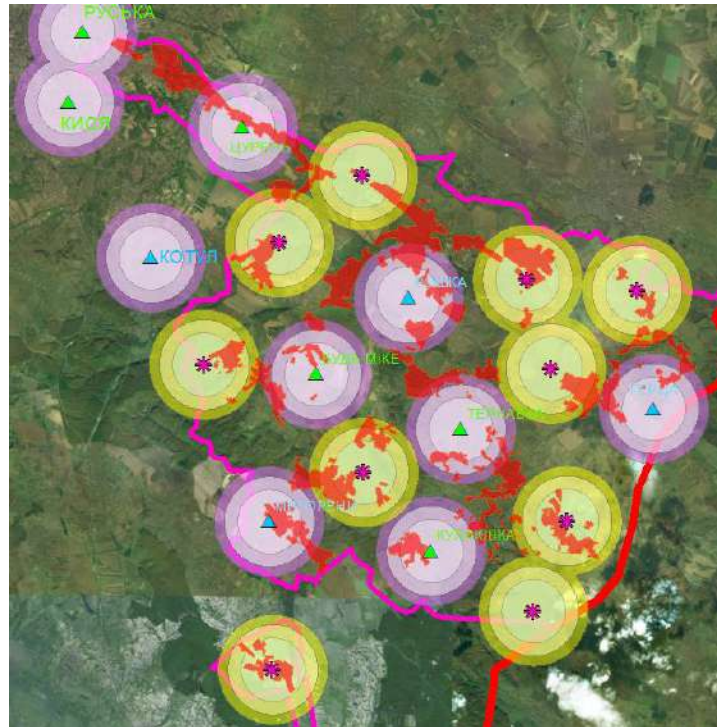


Figure 6: The possibility of drawing up topo plans on a scale of 1:2000, 1:1000 and 1:500 near Herts, Chernivtsi district, Chernivtsi region (image created using QGIS)



Figure 7: Location of points of polygonometry (image created using QGIS)

At present, as a result of the reconstruction of the road network and the development of

adjacent territories, a significant part (up to 70%) of these points is lost, which requires their restoration or densification. Given that this requires significant funds, it is advisable to create a dense filming (working) network localized to a specific place of search operations with the mandatory use of GPS receivers. In general, it was possible to obtain almost 600 polygonal objects for areas underpopulated areas for the entire Chernivtsi region. It was established that buffer coverage even of the largest radius of action does not exist for the entire part of the largest settlements in terms of area. In the case of smaller studied polygonal objects - settlements - the overlapping of the radius of the buffer is also not always monitored. The problematic point is strengthened when analyzing the possibility of creating topographic plans on a scale of 1:500 for the territory of the Chernivtsi region. That is, the area of areas of settlements that require geodetic support is increasing. The paper calculates the area of the areas of the territories of settlements that require additional geodetic support, as indicated above, on a scale of 1:25000-1:500 (Table 2). With the change in the scale series, the number of vectorized objects belonging to areas of non-compliance with geodetic support increases from 352 to 561, while the total number of vectorized objects in the territories of settlements of the studied object is about 600 (Fig. 8).

Table 2: Characteristics of the areas of settlements in the territory of the Chernivtsi region, regarding non-compliance with geodetic support.

№	Requirements for placement of SGN points according to the scale			The size of the territories of non-compliance with geodetic support		
	Scale	Area	Buffer radius, km	Number of vectorized objects.	Area - km ²	% of the total area of settlements in the region
1	1:10000-1:25000	30	3.1	352	1152.7	68.6
2	1:5000	20	2.52	450	1508.4	89.8
3	1:2000	15	2.19	497	1576.5	93.8
4	1:1000	10	1.78	536	1614.3	96.1
5	1:500	5	1.26	561	1632.4	97.2

When changing the above requirements (buffer area and radius), both the area and the percentage of non-compliance with geodetic support from the total area of settlements of Chernivtsi region increase. In particular, at the largest buffer scale of 3.1 km, the specified area and percentage are the lowest and amount to 1152.7 km² and 68.6%. Considering the possibility of creating plans at a scale of 1:500 for the territory of Chernivtsi region, the area of non-compliance with geodetic support as well as the percentage of the total area of settlements is the largest and is 1632.4 km² and 97.2%.

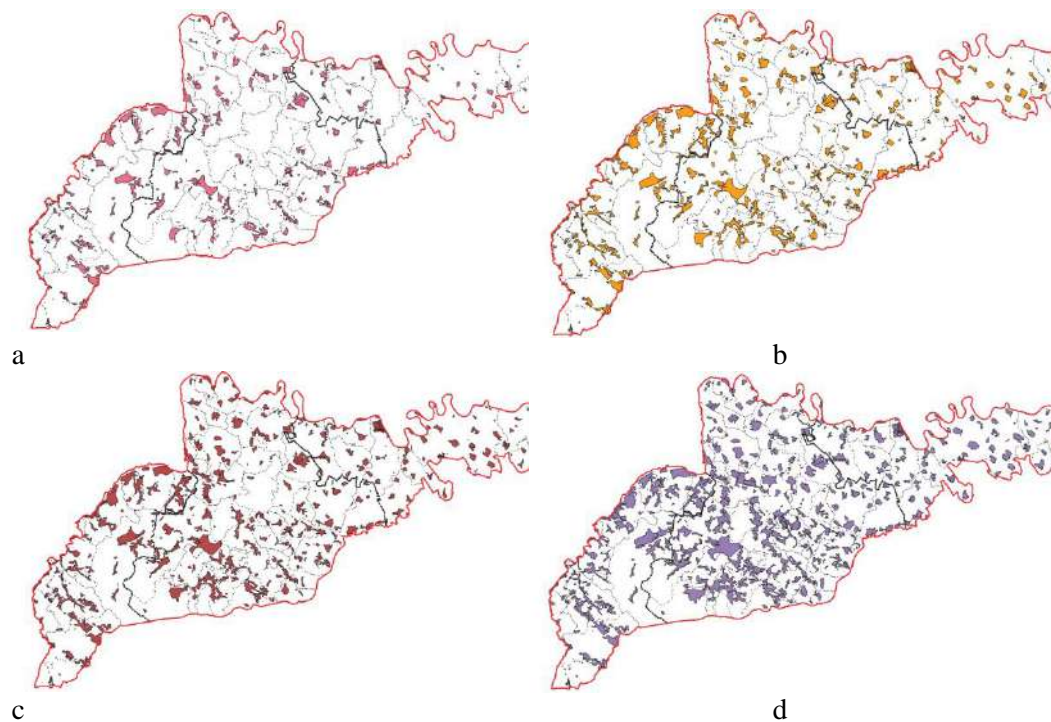


Figure 8: Areas of populated areas of the territory of Chernivtsi region, regarding non-compliance with geodetic support with a buffer radius of a) 3.1 km; b) 2.52 km; c) 2.19 km; and d) 1.78 km (image created using QGIS)

Discussion

For an objective assessment in general or the modern use of natural resources, it is important to map the territory with the exact positioning of individual geo-objects. Topographical and geodetic support of the research area showed the possibility of creating maps according to current requirements for a small scale. Unlike previous studies of geodetic support at the national (Karpinskyi and Hevel, 2022; Lepetyuk *et al.*, 2006; Sossa and Musienko, 2018; Trevogo, Ilkiv and Galyarnyk, 2022; Zayets, 2010), regional (Bilokrynytskyi, Darchuk and Melnyk, 2023; Darchuk *et al.*, 2021) levels, it was possible to use the QGIS functionality for the first time to determine and analyze the spatial characteristics of quantitative indicators of geodetic support inconsistency for the territory of Chernivtsi region. The following studies foresee the thickening of the state geodetic network. Projected points of different classes and values will allow you to draw up maps and plans on a large scale. The latter is quite important for the territories of settlements. Information about geodata, their exact location and attributes must be provided simultaneously for significant territories and regularly updated, while its objectivity must be ensured while maintaining the necessary accuracy of displaying the spatial position of objects. Currently, there are information databases in Ukraine, including on natural resources, in many different organizations and institutions. In recent years, due to the war in Ukraine, some portals and official state websites have closed access to geodata. Access and sharing of such information is essential for an accurate assessment. In the future, the formation of a geo-information base of topographic-geodetic data and other cartographic thematic information of various branches in the

raster and vector form of various scales is required. Among them, the formation of a geoinformation database of remote sensing of the earth with their appropriate processing in combination with traditional terrestrial methods is important. The war in Ukraine also negatively affects (there are significant restrictions even for educational institutions) the possibility of studying individual areas using unmanned aerial vehicles. The latter would allow for more accurate spatial characteristics of geo objects for creating base maps, including for the analysis of geodetic support (especially accurate visualization of the boundaries of settlements).

Conclusion

In the present study, an assessment of the spatial location of the DGM points for the territory of the Chernivtsi region by the modern administrative and territorial system was carried out. The number of geodetic points is 198 units of different classes. The largest number of SGN points is located within the Chernivtsi district - 109 units, which is 55% of the total number in the region, and in the Chernivtsi urban community - 41 units. It was established that there are areas of the region where there is a discrepancy in the average density of geodetic points with a total area of 2726.91 km² (33.7% of the total area). The largest area belongs to the Chernivtsi district and is 1281 km² (30% of the area of the administrative district). Among the basic units of the administrative-territorial system, the largest areas are in the Selyatynska village community - 238.85 km² (65% of the total area). Vectorization of settlements in the form of almost 600 polygonal objects was carried out. With the increase in scale, the possibilities of creating maps and plans for the territories of settlements of the Chernivtsi region, considering the existing points of SGN, are quite low. The territories of most settlements require additional design and creation of SGN points. The study helps to evaluate the permanent GIS approaches to the formation of geodetic data banks, to identify weak links of the most important geospatial basis, which is naturally lacking for the compilation of maps of the most important large-scale series. Further trends in the development of the geodetic industry make it possible to level these gaps through the development of permanent geodetic stations, with the subsequent involvement of GNSS receivers in static or RTK modes. Despite this, the analysis of modern geodetic support makes it possible to predict the volume of geodetic works when solving any economic problems that require an accurate cartographic basis, among which it is worth noting cadastral activity, construction work, utilization of natural resources, spatial planning, when drawing up project estimate documentation, etc. In addition, the theoretical and methodological provisions of the work can be used in similar studies for other similar objects in our and related areas.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	No	No
Collected the data	No	Yes	Yes	Yes	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	No	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	No	No	Yes	Yes
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Assessing the Constraints of COVID-19 Pandemic on Vegetable Growers: A Comprehensive Analysis

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Abstract

The onset of the COVID-19 pandemic raised major concerns for the agricultural sector, particularly for vegetable growers who are highly vulnerable due to the perishable nature of vegetables and reliance on labour-intensive operations that rely mainly on labour-driven operational practices. The research aims to provide a comprehensive analysis of the constraints vegetable growers face due to the COVID-19 Pandemic. Using an ex-post facto research design, we analysed the cause-and-effect relationship between variables among 240 vegetable growers from two districts and eight villages in Odisha, India. The findings reveal that fear of COVID-19 infection with an average garret score of 73.11 is impacting their willingness to work and interact, Restrictions on movement and social gatherings due to lockdown with an average garret score of 72.91 hindered farming operations, high cost of labour and agricultural inputs with an average garret score of 72.02 driven by reduced availability and increased demand, shortage of labour with an average garret score of 71.02, inadequate knowledge and awareness on COVID-19 pandemic with an average garret score of 70.25 and lack of transportation facilities due to mobility restrictions with an average Garret score of 72.07 are some of the critical constraints faced by vegetable growers. The research findings have several implications for policy or practice to mitigate future disruptions and enhance the resilience of the agricultural sector.

Keywords

COVID-19; Constraints; Agricultural resilience; Vegetable growers

Introduction

The COVID-19 pandemic had emerged as a health crisis of unprecedented scale and complexity which had multifaceted impacts on various aspects of the global society. It had far-reaching consequences across every sector with agriculture being no exception. As one of the hardest-hit industries, agriculture faced

significant challenges due to the pandemic. Agriculture, the backbone of India's economy, contributes 33% of the country's horticultural output, with a significant share coming from vegetables. India is one of the leading producers of vegetables in the world and ranks second after China (MoAFW, 2020). Vegetable cultivation plays a critical role in Indian agriculture, contributing substantially to the food supply chain, enhancing food security and nutrition, and supporting local economies through employment and income generation. The outbreak of the pandemic triggered a series of constraints that affected their ability to produce, distribute and market their produce effectively. It triggered a cascade of disruptions across supply chains, labour shortages and market access significantly impacting the operations of the vegetable farming system (Arumugam, Kanagavalli and Manida, 2020). These challenges not only strained their daily operations but also highlighted the vulnerabilities within vegetable farming threatening the livelihoods of vegetable growers. The pandemic started when farmers were ready to harvest and sell their Rabi crops and its impact continued into the subsequent Kharif season. As a result, farmers faced significant challenges in harvesting their produce, marketing it, and securing essential agricultural inputs for the next planting season (NABARD, 2020). During the early stages of the pandemic, the imposition of lockdowns, travel restrictions, quarantine measures and health concerns severely disrupted the agricultural workforce, further exacerbating the challenges faced by farmers and hindering the overall agricultural production cycle. Many urban workers who had lost their jobs and migrant workers from abroad returned home to their rural villages creating a labour surplus. At the same time, would-be migrant workers were restricted from traveling to village communities creating labour shortages (Kabir, Maple and Usher, 2021; Karim, Islam and Talukder, 2020; Kumar *et al.*, 2021). Vegetable farming often relies heavily on seasonal and migrant workers essential for planting, cultivating and harvesting crops. These labour shortages have not only delayed essential farming operations but also increased labour costs and operational inefficiencies (Bansal and Pande, 2020). Furthermore, in addition to labour shortages the pandemic had triggered widespread disruptions in agricultural supply chains. The virus wreaked havoc on the agricultural production sector which is at the heart of the food chain (Pu and Zhong, 2020). The agricultural supply chains were severely disrupted due to lockdowns, transportation restrictions, disruptions in distribution networks and manufacturing slowdowns. These interruptions resulted in shortages and delays in the availability of essential production inputs such as farm machinery, fertilizers, seeds and pesticides. The vegetable growers were adversely affected as they heavily depended on the timely supply of these inputs. The resultant supply chain issues also led to increased costs of inputs and uncertainty in their availability, impeding producers' ability to manage production and meet market demands (MoAFW, 2020). The pandemic also had a dramatic impact on market access and reduced demand for vegetable growers. The limitations on consumers' movement and market access coupled with the shutting down of food service establishments such as hotels, cafeterias and restaurants resulted in a sharp decline in the demand for fresh vegetables (FAO, 2020). Farmers faced serious financial challenges as a result of declining product demand, supply disruptions and being forced to sell below cost (Termeer, Brouwer and de Boef, 2020). With reduced demand and restrictions on selling farm produce, many vegetable growers faced financial strain due to the unsold surplus coupled with price volatility. However, the pandemic introduced a range of constraints that disrupted every facet of vegetable farming. The immediate and cascading effects of these disruptions highlight the need for a deeper understanding of the impact on agricultural practices and

food systems. This assessment is essential for evaluating the broader implications of agricultural sustainability and resilience, emphasizing the importance of developing adaptive strategies to safeguard the future of farming.

Material and Methods

Study Area

The study was administered in the state of Odisha, India. It is the eighth largest state in terms of area with a total area of 155,707 km² constituting about 4.87% of the country. Odisha is located between the latitudes 17.780N and 22.730N and longitudes 81.37E and 87.53E along with a coastline of 450 km in the eastern part of India. It is an agrarian state with a total cultivated area of about 61.50 lakh hectares and the majority of the population depends on agriculture for their livelihood. Odisha ranks seventh in terms of vegetable production with a share of 4.7% among the major vegetable-producing states of the country. It comprises 10 agro-climatic zones out of which two agro-climatic zones North Eastern Coastal Plain and East and South Eastern Coastal Plain with high potential for vegetable production were selected.

Selection of Sample Sites

From the agro-climatic zones in the area, Balasore (North Eastern Coastal Plain and Cuttack (East and South Eastern Coastal Plain) districts were purposively selected based on the highest Gross cropped Area (GCA) (Odisha Agriculture Statistics 2018-2019) which refers to the maximum total area of the districts under vegetable cultivation as compared the other districts across the region. Apart from those two blocks from each district and a two-gram panchayat from each block followed by two villages from each gram panchayat were randomly selected for the study. An ex-post facto research design was used to investigate the relationships between variables. A total of 240 vegetable growers were selected through proportionate random sampling for the study by covering 2 districts of 4 blocks and 8 villages of Odisha.

Data Collection and Analysis

Data was collected from primary and secondary sources. Primary data was obtained through personal interviews with the vegetable growers using a structured interview schedule along with focused group discussions. The personal interview involves one-on-one interaction with the vegetable growers to understand their personal views while the focused group discussions constitute a group of vegetable growers which encourages interaction among the participants for discussing the set of issues which are useful for understanding their collective perspectives and group dynamics. The collected data identified and categorized various constraints faced by vegetable growers into six key areas: psychological constraints, social constraints, economic constraints, production constraints, technological constraints, and marketing constraints. Each category highlighted specific challenges that impacted the growers' ability to sustain and manage their farming operations effectively during the pandemic.

Further, Garrett's Ranking Technique was used for analysis where the vegetable growers were asked to assign a rank to the constraints of each category according to its degree of severity from their point of view. Thereafter, the individual rank given by the vegetable growers was converted into per cent position by using the formula:

$$\text{Percent position} = 100 \left(\frac{R_{ij} - 0.5}{N_j} \right)$$

Where R_{ij} = Rank given to the i^{th} variable by the j^{th} individual

N_j = Number of variables ranked by the j^{th} individual.

The per cent position formula consists of two components such as R_{ij} which is the rank given to the i^{th} variable by the j^{th} individual and N_j which is the number of variables ranked by the j^{th} individual. Further, the per cent position calculations for each rank were thereby converted into scores by using Garrett's table given by Garret and Woodwoth (1969). The value of the Average Garret score for each constraint was obtained by adding together the scores of the individual vegetable growers divided by the total number of vegetable growers for whom the scores were added. Thus, the Average Garret score for each constraint was obtained and a rank was assigned accordingly identifying the significant constraints affecting the vegetable growers.

Results and Discussion

The pandemic exposed several critical issues that significantly disrupted the farming practices of vegetable growers. The findings of the study provide an overview of the various dimensions of constraints perceived by the growers, categorized as follows: Psychological Constraints, Social Constraints, Economic Constraints, Production Constraints, Technological Constraints and Marketing Constraints.

Psychological Constraints

The various psychological constraints are presented in table 1.

Table 1: Distribution of Respondents According to the Psychological Constraints

Sl.No.	Constraints	Rank given by the vegetable growers								Average Garret score	Rank
		R1	R2	R3	R4	R5	R6	R7	R8		
1.	Fear of socialization	5	183	15	11	6	10	8	2	63.70	II
2.	Increase in anxiety and depression	12	18	10	154	8	11	14	13	51.91	IV
3.	Fear of COVID-19 infection	192	5	8	10	7	6	3	9	73.11	I
4.	Insomnia, stress and nervousness	4	3	6	12	39	13	23	16	38.97	VI
5.	Fear of loss of livelihood	5	6	168	11	14	12	9	15	54.28	III
6.	Fear of theft and insecurity	7	9	13	10	142	16	24	19	45.54	V
7.	The feeling of restlessness and frustration	10	15	19	8	14	20	36	118	34.72	VIII
8.	Fear of social stigma	8	5	9	12	18	33	130	25	37.38	VII

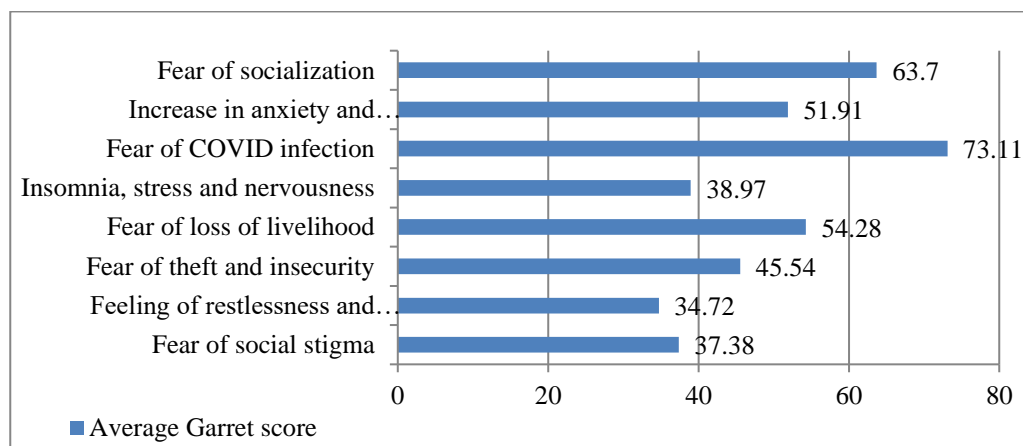


Figure 1: Psychological Factors Impacting Vegetable Growers

Fear of COVID-19 infection ranked as the most critical psychological constraint (Garrett score: 73.11, Rank I) (Figure 1) due to the unpredictable nature of viral transmission. The fear of socialization ranks second with a score of 63.70, followed by the fear of loss of livelihood at third with a score of 54.28, underscoring the importance of economic stability. Anxiety and depression increase, ranking fourth with a score of 51.91, while fear of theft and insecurity ranks fifth at 45.54. Other notable constraints include insomnia, stress, and nervousness (ranked sixth, 38.97), and fear of social stigma (seventh, 37.38). Lastly, feelings of restlessness and frustration are ranked eighth with a score of 34.72. These findings illustrate a range of psychological challenges, indicating the need for targeted mental health interventions. These psychological challenges likely stem from the widespread havoc caused by the pandemic, compounded by stringent measures such as social distancing and isolation, which significantly affected the growers' mindset and cognitive abilities. It acted as the mental and emotional barriers affecting their livelihood and critically hindering their decision-making abilities to manage farms along with the adoption of coping strategies to the changing circumstances. These findings align with those of Serafini *et al.* (2020), where the vegetable growers are prone to severe mental health risks and economic hardship, which also highlighted the detrimental psychological impact of the pandemic on individuals across various sectors.

Social Constraints

The study identified various social constraints faced by vegetable growers during the pandemic, as outlined in table 2. The constraints were ranked based on their average Garrett scores, indicating their severity.

According to figure 2, the most significant social constraint was restrictions on movement and social gatherings due to the lockdown, with an average score of 72.91, ranked first. This was attributed to the severe health risks associated with COVID-19 transmission. Low social or personal interactions ranked II, with a score of 61.38, highlighting the impact of reduced community engagement on farmers. Social distancing and quarantine protocols were ranked III, with an average score of 54.64, further limiting social and communal activities. Reverse migration of farm families ranked IV, with a

score of 48.90, reflecting the disruption caused by the return of migrant workers to rural areas. Lack of support and cooperation from neighbours and villagers ranked V, scoring 41.68, indicating weakened community ties during the pandemic. Limitations in various farming activities ranked VI, with an average score of 40.94, as lockdown measures hindered collaborative farming efforts. Restrictions in the accessibility to resources ranked VII, with a score of 34.34, underscoring the difficulty in obtaining essential inputs and services. These social constraints primarily arose due to the highly contagious nature of COVID-19, prompting the implementation of strict measures to minimize human interaction and control the virus's spread. They had far-reaching compounding effects on the psychological, economic and operational difficulties exacerbating the challenges faced by the vegetable growers. These social constraints can be addressed by strengthening community networks, improving access to resources and ensuring efficient agricultural support systems.

Table 2: Distribution of Respondents According to the Social Constraints

Sl.No.	Constraints	Rank given by the vegetable growers							Average Garret score	Rank
		R1	R2	R3	R4	R5	R6	R7		
1.	Social distancing and quarantine protocols	5	17	173	12	15	11	7	54.64	III
2.	Limitations in various farming activities	15	12	14	20	23	140	16	40.94	VI
3.	Low social or personal interactions	8	187	13	10	6	9	7	61.38	II
4.	Lack of support & cooperation from neighbours and villagers	10	7	8	14	147	21	33	41.68	V
5.	Restrictions in accessibility to resources	13	11	6	25	21	36	128	34.34	VII
6.	Restrictions on movement and social gatherings due to lockdown	196	12	9	7	6	8	2	72.91	I
7.	Reverse migration of farm families	7	17	14	161	9	13	19	48.90	IV

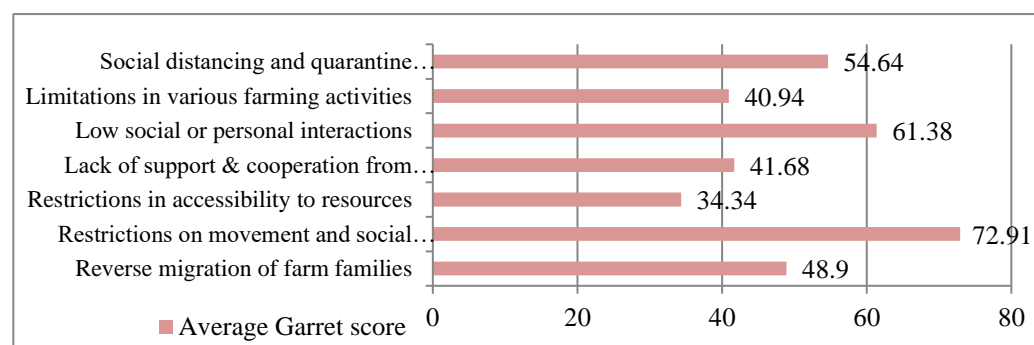


Figure 2: Social Constraints Impacting Vegetable Growers

Economic Constraints

The economic constraints are presented in table 3.

Table 3 Distribution of respondents according to the Economic Constraints

Sl.No.	Constraints	Rank given by the vegetable growers							Average Garret score	Rank
		R1	R2	R3	R4	R5	R6	R7		
1.	Drastic fall in farm income	7	19	15	159	9	13	18	49.17	IV
2.	High cost of labour and agricultural inputs	195	9	6	7	8	11	4	72.02	I
3.	Lack of regulated price policies	10	7	12	18	135	21	37	41.73	V
4.	High expenditure and indebtedness	8	15	9	21	33	41	113	35.11	VII
5.	Lack of awareness of financial assistance	14	12	24	20	18	123	29	40.90	VI
6.	Inaccessibility to credit and banking facilities	9	180	14	11	6	12	8	60.77	II
7.	Low cost of the farm produce in the market	8	10	166	13	17	12	14	53.40	III



Figure 3: Economic Constraints Impacting Vegetable Growers

Figure 3 indicates that the high cost of labour and agricultural inputs is the most significant economic constraint, exhibiting an average Garrett score of 72.02, thereby ranking it first. This may be due to the imbalance in the demand and supply of agricultural goods and services affecting vegetable growers followed by inaccessibility to credit and banking facilities with an average garret score of 60.77 being ranked-II and low cost of the farm produce in the market with an average garret score of 53.40 being ranked-III were put first, second and third in order of priority respectively. The economic constraints ranked as least important include: a drastic fall in farm income at rank IV, a lack of regulated price policies at rank V, a lack of awareness about financial assistance at rank VI, and high expenditure and indebtedness at rank VII. These constraints have average Garret scores of 49.17, 41.73, 40.90, and 35.11, respectively. These constraints had severely affected the efficient management of farm costs impacting the financial stability of vegetable growers. This may be because the pandemic had endangered the livelihoods of vegetable growers leading to economic shock thereby making them more

vulnerable to economic insecurity. Similar findings were obtained by Middendorf *et al.* (2021) and Kulkarni *et al.* (2022) where it was emphasized that disparities in financial security, resources and infrastructure facilities contextualize these issues challenging the vegetable growers.

Production Constraints

The various production constraints faced are presented in table 4.

Table 4: Distribution of Respondents According to the Production Constraints

Sl.No.	Constraints	Rank given by the vegetable growers						Average Garret score	Rank
		R1	R2	R3	R4	R5	R6		
1.	Increased cost of production	15	19	21	26	125	34	42.03	V
2.	High wage rates of labour at peak harvest times	11	24	156	20	13	16	52.30	III
3.	Disruptions in post-harvest management of farm produce	12	23	28	32	39	106	38.49	VI
4.	Shortage of labour	190	12	14	11	7	6	71.02	I
5.	Limitations in the availability of agricultural inputs	13	178	19	15	8	7	59.95	II
6.	Delay in harvesting and loss of yield	18	11	17	145	29	20	46.66	IV

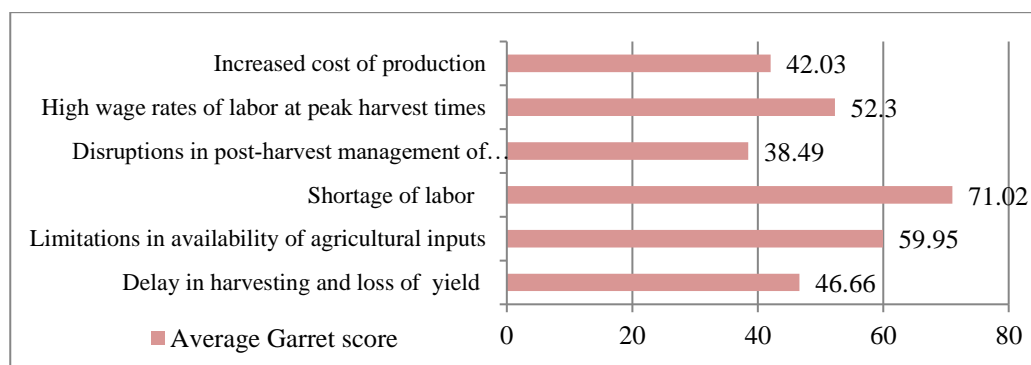


Figure 4: Production Constraints Impacting Vegetable Growers

Among the constraints from figure 4, shortage of labour is the most significant production constraint faced by the vegetable growers with an average garret score of 71.02 and ranked-I. This may be due to the movement restrictions across the nation due to the lockdown and shutdown, followed by limitations in the availability of agricultural inputs with an average garret score of 59.95 being ranked-II and high wage rates of labour at peak harvest times with an average garret score of 52.30 being ranked-III in the order of priority respectively. Delay in harvesting and loss of yield being ranked IV, increased cost of production ranked V and disruptions in post-harvest management of farm produce with a rank of VI are the least significant production constraints with average garret scores of 46.66, 42.03 and 38.49 respectively. These constraints disrupted key aspects of the agricultural operations affecting every stage of the agricultural cycle starting from planting to harvesting. It had resulted in loss of yields, lower quality of

produce and incurred financial loss to the vegetable growers. This may be due to the restrictions imposed by the government resulting in uneven demand and supply of essential commodities leading to drastic changes in price and severely affecting the production activities of vegetable growers. These results are supported by Harris *et al.* (2020) and NABARD (2020).

Technological Constraints

Technological constraints affecting vegetable growers are presented in table 5.

Table 5: Distribution of Respondents according to the Technological Constraints

Sl.No.	Constraints	Rank given by the vegetable growers						Average Garret score	Rank
		R1	R2	R3	R4	R5	R6		
1.	Lack of proper guidance and assistance for the farmers	19	176	14	12	8	11	60.03	II
2.	Lack of adequate infrastructural facilities	8	17	21	28	132	34	40.72	V
3.	Limitations in farm and market information	10	13	15	149	23	30	44.97	IV
4.	Lack of skill in various farming and non-farming activities	14	22	29	34	37	104	38.97	VI
5.	Inadequate knowledge and awareness on COVID-19 pandemic	183	17	15	10	6	9	70.25	I
6.	Lack of adequate extension support and other institutional technical services	12	21	164	19	16	8	53.13	III

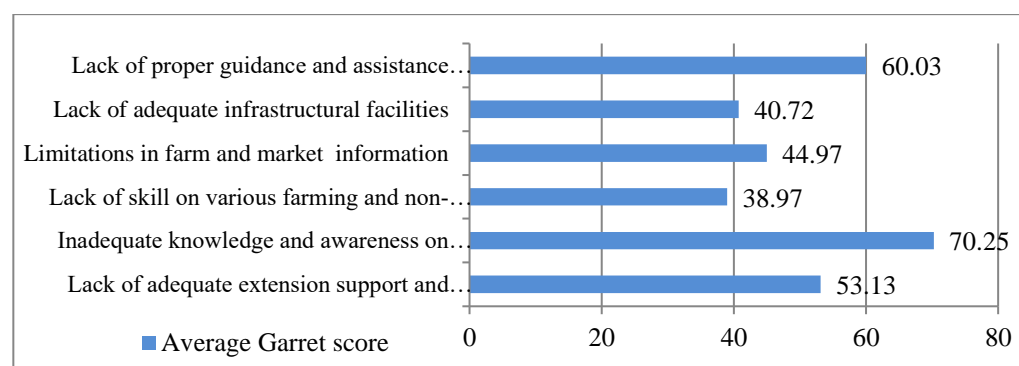


Figure 5: Technological Constraints Impacting Vegetable Growers

From figure 5, results revealed that inadequate knowledge and awareness of the COVID-19 pandemic is a critical technological constraint affecting vegetable growers with an average garret score of 70.25, ranked first. This may be due to a lack of adequate exposure to the various information sources, which influenced their mindset. The second most significant constraint was the lack of proper guidance and assistance for the farmers with an average garret score of 60.03, ranked second. This was followed by insufficient extension support and other institutional technical services, which ranked third with an average score of 53.13. Limitations in farm and market information were ranked fourth

with a score of 44.97, lack of adequate infrastructural facilities ranked fifth with a score of 40.72 and lack of skill on various farming and non-farming activities ranked sixth as the least critical technological constraint with an average Garrett score 38.97. It had a multifaceted impact on the efficiency of the vegetable growers affecting the resilience of vegetable farming systems. These challenges were likely exacerbated by inefficient implementation of the initiatives and inadequate support provided during the pandemic, further impacting the productivity and sustainability of vegetable growers.

Marketing Constraints

The marketing constraints are outlined in Table 6. From Figure 6, it can be concluded that the lack of transportation facilities due to mobility restrictions is the most critical issue affecting vegetable growers, with an average Garrett score of 72.07, ranked first. This is primarily attributed to the nationwide lockdown implemented to curb the spread of the virus. The second most significant constraint is the inaccessibility to marketing facilities, with an average Garrett score of 59.45, ranked second. This is followed by the restricted movement of farm produce, ranked third with a score of 51.86. Additional challenges include the perishable nature of farm produce, ranked fourth with a score of 46.23, changes in the demand and supply of farm produce, ranked fifth with a score of 42.35, and high price fluctuations resulting in distressed sales, which ranked sixth and is considered the least critical marketing constraint with an average Garrett score of 39.03. These constraints affected the ability of the farm produce to reach consumers and their effective distribution for ensuring consistent income for the vegetable growers. The challenges of the traditional market practices compounded the difficulties faced by vegetable farmers. These issues were largely driven by border closures and transportation restrictions during the lockdown, which significantly disrupted the supply chain and negatively impacted vegetable growers. These findings partially align with the study by Ragasa *et al.* (2021), highlighting similar challenges faced by agricultural producers during the pandemic.

Table 6: Distribution of Respondents according to the Marketing Constraints

Sl.No.	Constraints	Rank given by the vegetable growers						Average Garrett score	Rank
		R1	R2	R3	R4	R5	R6		
1.	Restricted movement of farm produce	16	21	144	19	23	17	51.86	III
2.	The perishable nature of the farm produce	11	18	32	130	20	29	46.23	IV
3.	Lack of transportation facilities due to mobility restrictions	199	13	10	7	3	8	72.07	I
4.	High price fluctuations resulting in a distress sale	16	19	24	37	45	99	39.03	VI
5.	Inaccessibility to marketing facilities	11	185	19	4	7	14	59.45	II
6.	Change in demand and supply of the farm produce	14	21	26	30	111	38	42.35	V

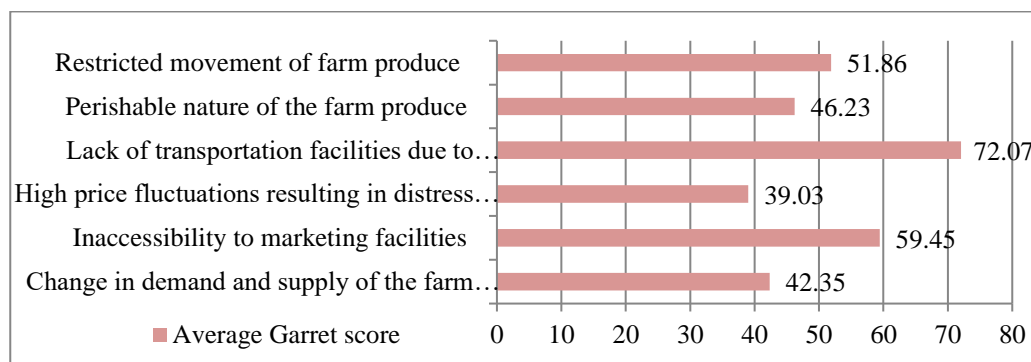


Figure 6: Marketing Constraints Impacting Vegetable Growers

Conclusion

The COVID-19 pandemic caused severe disruptions to the supply chains of perishable farm produce, particularly vegetables, which require rapid distribution and marketing to prevent spoilage. The outbreak led to significant deterioration of perishable goods, resulting in substantial losses for vegetable growers. The findings of the study revealed the fear of COVID infection, fear of socialization and fear of loss of livelihood as the primary psychological constraints followed by restrictions on movement and social gatherings due to lockdown, low social or personal interactions and social distancing and quarantine protocols as the major social constraints, high cost of labor and agricultural inputs, inaccessibility to credit and banking facilities and low cost of the farm produce in the market as the critical economic constraints, shortage of labor, limitations in availability of agricultural inputs and high wage rates of labor at peak harvest times as the indicative production constraints, inadequate knowledge and awareness on COVID-19 pandemic, lack of proper guidance and assistance for the farmers and lack of adequate extension support and other institutional technical services as important technological constraints whereas, lack of transportation facilities due to mobility restrictions, inaccessibility to marketing facilities, restricted movement of farm produce as evident marketing constraints faced by the vegetable growers. The findings of the research reveal numerous significant challenges faced by vegetable growers adversely impacting their production, marketing and financial sustainability. Thus, it is crucial to derive actionable strategies such as strengthening agri-value chains, improving financial accessibility, promoting sustainable agricultural practices and adopting new technology to enhance the resilience of vegetable growers. Further, focusing on these areas through targeted research ensures long-term holistic growth and development. The stress on vegetable growers during the pandemic highlights the importance of developing resilient agricultural practices by providing valuable insights into developing policies and strategies for enhancing agricultural sustainability that can better withstand future global crises.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	Yes
Editing of the article/paper	Yes	No
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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Formation of Elements of Yield Structure and Quality of Mustard Seeds Depending on Genotype and Mineral Nutrition

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Abstract

Given the steady increase in the Earth's temperature in the context of global climate change, which negatively affects the growth and development of most crops, the search for sustainable ecologically adapted plant species and ways to maintain their yields is of great practical importance. Mustard is one of the crops that can grow in drought conditions, which is driving demand for it. The article presents the results of studies of the peculiarities of the formation of the crop structure elements, yield and quality of mustard seeds depending on varietal characteristics and mineral nutrition. It was found that the application of phosphorus-potassium fertilizers, both main application and together with foliar fertilization with nitrogen fertilizers, provided a significant increase in the yield structure indicators – plant height in all phenological phases of mustard growth and development, the number of stems and pods per plant. The greatest increase in plant height of all varieties in phenological phases of growth and development, the number of stems and pods per plant was with the integrated use of phosphorus-potassium fertilizers as the main application and two-time foliar fertilization with nitrogen fertilizers. Indicators of the yield structure elements significantly depended on varietal characteristics. If in the rosette phase, the influence of the “fertiliser” factor was 71.0%, the “flowering” factor – 86.7%, and in the bud and ripening stages the influence of fertilizers was less and amounted to 47.2% and 38.3%, respectively, the influence of the “variety” factor was the greatest in the bud stage and amounted to 48.6% and in the ripening phase – 39.4%. The increase in yield structure indicators contributed to the improvement of mustard seed productivity - while on average, seed yield significantly increased with the use of mineral fertilizers compared to the control - without fertilizers, then seed quality – germination energy and germination, when applying mineral fertilizers did not provide a sufficient increase in these indicators, they were at the level of control and only the weight of 1000 seeds significantly increased both depending on the genotype and the use of mineral fertilizers, which provided an increase in the yield of seeds of all varieties.

Keywords

Geodetic support; GIS; Topographic and geodetic works; State geodetic network; Natural resources

Introduction

Oilseeds are a vital part of agriculture in many countries around the world (Srivastava *et al.*, 2024). The demand for oilseed crops regularly increases due to population surges, dietary choices, and biodiesel product requirements. Oilseed crops are the foremost source of vegetable oil due to their use for culinary purposes (Shah *et al.*, 2023). They are widely used in the food industry because they are healthy and have good functional properties (Zhang *et al.*, 2023). Among others, mustard is an important oilseed crop that can be grown even in arid and semi-arid regions (Shah *et al.*, 2023; Singh *et al.*, 2023), which is essential given global climate change.

It is known that mustard has been cultivated for various purposes since 3000 BC. It has been widely used as a spice and as an energy crop (Grygier, 2023; Kayacetin, 2020). The total area under mustard cultivation in the world is about 3.0 mln ha, with production and yields of 72.37 mln tons and 1980 kg/ha, respectively (Kalia *et al.*, 2021; Stankevych *et al.*, 2020). Ukraine is among the top ten world leaders in terms of mustard cultivation. This crop ranks fourth in oilseed production, following rapeseed, soybeans, and sunflower. (Petrova, 2020). The main external consumers of mustard seeds produced in Ukraine are European countries, which exported 14.3 tons of seeds in 2021 (Kolosok and Melnyk, 2023). In 2007, the area under mustard in all categories of farms was 173.57 thousand hectares, but since 2015 it has been significantly decreasing to 58.8 thousand hectares, while the seed yield has increased from 0.50 to 0.74 t/ha (Mykolayko and Karpuk, 2023). Seed yields and mustard oil quality depend on genetic characteristics, and environmental and agronomic growing conditions, such as irrigation, sowing fertilization, etc. (Kayacetin, 2019). Since Ukraine lacks environmentally adapted zonal technologies for growing mustard, which is a constraint to expanding its cultivation (Zhuykov *et al.*, 2024) and given the growing demand for its seeds, research into ways to increase its yield is relevant.

Insufficient implementation of modern cultivation and protection technologies is the main reason for the low productivity of mustard (Kumar *et al.*, 2020). One of the elements of modern technology in growing crops, including mustard, is balanced plant nutrition, which ensures an increase in both crop yields and the quality of grown products (Zolkin *et al.*, 2022). Fertilizers are one of the factors ensuring an increase in seed yield and quality improvement with simultaneous soil preservation and fertility enhancement (Vassilina, Umbetov and Vassilina, 2012). Mustard requires mineral nutrition throughout the vegetation period, and the maximum demand is reached during the flowering phase. During this period, it requires nitrogen, phosphorus, potassium and other macro- and microelements (Butenko *et al.*, 2022; Indira *et al.*, 2021). For the formation of 1 ton of white mustard seeds, 55–60 kg of nitrogen, 25–30 kg of phosphorus, and 25–35 kg of potassium are required. The removal of nutrients per unit of yield is not a constant value and depends on soil and climatic conditions, varietal characteristics and elements of cultivation technology (Jia *et al.*, 2021).

Sefaoglu *et al.* (2021) demonstrated that the dose of nitrogen has a direct impact on seed yield. With increasing nitrogen doses, the number of pods per plant, the number of seeds per pod, and the weight of 1000 seeds increased, and, accordingly, the seed yield increased. Nitrogen doses (50, 100, 150 and 200 kg ha⁻¹) increased seed yield by 80.4%, 108.3%, 88.9% and 149.8% compared to the control. According to Rozhkov *et al.* (2024), the highest yield of common mustard seeds (2.72-2.79 t/ha) was formed in the variants of combining pre-sowing

application of $N_{45}P_{45}K_{45}$ and $N_{45}P_{30}K_{30}$ with two variants of foliar fertilisation with different fertiliser mixtures. The increase in the dose of pre-sowing mineral fertilisers, as well as the inclusion of mono-elemental fertiliser Quantum Boron Active in the tank mixtures, did not significantly increase the biological yield of seeds, and the cost of cultivation increased significantly. According to Voloshchuk (2024), on grey forest surface glazed soils, the use of mineral fertilizers as the main fertilizer in a dose of $N_{30}P_{30}K_{35}$ and double fertilization with nitrogen in a dose of N_{30} in the rosette and bud stages provided an increase in leaf surface area by 3.1-5.6 thousand m^2/ha and net photosynthetic productivity by 0.30-0.53 g/m^2 per day and, accordingly, an increase in seed yield by 2.46 t/ha.

Mustard is selective when it comes to nutrient availability in the soil and is also highly sensitive to the soil's physical condition. This sensitivity is evidenced by the variations in the structure of the white mustard crop, which depends on different basic tillage and fertilization methods (Anastasya *et al.*, 2024; Fussy and Papenbrock, 2022). Thus, on the background of organic-mineral fertilization (with the predecessor straw left in the field and the addition of $N_{30}P_{30}K_{30}$), the highest mustard yield of 2.05 t/ha was ensured by the flat-cutting system of basic tillage, while the profitability of growing white mustard compared to the mineral fertilization system increased by 93-128%, depending on the system of basic tillage (Kirilyuk, Tymoshchuk and Kalchuk, 2019). Creating favourable growing conditions for mustard plants and the formation of high crop productivity is one of the main tasks that all agrotechnological measures for growing mustard seeds should be aimed at, and one of these measures is the use of mineral fertilizers (Chand *et al.*, 2021; Jakubus and Bakinowska, 2020).

These findings and studies highlight the research gaps which signifies the present need for this work. In light of the above facts, this research aims to find out the peculiarities of the formation of elements of the crop structure, yield and quality of mustard seeds depending on varietal characteristics and mineral nutrition. The objective of the study was to find out the influence of varietal characteristics in combination with the use of mineral fertilisers on the formation of elements of the crop structure - stems and pods on plants and their height and, accordingly, to determine the seed productivity of mustard. Identify the factors that influence the formation of these indicators.

Methodology

Study Area

The study on the effect of varietal characteristics and mineral fertiliser application on the formation of the yield structure elements of mustard seeds was conducted under conditions of unstable moisture of the Right-Bank Forest-Steppe of Ukraine at the experimental field of Pavlo Tychyna Uman State Pedagogical University of the Ministry of Education and Science of Ukraine, during 2020-2023. Five varieties of mustard were studied, four white – Etalon, Pidpocheretska, Ariadna and Oslava and one black – Tsarivna Pivnoch.

Research Scheme

The scheme of the experiment provides for the cultivation of seeds without fertilization – control and main application of phosphorus-potassium fertilizers in dose $P_{45}K_{45}$ without fertilization and with fertilization with nitrogen fertilizers in dose N_{15} on the seedlings, as

well as basic fertilization in dose $P_{45}K_{45}$ with two fertilization with nitrogen fertilizers in dose N_{15} on the seedlings and one fertilization with nitrogen fertilizers in dose N_{30} in the rosette-stem phase. The seeding rate was 2 mln seeds/ha, using the conventional line method. Superphosphate (20% active ingredient) was applied as phosphorus fertilizer, potassium chloride (54% active ingredient) as potassium fertilizer, and ammonium nitrate (34.4% of the active ingredient) was used for fertilisation.

Research Methods

Elements of the yield structure by growth and development stages of plants were determined by generally accepted methods of crop variety testing (Melnyk, 2016; Volkodav, 2000), seed yield – by weighing by plots from each replication, seed quality – germination energy, seed germination and weight of 1000 seeds according to the current NSTU (National standard of Ukraine, 2002). In the experiment, 5 varieties were studied, the placement of which was systematic in blocks, where the variants were placed systematically in each block of 4 variants, and 4 replications of each variant were randomised. In total, there were 16 variants and replications of each variety, and 80 in the experiment.

Soil and Weather Conditions

The soil of the experimental plot is podzolic heavy loamy chernozem with a humus content of 3.31%. The reaction of the soil solution is neutral - pH 6.5-6.7. The content of mobile phosphorus and potassium compounds is 80-130 mg/kg, which corresponds to the average availability. The period of sowing and germination in terms of temperature and moisture supply was typical for the zone, except for minor deviations in both average daily air temperatures and the amount of precipitation. In 2021, precipitation was at the long-term average, while 2020, 2022 and 2023 were characterized by a slight deficit.

Statistical Analysis

The reliability of the experimental data was determined by the calculation-comparative method using variance and correlation-regression analyses according to Fisher's method (Fisher, 2006) and methodological recommendations (Ermantraut, Prysiazniuk and Shevchenko, 2007).

Results and Discussion

Ali (2018) studied the conditions of the Northeastern Forest-Steppe of Ukraine on typical deep medium-humus coarse-dusty medium loamy black soil on loess rocks. It was concluded that an increase in fertilizer rates from $N_{30}P_{30}K_{30}$ to $N_{90}P_{90}K_{90}$ contributed to an increase in plant biometric parameters – increasing the height of white mustard plants by an average of 30%, the number of first-order branches by 3.6-5.1% and the leaf surface area by 9.5-15.8%, compared to the control – without fertilizers. Melnyk *et al.* (2019) observed a notable increase in the morphometric parameters of white at the highest background of $N_{90}P_{90}K_{90}$ fertilizers. The average height of plants was 92.5 cm, which is 11.8 cm higher than in the control, with the number of first-order branches increasing by 1.6 pcs. and amounted to 6.1

pcs. According to Shabbir (2021), in North-Eastern Forest-Steppe of Ukraine, the yield structure of grey mustard was the highest under the dose of mineral fertilizers N₉₀P₉₀K₉₀ using Vuxal Boron (3.0 l/ha) + Vuxal Bioamino Plant (3.0 l/ha) and amounted: the number of first-order branches - 4.87 pcs, the number of pods per plant - 68.92 pcs and the number of seeds per pod - 13.76 pcs.

According to our research, the height of the plants varied not only with the application of mineral fertilizers, but also from varietal characteristics in all phenological phases of plant growth and development, both in control and fertiliser applications. The control group without fertilizers showed the lowest plant height during seed ripening in the variety Etalon, while the highest height was observed in the variety Ariadna (Table 1).

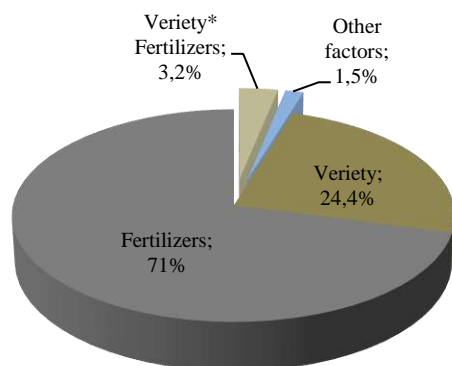
Table 1: Mustard plant height (in cm) depending on varietal characteristics and fertilizer application (average for 2020-2023)

Variant		Stages of growth and development			
		rosette	bud stage	flowering	ripening
variety	fertilizer application				
Etalon	No fertilizer - control	10.0	34.4	61.7	87.5
	P ₄₅ K ₄₅ in the main application without fertilizing	11.0	38.7	69.7	99.6
	P ₄₅ K ₄₅ in the main application + fertilizing N ₁₅ in the seedlings	11.4	39.3	74.6	93.1
	P ₄₅ K ₄₅ in the main application + two fertilizers N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	11.8	40.7	77.0	102.9
Tsarivna Pivnochki	No fertilizer - control	10.1	39.8	63.6	97.9
	P ₄₅ K ₄₅ in the main application without fertilizing	11.6	43.3	71.5	102.2
	P ₄₅ K ₄₅ in the main + fertilizing N ₁₅ in the seedlings	12.3	45.5	77.2	104.3
	P ₄₅ K ₄₅ in the main application + two fertilizers N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	12.7	47.4	78.8	105.3
Pidpecheretska	No fertilizer - control	9.5	35.4	63.6	97.1
	P ₄₅ K ₄₅ in the main application without fertilizing	10.9	38.4	69.0	100.0
	P ₄₅ K ₄₅ in the main application + fertilizing N ₁₅ in the seedlings	11.8	40.7	76.7	101.9
	P ₄₅ K ₄₅ in the main application + two fertilizers N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	12.0	43.5	78.5	103.4
Ariadna	No fertilizer - control	10.6	42.6	68.2	100.2
	P ₄₅ K ₄₅ in the main application without fertilizing	12.2	43.7	71.6	99.9
	P ₄₅ K ₄₅ in the main application + fertilizing N ₁₅ in the seedlings	12.6	46.1	79.3	104.2
	P ₄₅ K ₄₅ in the main application + two fertilizers N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	13.5	46.4	87.1	103.6

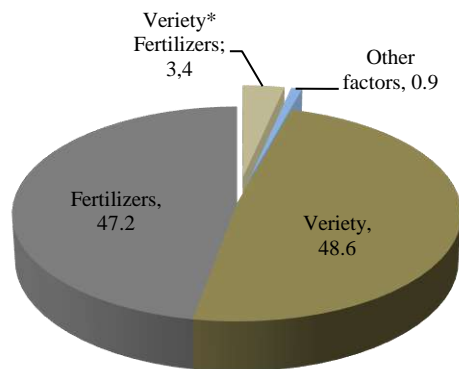
Variant		Stages of growth and development			
		rosette	bud stage	flowering	ripening
variety	fertilizer application				
Oslava	No fertilizer - control	10.5	36.1	64.4	98.0
	P ₄₅ K ₄₅ in the main application without fertilizing	12.5	40.4	73.2	105.9
	P ₄₅ K ₄₅ in the main application + fertilizing N ₁₅ in the seedlings	12.8	41.7	75.0	111.0
	P ₄₅ K ₄₅ in the main application + two fertilizers N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	13.9	44.0	81.0	106.1
LSD ₀₅ general		0.23	0.56	0.52	0.57
LSD ₀₅ variety		0.12	0.28	0.26	0.29
LSD ₀₅ fertilizer		0.10	0.25	0.23	0.26

The height of plants of Tsarivna Pivnoch, Pidpecheretska and Oslava varieties during the seed ripening phase in the control ranged from 97.1 to 98.0 cm, with no significant difference. The reaction of all varieties to the mineral fertiliser application, both main application and foliar fertilization, was almost the same. The increase in plant height of all varieties, except Etalon and Oslava, in the rosette phase averaged 2.1-2.2 cm, in Etalon it was significantly lower, and in Oslava it was significantly higher. The greatest increase in plant height of all varieties in the phenological phases of growth and development was with the combined application of phosphorus-potassium fertilizers as the main and two-time foliar fertilization with nitrogen fertilizers. A significantly greater increase in plant height was noted in the interphase period “bud stage-flowering”.

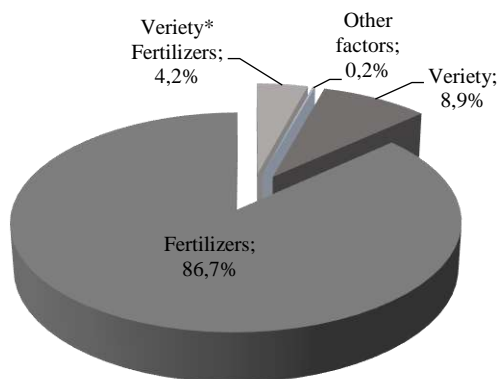
Variance analysis of the influence of the studied factors on the plant height during the cultivation of mustard seeds revealed that the greatest influence was the factor “fertilizer”, in all plant growth and development stages (Figure 1).



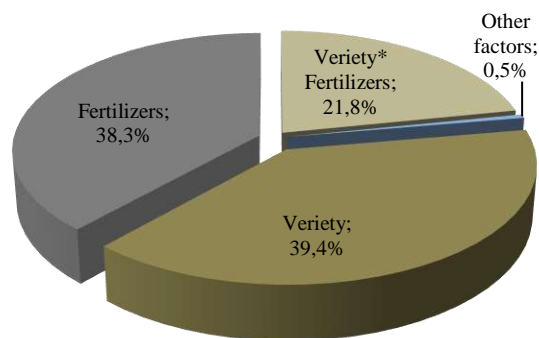
a



b



c



d

Figure 1: Influence of factors on the formation of plant height by stages of plant growth and development (average for 2020-2023) showing: a) Rosette stage; b) Bud stage; c) Flowering stage; and d) Ripening stage

In the rosette stage, the influence of the “fertiliser” factor was 71.0%, the “flowering” factor – 86.7%, and in the bud and ripening stages, the influence of fertilizers was less and amounted to 47.2% and 38.3%, respectively. In the budding stage, the effect of the factor “variety” was the highest and amounted to 48.6% and in the ripening stage – 39.4%. The effect of the interaction of “fertiliser*variety” factors in all phases of plant growth and development was insignificant.

Melnyk and Zherdetska (2017) found that in grey mustard plants, when fertilised with $N_{30}P_{30}K_{30}$ and $N_{60}P_{60}K_{60}$, the number of first-order branches increased by 0.4 and 0.8 units compared to the control, and amounted to 3.7 and 4.1 units, respectively.

We observed a similar growth of pods and stems on mustard plants when phosphorus-potassium mineral fertilizers were applied as the main fertilizer, and mainly with foliar fertilization with nitrogen fertilizers, depending on the varietal characteristics. A significantly smaller number of pods was formed on plants in the control – without mineral fertilizers in all varieties (Table 2).

Table 2: The number of pods per plant, pcs. Depending on the genotype and mineral fertiliser application during the ripening phase (average for 2020–2023)

Variant – <i>fertilizers</i>	Variety				
	<i>Tsarivna Pivnoch</i>	<i>Etalon</i>	<i>Pidpecheretska</i>	<i>Ariadna</i>	<i>Oslava</i>
No fertilizer - control	66.8	54.4	61.8	69.6	69.2
$P_{45}K_{45}$ in the main application without fertilizing	80.1	69.7	73.4	81.8	74.8
$P_{45}K_{45}$ in the main application + fertilizer N_{15} in the seedlings	105.8	83.8	89.2	90.7	91.0
$P_{45}K_{45}$ in the main application + two fertilizing N_{15} in the seedlings + N_{30} in the rosette-stemming phase	118.7	96.3	101.3	106.0	107.1
LSD ₀₅ general	1.99				
LSD ₀₅ variety	0.99				
LSD ₀₅ fertilizer	0.89				

The highest number of pods in the control was in the varieties Ariadna and Oslava, respectively – 69.6 and 69.2 pieces, significantly less compared to the above varieties – in the variety Tsarivna Pivnoch – 66.8 pieces, the variety Pidpecheretska – 61.8 pieces and the least in the variety Etalon – 54.4 pieces. A similar dependence on the fertiliser use was observed. In addition to the control, the introduction of only phosphorus-potassium fertilizers in the main fertilizer provided a reliable increase in the pod number in all varieties compared to the control. The highest pod number was created on plants of varieties Ariadna - 81.8 pieces or 12.2 pieces more, and Tsarivna Pivnoch - 80.1 pieces or 13.3 pieces compared to the control, and the smallest - 73.4 pieces of the variety Pidpecheretska or 11.6 pieces less than in the control. Etalon variety's response to fertilisation was effective, which provided the greatest increase in pods (15.3 pieces) compared to the control.

Combined use of the main fertilizer and foliar fertilization provided a noticeable increase in pods both in comparison with the control and the application of fertilizers alone without fertilizing all varieties. One-time foliar fertilization resulted in the greatest

increase in pods compared to the control and the application of only the main fertilizer – the varieties Tsarevna Severa and Etalon, respectively – increasing by 39 and 29.4 pods. Two applications of foliar fertilization increased pods per variety, ranging from 36.4 to 51.9 pieces compared to the control. In contrast, the main fertilizer led to a smaller increase, varying from 12.1 pieces (Pidpecheretska) to 16.1 pieces (Oslava). The expediency of conducting two foliar fertilization should be determined by the increase in the yield of mustard seeds. Analysis of the factors that influenced the pod number showed that the greatest influence was the factor of “fertilizer” and amounted to 85.6%, the influence of the “variety” was less – 10.9% (Figure 2).

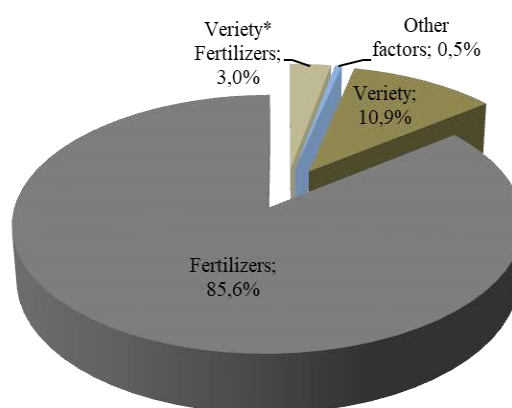


Figure 2: Influence of factors on pod formation depending on varietal characteristics and fertilization (average for 2020-2023)

Similar dependencies were found in the formation of mustard stems depending on the use of mineral nutrition and varietal characteristics. The smallest stem number was formed in the control – without fertilizers, and the use of mineral fertilizers provided a significant increase in all varieties (Table 3).

Table 3: Number of stems per plant, pcs. Depending on genotype and mineral fertiliser application during the ripening phase (average for 2020-2023)

Variant – fertilizers	Variety				
	Tsarivna Pivnochi	Etalon	Pidpecheretska	Ariadna	Oslava
No fertilizer - control	3.1	2.6	3.4	3.9	4.0
P ₄₅ K ₄₅ in the main application without fertilizing	4.3	3.4	4.8	4.8	4.9
P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	5.1	4.4	5.2	5.7	5.9
P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	6.0	5.0	6.1	6.5	6.6
LSD ₀₅ general	0.27				
LSD ₀₅ variety	0.14				
LSD ₀₅ fertilizer	0.12				

A significantly greater number of stems both in the control and under mineral nutrition was formed by varieties Oslava and Ariadna, no significant difference was found, the smallest – being by variety Etalon. The use of phosphorus-potassium fertilizers in the main fertilizer provided an increase in the number of stems of Oslava and Ariadna varieties by 0.9 pcs. or by 22.5 and 23.1%, respectively, compared to the control. The largest increase in stems was in the varieties Tsarivna Pivnochii – 1.2 pcs. or 38.7% and Pidpecheretska – 1.4 pcs. or 41.2%. The integrated use of the main fertilizer and one-time foliar fertilization provided a considerable increase in the number of stems of all varieties compared to the control and the main fertilization. The highest stem number was obtained with two-time foliar fertilization on the background of the main fertilizer.

The analysis of variance revealed that the greatest influence on the formation of mustard stems was the factor “fertilizer” – 74.7%, the influence of the “variety” was 22.4%, and the interaction of them and other factors was insignificant (Figure 3).

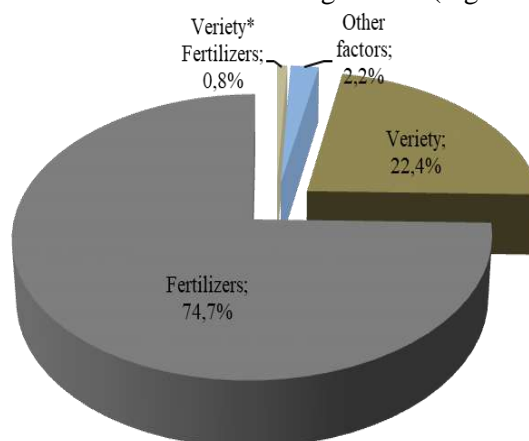


Figure 3: Influence of factors on stem formation depending on varietal characteristics and fertilization (average for 2020-2023)

Improvement of the yield structure indicators contributed to the increase in the seed productivity of mustard - if on average, the seed yield of the varieties significantly increased with the mineral fertilizers application compared to the control – without fertilizers, then the quality of seeds – germination energy and germination, when applying mineral fertilizers did not provide a significant increase in these indicators, they were at the level of the control (Table 4).

The weight of 1000 seeds, on the other hand, varied depending on the varietal characteristics and the use of mineral fertilizers. The highest weight of 1000 seeds (more than 4 g) was in the varieties Tsarivna Pivnochii, Pidpecheretska and Oslava. The highest weight of 1000 seeds was obtained with the combined use of phosphorus-potassium mineral fertilizers as the main fertilization and two foliar fertilizations with nitrogen fertilizers on the seedlings and in the rosette-stem phase. Increasing the weight of 1000 seeds depending on the genotype and the use of mineral fertilizers provided an increase in the yield of seeds of all varieties compared to the control.

Table 4: Quality of mustard seeds depending on varietal characteristics and fertilizer application (average for 2020-2023)

Variant		Germination energy, %	Germination, %	Mass of 1000 seeds, g
Variety	Fertilizer Application			
Etalon	No fertilizer - control	94	95	3.17
	P ₄₅ K ₄₅ in the main application without fertilizing	92	93	3.33
	P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	97	97	3.79
	P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	95	95	3.83
Tsarivna Pivnochii	No fertilizer - control	97	97	4.53
	P ₄₅ K ₄₅ in the main application without fertilizing	97	98	4.65
	P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	98	98	4.76
	P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	97	98	4.72
Pidpech-eretska	No fertilizer - control	97	98	4.81
	P ₄₅ K ₄₅ in the main application without fertilizing	95	96	4.58
	P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	94	95	4.81
	P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	96	96	4.89
Ariadna	No fertilizer - control	96	95	3.52
	P ₄₅ K ₄₅ in the main application without fertilizing	96	96	3.67
	P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	97	97	3.81
	P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	97	97	3.99
Oslava	No fertilizer - control	96	96	4.74
	P ₄₅ K ₄₅ in the main application without fertilizing	97	97	4.67
	P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	96	97	4.84
	P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	95	96	4.96
LSD ₀₅ general		1.4	1.3	0.28
LSD ₀₅ variety		0.7	0.7	0.14
LSD ₀₅ fertilizer		0.6	0.6	0.13

This study showed that plant density and fertilization had a significant impact on black mustard yields. Gubenko and Lyubchych (2020) have determined that in the Right-Bank Forest-Steppe of Ukraine on grey forest light loamy soils, the mineral fertiliser application even in small quantities (60 kg/ha of P and 90 kg/ha of K) led to an increase in seed yields – by 0.84 t/ha without fertilization and by 0.77 t/ha with fertilization. The highest increases in seed yields were observed with the combined application of nitrogen, phosphorus and potassium, which amounted to 0.60–1.06 t/ha (without micro fertilizer) and 0.48–0.98 t/ha (with micro fertilizer) compared to the control (without fertilizer). According to Melnyk *et al.* (2019), in the North-Eastern Forest-Steppe of Ukraine, the introduction of N₃₀P₃₀K₃₀ and N₆₀P₆₀K₆₀ provided a significant increase in the yield of white mustard to 1.92 and 2.13 t/ha, which is 0.34 and 0.55 t/ha more than in the control, respectively.

According to the results of our research, the greatest increase in yield was obtained with the combined application of the main phosphorus-potassium fertiliser with two fertilisations with nitrogen fertilisers (Table 5). The introduction of P₄₅K₄₅ with two fertilisers N₁₅ and N₃₀ in the rosette-stemming phase increased the yield by 0.37-0.52 t/ha or 0.19-0.26 t/ha compared to the variant where the plants were not fertilised. The correlation and regression analysis revealed an average correlation between the increase in the weight of 1000 seeds and the increase in seed yield, the correlation coefficient is 0.61.

Table 5: Increase in seed yield (t/ha) compared to the control, depending on the genotype and mineral fertiliser application (average for 2020–2023)

Variant – <i>fertilizers</i>	Variety				
	<i>Tsarivna Pivnochi</i>	<i>Etalon</i>	<i>Pidpech-eretska</i>	<i>Ariadna</i>	<i>Oslava</i>
P ₄₅ K ₄₅ in the main application without fertilizing	0.26	0.14	0.18	0.20	0.27
P ₄₅ K ₄₅ in the main application + fertilizer N ₁₅ in the seedlings	0.48	0.41	0.35	0.43	0.39
P ₄₅ K ₄₅ in the main application + two fertilizing N ₁₅ in the seedlings + N ₃₀ in the rosette-stemming phase	0.52	0.46	0.37	0.47	0.43
LSD ₀₅ general	0.04				
LSD ₀₅ variety fertilizer	0.02				

Conclusion

The study was aimed at finding out the peculiarities of the formation of crop structure elements, yield and quality of mustard seeds depending on varietal characteristics and mineral nutrition. It was found that the use of mineral fertilizers provided a significant increase in the yield structure indicators – plant height at all stages of growth and development, and the number of stems and pods per plant, which contributed to an increase in mustard yield and seed quality depending on varietal characteristics. The combined application of the main fertilizer and foliar feeding provided a significant increase in stems and pods both in comparison with the control and the application of fertilizer alone without feeding all varieties. It was highest with the combined use of phosphorus-potassium mineral fertilizers as the main fertilizer and two foliar fertilizers

with nitrogen fertilizers on the seedlings and in the rosette-stem stage. Analysis of variance revealed that the mustard height was most significantly influenced by the factor “fertiliser” with an influence index in the range of 38.3-86.7%, depending on the phenological phase of plant growth and development. It was found that the greatest increase in plant height of all varieties was observed with the main application of $P_{45}K_{45}$ with two fertilisations of N_{15} after germination and fertilisation of N_{30} in the rosette-stem phase. In particular, in the Oslava variety, the height of plants in the ripening phase increased by 8.1 cm compared to the variant without fertiliser. Similar results were obtained when analysing the factors that influenced the number of pods and stems. It was determined that the influence of the “fertiliser” factor was the largest, with values of 85.6% and 74.7%, respectively. The number of knots and stems in all varieties was significantly lower in the variant without mineral fertilisers. Thus, with the main application of $P_{45}K_{45}$ with two fertilisations of N_{15} after germination and fertilisation of N_{30} in the rosette-stem phase, the Tsarevna Severa variety formed 51.9 more pods and 2.9 more stems than the control without fertilisation. On average, the seed yield of the varieties significantly increased by 0.24 t/ha with the mineral fertiliser application compared to the control without fertilisers and amounted to 0.41 t/ha with the main use of $P_{45}K_{45}$ with N_{15} fertilisation on the germination stage and 0.45 t/ha with the main use of $P_{45}K_{45}$ with two fertilisations of N_{15} on the germination stage and N_{30} fertilisation in the rosette-stemming stage.

Taking into account the results obtained, it is advisable to continue these studies using complex water-soluble fertilisers that include macro- and microelements, which can reduce the cost of seeds.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	Yes	No	Yes	No
Collected the data	Yes	No	No	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes	No
Wrote the article/paper	Yes	Yes	No	No	Yes
Critical revision of the article/paper	Yes	Yes	Yes	Yes	No
Editing of the article/paper	Yes	No	No	No	Yes
Supervision	No	Yes	Yes	Yes	Yes
Project Administration	Yes	No	No	No	Yes
Funding Acquisition	No	Yes	Yes	Yes	No
Overall Contribution Proportion (%)	25	20	20	20	15

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Knowledge of Agriculture Students towards Entrepreneurship in Odisha of India

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Abstract

Generating entrepreneurial knowledge among students is a way to solve the problem of food and job security in India. Therefore, the present study was undertaken in agriculture colleges of Odisha to explore and improve their entrepreneurial knowledge. The respondents were final-year students in their B.Sc. (Agriculture) undergraduate course. The data were collected through a pretested survey questionnaire. After analysis of the collected, it was found that the majority (62.04%) of the respondents had a medium level of entrepreneurial knowledge. Among various components of entrepreneurial knowledge, the respondents had more knowledge of legal requirements and marketing than credit and finance and technological adaptation. The analysis showed significant positive correlations between entrepreneurial knowledge and attributes like Economic, Social, and Scientific Aptitude, Decision-Making, Leadership, and Information Access, with Leadership Ability being the most influential. In contrast, Family Type and Higher Land Holding had significant negative correlations with infrastructure and legal knowledge, suggesting that students from joint families or with larger landholdings had slightly lower exposure to these entrepreneurial resources. This highlights the importance of individual skills and suggests that family structure and landholding background can also impact entrepreneurial competency.

Keywords

Entrepreneurial knowledge; Agriculture students; Odisha; Technological adaptation; Educational interventions

Introduction

For the growing population of India, food and job security are becoming scarce and our country is going to face a dangerous stage (Senapati and Padhi, 2020). However, this problem can be solved by generating entrepreneurial knowledge among people (Senapati and Padhi, 2020). As today's students are the future of the nation, government should focus on them in developing their

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entrepreneurial knowledge (Dauda and Esther, 2023). Every institution in India has helped them in this matter from childhood, but the higher education institutes focus mostly and seriously on the development of entrepreneurial knowledge among students (Roy and Mukherjee, 2017; Subramanian, Dubey and Singh, 2012)). Therefore, institutions at the undergraduate level are introducing entrepreneurship-related courses. Mostly, in agriculture colleges, students are not only reading entrepreneurship courses, but they are also practising the various entrepreneurial process (Wang, 2019). They are involved in practices for the preparation of agricultural products like jam, jelly, mushrooms, pickles, juice etc. The students are involved in growing flowers, fruits, vegetables, cereals, pulses etc. with higher profit. They are using advanced technologies to generate more income from agriculture practices (Dangore, Wakle and Raut, 2020). They are also in preparation of hybrid seeds and HYV seeds and selling and exporting those seeds (Neesh *et al.*, 2020). They are involved in income generation activities of agricultural institutions. In their course, ELP (Experiential Learning Programme) is added, where they are being trained in both business and skill-based programs like organic farming, Azola preparation, seed production, food processing units, post-harvest management practices etc. (Thorat, Deshmukh, and Shriram, 2021). So, during undergraduate courses, students are getting knowledge on entrepreneurship.

Therefore, this study entitled “Entrepreneurial Knowledge of Agriculture Students in Odisha state of India” is an attempt to know the entrepreneurial knowledge of the agriculture students in Odisha state of India, so that based on their knowledge level and lacuna in any particular type of knowledge related to entrepreneurship, teachers will be able guide and can give training to build up their efficiency and capabilities to be an entrepreneur. This will be helpful to make Odisha state particularly self-sufficient and will help support food security throughout the state. As agriculture students are from mostly all the villages of Odisha. Similar studies can be done in all states and India, so that based on the demand and need of the students regarding knowledge on entrepreneurship, teachers will be able to guide and govt can also support them in this matter. The courses offered to agriculture undergraduate can be redesigned to make them knowledgeable and self-sufficient to earn money in their upcoming future.

The following hypotheses were tested in this study:

- H₁: The entrepreneurial knowledge of agriculture students in Odisha are at a low level on average.
- H₂: Socio-economic factors do not significantly influence the entrepreneurial knowledge of agriculture students in Odisha.
- H₃: Personal attributes do not significantly influence the entrepreneurial knowledge of agriculture students in Odisha.
- H₄: There is no significant difference in the entrepreneurial knowledge based on gender, caste and family major occupation.

Accordingly, the study is guided by the following objectives:

- To evaluate the levels of entrepreneurial knowledge among agriculture students in Odisha.
- To analyze the relationship between socio-economic factors and entrepreneurial knowledge.

- To know the relationship between the personal attributes and entrepreneurial knowledge of the respondents.
- To assess the differences in entrepreneurial knowledge based on gender, caste and family major occupation.

Methodology

This research adopted a quantitative framework, leveraging cross-sectional data to provide a comprehensive analysis. The respondents were B.Sc. (Agriculture) final year bachelor's degree students of all the 9 agriculture colleges in Odisha, India (Table 1). All nine agricultural colleges in Odisha were selected for the study to comprehensively assess the entrepreneurial knowledge of final-year B.Sc. (Agriculture) students, representing diverse socio-economic and regional backgrounds. This inclusive approach ensures a holistic understanding of their knowledge levels and gaps, enabling teachers to design targeted training programs to enhance their entrepreneurial capabilities. The study leverages a quantitative framework with cross-sectional data, providing actionable insights to improve curriculum effectiveness and guide state-level strategies for fostering entrepreneurship in agriculture. The data required for the study of entrepreneurial knowledge were collected through a survey questionnaire which was developed with the help of non-respondent students, experts and literature such as:

- 1) Infrastructure (Audretsch, Heger and Veith, 2015; Calvo *et al.*, 2019; Qandah *et al.*, 2021).
- 2) Legal requirement (Siemieniak and Rembiasz, 2019; Plumly *et al.*, 2008)
- 3) Technological adaptation (Carayannis *et al.*, 2006; Abdelfattah, Al Halbusi, and Al-Brwani, 2023; Ardelean, 2021; Laranja and Fontes, 1998)
- 4) Credit and finance (Tran *et al.*, 2024; Seghers, Manigart and Vanacker, 2012; Sutikno, 2022)
- 5) Marketing (Øystein 2005; Karyaningsih, 2020; Gilmore and Carson, 1999; Besterfield *et al.*, 2013).

Table 1: Details of the study area and respondents

Sl. No.	Name of the College	Name of the District	Total No. of Students in Final Year B.Sc. (Hons.) Agriculture
1.	Institute of Agricultural Sciences, Siksha 'O' Anusandhan, Bhubaneswar	Khordha	352
2.	M.S. Swaminathan School of Agriculture, CUTM, Paralakhemundi	Gajapati	275
3.	Gandhi Institute of Engineering and Technology (GIET), Gunupur	Rayagada	160
4.	MITS Institute of Professional Studies (MIPS)	Rayagada	94
5.	CV Raman Global University	Khordha	34
6.	SRI SRI University	Cuttack	111
7.	College of Agriculture, OUAT, Chiplima	Sambalpur	59

8.	College of Agriculture, OUAT, Bhawanipatna	Kalahandi	98
9.	College of Agriculture, OUAT, Bhubaneswar	Khordha	200
Total	9 colleges		1383

For capturing responses on the Entrepreneurial knowledge of the respondents, a three-point Likert scale: Most essential (3), Essential (2) and not essential (1) was used. Permissions were taken from all the concerned authorities of the study institutions for data collection from the final year students of B.Sc. (Agriculture) and after that, institutions were visited. Interaction and discussion were made with the professors, assistant professors and students on the objectives framed under the study and data collection process. After that, questionnaires in Google Forms were distributed to all the final year students of agriculture in Odisha students during 2023-24 through personal visits to the colleges one by one individually with the help of concerned faculties and authorities by using WhatsApp groups and emails for communication. While using WhatsApp and emails facilitated quick communication and response collection, potential limitations included accessibility issues for students with limited internet access, potential non-responsiveness, and a lack of personal interaction that could influence the accuracy of responses. To mitigate these issues in future studies, a mixed-methods approach combining online and offline data collection could be adopted, ensuring inclusivity and higher response accuracy. Additionally, follow-ups through personal visits or phone calls could address non-responsiveness and enhance data reliability. A total of 588 questionnaires were returned during the study. Out of these, 569 questionnaires were deemed suitable for analysis based on specific inclusion and exclusion criteria. The inclusion criteria required that the questionnaires be fully completed, with clear and valid responses to all items on the three-point Likert scale. Questionnaires with incomplete responses, ambiguous answers, or missing data were excluded from the analysis to ensure the reliability and validity of the results. After applying these criteria, the finalized dataset was analyzed using SPSS v21. The final questionnaire is attached as Annexure.

Results

Entrepreneurial Knowledge of the Agriculture Students in Odisha

The analysis of entrepreneurial knowledge among agriculture students in Odisha (Table 2), based on a sample of 569, reveals varying levels of understanding across different dimensions of entrepreneurship, including Infrastructure, Legal Requirements, Technological Adaptation, Credit and Finance, Marketing, and Overall Entrepreneurial Knowledge. For Infrastructure, the average mean score was 2.63, with 17.93% of students having low knowledge, 50.09% medium, and 31.99% high, ranking it third overall. Legal Requirements had the highest average mean score of 2.67, with 19.86% of students with low knowledge and 80.14% at medium, but none reaching high knowledge. Technological Adaptation, with an average mean score of 2.59, ranked fifth, where 19.86% had low knowledge, 50.97% medium, and 29.17% high. Credit and Finance had an average mean score of 2.61, ranking fourth, with 20.39% of students with low knowledge, 48.33% at medium, and 31.28% at high. Marketing, with an

average mean score of 2.66, ranked second, where 19.33% of students had low knowledge, 80.67% medium, and none high. Overall Entrepreneurial Knowledge had an average mean score of 2.63, with 17.75% of students at low knowledge, 62.04% at medium, and 20.21% at high knowledge levels.

Table-2: Rank and Level of Entrepreneurial Knowledge (n=569)

<i>Factors of Entrepreneurial Knowledge</i>	<i>Average Mean Score*</i>	<i>Rank</i>	<i>Level</i>		
			<i>Low</i>	<i>Medium</i>	<i>High</i>
<i>Infrastructure</i> (For Levels Mean=2.63, SD=0.35)	2.63	III	102 (17.93%)	285 (50.09%)	182 (31.99%)
<i>Legal requirement</i> (For Levels Mean= 2.67, SD= 0.35)	2.67	I	113 (19.86%)	456 (80.14%)	0 (0.0%)
<i>Technological adaptation</i> (For Levels Mean= 2.59, SD= 0.36)	2.59	V	113 (19.86%)	290 (50.97%)	166 (29.17%)
<i>Credit and Finance</i> (For Levels Mean= 2.61, SD= 0.38)	2.61	IV	116 (20.39%)	275 (48.33%)	178 (31.28%)
<i>Marketing</i> (For Levels Mean= 2.66, SD=0.34)	2.66	II	110 (19.33%)	459 (80.67%)	0 (0.0%)
<i>Overall Entrepreneurial knowledge</i> (For Levels Mean: 2.63, SD: 0.3)	2.63		101 (17.75%)	353 (62.04%)	115 (20.21%)

*Minimum score = 1, and maximum score = 3

Correlation among Variables

The correlation analysis aimed to understand the relationship among various socio-economic attributes, personal attributes and entrepreneurial knowledge of the respondents. After analysis, the results depicted in Table 3 revealed both positive and negative significant correlations with entrepreneurial knowledge across various dimensions. On the positive side, Economic Aptitude, Social Aptitude, Scientific Aptitude, Decision-Making Ability, Leadership Ability, and Source of Information exhibited significant positive correlations, with Leadership Ability showing the strongest association, particularly in credit and finance knowledge. Social and Scientific Aptitude were also notably influential, emphasizing the importance of interpersonal and technical skills for entrepreneurial success. Conversely, Family Type and Parents' Higher Land Holding showed significant negative correlations with specific dimensions of entrepreneurial knowledge, particularly with infrastructure and legal requirements. This suggested that students from joint families or those with higher landholdings may have had slightly lower exposure to certain entrepreneurial resources, potentially due to different resource management or family responsibilities. These findings indicated that while fostering individual skills could strengthen entrepreneurial competencies, addressing the nuances of family structure and landholding background might also be beneficial.

Table 3: Spearman's Rank Correlations

Sl. No.	Variables	Infra-structure	Legal Requirement	Technological Adaptation	Credit and Finance	Marketing	Overall Entrepreneurial Knowledge
1	Locality	-0.062	-0.042	-0.043	-0.03	-0.026	-0.05
2	Family Type	-.085*	-.089*	-0.043	-0.043	-0.081	-.087*
3	Family Size	-0.065	-0.06	-0.057	-0.028	-0.024	-0.063
4	House Types	-0.012	0.031	0.015	0.057	0.047	0.035
5	Education of the head of the family	-0.002	-0.033	-0.031	0.044	0.022	0.007
6	Family Annual Income	-0.05	-0.072	-0.078	-.084*	-0.004	-0.066
7	Parents Land Holding	-.094*	-.087*	-0.071	-0.049	-0.059	-0.081
8	Economic Aptitude	.126**	.130**	.133**	.157**	.138**	.165**
9	Social Aptitude	.217**	.276**	.250**	.279**	.238**	.300**
10	Scientific Aptitude	.227**	.231**	.259**	.257**	.216**	.283**
11	Decision-Making Ability	.272**	.251**	.171**	.277**	.283**	.291**
12	Leadership Ability	.265**	.290**	.297**	.350**	.290**	.354**
13	Source of Information	.219**	.211**	.267**	.195**	.189**	.258**

**Significance at 1% level (two-tailed)

*Significance at 5% level (two-tailed)

Entrepreneurial Knowledge Based on Gender

To compare entrepreneurial knowledge between male and female agriculture students in Odisha across various dimensions, researchers employed the Mann-Whitney-U Test (Table 4). Factors examined included Infrastructure, Legal Requirements, Technological Adaptation, Credit and Finance, Marketing, and Overall Entrepreneurial Knowledge. For Infrastructure, male students had a mean rank of 288.96, while females had 282.03, with a Mann-Whitney U of 38,683.5, Z-score -0.509 and p-value 0.611, revealing no significant differences in the case of gender. In the Legal Requirements category, males scored a mean rank of 285.58 and females 284.57, with a Mann-Whitney U of 39,509.0, Z-score of -0.075, and p-value of 0.941, again showing no significant disparity. Technological Adaptation results indicated mean ranks of 296.01 for males and 276.73 for females, with a Mann-Whitney U of 36,963.0, Z-score of -1.411, and p-value of 0.158, demonstrating no significant statistical difference. Credit and Finance dimension yielded mean ranks of 291.42 for males and 280.18 for females, with a Mann-Whitney U of 38,084.0, Z-score of -0.824, and p-value of 0.410, indicating no significant gender gap. Marketing results showed mean ranks of 286.51 for males and 283.87 for females, with a Mann-Whitney U of 39,282.0, Z-score of -0.194, and p-value of 0.846, suggesting

no significant difference. Lastly, Overall Entrepreneurial Knowledge analysis produced mean ranks of 291.78 for males and 279.91 for females, with a Mann-Whitney U of 37,994.5, Z-score of -0.854, and p-value of 0.393, further supporting the absence of significant gender-based differences.

Table 4: Mann-Whitney U Test (Entrepreneurial Knowledge based on Gender)

	<i>Infra-structure</i>	<i>Legal Requirement</i>	<i>Technological Adaptation</i>	<i>Credit and Finance</i>	<i>Marketing</i>	<i>Overall Entrepreneurial Knowledge</i>
Mann-Whitney U	38683.500	39509.000	36963.000	38084.000	39282.000	37994.500
Wilcoxon W	91658.500	92484.000	89938.000	91059.000	92257.000	90969.500
Z	-.509	-.075	-1.411	-.824	-.194	-.854
Asymp. Sig. (2-tailed)	.611	.941	.158	.410	.846	.393

a. Grouping Variable: Gender

Entrepreneurial Knowledge Based on Caste

To investigate differences in entrepreneurial knowledge between agricultural students in Odisha from the Lower, Middle, and Upper caste groups, a Kruskal-Wallis test was utilized. The analysis focused on six dimensions: Infrastructure, Legal Requirements, Technological Adaptation, Credit and Finance, Marketing, and Overall Entrepreneurial Knowledge (Table 5). With a Chi-Square of 0.328, two degrees of freedom, and a p-value of 0.849, the mean ranks for infrastructure were 276.34 (Lower Caste), 288.26 (Middle Caste), and 285.48 (Upper Caste), indicating no discernible variance in perception. With a Chi-Square of 1.347, two degrees of freedom, and a p-value of 0.510, Legal Requirements revealed mean rankings of 269.10 (Lower Caste), 293.30 (Middle Caste), and 284.44 (Upper Caste), further suggesting no significant difference.

The mean ranks for technological adaptation were 262.22 for the Lower Caste, 300.97 for the Middle Caste, and 281.66 for the Upper Caste. A Chi-Square of 3.654, two degrees of freedom, and a p-value of 0.161 indicated that there was no significant difference between the castes. With a Chi-Square of 4.386, two degrees of freedom, and a p-value of 0.112, Credit and Finance showed mean ranks of 257.02 (Lower Caste), 300.69 (Middle Caste), and 283.33 (Upper Caste), indicating no significant difference. With a Chi-Square of 1.923, two degrees of freedom, and a p-value of 0.382, the mean rankings in the Marketing dimension were 263.94 for Lower Caste, 284.75 for Middle Caste, and 291.23 for Upper Caste, indicating no significant variance. Last but not least, there was no significant difference between the caste categories for Overall Entrepreneurial Knowledge, with mean rankings of 262.34 (Lower Caste), 295.99 (Middle Caste), and 284.72 (Upper Caste) with a Chi-Square of 2.469, 2 degrees of freedom, and a p-value of 0.291.

Entrepreneurial Knowledge Based on Family Major Occupation

Taking into account the principal occupation of their family, the Kruskal-Wallis Test was utilized to examine differences in entrepreneurial knowledge among agriculture students

in Odisha (Table 6). The analysis covered several aspects: Infrastructure, Legal Requirements, Technological Adaptation, Credit and Finance, Marketing, and Overall Entrepreneurial Knowledge. For Infrastructure, the test revealed mean ranks of Labour (154.50), Caste Occupation (338.75), Cultivation (302.91), Business (284.50), Private Job (289.61), and Government Job (280.70), with a Chi-Square of 2.756, 5 degrees of freedom, and a p-value 0.738, indicating no significant differences across family occupations. In the Legal Requirements category, mean ranks were Labour (116.25), Caste Occupation (361.88), Cultivation (312.19), Business (284.92), Private Job (256.33), and Government Job (286.99), with a Chi-Square of 7.227, 5 degrees of freedom, and a p-value of 0.204, suggesting no significant variations based on family occupation. Technological Adaptation showed mean ranks of Labour (262.00), Caste Occupation (361.88), Cultivation (313.40), Business (287.78), Private Job (274.63), and Government Job (279.82), with a Chi-Square of 3.394, 5 degrees of freedom, and a p-value of 0.639, demonstrating no significant differences across family occupations. For Credit and Finance, mean ranks were Labour (73.25), Caste Occupation (271.00), Cultivation (288.35), Business (300.16), Private Job (274.30), and Government Job (281.60), with a Chi-Square of 5.187, 5 degrees of freedom, and a p-value of 0.394, indicating no significant variations. Marketing displayed mean ranks of Labour (116.50), Caste Occupation (411.75), Cultivation (281.59), Business (298.99), Private Job (257.24), and Government Job (285.56), with a Chi-Square of 7.951, 5 degrees of freedom, and a p-value of 0.159, suggesting no significant differences. Lastly, Overall Entrepreneurial Knowledge showed mean ranks of Labour (122.25), Caste Occupation (348.50), Cultivation (305.19), Business (291.26), Private Job (265.45), and Government Job (283.27), with a Chi-Square of 4.722, 5 degrees of freedom, and a p-value of 0.451, indicating no significant variations across family occupations.

Table 5: Kruskal-Wallis test (Entrepreneurial Knowledge Based on Caste)

	<i>Infra-structure</i>	<i>Legal Requirement</i>	<i>Technological Adaptation</i>	<i>Credit and Finance</i>	<i>Marketing</i>	<i>Overall Entrepreneurial Knowledge</i>
Chi-Square	0.328	1.347	3.654	4.386	1.923	2.469
df	2	2	2	2	2	2
Asymp. Sig.	0.849	0.510	0.161	0.112	0.382	0.291

Table 6: Kruskal-Wallis test (Entrepreneurial knowledge based on Family major occupation)

	<i>Infra-structure</i>	<i>Legal Requirement</i>	<i>Technological Adaptation</i>	<i>Credit and Finance</i>	<i>Marketing</i>	<i>Overall Entrepreneurial Knowledge</i>
Chi-Square	2.756	7.227	3.394	5.187	7.951	4.722
Df	5	5	5	5	5	5
Asymp. Sig.	0.738	0.204	0.639	0.394	0.159	0.451

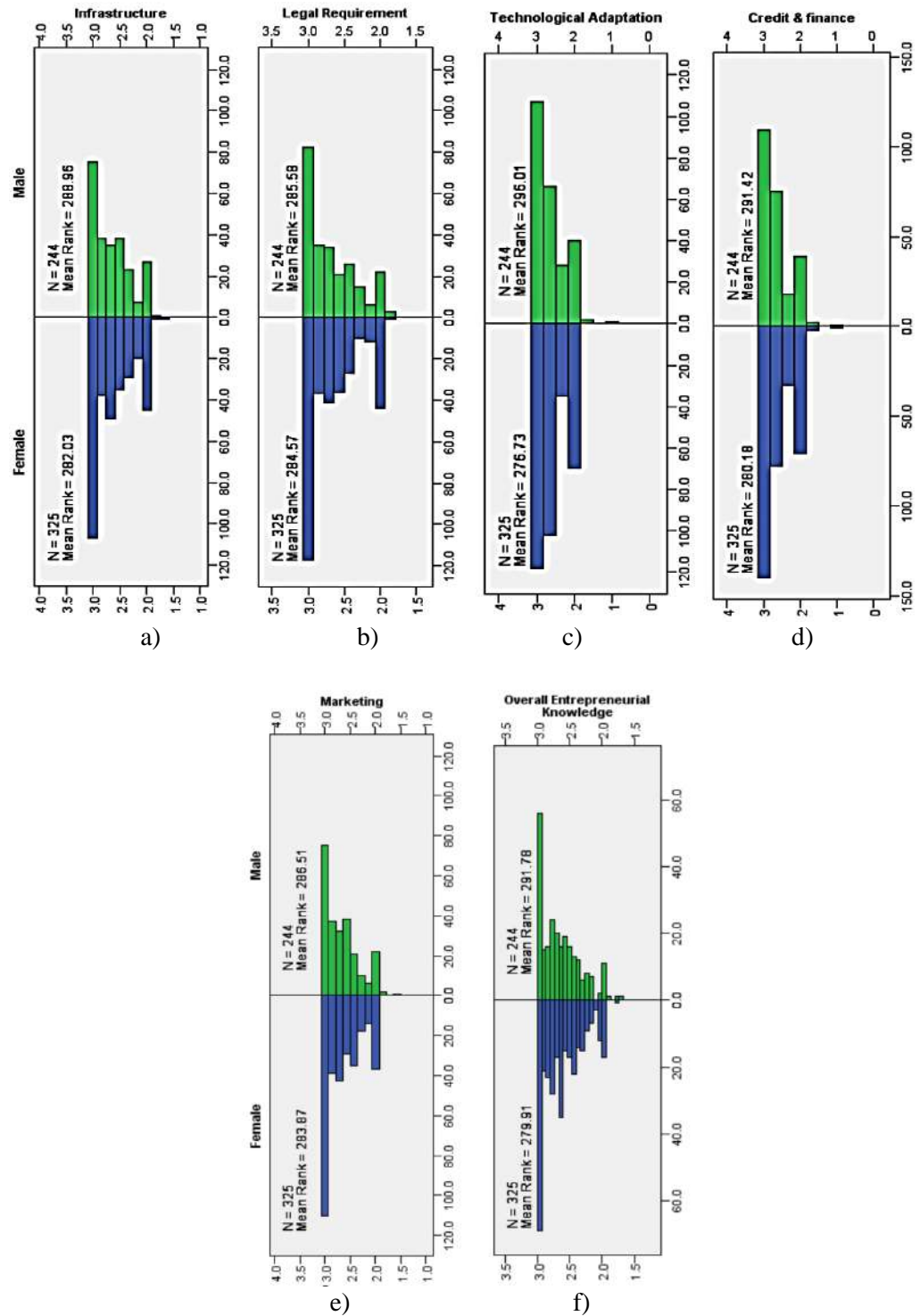


Figure 1: Comparison between Entrepreneurial Knowledge of Students: a) Infrastructure, b) Legal requirement, c) Technological adaptation, d) Credit & Finance, e) Marketing, f) Overall entrepreneurial knowledge

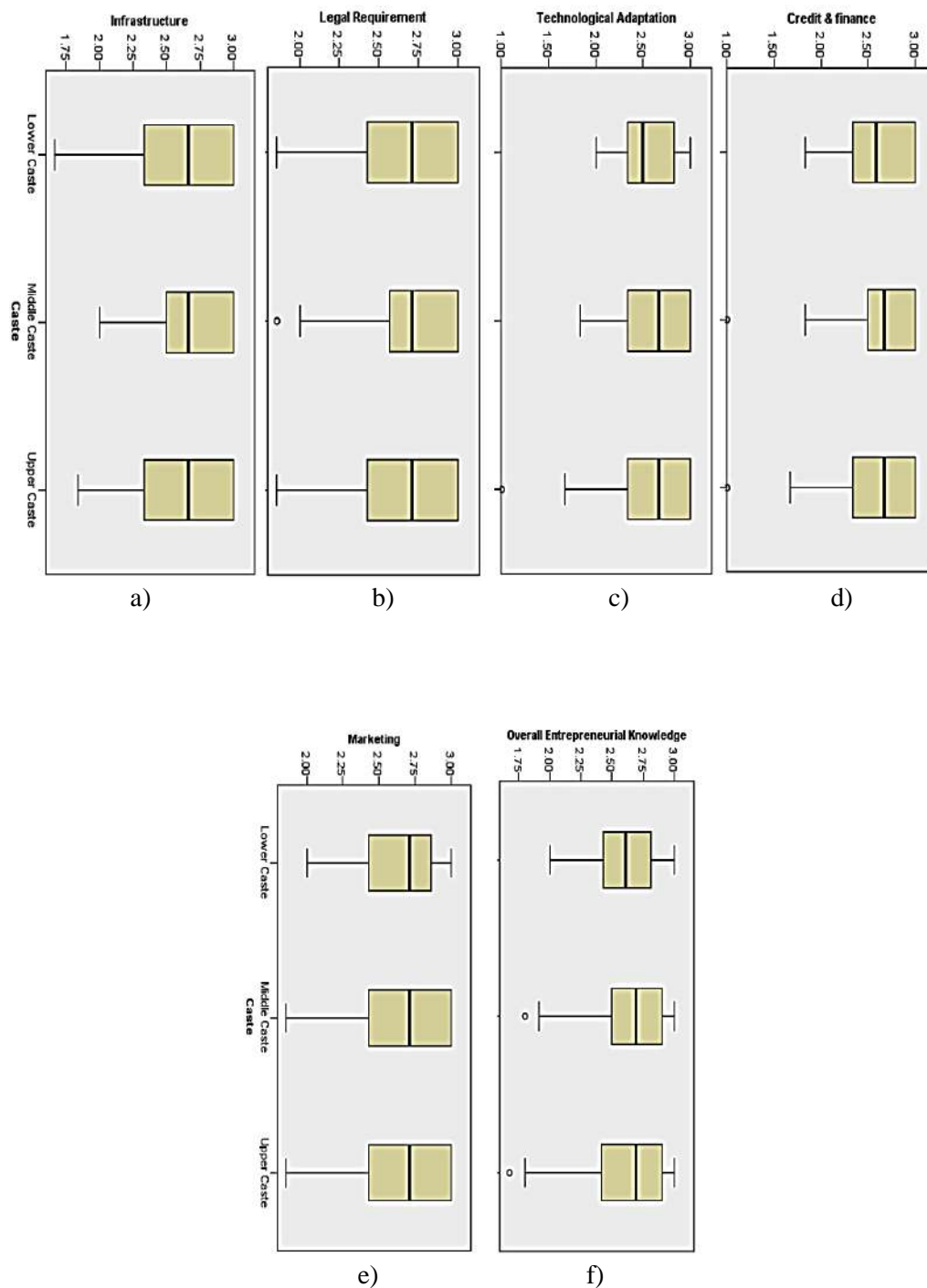


Figure 2: Kruskal-Wallis Test based on Caste: a) Infrastructure, b) Legal requirement, c) Technological adaptation, d) Credit & Finance, e) Marketing, f) Overall entrepreneurial knowledge

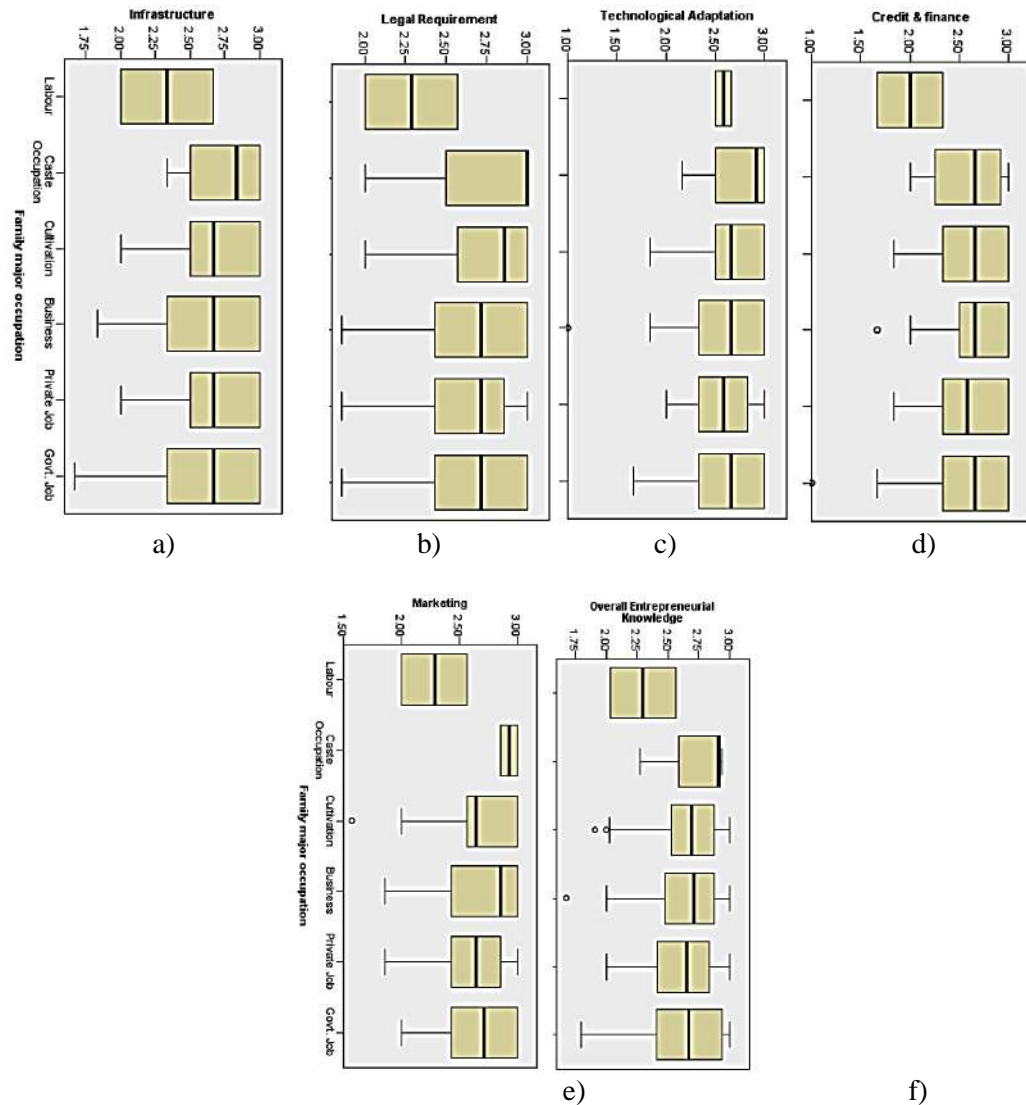


Figure 3: Kruskal-Wallis Test based on Family Major occupation: a) Infrastructure, b) Legal requirement, c) Technological adaptation, d) Credit & Finance, e) Marketing, f) Overall entrepreneurial knowledge

Discussion

The results indicate that agriculture students in Odisha possess varying degrees of entrepreneurial knowledge across different dimensions. Legal Requirements rank highest in terms of average mean score, with the majority of students (80.14%) possessing medium-level knowledge and no students reaching a high level of understanding. This highlights a strong foundational knowledge of legal aspects but also suggests a potential area for further development to achieve higher competency. Marketing knowledge also ranks highly, with 80.67% of students having medium-level knowledge, indicating a well-rounded understanding in this area. However, like Legal

Requirements, no students reached a high knowledge level, which could point to gaps in advanced marketing concepts. In contrast, Technological Adaptation ranks lowest, with a significant portion of students (19.86%) having low knowledge, and only 29.17% reaching high knowledge. This suggests that technological aspects of entrepreneurship might be an area where students are less confident or where educational interventions could be more focused. Infrastructure and Credit and Finance show a more balanced distribution of knowledge levels, with substantial portions of students achieving high knowledge (31.99% and 31.28%, respectively). These areas, while important, do not exhibit the same knowledge gaps as Technological Adaptation. Overall, while most students possess medium-level entrepreneurial knowledge, there is a clear need for enhanced education and resources in specific areas, particularly to elevate students from medium to high knowledge levels. Focusing on advanced concepts in legal requirements, marketing, and technological adaptation could help bridge the gaps identified in this study, ultimately better-preparing students for entrepreneurial challenges in the agricultural sector. Similar findings are reported by Soam *et al.*, (2023).

The correlation analysis indicates that there are generally weak relationships between family background factors and various dimensions of entrepreneurial knowledge among agriculture students in Odisha. The negative correlations observed in some cases suggest that more diverse or complex family backgrounds might slightly reduce students' perceived knowledge in areas such as infrastructure, legal requirements, and overall entrepreneurial knowledge. Nevertheless, these correlations are not strong, indicating that the entrepreneurial knowledge of students in agriculture is not significantly influenced by their family background. This suggests that other factors, such as formal educational programs, availability of resources, or individual drive, may have a greater impact on the development of entrepreneurial skills and knowledge among these students than their family circumstances. Similar results are also obtained by Georgescu and Herman (2020). The weak correlations also imply that interventions aimed at improving entrepreneurial knowledge might not need to focus heavily on family background, but rather on providing equal access to education and resources for all students. Future research could explore other potential factors influencing entrepreneurial knowledge to develop more targeted educational programs and policies.

According to the Mann-Whitney U Test findings, no statistically significant disparity exists between male and female students of agriculture in Odisha regarding various aspects of entrepreneurial knowledge. The analysis shows that both male and female students possess similar levels of understanding and competence in infrastructure, legal requirements, technological adaptation, credit and finance, and marketing. The overall entrepreneurial knowledge, when compared across genders, also reflects no significant disparity.

This lack of significant difference may suggest that the educational environment and exposure to entrepreneurial knowledge are relatively uniform across genders in the study population. It could also indicate that both male and female students have equal access to resources, opportunities, and information regarding entrepreneurship in agriculture. The findings emphasize the importance of continuing to provide equal opportunities and resources for both genders in agricultural education to foster a more inclusive entrepreneurial environment. Additionally, future research could explore other factors that may influence entrepreneurial knowledge, such as socio-economic background,

educational interventions, and regional disparities, to provide a more nuanced understanding of the entrepreneurial capabilities of agriculture students in Odisha.

According to the Kruskal-Wallis Test findings, no statistically significant variations were observed in the entrepreneurial knowledge of agriculture students in Odisha when considering their caste. This lack of significant differences was consistent across all evaluated dimensions, which encompassed Infrastructure, Legal Requirements, Technological Adaptation, Credit and Finance, Marketing, and Overall Entrepreneurial Knowledge. The average rankings across caste groups were found to be similar, with p-values exceeding the 0.05 threshold for statistical significance in all dimensions. This suggests that caste background does not significantly impact these students' entrepreneurial knowledge. These findings suggest that entrepreneurial education and opportunities may be uniformly distributed across different caste groups in Odisha, leading to similar levels of knowledge and understanding. This could be a positive indicator of equitable access to resources and educational content across caste lines. However, it may also imply that other factors, such as socio-economic status, access to mentorship, or regional disparities, could be more influential in shaping entrepreneurial knowledge than caste alone. Subsequent studies could investigate additional variables to obtain a more thorough insight into the factors influencing entrepreneurial knowledge among students of agriculture in Odisha.

According to the Kruskal-Wallis Test findings, no statistically significant variations were observed in the entrepreneurial knowledge among agriculture students in Odisha when examining their families' primary occupations. The p-values exceeded the 0.05 significance level in all dimensions—Infrastructure, Legal Requirements, Technological Adaptation, Credit and Finance, Marketing, and Overall Entrepreneurial Knowledge—showing that family occupation has no discernible impact on students' entrepreneurial knowledge. These findings suggest that entrepreneurial knowledge among agriculture students is consistent regardless of their family's occupational background. This could imply that educational programs and resources related to entrepreneurship are uniformly accessible to students, regardless of their socio-economic background. However, it may also highlight the need to explore other factors that could impact entrepreneurial knowledge, such as individual motivation, access to technology, or regional differences. Further research could help to identify these factors and provide more tailored interventions to enhance entrepreneurial education for agriculture students in Odisha.

Conclusion

The research on the entrepreneurial knowledge of agriculture students in Odisha reveals a varied landscape, with certain strengths and clear areas for improvement. The study indicates that students possess a solid foundation in Legal Requirements and Marketing, with the majority demonstrating medium-level knowledge in these areas. However, the absence of students reaching high knowledge levels in these critical domains suggests the need for more advanced educational interventions to enhance their competency.

Technological Adaptation emerges as a particularly challenging area, with a significant portion of students exhibiting low knowledge. This highlights the importance of focusing educational efforts on improving students' confidence and capability in technological

aspects of entrepreneurship. While Infrastructure and Credit and Finance show more balanced knowledge distributions, the relatively lower scores in Technological Adaptation underscore a critical gap that needs addressing.

The analysis of correlations indicates that students' entrepreneurial knowledge is minimally influenced by their family background. This suggests that other factors, such as formal educational experiences and resource availability, may have a more substantial influence on their entrepreneurial understanding. This finding reinforces the need for educational strategies that provide equal access to resources and opportunities, irrespective of students' familial backgrounds.

Statistical analysis using the Mann-Whitney U Test reveals no notable disparities in entrepreneurial knowledge between male and female students, indicating a consistent educational experience across genders. Likewise, the Kruskal-Wallis Test outcomes show no significant variations based on caste or family occupation, suggesting that entrepreneurial learning and prospects are evenly distributed among these socio-demographic categories.

Overall, the study highlights the necessity of enhancing educational programs to bridge the knowledge gaps identified, particularly in advanced concepts of legal requirements, marketing, and technological adaptation. The uniformity observed across gender, caste, and family occupation groups suggests that educational interventions should focus on content quality and accessibility rather than demographic targeting. Future research could explore additional factors influencing entrepreneurial knowledge, such as socio-economic status, access to mentorship, and regional disparities, to develop more targeted and effective educational policies for agriculture students in Odisha.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	Yes
Editing of the article/paper	Yes	No
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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Analysis of the Climate Vulnerability of Summer Vegetable-Producing Households in the Trishuli-Narayani River Corridor, Nepal

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Abstract

The impact of climate change on agricultural livelihoods is significant, particularly for summer vegetable growers in the Trishuli-Narayani River corridor of Nepal, which includes the Chitwan, Dhading, and Nuwakot districts. A survey was conducted with 300 farmers—100 from each district—using vulnerability assessment tools that included 57 indicators: 18 for exposure, 17 for sensitivity, and 21 for adaptive capacity. Finally, principal component analysis was performed with normalized data to assess vulnerability across districts. Our study revealed significant variations in vulnerability. Chitwan exhibited moderate vulnerability (index range: -4.9 to +5.8) because of better access to resources and infrastructure, enhancing its adaptive capacity. Dhading faced greater vulnerability (-5.7 to +7.1) because of a combination of high exposure to climate hazards and lower adaptive capacity. However, in Nuwakot, it was found an extended range of vulnerability indices (-4.2 to +7.3) among summer vegetable farmers. The above results summarize the need for specific interventions in each district. Dhading, with a high number of vulnerable farmers, may require more significant support in allocating resources and capacity building. The Nuwakot district should focus on addressing internal disparities and ensuring access to resources and infrastructure development for all farmers. This study highlights the importance of localized, context-specific adaptation plans to support the resilience of agricultural communities facing climate risks. This underscores the effectiveness of a multidimensional vulnerability assessment approach in agricultural contexts. Future research could explore the most effective methods for capacity strengthening and investigate ways to encourage the adoption of climate-resilient cultivation practices.

Keywords

Adaptive capacity; Adaptation strategies; Vulnerability index

Introduction

Climate change is one of the major risks of the world, particularly in developing countries such as Nepal, which affects farming communities that heavily depend on natural resources and hence threatens their livelihoods (Gum *et al.*, 2009; Uprety *et al.*, 2017; Yang *et al.*, 2021). Climate change effects have already been observed in Nepal and are anticipated to increase further in the upcoming years. Agriculture, a major economic sector of Nepal, is highly vulnerable to climate change. Among different crops, summer vegetables play an important role in the economy and food security of farmers in Nepal (IPCC, 2022). Changing climate patterns drastically affect, causing altered growth cycles, increased pest infestations, and reduced yields of summer vegetables (Potop *et al.*, 2014). A major study by Phuyal (2013) suggested the urgency of understanding and enhancing the adaptive capacity of summer vegetable growers against climate change.

According to the sixth assessment report, climate change is already disturbing agricultural practices with shifts in temperature, fluctuation in precipitation levels, and the disturbances in frequency and magnitude of extreme climatic events around the globe (IPCC, 2022). Hence, new adaptation and mitigation strategies are essential to secure food security and sustainable livelihoods for farmers (Nelson *et al.*, 2010). In Nepal, the situation is more disturbing due to the country's diverse terrain and climatic conditions (Phuyal, 2013). While developing and implementing adaptation measures it is important to address the site-specific problems and climate vulnerabilities to mitigate emerging climatic issues, enhancing adaptive capacity and climate resilience (Burton *et al.*, 2006; van Aalst *et al.*, 2008) but depending on biophysical indicators, such as exposure and sensitivity only to measure vulnerability could lead to misleading policy implications (Piya *et al.*, 2012).

The IPCC defines vulnerability as the tendency to be adversely affected by climate change with three key dimensions considered; e.g. exposure (i.e. the degree of system exposure to climate hazards), sensitivity (i.e. susceptibility to climate-induced challenges), and adaptive capacity (i.e. the system's ability to adjust to climate change) (IPCC, 2022). Understanding these three dimensions is very important to develop effective climate adaptation strategies for farmers. Different studies have earlier emphasized the importance of local knowledge, resource management, and infrastructural improvements in enhancing resilience as well (Malla, 2008). Such information helps policymakers to identify effective measures, optimize resource allocation, and encourage sustainable practices (Rezvani *et al.*, 2023). Frequent fluctuations in temperature, erratic precipitation, and extreme weather events are observed in the different parts of Nepal e.g. Chitwan, Dhading, Nuwakot, etc. (Shrestha and Aryal, 2011). Variations in the adaptive capacity, exposure to climate risks, and sensitivity to agricultural practices significantly influence overall vulnerability to climate change affecting the livelihood of summer vegetable growers in these districts (Gautam *et al.*, 2013).

Thus, this study aimed to find out the adaptive capacity of summer vegetable growers to climate change in the Trishuli-Narayani River corridor of Chitwan, Dhading, and Nuwakot which were recognized as highly vulnerable to floods, unpredictable rainfall patterns, and prolonged droughts. Though there were certain limitations, our focus was to understand how demography, economy, and social factors influence the adaptive capacity of vegetable farmers. The null hypothesis of the study was said as none of the socioeconomic, political, demographic, institutional or environmental factors affect the vulnerability through adaptive capacity, exposure and sensitivity. The objective of the study was to assess the climate change vulnerability of summer vegetable growers in different study districts in absolute and relative contexts. By thoroughly evaluating those factors with a methodological framework incorporating a comprehensive set of indicators of adaptive capacity, exposure, and sensitivity, this study will provide insights into the adverse effects of climate change and which are key contributing factors to their vulnerability. This comprehensive analysis aimed to assist policymakers and stakeholders, providing insights to develop climate resilience in the region.

Methodology

With the help of primary-level data generated from household surveys among summer vegetable growers, a vulnerability analysis of each household was done. Principal Component Analysis (PCA) was used to calculate vulnerability indices for each household with the help of normalized indicators of exposure, sensitivity and adaptive capacity and finally, vulnerability categorization was done.

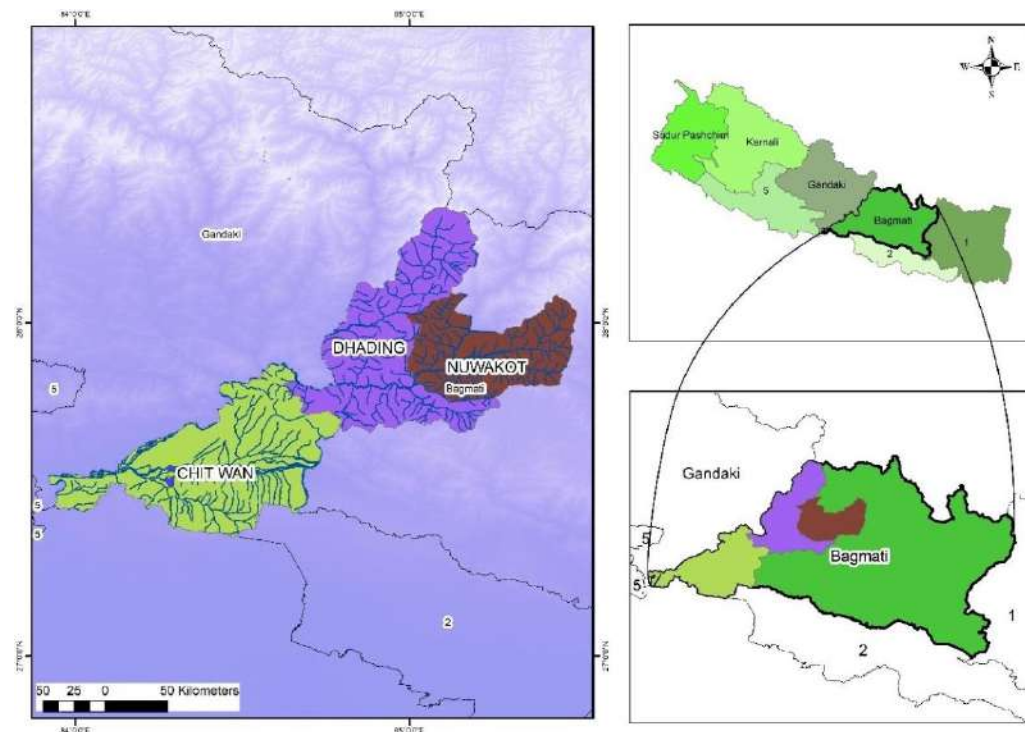


Figure 1: Map of Nepal showing research area in Bagmati Province: Chitwan, Dhading, and Nuwakot

Description of the Study Area

The study was carried out within the Trishuli-Narayani River Corridor of Chitwan, Dhading, and Nuwakot districts, which were chosen due to their high vulnerability to climatic hazards affecting summer vegetable growers. Chitwan district is located in the lowlands (27.61°N, 84.88°E), Dhading district is in the mid-hills (27.90°N, 85.19°E), and Nuwakot district is extended up to the high hills (27.68°N, 85.42°E). This variation in elevation, ranging from roughly 27.61°N to 27.90°N latitude and 84.88°E to 85.42°E longitude, plays a role in the climatic vulnerabilities experienced by farmers (Dandekhya *et al.*, 2017; Luitel *et al.*, 2020; Rai *et al.*, 2022). These areas have distinctly different geographical and climatic conditions, making them suitable for studying the differences in impacts of climate change on summer vegetable farming.

Sample Size and Sampling Techniques

Summer vegetables production area from Chitwan district i.e. Sisai/Sisabazar/Meghauli, Haraiya/Saranpur and Chaukidada/Biretar/Kusumtar, from Dhading district i.e. Benighat, Galchhi and Gajuri, and Nuwakot district i.e. Bidur and Belkot were identified along the Trishuli Narayani River corridor with the help of Agriculture Development Office (ADO) of the respective district. ADO is a district-level authorized government organization assigned for extension and agricultural policy-level work at the ground level. Members from groups of farmers including small, medium, marginalized etc were identified with the help of ADO. The simple random sampling technique was used to finalize 100 summer vegetable growers from each district from a list of summer vegetable growers provided by the respective Agriculture Development Office (ADO) of each district, with 300 growers in total. A pre-tested questionnaire was used for the household survey to collect the primary information for vulnerability analysis.

Indicators for Vulnerability

Vulnerability to climate change is generally influenced by various factors. Indicators for exposure, sensitivity, and adaptive capacity were selected based on the theoretical frameworks. Indicators for the exposure included temperature change, precipitation patterns, the number of extreme weather events, etc. The sensitivity indicators focused on the impacts of climate-related disasters on livelihoods. Adaptive capacity indicators were developed from the IPCC livelihoods framework and household assets such as physical, human, natural, financial, social capital, etc. were considered as indicators (IPCC, 2007; Nelson *et al.*, 2010).

Indicators for Adaptive Capacity

The indicators in Table 1 provide a comprehensive view of the adaptive capacity of summer vegetable growers in Chitwan, Dhading, and Nuwakot. These indicators cover various aspects, such as demographic information, educational level, income sources, land ownership, and access to resources.

Table 1: Indicators for adaptive capacity used in vulnerability assessment among summer vegetable growers in research areas

<i>Component for adaptive capacity</i>	<i>Indicators</i>	<i>Description of the indicators</i>	<i>Unit</i>
Location	Dhading dummy	Residents of the study area compared to Dhading district	Dummy (1 if resident, 0 otherwise)
Location	Nuwakot dummy	Whether the household is from Nuwakot district	Dummy (1 if from Nuwakot, 0 otherwise)
Education	No years of education	Household head's ability to read and write	Years
Demographics	Household head age	Age of the household head	Years
Demographics	Household head sex	Sex of the household head	Male/Female
Demographics	Ethnic category	Ethnic group of the household head	Categorical
Household size	No Household members	Total number of people in the household	Count
Migration	Migrant members of the home	Number of household members living elsewhere	Count
Income diversification	Income from non-agriculture source	Income from sources other than agriculture (Nepalese rupees)	NRs (thousands)
Agricultural experience	Experience in agriculture	Number of years involved in agriculture	Years
Experience in vegetable	Experience in summer vegetable farming	Number of years involved in vegetable farming	Years
Land ownership	Land ownership	Amount of land owned by the household	Kattha (0.0126 ha)
Land use	Area coverage by vegetable	Area of land used for summer vegetables	Kattha (0.0126 ha)
Food security	Food sufficiency	Whether the household produces enough food for itself	Yes/No
Climate change awareness	Knowledge of climate change	Whether the household is aware of climate change	Dummy (1 if aware, 0 otherwise)
Pest management	Beneficial insects seen on the farm	Increase in the number of beneficial insects	Count
Access to services	Access to extension services	Whether the household receives agricultural extension services	Dummy (1 if receives services, 0 otherwise)
Access to information	Access to communication	Whether the household has access to communication services	Dummy (1 if has access, 0 otherwise)
Access to finance	Access to credit	Whether the household has access to credit services	Dummy (1 if has access, 0 otherwise)

<i>Component for adaptive capacity</i>	<i>Indicators</i>	<i>Description of the indicators</i>	<i>Unit</i>
Training	Training number	Number of trainings received on climate change adaptation	Count
Social capital	Involvement in cooperatives	Whether the household participates in cooperatives	Dummy (1 if participates, 0 otherwise)

Indicators for Exposure

The indicators for exposure were selected based on the hypothesis that a higher rate of change in temperature and precipitation, as well as a higher frequency of floods, droughts, and hailstorms, would signify higher exposure to climate change and severe weather conditions. Table 2 presents indicators of exposure to climate change for summer vegetable growers in Chitwan, Dhading, and Nuwakot. These indicators are essential for understanding the extent to which farmers are exposed to various climate-related events and their impacts on their agricultural practices. These exposure indicators highlight the challenges faced by farmers in the study area and underscore the urgent need for adaptive strategies and resilience-building measures.

Table 2: Indicators for exposure used in vulnerability assessment among summer vegetable growers in research areas

<i>Component for exposure</i>	<i>Indicators</i>	<i>Description of the indicators</i>	<i>Unit</i>
Crop disease	Notice of changes in the Field with new diseases	Increase in the number of new diseases	Dummy (1 if increased, 0 if not)
Insect pest	Notice of changes in the field with new insects	Increase in the number of new insects	Dummy (1 if increased, 0 if not)
Weeds	Notice of changes in the field with new weeds	Increase in the number of new weeds	Dummy (1 if increased, 0 if not)
Pollinators	Notice a decrease in pollinators	Decrease in the number of pollinators	Dummy (1 if decreased, 0 if not)
Income Impacts	Have IPA changed	Effect of climate change on income per unit area	Dummy (1 if increased, 0 if not)
Market impacts	CC effect on market prices	Change in market prices due to climate change	Dummy (1 if increased, 0 if not)
Summer temperature	Increase in summer temperature	Increase in average summer temperature	Dummy (1 if increased, 0 if not)
Hot days	Increase in hot days	Increase in the number of hot days	Dummy (1 if increased, 0 if not)
Delayed precipitation	Delay in monsoon	Delay in the arrival of the monsoon season	Dummy (1 if delayed, 0 if not)
Intensity of precipitation	Increase in intensity of summer rainfall	Increase in summer rainfall intensity	Dummy (1 if increased, 0 if not)
Frequency of precipitation	Increase in frequency of summer rainfall	Increase in the number of summer rainfall events	Dummy (1 if increased, 0 if not)
Duration of precipitation	Increase in summer rainfall	Increase in summer rainfall events	Dummy (1 if increased, 0 if not)

<i>Component for exposure</i>	<i>Indicators</i>	<i>Description of the indicators</i>	<i>Unit</i>
Droughts	Increase in droughts	Increase in the number of droughts in the past 10 years	Dummy (1 if increased, 0 if not)
Water availability	Decrease in water level	Decrease in water table level	Dummy (1 if decreased, 0 if not)
Floods	Frequency of floods	Number of floods in the last 10 years	Count
Droughts	Frequency of droughts	Number of droughts in the last 10 years	Count
Windstorms	Frequency of windstorms	Number of windstorms in the last 10 years	Count
Landslides	Frequency of landslides	Number of landslides in the last 10 years	Count

Indicators for Sensitivity

Sensitivity points out the extent to which a system is influenced by climate-related factors. The indicators for sensitivity were selected to reflect the livelihood impacts of climatic disasters. The hypothesis is that greater impacts, such as deaths and losses of land, livestock, and crops, would indicate greater sensitivity to such events. Table 3 presents indicators of sensitivity to climate-related stimuli among summer vegetable growers in Chitwan, Dhading, and Nuwakot. These indicators focus on factors such as water availability, irrigation sources, and the physical features of the land. Farmers' sensitivity to climate-related stimuli is influenced by factors such as distance from rivers and irrigation canals. The availability of facilities such as irrigation channels, tube wells, and ponds also affects sensitivity.

Table 3: Indicators for sensitivity used in vulnerability assessment among summer vegetable growers in research areas

<i>Component for sensitivity</i>	<i>Indicators</i>	<i>Description of the indicators</i>	<i>Unit</i>
Male children in the household	Below 15 years male	Number of male children under 15 years old	Count
Female children in the household	Below 15 years female	Number of female children under 15 years old	Count
Male adults in the household	Above 60 years male	Number of male household members over 60 years old	Count
Female adults in the household	Above 60 years female	Number of female household members over 60 years old	Count
Livelihood source	Agriculture as the primary source of income	Whether agriculture is the main source of income for the household	Dummy (1 if primary source, 0 otherwise)
Income impacts	Income from agriculture	Income generated from agriculture (Nepalese rupees)	NRs (thousands)
Land loss	Land damaged by climate hazards	Amount of land damaged by climate hazards	Kattha (0.0126 ha)
Crop loss	Crops damaged	Amount of crops damaged by climate hazards	Quintal

Livestock loss	Animal died	Number of animals lost due to climate hazards	Count
Access of river	Distance from river	Distance from the nearest river	Kilometres
Access to an irrigation canal	Distance from an irrigation canal	Distance from the nearest irrigation canal	Kilometres
Access of irrigation	Facility of irrigation	Whether the household has access to irrigation	Dummy (1 if has access, 0 otherwise)
River for irrigation	The facility of the river for irrigation	Uses river water for irrigation	Dummy (1 if used, 0 otherwise)
Borehole for irrigation	Facility of borehole	Uses borehole water for irrigation	Dummy (1 if used, 0 otherwise)
Irrigation channel	Facility of irrigation channel	Uses irrigation canal water for irrigation	Dummy (1 if used, 0 otherwise)
Tube well for irrigation	The facility of tube well	Uses tube well water for irrigation	Dummy (1 if used, 0 otherwise)
Pond for irrigation	Facility of pond	Uses pond water for irrigation	Dummy (1 if used, 0 otherwise)

Data Analysis

The data were normalized and then it was used to calculate indices of adaptive capacity, exposure and sensitivity. After that, the vulnerability indices were calculated for each household of summer vegetable farmers (IPCC, 2007; Lien, 2019). Suitable indicators were taken and normalized via the following formula provided.

Normalized value = (Observed value - Mean)/Standard deviation of the indicators

The data were subsequently analyzed via descriptive statistics, and indices for adaptive capacity, exposure, and sensitivity were calculated. Principal component analysis (PCA) was applied to assign weights to the identified indicators. The first Eigenvalue scores obtained from PCA were used as a weight for vulnerability analysis in the study. The indices were calculated via the following formula.

$$I_j = \sum_{i=1}^k b_i \left(\frac{a_{ji} - x_i}{s_i} \right) \quad - \quad \text{Equation 1}$$

Where,

i = respective value of index

b = loadings from the first component from PCA (PCA1) taken as weights for the respective indicators

a = indicator value

x = mean indicator value

s = standard deviation of the indicators

The vulnerability indexes for each household were then calculated using Equation 2 given below.

$$V = E + S - AC \quad \text{- Equation 2}$$

Where,

V = Vulnerability index,

E = Exposure index,

S = Sensitivity index and

AC = Adaptive capacity index for the respective household

Results

Descriptive Characteristics of Adaptive Capacity, Exposure, and Sensitivity

Table 4 describes the various indicators of adaptive capacity, exposure, and sensitivity among summer vegetable growers in Chitwan, Dhading, and Nuwakot.

Adaptive Capacity Indicators

The average age of the household heads was 49.72 years old, indicating a mature population of summer vegetable growers. Households had been engaged in agriculture for an average of 22.01 years, specifically in summer vegetable farming, for 17.13 years. The average landholding area was 16.04 hectares, with 4.09 hectares dedicated to summer vegetables. Only 15% of the households relied primarily on agriculture for their income. However, 68% were aware of climate change, and 85% had access to communication services. Involvement in the cooperatives was moderate, with 76% of the households involved among respondent vegetable growers.

Exposure Indicators

Farmers reported significant changes in field conditions due to climate-related events. These included increases in new diseases, insects, and weeds. A notable decrease in pollinators and an increase in beneficial insects were observed, indicating ecosystem changes. Over the past 10 years, the frequency of floods and droughts has been notably high, averaging 2.07 floods and 3.86 droughts, respectively.

Sensitivity Indicators

Sensitivity to climate-related stimuli is influenced by water availability, irrigation sources, and topography. Farmers were, on average, 1.86 kilometres away from rivers and 0.33 kilometres from irrigation canals. Approximately 55% of the farmers reported a lack of water sources, impacting crop production. However, 71% had access to irrigation facilities, with 23% using rivers and 13% using boreholes for irrigation. On average, 5,334.18 hectares of land were damaged by climate hazards, with crop losses averaging 93,883.33 tons. Additionally, an average of 7.85 animals died due to climate hazards.

Table 4: Descriptive characteristics of the adaptive capacity, exposure and sensitivity of summer vegetable growers in the research areas

<i>Indicators</i>	<i>Avg (Std)</i>	<i>Indicators</i>	<i>Avg (Std)</i>	<i>Indicators</i>	<i>Avg (Std)</i>
<i>Adaptive Capacity</i>					
Dhading dummy	0.33 (0.47)	Nuwakot dummy	0.33 (0.47)	No. of years of education	6.80(3.79)
Age of HH	49.72 (14.74)	Sex of HH	0.17 (0.37)	Ethnic Category	0.55 (0.49)
No. of HH members	6.01 (2.75)	HHM staying away from home	0.67 (1.38)	Income from non-agriculture (in thousands)	183.36 (317.46)
Experience in agriculture	22.01 (11.77)	Experience in summer vegetable production	17.13 (9.61)	Own land holding	16.04 (15.68)
Area of vegetable	4.09 (4.26)	Food sufficiency	0.19 (0.39)	Knowledge of CC	0.68 (0.46)
Beneficial insects on farm	0.33 (0.47)	Access to ext. service	0.66 (0.47)	Assess to communication	0.85 (0.35)
Access to credit	0.51 (0.50)	Training number	0.55 (1.03)	Involvement in cooperatives	0.76 (0.42)
<i>Exposure</i>					
Change in field new disease	0.81 (0.38)	Change in field new insect	0.79 (0.40)	Appearance of new weeds	0.58 (0.49)
Notice a decrease in pollinators	0.67 (0.46)	Have IPA changed	0.69 (0.46)	CC effect on market prices	0.22 (0.41)
Increase in summer temp	0.75 (0.42)	Increase in hot days	0.73 (0.44)	Delay in monsoon	0.7 (0.45)
Increase in intensity of summer rainfall	0.63 (0.48)	Increase in frequency of summer rainfall	0.63 (0.48)	Increase in summer rainfall	0.64 (0.47)
Increase in drought	0.71 (0.45)	Decrease in water level	0.66 (0.47)	Frequency of flood	2.07 (3.17)
Frequency of drought	3.86 (2.87)	Frequency of hailstorm	2.50 (1.98)	Frequency of windstorm	3.01 (2.23)
Frequency of landslides	1.25 (2.24)				
<i>Sensitivity</i>					
Below 15 yrs male	0.69(0.77)	Below 15 yrs female	0.66 (0.84)	Sixty years above male	0.33(0.48)
Sixty years above female	0.32 (0.50)	Agriculture as a primary income	0.84 (0.36)	Income from Ag in _000	228.83 (137.69)
Land damaged by climate hazards	5334.18 (92375.99)	Crops losses	93883.33 (226985.97)	Animal died	7.85 (64.38)
Distance from river	1.86 (1.63)	Distance from an irrigation canal	0.33 (0.36)	Facility of irrigation	0.71 (0.45)
The facility of the river for irrigation	0.23 (0.42)	Facility of boring	0.13 (0.34)	Facility of irrigation channel	0.54 (0.49)
Facility of tube	0.16 (0.37)	Facility of pond	0.050.21)		

Indices of Adaptive Capacity of Chitwan, Dhading and Nuwakot

The adaptive capacity among summer vegetable farmer respondents varied across the research area (Figure 1), which demonstrated the level of differences in adaptive capacity among these districts.

Farmers from Chitwan presented a broader range of adaptive capacity, from approximately -2.5 to -6.2. This wide range indicates a mix of challenges and successful adaptation strategies among farmers. In Dhading, the range of adaptive capacity was narrower, from approximately -4.2 to -2.8, with predominantly negative values. This suggests significant obstacles to adaptation in Dhading. Like Dhading, Nuwakot had a narrower range, from approximately -1.9 to -3.1. This range indicates both challenges and successes in the farmers' ability to adapt.

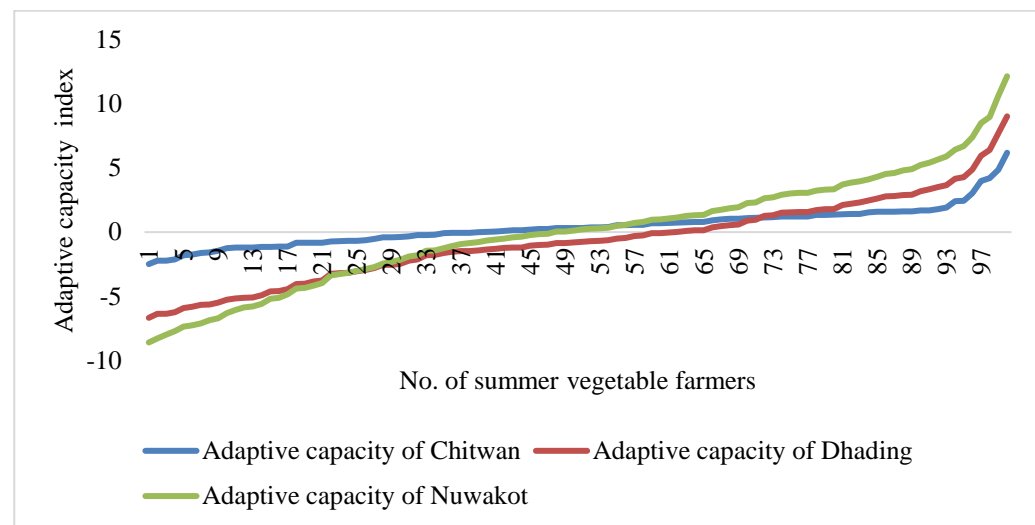


Figure 1: Adaptive capacity index of summer vegetable growers in the research area

Exposure Indices of Chitwan, Dhading and Nuwakot

The exposure index of summer vegetable growers in the research areas delineated the degree of vulnerability to various environmental stressors and socioeconomic factors (Figure 2). The exposure index of Chitwan ranged from approximately -2.5 to -2.3, reflecting a spectrum of challenges and potential opportunities. Dhading exhibited a wider range, ranging from nearly -6.0 to 2.6, indicating potentially heightened vulnerability among farmers. Nuwakot displayed a broad range, from approximately -5.3 to -3.0, highlighting the diverse exposures that farmers face.

Negative values suggest greater susceptibility to adverse conditions, whereas positive values imply resilience or less vulnerability. The data underscore the intricate interplay of factors impacting farmers' livelihoods, emphasizing the need for targeted interventions and adaptive strategies to mitigate risks and enhance resilience in the face of evolving environmental and socioeconomic dynamics. Exposure indicators, such as temperature fluctuations and extreme weather events, significantly impact vulnerability.

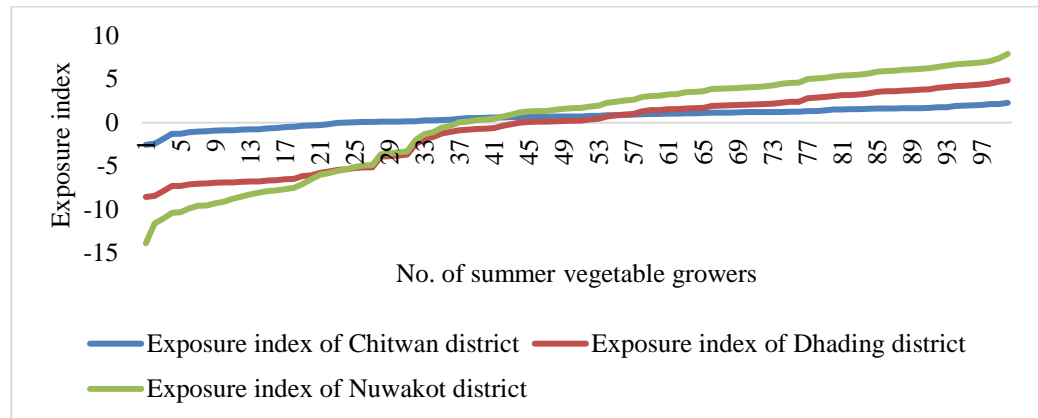


Figure 2: Exposure indices of summer vegetable growers in the research areas

Sensitivity Indices of Chitwan, Dhading and Nuwakot

The sensitivity index among summer vegetable growers in the Chitwan, Dhading, and Nuwakot districts provides insights into their susceptibility to various stressors and changes in environmental and socioeconomic conditions. In Chitwan, the sensitivity score ranged from approximately -2.9 to +3.2, indicating a spectrum of sensitivities among farmers, with some experiencing greater vulnerability than others. Dhading displayed a narrower range, ranging from approximately -3.9 to +2.5, suggesting potentially heightened sensitivity among farmers in this district, with some facing significant challenges. Similarly, in Nuwakot, the sensitivity score ranged from approximately -2.8 to +3.6, highlighting diverse levels of sensitivity among farmers, with some exhibiting greater vulnerability to external factors. Negative values indicate greater sensitivity, whereas positive values suggest lower vulnerability or resilience. The data underscore the complex interplay of factors influencing farmers' sensitivity and emphasize the importance of targeted interventions and support mechanisms to increase resilience and mitigate risks in agricultural communities. The sensitivity indicators, which focus on the livelihood impacts of climate-related disasters, highlight the importance of the local context in vulnerability assessments.

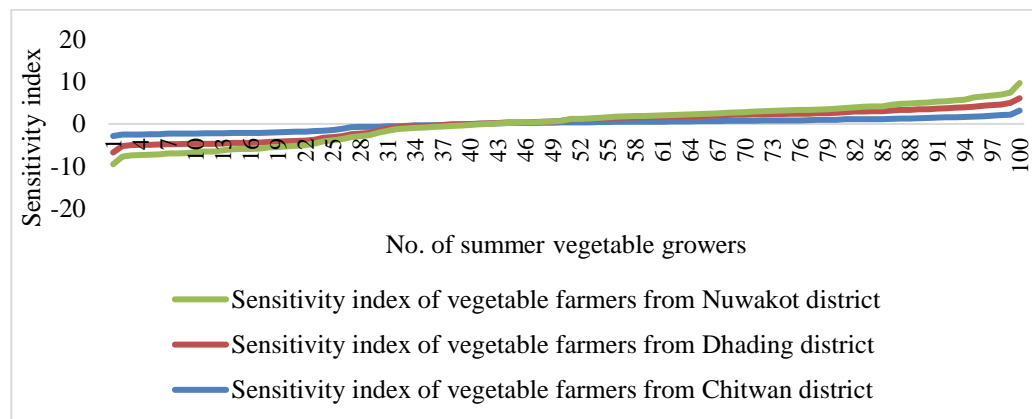


Figure 3: Sensitivity index of the summer vegetable growers in the research area

Vulnerability Indices of Chitwan, Dhading and Nuwakot

Building on the concepts of exposure, sensitivity, and adaptive capacity discussed earlier, the vulnerability indices among summer vegetable growers in the Chitwan, Dhading, and Nuwakot districts provide a measure of their susceptibility to various risks and stressors, encompassing both socioeconomic and environmental factors. Figure 4 visually shows the distribution of the range of vulnerability indices among the vegetable growers in the research areas.

In Chitwan, the vulnerability index among summer vegetable growers ranged from approximately -4.9 to +5.8, indicating a wide scale of vulnerability among them in the district. This range showed that some farmers faced higher risk, and others experienced relatively lower vulnerability. Similarly, in Dhading, the vulnerability index ranged from approximately -5.7 to +7.1. This suggested that farmers in this district may experience even higher extremes in vulnerability, with some facing considerable challenges to their livelihoods, whereas others are more resilient to the impacts caused. Whereas, in Nuwakot, the vulnerability index ranged from approximately -4.2 to +7.3, again highlighting diverse levels of vulnerability among summer vegetable farmers. Some farmers in Nuwakot presented high susceptibility to external factors and changes, whereas others showed a greater capability to fight these conditions. Negative signs with the vulnerability index indicated higher vulnerability, suggesting that the farmers were more susceptible to adverse conditions and positive signs suggested lower susceptibility or higher resilience among farmers. These data suggested the need for targeted interventions and support mechanisms to increase resilience and mitigate risks, thereby improving the livelihoods of summer vegetable farmers in three districts. The varying vulnerability indices among farmers in the three districts highlighted the significant influence of geographic and climatic diversity.

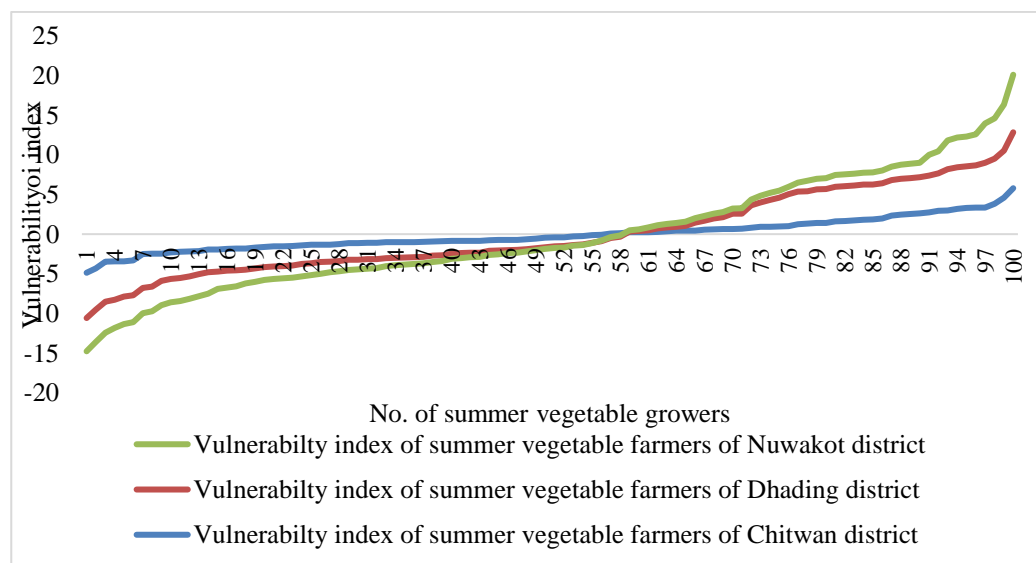


Figure 4: Vulnerability indices of summer vegetable growers in the research areas

Vulnerability Spectrum among Summer Vegetable Growers

Table 5 provides an overall snapshot of the vulnerability assessment conducted on 300 summer vegetable growers from three districts in Nepal i.e. Chitwan, Dhading, and Nuwakot. The data revealed a diverse range of vulnerability levels among these farmers, as measured by a vulnerability index that considers both socioeconomic and environmental factors. In Chitwan, 31% of the farmers fall under the "highly vulnerable" category, indicating significant challenges. However, a contrasting 46% are classified as "less vulnerable," suggesting a wider spectrum of vulnerability compared with other districts. The average vulnerability index for Chitwan is -0.11, placing it in the "slightly vulnerable" category. The standard deviation of 4.71 signifies a moderate spread of vulnerability scores within the district. In Dhading, the highest proportion (41%) of farmers were categorized as "highly vulnerable," highlighting that a potentially larger population faces critical challenges. The average vulnerability index in Dhading is 0.09, which is closer to the average vulnerability level. However, the standard deviation of 5.71 indicates a wider range of vulnerability scores than Chitwan does. In Nuwakot, 31% of the farmers were classified as "highly vulnerable", and 47% were classified as "less vulnerable." The average vulnerability index for Nuwakot is -0.10, suggesting slight vulnerability. The standard deviation of 7.30 reveals the highest spread of vulnerability scores among the three districts.

Table 5: Vulnerability categorization due to climate change of summer vegetable growers in the research areas

<i>District</i>	<i>Highly vulnerable (%)</i>	<i>Moderately vulnerable (%)</i>	<i>Less vulnerable (%)</i>	<i>Average vulnerability index</i>	<i>Standard deviation</i>
Chitwan	31	23	46	-0.11	4.71
Dhading	41	18	41	0.09	5.71
Nuwakot	31	22	47	-0.10	7.3

Discussion

In our study, we determined the range of different vulnerability experiences of summer vegetable growers in three different districts. Each district, with its problems and opportunities, has a different range of vulnerability indices, and farmers are tackling these indices in a specific way. Vulnerability indices ranged from -4.9 to +5.8 in Chitwan district, from -5.7 to +7.1 in Dhading district and -4.2 to +7.3 in Nuwakot district among identified summer vegetable farmers for this study purpose. Vulnerability assessment tools were applied where principal component analysis was performed generating an index ranging from -10 to +10 with -10 denoting highly vulnerable and +10 as the least vulnerable due to climate change and associated parameters. The study may not fully include all the dimensions of vulnerability, i.e. qualitative aspects like cultural practices or social networks, which may also influence adaptive capacity.

In Chitwan, among summer vegetable growers, strong adaptive capacity was found, which is due to better access to different resources and infrastructures which is similar as reported by Regmi *et al.* (2010), who emphasized the importance of resource availability for climate-resilient agriculture. Different interventions should be done to address the varied level differences in resources and support among farmers across different places, hence facing significant obstacles to adaptation. Paudel *et al.* (2014) also suggested the need for a similar level of interventions in their research areas as well. It was found that Nuwakot should focus on improving the accessibility of resources and infrastructure to mitigate the impacts of climate change. Also in Chitwan and Dhading as well, it was found that different socioeconomic factors significantly affect the functional access to existing resources like climate information services which are useful tools to strengthen the adaptation capacity (Bajracharya *et al.*, 2023; Rai *et al.*, 2022).

Tiwari *et al.* (2014) identified those key challenges in their regions as well. Our findings also uphold the results of Adhikari *et al.* (2015). They also reported different vulnerability levels across different districts and the nature of vulnerabilities varies, reflecting the unique nature of each region. In similar research in the central part of Nepal, it was found that low resources, inadequate income, and finally food insecurity were the primary causes of vulnerability due to climate change (Giri *et al.*, 2021). To address those challenges, collective efforts by the government offices, different organizations, and residents were important. Enhancing awareness among people, infrastructure development, and access to resources will be crucial in building resilient agricultural communities capable of coping with climate change. Manandhar *et al.* (2011), and Gentle and Maraseni (2012) also highlighted similar importance of those factors in their research areas.

In our study, we found 56.33% of summer vegetable growers among our respondents had a –ve vulnerable coefficient whereas 43.66% of respondents found with +ve vulnerable coefficient. Concerning such information, local bodies, respective Agriculture Development Office (ADO) and other agriculture institutes should intervene. By adopting site-specific interventions, the vulnerability of summer vegetable farmers in all three districts can be significantly reduced. That would improve their livelihoods and resilience against climate-related risks. Adger (2006), Eakin and Luers (2006), and Smit and Wandel (2006) also highlighted the similar importance of building resilience to climate change and its effects on farming. As found in our research areas, at the policy level, especially the local governments are mobilizing natural resources and social capital efficiently so that an adequate supply of adaptation services will be available at the farmers' level in Nepal (Karki *et al.*, 2021). Hence it follows the Local Adaptation Plans of Action (LAPA) and National Adaptation Programme of Action (NAPA) by refining local adaptation strategies and addressing barriers like resource constraints supporting climate-smart agriculture (GoN, 2011) and ecosystem-based adaptation while providing evidence for policy implementation, fostering collaborations, and promoting climate resilient agricultural practices, crop diversification according to Agriculture Development Strategy 2015-2035 (GoN, 2015).

Conclusion

This study analyzed the vulnerability status due to climate change in the Chitwan, Dhading, and Nuwakot districts of Nepal and found distinct variations in vulnerability among vegetable growers from these districts. It was found that Dhading was the most vulnerable district due to its high exposure to climate hazards, lower adaptive capacity, and limited access to different resources to vegetable farmers whereas, Chitwan, with lower vulnerability than Dhading, can be linked with better access to resources and infrastructure, enhancing its resilience to climate change. With this situation, Nuwakot reported a wide range of vulnerability indices reflecting enormous differences among the vegetable growers in the district. Thus, our study revealed that socioeconomic factors among summer vegetable growers affect how they utilize the resources available hence showing there is a need for specific interventions based on the vulnerabilities of each region. With high numbers of vulnerable vegetable growers, Dhading may require more infrastructural support in terms of resources and capacity building and Nuwakot, we should address fair access to resources and infrastructure development as well among all vegetable growers across the district. Policymakers must prioritize resource allocation, capacity-building initiatives, and infrastructure development to mitigate the adverse effects of climate change on vulnerable farming populations at the local level. By addressing these key areas, we can support sustainable agricultural practices in those districts. Our research contributes to a deeper understanding of how climate change impacts the vulnerability of agricultural communities. This study provides a foundation for developing effective adaptation strategies tailored to specific regional needs and these findings underscore the need for integrating localized research into national frameworks to enhance climate resilience in agriculture. Future research could explore the most effective methods for capacity building and investigate ways to encourage the adoption of climate-resilient agricultural practices among vegetable growers.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes
Collected the data	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The Current State of the Natural Resource Potential of the Seaside Regions of Ukraine

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Abstract

This study examines the state of the natural resource potential of the coastal regions of Ukraine, related to Russian aggression against Ukraine. The cited studies show that Ukraine has developed several legislative and regulatory acts in the field of use of the natural marine environment and adjacent territories, which correspond to international and European legal acts. Grossly violating international law, Russia caused significant economic damage not only to the population of the annexed territories but also to the environment. According to the Ministry of Environment of Ukraine, more than 3,600 crimes against the environment were recorded. This is the pollution of sea waters, the destruction of nature-protected areas, flora and fauna unique to this region. Damages caused to the environment are preliminarily estimated at more than 60 billion US dollars. The research methodology is based on statistical analysis of expert assessments given in official open state sources and mass media. Analytical studies made it possible to establish certain types of biodiversity that will be difficult to reproduce, as well as to outline the magnitude of the main catastrophic consequences of Russian aggression not only for Ukraine but also for the entire civilized world. Based on the conducted research, the conclusions were made that the existing international legal acts do not fully ensure adequate protection and protection of the environment, which in turn necessitates the development and improvement of effective legal, economic and other mechanisms of responsibility for ecocide. At this stage of military aggression in Ukraine, issues of environmental monitoring and assessment of growing losses come to the fore.

Keywords

Coastal areas; Natural resource potential; Military aggression; Rating; Damages

Introduction

Marine resources contribute to human well-being by providing food security and creating jobs. Almost 90% of the volume of freight transportation of goods is carried out by sea transport, and approximately 50% of all international tourist trips. The ocean is valued at more than US\$24 trillion, while the annual “gross marine product” is at least US\$2.5 trillion, which according to the World Bank ranks seventh in the national GDP of the world economy (WWF, 2015). The economic activity of the coastal regions of the state largely depends on the ability to effectively use three natural ecosystems - terrestrial, coastal and marine. The UN Convention on the Law of the Sea (UNCLOS, 1997) is considered to be an important legal factor in the development of the system of using natural mineral resources in international practice. The Convention defines the rights and responsibilities of nations regarding the use of the oceans and seas, establishing principles of management for business, and environmental protection. This document introduced several provisions, including the establishment of maritime areas and their respective limits of exclusive economic zones (EEZ), jurisdiction on the continental shelf, deep-sea mining, and the regime for the protection. The implementation of UNCLOS influenced the evolution of the economic development of individual states (Balla, 2016). The European Union exercises collective jurisdiction over the largest exclusive economic maritime zone in the world, comprising more than 20 million km². The EU maritime economy employs more than 3.6 million people, generating a gross added value of almost 500€ billion per year. The single market for fish products in the EU is one of the largest in the world (Balla, 2017). The economic independence of Ukraine, its sustainable development and its integration into the Euro-Atlantic political, legal and security space largely depend on the effectiveness of the implementation of the state's maritime policy within the framework of global and European legal acts regarding the use of the natural resource potential of the marine environment. The Black and Azov Seas, which wash the shores of Ukraine, belong to the Atlantic Ocean basin. These seas are of great economic importance as a promising region for the production of hydrocarbon raw materials, an area for fishing, an important transport highway, and a region of great recreational potential. According to expert assessments, the potential of the Azov and Black Seas within the economic zone of Ukraine can ensure an increase in the annual volume of commercial products produced from the aquatic biological resources of the seas by approximately 56 million US dollars. The impact of Russia's military aggression on the sea is complex and multi-vectored, because it not only shook security in this region, but also led to changes in shipping and water management, affected marine biological and hydrological research that Ukrainian scientists have been conducting for decades, and became a new environmental challenge. As a result of the pollution of the marine environment, the unbalanced use of natural resources, as well as the lack of a system of integrated management of the use of natural resources of the Azov and Black Seas, Ukraine lost (approximately) 50 million US dollars every year. Throughout the Russian aggression in Ukraine, a report has been published annually on the direct damage to the infrastructure, which amounted to 155 billion US dollars. Unfortunately, however, it lacks data on environmental damage (KSE, 2024). According to data from the Ukrainian government, 600 species of fauna and 750 species of flora were damaged or destroyed (Ecological, 2023). As of August 2024, due to Russia's armed aggression, damage to the environment of Ukraine amounted to more than 60 billion US dollars (Economic Truth, 2024). Currently, there

are several publications related to the impact of military aggression on certain types of natural resources: forest (Senchyn, 2022), soil (Dmytruk, 2022) and comprehensive studies analyzing the impact of Russian aggression on land, water, and biological resources (Strokal *et al.*, 2023). Research on the impact of environmental change on people's health and their psychological state (Khrushch *et al.*, 2023), and training of specialists to assess damage caused by military aggression (Makarenko *et al.*, 2022; Otsinka, 2023) deserve special attention. Given that Ukraine is a maritime state, in our opinion, issues related to the impact of Russian aggression on the coastal regions, including the flora and fauna, deserve special research.

The purpose of this publication is to draw the attention of the global communities to the problem of protecting the unique natural environment of the coastal territories of Ukraine, certain species of flora and fauna that are suffering from Russian aggression and are on the verge of destruction. The achievement of the set goal is ensured by the concentration of a single document of statistical data on the damage caused by Russian aggression to the coastal regions. The practical significance of the publication lies in the awareness of the magnitude of damages caused to the environment of the coastal regions of Ukraine, the use of these data by national and international institutions for the development and improvement of legal, technical and economic mechanisms for the assessment of damages, their compensation and legal responsibility for their infliction.

Methodology

The methodology of these studies includes problem formulation, collection and analysis of geospatial information, processing of input information, interpretation of the obtained results and development of conclusions and proposals on this basis. The main issue of the study is the confirmation of facts regarding the impossibility of suspending the destruction of the natural resource potential of the environment by aggressive military actions using modern legal mechanisms. The research methodology is based on the analytical analysis of statistical data on the damage caused by Russian aggression to Ukraine, publicly available by mass media, government institutions, and individual publications for the period 3 from 2022 to August 2024. Processing incoming geospatial information allows us to determine not only the amount of damage in monetary terms but also to identify individual species of flora and fauna that will be practically impossible to reproduce. It should be noted that since Russia's aggression continues, the numerical values of the losses are not final, but constantly change in time. as well as on the territory. Thus, the reliability of the given data corresponds to the date of their determination.

Research of Natural Resource Potential of the Azov-Black Sea Basin of Ukraine

Natural resource potential of the Azov-Black Sea basin of Ukraine in the pre-war period

Ukraine has the largest length of sea coast among the countries of the Azov-Black Sea basin (2,759.2 kilometres) and more than 72 thousand square kilometres of the exclusively maritime economic zone. A significant part of the national gross domestic product is formed by five oblasts of Ukraine, which have access to the sea and occupy about 27 per cent of its territory. The majority of the population in this territory lives at

a distance of no more than 60 kilometres from the sea and is closely related to maritime activities (Morska, 2018). In the late 1990s, the realization of the importance of marine natural resources and the recognition of the actual and potential value of the marine environment as an economic resource led to increased competition for its management. Until 2014, Ukraine controlled 137,000 square kilometres of the seas. This territory is called an exclusive zone. And within these limits, it is Ukraine that has the right to explore and extract minerals (Figure 1.)



Figure 1: Map of Ukraine before full-scale aggression (Uk.wikipedia, 2024)

About 150 species of zooplankton organisms have been found within the economic zone of Ukraine. The macrophyte flora of the Ukrainian part of the Black Sea shelf includes about 270 species. The algal flora is dominated by red algae (about 140 species). Plant communities are widespread at a depth of 0 to 20 m, but the largest thickets of macrophytes are concentrated at a depth of 1 to 5 m (Okeanografniy, 2009). Aquatic biological resources of the sea are the most important for coastal regions, and fisheries play a significant role in providing the population with food. The ichthyofauna includes almost 200 species and subspecies, including occasional freshwater and marine fish known from isolated finds. The basis of the ichthyofauna is marine fish. The main commercial fish species in the Azov-Black Sea basin in recent decades are sprat and hamsa. In the Black Sea, the share of these species from the total catch of Ukraine is more than 98%. In the Sea of Azov, fishing is based on Lyulka, halibut, pylengas and zander. Over the past ten years, there has been a reduction in the catch of aquatic biological resources by almost 2.5 times (Morska, 2018). On the Ukrainian shelf, significant reserves of minerals have been explored, including up to 1751,3 billion m³ of

natural gas and up to 409.8 million tons of crude oil, which is more than 40 per cent of Ukraine's total hydrocarbon reserves (Decree, 2024)¹. At the same time, only 4 per cent of them were mined, while up to 70 per cent of explored reserves were extracted from coastal deposits. 4-5% of the subsoil of Ukrainian water areas has been explored. According to these data alone, about two trillion cubic meters of gas are already stored in the exclusive economic zone of Ukraine. Ukraine will use approximately that much in just 50 years. In 2013, Ukraine's foreign companies issued a permit for oil production in the Black Sea. The agreement provided for work until 2063 and investments in the amount of 4 billion US dollars (VoA, 2021). Ukrainian geologists note that Crimea is very rich in natural minerals. For example, from the total reserves of Ukraine, about 50% of flux limestone, 30% of iron ore and 25% of soda are stored in this territory. The peninsula is also rich in deposits of bromine and potassium salt. Favourable natural and climatic conditions make it possible to develop resorts and tourism in the coastal strip of the Black and Azov seas. The length of the sea coast of Ukraine is more than 2,700 km, of which 1,160 km are valuable beaches. Two main regions of concentration of natural recreational resources are distinguished here - Crimean and Azov-Black Sea. A valuable element of Ukraine's recreational potential is deposits of healing mud of marine origin. The presence of attractive and diverse landscapes, sources of mineral water and mud creates all the conditions for the formation of a highly developed industrial recreational and tourist complex.

Natural resource potential during the period of occupation

Due to annexation and Russian aggression, the area of the Black Sea and Azov Sea controlled by Ukraine decreased by three times (Figure 2).

According to government information, almost 3,600 Russian crimes against the environment were recorded during the full-scale invasion. The war caused losses worth 55 billion dollars to Ukraine. In addition, hundreds of thousands of square kilometres of land are potentially contaminated by mines and shells. The level of seawater pollution in certain water areas of the coastal strip exceeds the maximum permissible concentrations of oil products, phosphorus and phenols by an average of five times (Society, 2023). In addition, significant water areas of the territorial sea of Ukraine and coastal defence strips are filled with minefields of the aggressor country (Russia). The main effects of war on coastal and marine ecosystems include chemical and acoustic pollution, physical damage to natural habitats, and the decline of conservation activities. Military actions also hinder ecological monitoring. According to official data, compensation for losses of mineral resources in the Crimea, and on the Black Sea shelf alone amounts to about 50 billion dollars. Currently, Ukraine does not control the pumping of gas at the wells of the state company Chornomornaftogaz, which were seized by Russia. This is about two billion cubic meters of gas per year. Experts note that Russia conducts mining in a barbaric manner, and in 5-10 years these deposits may be flooded and will not be subject to further exploitation. Military actions significantly influenced and changed the system of management and control of overfishing. Changes

¹ Decree of the President of Ukraine (2024). On the decision of the National Security and Defense Council of Ukraine dated July 17, 2024 "On the Maritime Security Strategy of Ukraine" Document 468/2024, adopted on July 17, 2024.

in the intensity and location of fishing affect fish stocks. Analysis by FAO showed that Ukrainian marine fishing fleets were out of action during 2022, losing almost the entire annual catch of 13,000 tons of fish. The total losses of the fishing industry in 2022 amounted to 47 million US dollars, including 25.4 - fisheries and 21.6 - aquaculture (Society, 2023; State, 2023). To determine real military aggression on the ecology of the seas, estuaries and wetlands, special further research is needed. Significant areas of coastal and marine water areas were protected at 20 objects of national significance. Since February 2022, access to two nature conservation areas has been lost: the Black Sea Biosphere Reserve and National Nature Park "Biloberezhya Svyatoslav", located in the Kherson region. All nature reserves of Ukraine, which include marine water areas, and Biosphere Reserve "Askania-Nova" are under occupation, along with seven coastal national nature parks and one biosphere reserve. Some of these territories are located directly in the zone where hostilities are taking place or where the Russian military is stationed, such as the Kinburn Spit and Dzharylgach Island in the Black Sea. On the Kinburn spit, 131 fires were recorded during the year of full-scale invasion.



Figure 2: Map of Ukraine with occupied territories (Uk.wikipedia, 2024)

The 2022 fires were the largest in decades and affected more than 5,000 hectares, including steppe and coastal ecosystems and nesting sites for approximately 100 bird species. The construction of fortifications and trenches, and numerous explosions damage vegetation and ground cover. The territories of Ukraine with an area of 174,000 square meters are considered to be mined (Ukrinform, 2023). Satellite data indicate the construction by the occupiers of fortifications and military fortifications in the coastal zone of the Emerald Network, which includes territories and water areas where rare types

of settlements in Europe are preserved. In addition to the Emerald Network, there are other water areas and coastal areas that are important for the preservation of species and habitats that are rare not only for Ukraine but for the entire planet. These are, for example, which were created within the framework of the Ramsar Agreement (Convention, 1996). According to 2.9 million hectares of Ukrainian territories of the Emerald Network, 17 wetlands with an area of more than 600,000 hectares will be at risk due to war (not only in the coastal zone). Environmental protection objects were seriously affected by the Russians' detonation of the Kakhovskaya HPP, which took place. Several objects of the nature reserve fund were in the flood zone, in particular, the Nizhny Dnipro National Nature Park, The significant volumes of freshwater contaminated with fertilizers, fuel lubricants, and sewage entered the Black Sea. The analysis of satellite data allowed scientists to calculate that after the explosion of the Kakhovskaya HPP, polluted river waters reached the mouth of the Danube River, covering more than 7,300 km² of seawater. In Odesa Bay, scientists recorded a rapid desalination of water and a drop in salinity from 14 to 4 ppm, and in some coastal areas in certain periods — a very high concentration of nitrogen, may be a sign of water pollution by sewage. A sharp decrease in salinity led to the death of certain hydrophones (underwater inhabitants) — colonies of mussels, fry, and fish eggs — which may further affect changes in the entire coastal ecosystem. Due to the ingress of so much fresh polluted water, the seawater began to bloom due to the massive development of microalgae. The estimated damage to water resources is approximately 500 million dollars. This is without the damage to the nature reserve fund, soils, biodiversity, forest and other natural resources (Kakhovsky, 2023).

Discussion

National legal acts on the use of the natural resource potential of coastal areas

The legal basis for the use of the natural resource potential of the coastal territories of Ukraine should be based on the existing international and national legislative and regulatory framework. First of all, the national legal framework should be based on the UN Convention and, as a European country, on the Directives of the European Union on this issue. In 2005, the European Commission included in its strategic tasks the need for a comprehensive maritime policy. The concept of the European Union's Integrated Maritime Policy (IMP) became official in European policy in 2006 (EC, 2006). On October 10, 2007, the European Commission presented the well-known Blue Book study (EC, 2007). The Blue Paper laid the structure and cross-sectoral tools needed for an integrated EU maritime policy. EU "blue economy" sectors have a high potential for growth: blue energy, aquaculture, marine, coastal and cruise tourism, marine mineral resources, blue biotechnology, etc. The Blue Book is the main guide for the development of the maritime economy. Coastal areas play an important role in the European economy, as they are home to the EU population, a wide range of human activities (tourism, recreation, holiday housing, fishing and aquaculture) and most of the transport and communication infrastructure. Intensive development and significant concentration of the above-mentioned types of activities often pose threats to coastal ecosystems and natural resources. In this regard, the EU has developed the concept, which should be implemented as a tool for the integrated management of processes affecting the coastal zone to further address the interaction of land and sea to ensure sustainable development.

In 2002, the European Commission issued a Recommendation (EC, 2002) which established specific principles to be followed by EU member states to ensure. The central place in the marine research strategy belongs to the marine bases of all EU countries (Balla, 2017) and covers the full cycle from their initial observation to interpretation, processing and dissemination. Maritime (2018) defines the strategy and main directions for further development of Ukraine as a maritime state. It delimits the powers of the executive authorities on maritime activities; determines priorities for ensuring maritime safety; establishes legal mechanisms for the ownership rights of the Ukrainian people to the exclusive (marine) economic zone of Ukraine; harmonizes the principles of state maritime policy with the interests of the socio-economic development of coastal regions. Special attention is paid to activities in the coastal regions. First of all, this is the solution to issues related to maritime spatial planning and an integrated coastal management system related to the use, restoration and protection of the coastal zone of the Black and Azov Seas; the creation of a network of marine objects; water areas with regulated economic activity and the development of regional investment maps of the seaside regions in the directions "marine industry" - "recreational and tourist sphere" (Law of Ukraine, 1995)² defines that the marine areas externally adjacent to the territorial sea of Ukraine, including the areas around the islands belonging to it, constitute the exclusive (marine) economic zone of Ukraine. In this zone, Ukraine can regarding the exploration, development, management and conservation of natural resources. (Law of Ukraine, 2019)³ establishes the status and defines the legal regime of the adjacent zone of Ukraine, as well as the procedure for Ukraine to exercise its rights as a coastal state in this zone. By the UN Convention on the Law of the Sea. The Law of Ukraine on recognition of Ukraine as the legal successor of the Union of the SSR concerning participation in the Convention on Wetlands of International Importance⁴, mainly as a Habitat for Waterfowl (Law of Ukraine, 1996)⁵. Marine (2021) noted that the growth of anthropogenic load on the Sea of Azov and the Black Sea caused their unsatisfactory ecological condition. The main goals of this strategy are, in particular, the introduction of monitoring of the Black Sea; establishing and rendering in nature the boundaries of seas, sea bays and estuaries and ensuring the regularization of the coastal protective strip of seas; creation of an information system for forecasting the movement of oil products on the surface; implementation of other measures; creation of a system of integrated management of nature use within the water protection zone of the seas, the coastal strip of the seas, territorial sea waters of Ukraine; improvement of economic mechanisms for regulating the use of natural resources, including the use of seas for shipping and hydropower purposes; improvement of the legal framework for the implementation of state policy in the sphere of protection and reproduction of the environment, development of fisheries. The findings of the study indicate the need to develop effective

² Law of Ukraine. On the Exclusive (Maritime) Economic Zone of Ukraine (Vedomosti Verkhovna Rada of Ukraine (VVR), 1995, No. 21, Article 152).

³ Law of Ukraine. On the Adjacent Zone of Ukraine (Vedomosti Verkhovna Rada (VVR), 2019, No. 3, Article 20).

⁴ Convention on Wetlands of International Importance especially as Waterfowl Habitat Ramsar, Iran, 2.2.1971 as amended by the Protocol of 3.12.1982 and the Amendments of 28.5.1987 Paris, 13 July 1994 Director, Office of International Standards and Legal Affairs United Nations Educational, Scientific and Cultural Organization (UNESCO).

⁵ Law of Ukraine. On the participation of Ukraine in the Convention on Wetlands lands of international importance, mainly as a habitat for waterfowl (Vedomosti of the Verkhovna Rada of Ukraine (VVR), 1996, N 50, Article 279).

practical mechanisms to stop the destruction of the natural environment by aggressive military actions.

The conducted analytical review of the state of the natural resource potential of the coastal regions of Ukraine, and the compliance of national regulatory and legal documents with international and European jurisdiction allowed us to identify both general and local trends in the problem of environmental protection and protection as a result of military aggression. First of all, at the international level, legal documents that would ensure irreversible processes of urgent compensation for damage caused to the ecosystem are not sufficiently developed. To implement this provision, it is necessary to create both a legislative framework and separate specialized judicial instances and bodies to ensure the implementation of court decisions. On the specific example of Russian aggression against Ukraine, the destruction of 17 wetlands included in the international protection system was established, the irreparable loss of mussel colonies, fry of certain fish species in the Black Sea. Fires on the Kinbur Spit destroyed the nesting of more than 100 bird species. Studies have shown that the marine environment has a significant impact on the stability of the development of the economy of coastal regions. However, the aggression completely suspended fishing, tourism and shipping. Total losses are estimated at billions of dollars. Compensation for damage and restoration of ecosystems should be compensated by the aggressor, primarily at the expense of its assets located in other countries. It should be noted that the authors did not set the goal of developing special documents on environmental protection and conservation, but tried to prove to the international community the magnitude of the existing catastrophe, focusing attention on the need to develop appropriate mechanisms to prevent such phenomena in the future.

Conclusion

Due to Russian aggression, Ukraine is experiencing immense economic, human, and environmental losses that often cannot be recovered. One of these regions is the coastal south of Ukraine, where the aggressor uses the method of destroying not only industrial and social infrastructure but also causing unique nature reserves and biodiversity. The destruction of the Kakhovskaya Hydroelectric Power Plant, along with the devastation of the Nizhny Dnieper National Nature Park and the white coast of Svyatoslav National Nature Park, has severely impacted wetlands of international importance covering more than 600,000 hectares. Additionally, the occupiers have constructed fortifications and military installations in the coastal zone of Ukraine's Emerald Network. This network includes territories and water areas that are home to rare species of fauna and flora. In Europe, crimes against human civilization can be interpreted as ecocide, for which there should be legal responsibility at the international level. The national legal framework for the use and protection of the natural resource potential of the state's coastal territories within its borders is generally brought into line with the UN Charter, Convention on the Law of the Sea of 1982 and other world and European documents. It is necessary to carry out constant purposeful monitoring of the aggressor to improve measures of a legal, economic, social, educational, informational and organizational nature; aimed at protecting the natural environment, and ensuring environmental safety.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	Yes
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Exploring the Entrepreneurial Skills of Agriculture Students in Odisha, India

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Abstract

Entrepreneurial skills play a crucial role in making this world sustainable and self-sufficient for any country. It supports innovations so that new and innovative ideas can be generated in the minds of the people, mostly young minds. In this present study, the entrepreneurial skills of agriculture students are focussed and studied carefully so that agricultural improvement as well as national development can be achieved through shaping these skills using proper training and education at the institutional level. Planning, Enterprise Management, Credit & Finance, and Marketing skills are undertaken in the study to examine the entrepreneurial skills of the students. The data on entrepreneurial skills was collected from the respondents through the pre-tested questionnaire. Out of the total questionnaire responses received, 569 responses were found suitable for analysis for this study. The results obtained from the study state that the majority (61.16%) of the respondents had a medium level of entrepreneurial skills. Credit and Finance skills ranked highest followed by marketing skills. It was also noted that the respondents needed higher Enterprise management and planning skills. There was no significant influence of caste, locality and family size on entrepreneurial skills. However, attributes such as Economic Aptitude, Social Aptitude, Scientific Aptitude, Decision-Making Ability, Leadership Ability and Source of Information had highly statistically significant effects on entrepreneurial skills. In Odisha particularly, the focus should be given to the agriculture students' credit & finance and marketing skills. This research will be helpful for educational institutions in shaping education patterns and improving the entrepreneurial skills of students.

Keywords

Agriculture students, Entrepreneurial skills of Agriculture Students, Odisha, Odisha Students

Introduction

Entrepreneurship is a prime factor which can be used to improve the socio-economic status of the country. It contributes hugely to the growth of the national GDP (Acs, Desai and Hessels, 2008).

Odisha's growth is influenced by several factors including private sector participation in industrial activity and mining activities, along with improved primary education, health care, and agricultural productivity (Misra and Ghadai, 2017). Due to globalization and changes in technical aspects, the agriculture industry is also being changed severely. The adoption of new technologies is essential for exploring new opportunities in agriculture. Entrepreneurial orientation, which includes risk-taking and proactiveness, is crucial for technology adoption (Passarelli, Bongiorno and Cariola, 2021). To cope with this changing agriculture sector, entrepreneurial aspects need to be focussed. More than 65 per cent of the population in India is primarily dependent on cultivation (Samaddar, 2006). The essence of the agricultural sector identifies specific ways of improvement and highlights the role and importance of economic and social factors in its development (Riabokon, 2021). For the development of the agriculture sector, various institutions have been established (Putsenteilo *et al.*, 2020). In Northern State Agricultural Universities (SAUs), approximately 87% of students enrolled in the B.Sc. Agriculture programs successfully graduate, while about 13% drop out before completing their degrees. A small percentage of students are admitted through the ICAR-AIEEA (UG) against reserved seats. After completing their undergraduate degrees, a substantial portion of agriculture graduates pursue further education, with 43% opting for master's programs and 28% for Ph.D. programs. Around 52% of agriculture graduates find employment in both public and private sectors, indicating a relatively strong job market for these graduates (Gupta, Mann and Sidhu, 2020). The Indian government has implemented various agriculture schemes, such as PM-KISAN, to provide direct income support to farmers and improve farm productivity (Tripathi *et al.*, 2023). Yet, there has not been any substantial growth in this sector in the last decade. This highlights the need for further research to identify gaps and problems that need to be focussed and should be fulfilled. Among several aspects, the entrepreneurial skills of agriculture students need to be enhanced and their entrepreneurial training and skill development need to be critically analyzed. Coding and digital skills have a statistically significant positive impact on students' entrepreneurial engagement and student entrepreneurship (Sansone *et al.*, 2024). Self-awareness, problem-solving, and effective communication positively influence the development of entrepreneurial skills, which in turn significantly strengthen students' entrepreneurial confidence (Vera *et al.*, 2024). However, students' confidence in certain entrepreneurial skills declined significantly over time in live projects, suggesting the need for more structured and timely learning interventions (Chang and Rieple, 2013). Therefore, entrepreneurial skills that need critical development should be identified, and proper strategies should be followed to improve those skills.

In states such as Odisha, where most people depend on agriculture for their livelihood security, they need to develop entrepreneurship among them. Therefore, if agriculture students have entrepreneurial skills, then it will definitely improve this society as well as it will secure their future. This will also ensure agribusiness development and innovative solutions for the problems; ultimately, they can be part of the country's economic growth (Aliabadi *et al.*, 2019).

Agriculture is a unique sector because it is dynamic and unpredictable in nature. It mostly depends on the weather conditions, severe fluctuation in the market and many other socio-economic factors. Therefore, entrepreneurial skills are very much required to be a good entrepreneur in this agriculture sector so that he or she will be a good analyser of

the present condition of the market and accordingly, he or she will be able to fulfil the demand of the customers. Therefore, this study focuses on four fundamental entrepreneurial skills: Planning, Enterprise Management, Credit & Finance, and Marketing. These skills are very much required to be a successful entrepreneur in the agriculture sector. Entrepreneurial success in the agriculture sector relies on key skills like planning, enterprise management, credit and finance, and marketing. Planning ensures structured decision-making by focusing on crop selection, resource allocation, and risk management, aiding in sustainable and profitable production while addressing challenges like climate change (Birley and Westhead, 2017; Morris *et al.*, 2017; Van Auken *et al.*, 2006). Enterprise management emphasizes productivity, waste reduction, and adaptability to market changes through efficient use of land, labour, and capital (Aliabadi *et al.*, 2019; Beck *et al.*, 2015; Birley and Westhead, 2017). Credit and finance skills help overcome capital barriers, enabling entrepreneurs to manage risks, cash flow, and investment opportunities effectively (Ataei *et al.*, 2021; Beck *et al.*, 2015). Lastly, marketing ensures customer needs are met profitably by leveraging market trends, branding, and pricing strategies to maximize returns and capitalize on opportunities (Aliabadi *et al.*, 2019; Kotler and Armstrong, 2018; Kotler and Keller, 2016).

In Odisha, there is a diverse agro-climatic situation and agricultural base where farmers depend on traditional farming techniques. This gives vast scope for agriculture students to start various agroclimatic-based enterprises by developing entrepreneurial skills among them. A study conducted by Najafabadi, Zamani and Mirdamadi (2016) shows that entrepreneurial abilities account for 63% of the entrepreneurial aspirations among agricultural students. Young people in agriculture require entrepreneurial abilities for successful and expanding enterprises. These skills include personal attributes, social competencies, and the capacity for critical and innovative thinking (Bolarinwa and Okolocha, 2016). By knowing entrepreneurship skills, students will be able to promote mechanisation and advanced technologies in the farming sector (Chandrasekhar *et al.*, 2006). For agricultural students in China, the practical application of entrepreneurship serves as a mediating factor between the entrepreneurship curriculum and students' satisfaction with their entrepreneurship education (Huang *et al.*, 2022).

Therefore, this present study was undertaken to assess the skills of agriculture students in Odisha towards entrepreneurship across these four fundamental skills. It will evaluate the readiness of the agriculture students to be engaged in entrepreneurial activities and identify the gaps in their entrepreneurial skill development. The following hypotheses were tested in our study:

- H₁: The entrepreneurial skills of agriculture students in Odisha are at a low level on average.
- H₂: Socio-economic factors do not significantly influence the entrepreneurial skills of agriculture students in Odisha.
- H₃: Personal attributes do not significantly influence the entrepreneurial skills of agriculture students in Odisha.
- H₄: There is no significant difference in the entrepreneurial skills based on gender, caste & family major occupation.

Accordingly, the study is guided by the following objectives:

- To evaluate the levels of entrepreneurial skills among agriculture students in Odisha.
- To analyze the relationship between socio-economic factors and entrepreneurial skills.
- To know the relationship between the personal attributes and entrepreneurial skills of the respondents.
- To assess the differences in entrepreneurial skills based on gender, Caste and Family major occupation.

Methodology

This research adopted a quantitative approach using a cross-sectional survey to explore the entrepreneurial skills of final-year B.Sc. (Agriculture) students across nine agricultural colleges in Odisha, India, focusing on critical skills such as Planning, Enterprise Management, Credit and finance, and Marketing. To study these skills, a questionnaire was developed by doing a pilot study and with the help of a review of literature as well as experts in entrepreneurship. After that, this raw questionnaire was administered to 40 non-respondent agriculture students for pretesting. Reliability and validity test was done in SPSS after collecting the data in pre-testing to keep the most relevant statements for the study. The pretested questionnaire developed for the study was distributed in Google form to all the final-year agriculture students of Odisha in the academic year 2023-2024 to participate. The data were collected through Google form via the developed structured survey questionnaire, designed to measure students' perceptions of entrepreneurial skills using a three-point Likert scale (Most essential, Essential, Not essential).

The choice of a three-point Likert scale for this study was guided by the need for simplicity and clarity in response collection. A three-point scale—comprising "Most Essential," "Essential," and "Not Essential"—offers respondents a straightforward framework to express their perceptions of entrepreneurial skills. Unlike more granular scales, such as five-point or seven-point options, the three-point scale minimizes cognitive load and reduces the likelihood of confusion among respondents, particularly when the target population may vary in familiarity with Likert-type scales or possess differing levels of comprehension. Moreover, the three-point scale is particularly effective in ensuring that respondents focus on the essential aspects of the measured constructs, fostering precise and actionable data collection. While it is acknowledged that this format may limit the range of variability and the granularity of responses, it was deemed a suitable trade-off to maintain clarity and encourage higher response rates. This choice aligns with the objectives of the study to prioritize the identification of core perceptions without overcomplicating the data interpretation process. Socio-economic attributes were also captured to explore potential correlations. Data collection took place over two months, combining in-person visits and digital distribution via Google Forms and institutional WhatsApp groups. Google was prepared in such a way that one respondent can submit only once through his/her Gmail ID so that duplication of data will not occur. To collect correct responses from the respondents, their identity proof like registration no. and name etc. were not put in the Google form. 569 valid responses were retained after screening for completeness and consistency. Descriptive statistics, including mean, frequencies, and SD, were used to summarize the data. At the same

time, inferential analyses, such as correlation, were performed to identify relationships between entrepreneurial skills and independent (Socioeconomic and Individual attributes) variables. The independent variables taken under study were Caste, Locality, Family Type, Family Size, House Types, Education of the head of the family, Family Annual Income, Parents Land Holding, Economic Aptitude, Social Aptitude, Scientific Aptitude, Decision-Making Ability, Leadership Ability and Source of Information. Based on the Cut-off Score Method (AllPsych, n.d.), the level of entrepreneurial skills was categorised into Low (Scores less than Mean - SD), Medium (Scores between Mean - SD and Mean + SD) and High (Scores greater than Mean + SD). The Cut-off Score Method was used because it objectively categorizes entrepreneurial skills into Low, Moderate, and High levels based on statistical thresholds (Mean \pm SD). This ensures standardized, unbiased classification and simplifies interpretation, especially in datasets with varying distributions. It is a widely accepted approach in behavioural and social science research. Test statistics like Mann Whitney U and Kruskal Wallis tests were also performed through the software IBM SPSS Statistics v21.

Statistical Tests Used in the Study

After the normal distribution test was done in SPSS, it was found that the data were not following normal distribution. So, the following non-parametric tests were taken for statistical analysis.

1. Mann-Whitney U Test: The Mann-Whitney U test, a non-parametric test, is used to compare differences between two independent groups when the data does not meet the assumptions of normality. This test is suitable for ordinal data or continuous data that do not follow a normal distribution, making it ideal for social science studies where responses often do not meet parametric assumptions.

Formula:

For two groups X and Y, each with n_1 and n_2 observations, respectively, the U statistic is calculated as:

$$U = n_1 n_2 + \frac{n_1(n_1 + 1)}{2} - R_1$$

Where R_1 is the sum of the ranks for group X.

In this study, the Mann-Whitney U test was employed to assess differences between two demographic groups to determine if a statistically significant difference existed between their entrepreneurial skills variables.

2. Kruskal-Wallis Test: The Kruskal-Wallis test is an extension of the Mann-Whitney U test for comparing more than two independent groups. It assesses whether the medians of these groups differ significantly, making it suitable for ordinal data or non-normally distributed continuous data across multiple groups.

Formula:

The test statistic H is calculated as:

$$H = \frac{12}{N(N + 1)} \sum_{i=1}^k \frac{R_i^2}{n_i} - 3N(N + 1)$$

Where:

N is the total number of observations,

k is the number of groups,

R_i is the sum of ranks for group i,

N_i is the number of observations in group i.

The Kruskal-Wallis test was applied to compare entrepreneurial skills across multiple demographic groups to know whether differences exist across these groupings in the context of entrepreneurial skills.

Results

Skills of the Agriculture Students towards Entrepreneurship

The analysis of factors influencing entrepreneurial skills highlighted that Credit & Finance were the strongest components, securing the top rank and emphasizing their critical role in equipping students with financial management and credit system competencies essential for entrepreneurial success. Marketing ranked second, underscoring the importance of promoting and selling agricultural products, though improvements in digital marketing and branding could further enhance this skill. Planning Skills, ranked third, reflected moderate proficiency in goal setting and resource organization, indicating the need for greater focus on strategic and long-term planning. Enterprise Management ranked fourth, revealed a gap in managing business operations, decision-making, and leadership, emphasizing the necessity for targeted interventions to strengthen these competencies. These findings suggest that while students excel in financial and marketing aspects, addressing deficiencies in planning and enterprise management is vital for developing comprehensive entrepreneurial skills in the agricultural sector.

Table 1 illustrates the ranking and level of Entrepreneurial Skills among the respondents.

For Planning Skills, the majority (46.4%) demonstrated medium proficiency, while a notable 31.81% exhibited high levels, reflecting the potential for strong organizational and goal-setting abilities. Similarly, in Enterprise Management, most respondents (49.21%) were in the medium category, with 29.0% achieving high levels, indicating moderate competence in managing business operations. Conversely, Credit & Finance and Marketing showed the highest concentration in the medium category, with 80.84% and 80.32% of respondents, respectively, but no respondents achieved high proficiency in these areas, highlighting significant gaps in financial and marketing expertise. Overall, the entrepreneurial skills distribution showed that while 61.16% of respondents possessed medium-level skills and 22.67% had high proficiency, a considerable 16.17% fell into the low category, underscoring the need for targeted interventions to improve financial and marketing skills while strengthening planning and enterprise management capabilities.

Correlation Analysis

The Spearman's Rank Correlation analysis (Table 2) highlighted significant relationships between various factors and entrepreneurial skill components, emphasizing the critical role of individual attributes. Leadership Ability, Social Aptitude, Scientific Aptitude,

and Decision-Making Ability showed strong positive correlations with planning, enterprise management, credit and finance, marketing, and overall entrepreneurial skills, all statistically significant at the 0.01 level, underscoring their importance in fostering entrepreneurial growth. Economic Aptitude and Source of Information also demonstrated moderate positive correlations, with significance at the 0.01 and 0.05 levels, reflecting the value of proactive decision-making and access to information in skill enhancement. In contrast, socioeconomic factors like Family Type and Parents' Land Holding showed significant negative correlations with planning and overall entrepreneurial skills at the 0.05 level, suggesting these traditional constraints might hinder entrepreneurial development. Other variables, such as Caste, Locality, and Family Annual Income, exhibited negligible correlations, indicating limited influence. These findings emphasize the need for targeted interventions to strengthen individual attributes while addressing socio-economic barriers to promote comprehensive entrepreneurial skill development among agriculture students.

Table 1: Rank & Level of Entrepreneurial Skills (n=569)

<i>Factors of Entrepreneurial Skills</i>	<i>Rank</i>	<i>Level</i>		
		<i>Low</i>	<i>Medium</i>	<i>High</i>
1. <i>Planning Skills</i> (Mean=2.62, SD=0.35)	III	124 (21.79%)	264 (46.4%)	181 (31.81%)
2. <i>Enterprise management</i> (Mean= 2.60, SD= 0.36)	IV	124 (21.79%)	280 (49.21%)	165 (29.0%)
3. <i>Credit & Finance</i> (Mean= 2.67, SD= 0.37)	I	109 (19.16%)	460 (80.84%)	0 (0.0%)
4. <i>Marketing</i> (Mean= 2.65, SD= 0.36)	II	112 (19.68%)	457 (80.32%)	0 (0.0%)
Overall Entrepreneurial Skills (Mean: 2.63, SD: 0.36)		92 (16.17%)	348 (61.16%)	129 (22.67%)

Note: Mean=Average Mean Score

Table 2: Spearman's Rank Correlations

<i>Sl. No.</i>	<i>Variable</i>	<i>Planning Skill</i>	<i>Enterprise Management Skill</i>	<i>Credit & Finance Skill</i>	<i>Marketing Skill</i>	<i>Overall Entrepreneurial Skill</i>
1	Caste	-0.032	-0.004	0.024	0.035	0.01
2	Locality	-0.064	-0.027	-0.025	-0.009	-0.039
3	Family Type	-0.093*	-0.07	-0.043	-0.059	-0.082*
4	Family Size	-0.033	-0.032	-0.031	-0.059	-0.046
5	House Types	-0.03	0.015	0.058	0.061	0.032
6	Education of the head of the family	0.021	-0.001	0.043	0.041	0.042
7	Family Annual Income	-0.07	-0.039	-0.077	0.01	-0.047
8	Parents Land Holding	-0.087*	-0.086*	-0.079	-0.071	-0.096*
9	Economic Aptitude	0.166**	0.156**	0.086*	0.122**	0.163**

Sl. No.	Variable	Planning Skill	Enterprise Management Skill	Credit & Finance Skill	Marketing Skill	Overall Entrepreneurial Skill
10	Social Aptitude	0.272**	0.221**	0.216**	0.264**	0.283**
11	Scientific Aptitude	0.246**	0.225**	0.197**	0.184**	0.246**
12	Decision-Making Ability	0.261**	0.226**	0.262**	0.188**	0.273**
13	Leadership Ability	0.325**	0.279**	0.240**	0.228**	0.308**
14	Source of Information	0.207**	0.140**	0.086*	0.138**	0.166**

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

Gender and Entrepreneurial Skills

The Mann-Whitney U Test assessed the differences in entrepreneurial skills between male and female agriculture students in Odisha across four key areas: Planning, Enterprise Management, Credit and finance, and Marketing. The results revealed no significant differences in any of these dimensions, with p-values of 0.454 for Planning ($U = 38231.500$, $Z = -0.749$), 0.333 for Enterprise Management ($U = 37812.000$, $Z = -0.967$), 0.582 for Credit & Finance ($U = 38637.500$, $Z = -0.551$), and 0.236 for Marketing ($U = 37424.000$, $Z = -1.186$). Furthermore, the overall entrepreneurial skillset, which combined these four dimensions, also showed no significant difference between genders, with a p-value of 0.237 ($U = 37363.000$, $Z = -1.183$). These results indicate that the distribution of entrepreneurial skills is comparable between male and female students, suggesting that gender does not significantly influence entrepreneurial competencies within the sample. The test statistics confirm that gender equality in entrepreneurial skills is present among agriculture students in this context (Table 3).

The figure visually represents the outcomes of the Mann-Whitney U Test, comparing the entrepreneurial skills of male and female agriculture students across various dimensions. The figure's primary objective is to examine notable distinctions between males and females regarding various entrepreneurial aspects. These include Planning, Enterprise Management, Credit & Finance, Marketing, and overall Entrepreneurial Skills. Each skill category is compared based on gender, and the results show that the distribution of skills is similar across both groups, indicating no significant difference in entrepreneurial abilities between male and female students. The figure emphasizes the statistical findings of gender equality in entrepreneurial competencies among agriculture students (Figure 1).

Caste and Entrepreneurial Skills

The Kruskal-Wallis test assessed the distribution of entrepreneurial skills across different caste categories among agriculture students in Odisha, focusing on Planning, Enterprise Management, Credit and Finance, Marketing, and overall Entrepreneurial Skills. The results showed no significant differences in any of the skill dimensions across caste categories. For Planning Skill, the p-value was 0.199 with a chi-square value of

3.232 (df = 2); for Enterprise Management Skill, the p-value was 0.275 with a chi-square value of 2.583 (df = 2); for Credit & Finance Skill, the p-value was .478 with a chi-square value of 1.476 (df = 2); for Marketing Skill, the p-value was 0.345 with a chi-square value of 2.130 (df = 2); and for overall Entrepreneurial Skill, the p-value was 0.220 with a chi-square value of 3.024 (df = 2). In all cases, caste does not significantly influence the students' distribution of these entrepreneurial skills (Table 4).

Table 3: Mann-Whitney U Test based on gender

	<i>Planning Skill</i>	<i>Enterprise Management Skill</i>	<i>Credit & Finance Skill</i>	<i>Marketing Skill</i>	<i>Entrepreneurial Skill</i>
Mann-Whitney U	38231.500	37812.000	38637.500	37424.000	37363.000
Wilcoxon W	91206.500	90787.000	91612.500	90399.000	90338.000
Z	-0.749	-0.967	-0.551	-1.186	-1.183
Asymptotic Significance (2-tailed)	0.454	0.333	0.582	0.236	0.237

Based on the Kruskal-Wallis test findings and supporting box plot data, no statistically meaningful variations were observed in the distribution of Entrepreneurial Skill components (Planning, Enterprise Management, Credit & Finance, and Marketing) or overall Entrepreneurial Skill among different caste groups. The box plots show consistent median values, similar interquartile ranges, and an absence of significant outliers across all skills, suggesting that the distribution of these skills is uniform among the different caste categories. The p-values for all skills are above the 0.05 threshold, confirming that caste does not significantly influence the entrepreneurial skills assessed in this study (Figure 2).

Table 4: Kruskal Wallis Test based on Caste

	<i>Planning Skill</i>	<i>Enterprise Management Skill</i>	<i>Credit & Finance Skill</i>	<i>Marketing Skill</i>	<i>Entrepreneurial Skill</i>
Chi-Square	3.232	2.583	1.476	2.130	3.024
df	2	2	2	2	2
Asymptotic Significance	0.199	0.275	0.478	0.345	0.220

Family Major Occupation and Entrepreneurial Skills

The test Kruskal-Wallis was conducted to know the differences in skills in entrepreneurship of the agriculture students in Odisha based on their family's major occupation. The test examined Planning Skill (Chi-square = 6.780, p = 0.238), Enterprise Management Skill (Chi-square = 3.116, p = 0.682), Credit & Finance Skill (Chi-square = 7.489, p = 0.187), Marketing Skill (Chi-square = 6.047, p = 0.302), and overall Entrepreneurial Skill (Chi-square = 6.063, p = 0.300). The analysis revealed no statistically significant variations in entrepreneurial abilities among different family occupation groups, as all p-values exceeded the 0.05 significance threshold (Table 5).

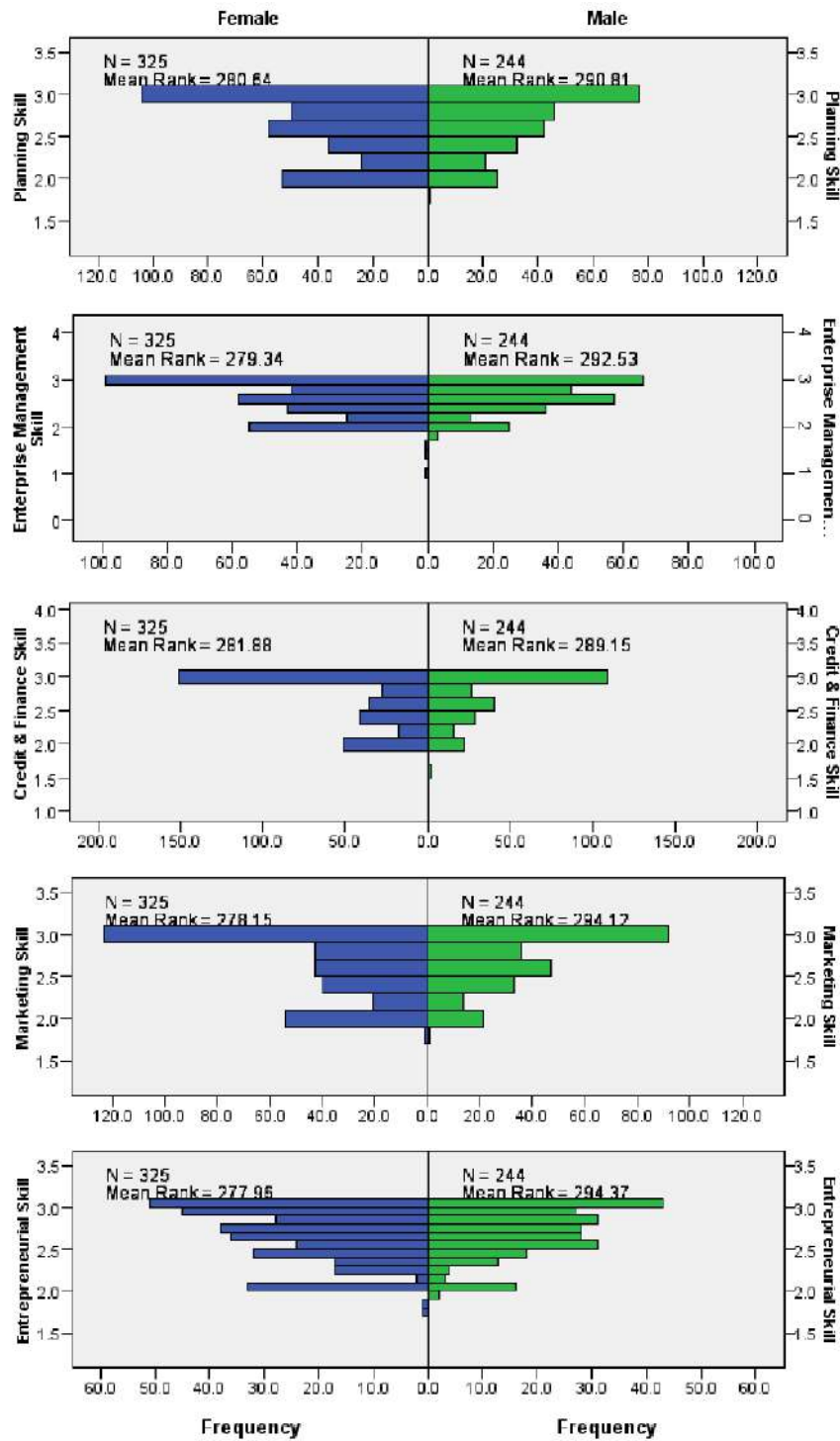


Figure 1: Mann-Whitney U Test based on Gender

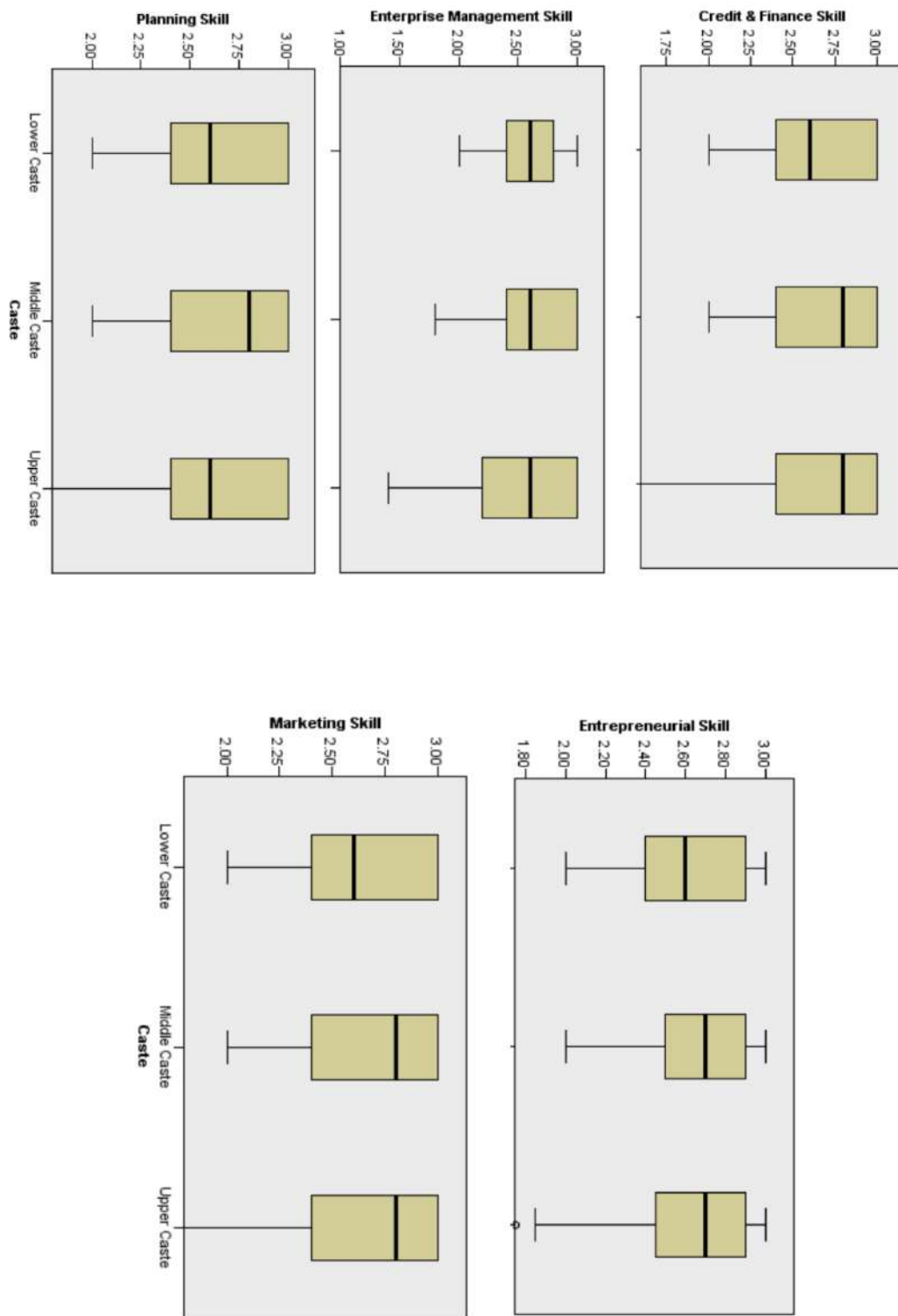


Figure 2: Kruskal Wallis Test based on Caste

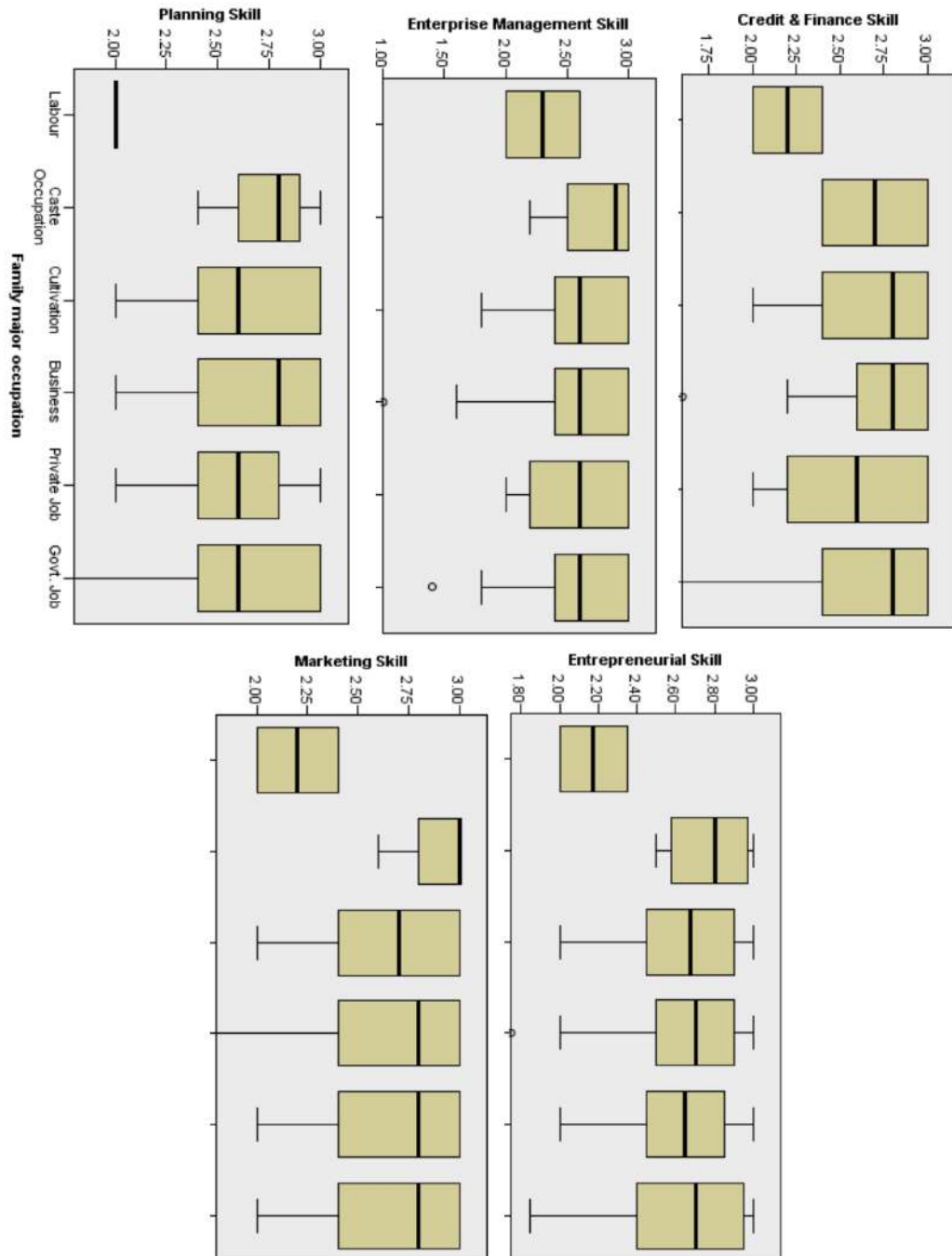


Figure 3: Kruskal Wallis Test based on Family Major Occupation

The box plots corresponding to the Kruskal-Wallis test for entrepreneurial skills, based on family major occupation, visually represent the distribution of scores across various family backgrounds. For Planning Skills, the spread of scores is relatively consistent across categories, with some minor variations, indicating no significant difference ($p = 0.238$). The Enterprise Management Skill box plot shows similar distributions across all

categories, which aligns with the non-significant p-value of 0.682. The Credit & Finance Skill plot displays slight variations, particularly in the interquartile range, but these differences are not statistically significant ($p = 0.187$). For Marketing Skills, the box plot reveals a broad distribution, yet there is no statistically significant difference across the family occupation categories ($p = 0.302$). Finally, the overall Entrepreneurial Skill box plot also shows no notable differences, with a p-value of 0.300, confirming no significant variation between groups (Figure 3).

Table 5: Kruskal Wallis Test based on Family Major Occupation

	<i>Planning Skill</i>	<i>Enterprise Management Skill</i>	<i>Credit & Finance Skill</i>	<i>Marketing Skill</i>	<i>Entrepreneurial Skill</i>
Chi-Square	6.780	3.116	7.489	6.047	6.063
df	5	5	5	5	5
Asymptotic Significance	0.238	0.682	0.187	0.302	0.300

Discussion

The findings of this research provide valuable insights into the entrepreneurial skill set of agriculture students in Odisha, highlighting both strengths and areas for improvement. Credit & Finance emerged as the strongest component, ranking first in the analysis. This reflects the critical importance of financial management skills for agricultural entrepreneurs, as effective handling of finances, credit systems, and funding opportunities is crucial for the sustainability and growth of any business. The fact that many students demonstrated proficiency in this area is encouraging, but the absence of students with high proficiency indicates room for further development. Strengthening financial literacy and practical exposure to credit management through targeted interventions in the curriculum or extracurricular programs could better equip students to handle the complexities of financial decision-making in entrepreneurial ventures.

Marketing skills, ranked second, were also a key strength among students. This skill is crucial in the context of agriculture, where promoting and selling products is essential to the success of farming ventures. While the medium proficiency levels are promising, the lack of high proficiency in marketing is a concern. This gap presents an opportunity for students to further develop their marketing acumen, particularly in areas like digital marketing, branding, and market research. Given the growing importance of online platforms and social media in modern agriculture, integrating digital marketing strategies into agricultural education could help students gain a competitive edge in the marketplace.

Planning skills ranked third, with 31.81% of respondents demonstrating high proficiency. This finding suggests that many students have a strong foundation in setting goals and organizing resources, which is critical for entrepreneurial success in agriculture. However, the fact that 46.4% of students demonstrated medium proficiency indicates that planning skills may not be sufficiently developed across the board. To address this, agricultural education programs could focus more on strategic and long-term planning, emphasizing scenario analysis, business forecasting, and risk management. Practical exercises that challenge students to develop comprehensive

business plans could foster better decision-making and resource allocation in real-world entrepreneurial settings. Enterprise management ranked fourth, revealing significant gaps in business operations management, leadership, and decision-making. With only 29.0% of students achieving high proficiency in this area, it is clear that this is a key area for intervention. Strong leadership and decision-making abilities are essential for managing the complexities of agricultural enterprises. The findings suggest that students may benefit from more hands-on experience in running small-scale agricultural businesses or simulation exercises that focus on operations, leadership, and crisis management. Integrating leadership development into the curriculum and offering mentorship opportunities from successful agricultural entrepreneurs could also help bridge this gap. The overall distribution of entrepreneurial skills shows that while a majority of students (61.16%) possess medium-level skills, a notable 16.17% fall into the low proficiency category. This highlights the need for targeted interventions to elevate students' competencies in key areas, particularly Credit & Finance, Marketing, and Enterprise Management. By addressing these deficiencies, agricultural education can better prepare students for the challenges of starting and sustaining entrepreneurial ventures in the agricultural sector. While the results indicate that students in Odisha exhibit strong financial and marketing skills, significant gaps in planning and enterprise management need to be addressed. Focusing on these areas will ensure that agriculture students are equipped with a comprehensive set of entrepreneurial skills, enhancing their readiness to launch successful businesses in the agricultural sector. Tailored interventions and an enhanced curriculum focusing on strategic planning, digital marketing, and enterprise management will be essential in fostering a more robust entrepreneurial ecosystem in Odisha.

Interestingly, 22.67% of the students exhibit high-level entrepreneurial skills, demonstrating that a substantial portion of students are well-prepared for entrepreneurial ventures. These students likely have a solid grasp of the necessary competencies, such as decision-making, resource management, and strategic thinking, which are crucial for the success of agricultural businesses. Their readiness suggests that current entrepreneurship education programs are effective for some but not all. However, the presence of 16.17% of students in the low-skill category reveals a gap in preparedness. This group represents a significant portion of the student population that is not adequately equipped for entrepreneurship, potentially due to a lack of targeted education or practical exposure to entrepreneurial activities. The fact that these students are not reaching the necessary competency levels signals a need for a more comprehensive and inclusive approach to entrepreneurship education. By enhancing training in these areas, along with fostering skills like problem-solving, leadership, and innovation, a more robust entrepreneurial education framework can be developed. This will not only raise the competency of students in the medium and low categories but also ensure that all students are adequately prepared to thrive in the agricultural industry.

While the analysis shows a solid foundation in entrepreneurial skills among the majority of students, the need for a holistic and integrated educational approach is clear. Strengthening education in planning & enterprise management skills will be critical in ensuring that all students, regardless of their starting point, are equipped with the skills necessary to succeed in the rapidly evolving agricultural sector. Incorporating hands-on practical training in agricultural education programs increases students' understanding of

real-world phenomena and grants them new skill sets (Wells, 2014). Incorporating hands-on practical training in agricultural education programs through international volunteer assignments can help graduate students gain practical experience, improve interpersonal skills, and enhance cultural competencies (Zickafoose and Wingenbach, 2023).

The correlation analysis sheds light on the multifaceted influences on entrepreneurial skills among agriculture students in Odisha. The findings indicate that socio-economic factors such as caste, locality, family size, house types, and the education level of the head of the family do not significantly impact the development of entrepreneurial skills. However, family structure, as represented by family type, seems to exert some influence, as negative correlations suggest that students from nuclear or smaller families may face challenges in developing entrepreneurial planning and overall skills. This finding calls for a deeper understanding of how family dynamics shape entrepreneurial ambitions and skill acquisition. Interestingly, parents' landholding is inversely related to entrepreneurial skill development. Students from families with more extensive landholdings appear to have less necessity to develop these skills, likely due to the economic stability provided by the land. This may reduce their motivation to engage in entrepreneurial activities. In contrast, students with higher *economic aptitude* tend to develop more vital entrepreneurial skills, indicating that understanding economic principles is critical in navigating entrepreneurial ventures. Moreover, *social and scientific aptitudes* stand out as pivotal factors. The significant positive correlations between these aptitudes and entrepreneurial skills underscore the importance of networking, communication, and scientific reasoning in fostering entrepreneurial competencies. Students who demonstrate strong social skills are likely to excel in areas like marketing, where interaction and relationship-building are essential. At the same time, those with scientific aptitude are better equipped to innovate and adapt to the technical demands of modern agricultural entrepreneurship.

To foster decision-making ability, leadership skills, and information-seeking behaviour through curriculum design and extracurricular programs, agricultural education must be strategically structured to address these key competencies. These traits are critical for entrepreneurial success, and educational frameworks can be enhanced to better develop these skills among students. Curriculum design should incorporate decision-making frameworks and problem-solving methodologies that allow students to engage with real-world agricultural business challenges. Agricultural students could benefit from simulation-based learning and case studies that replicate situations like crop management decisions, resource allocation, or managing supply chain disruptions. By applying theoretical knowledge to practical scenarios, students learn to make sound decisions under uncertainty, which is a fundamental aspect of entrepreneurship. Additionally, project-based learning can be incorporated into the curriculum, where students work on real-world agricultural projects requiring decisions that directly impact the outcome. These projects could involve designing sustainable farming systems or managing the business side of an agricultural operation. By leading these projects, students can gain first-hand experience in making high-stakes decisions and refining their decision-making processes. Furthermore, incorporating workshops focused on risk management, crisis management, and business strategy will help students enhance their ability to think critically and make informed decisions.

Leadership skills are indispensable for agricultural entrepreneurs, and these can be developed through both curricular and extracurricular activities. Within the curriculum, students can take on leadership roles in group projects related to agricultural business management, such as marketing, production planning, or financial management. These projects should simulate real-world agricultural business challenges, allowing students to apply leadership skills in a controlled but realistic environment. Courses that emphasize team management, strategic planning, and operational leadership will further strengthen their ability to guide teams toward successful outcomes. Extracurricular programs also play a vital role in cultivating leadership skills. Agricultural education programs should offer students the opportunity to take part in student-run agricultural cooperatives or entrepreneurial clubs, where they can practice leading teams and managing agricultural projects. Collaboration with local agribusinesses for internships or apprenticeships would also provide students with hands-on experience in leadership roles. By taking part in leadership training workshops and working on community-based agricultural projects, students will gain the practical skills needed to lead agricultural ventures in the future. Source of Information is another critical component of entrepreneurial success, as it allows students to stay informed and adaptable in a constantly changing agricultural industry. The curriculum should focus on developing students' research and technological skills by teaching them how to access and analyze agricultural data, market trends, and industry innovations. Students can be encouraged to explore agricultural research databases, use data analytics tools in farm management, and keep up with emerging topics such as sustainable farming practices and new technologies in agriculture. In addition to formal coursework, students should be encouraged to engage in research projects that explore current challenges in agriculture. These projects can involve topics like the adoption of new technologies, climate resilience, or market access strategies for smallholder farmers. Mentorship programs, where experienced professionals guide students in researching and applying new knowledge, would also be beneficial. Encouraging students to participate in agricultural conferences, seminars, and workshops will expose them to the latest industry developments and further develop their ability to seek out and apply relevant information.

Extracurricular programs are key to providing students with opportunities to apply decision-making, leadership, and information-seeking skills in a dynamic, real-world context. Leadership camps, decision-making challenges, and entrepreneurial competitions can simulate real-life agricultural business scenarios, allowing students to practice these skills in a competitive yet supportive environment. These activities can be organized in collaboration with local businesses, agricultural cooperatives, and industry leaders, further enriching the students' experience. Furthermore, agricultural education programs could partner with agricultural organizations and research institutions to organize workshops, hackathons, or industry forums focused on solving current agricultural problems. Through these events, students can tackle complex issues in agriculture, where they will need to make decisions, lead teams, and actively seek out innovative solutions. This hands-on approach to learning will deepen their understanding of entrepreneurship and prepare them to take on leadership roles in the agricultural sector. By strategically integrating decision-making, leadership skills, and sources of information into both the curriculum and extracurricular activities, agricultural education can better prepare students for entrepreneurial success. Encouraging hands-on learning through decision-making simulations, leadership opportunities through team-based projects, and fostering a culture of continuous learning will equip students with the essential skills to navigate the

challenges of agricultural entrepreneurship. These recommendations ensure that students not only gain technical knowledge but also develop the practical skills necessary to succeed as future leaders in the agricultural industry.

So, the results suggest that while some socio-economic factors such as family income or size may not significantly affect entrepreneurial skills, attributes like economic, social, and scientific aptitude, leadership, decision-making ability, and source of information are crucial. These findings highlight the need for targeted skill development programs focusing on enhancing these attributes, especially for students from wealthier or more agriculturally stable families who may lack the need to develop entrepreneurial competencies organically.

The results of the Mann-Whitney U Test reveal that gender does not play a significant role in the entrepreneurial skills of agriculture students in Odisha. Across all vital entrepreneurial dimensions—planning, enterprise management, credit & finance, and marketing—both male and female students exhibit comparable skill levels. This outcome supports the notion that agricultural entrepreneurship, at least in the studied cohort, is not influenced by gender differences. The findings align with contemporary trends in entrepreneurship, where opportunities and competencies are increasingly accessible regardless of gender. It also indicates the agricultural education system in Odisha, which seems to provide an equitable environment for skill development among all students, irrespective of gender. However, it is essential to consider that while these results demonstrate equality in skills, future research could explore factors beyond gender, such as socio-economic background or access to resources, to understand disparities in entrepreneurial success further. Additionally, qualitative studies could provide deeper insights into the experiential aspects of entrepreneurship for male and female students in agriculture.

The results of the Kruskal-Wallis test suggest that caste does not significantly influence the entrepreneurial skills of agriculture students in Odisha. The skill levels are similar among students from different caste categories across the critical dimensions of Planning, Enterprise Management, Credit and Finance, Marketing, and overall Entrepreneurial Skills. This finding indicates that caste is not a determining factor in the entrepreneurial competency of students, reflecting a potential levelling of skill development opportunities regardless of caste background. These results align with recent trends in education and entrepreneurship, where access to resources, skill-building opportunities, and educational interventions are becoming more inclusive. The findings highlight the equitable distribution of entrepreneurial skills among students from various social backgrounds, underscoring the efforts made to bridge traditional social divides in skill development. However, while caste does not appear to affect entrepreneurial skills, future studies could explore other socio-economic factors that might influence entrepreneurial outcomes, such as family income or educational access. This analysis provides valuable insights for policymakers aiming to foster an inclusive entrepreneurial ecosystem, ensuring that students from all caste backgrounds are equally prepared for entrepreneurial ventures. The box plots also suggest that the entrepreneurial skills measured in this sample are uniformly distributed across caste categories, highlighting that other factors, rather than caste, may be more influential in determining these skills. This aligns with the findings from the Kruskal-Wallis test, where no p-value reached

statistical significance, further reinforcing that caste is not a differentiating factor in this analysis. In summary, the box plot images corroborate the non-significant results of the Kruskal-Wallis test, suggesting homogeneity in entrepreneurial skills across caste groups in this sample. Future studies may explore other socio-economic or educational factors to understand better what influences entrepreneurial skills in this context.

The findings of the Mann-Whitney U and Kruskal-Wallis tests reveal that gender, caste, and family major occupation do not significantly impact the entrepreneurial skills of agriculture students in Odisha. These results suggest that opportunities for skill development in critical areas such as Planning, Enterprise Management, Credit & Finance, and Marketing are accessible to students regardless of their caste or family background. This aligns with the increasing inclusivity in education and entrepreneurship, where access to resources, educational interventions, and skill-building opportunities are becoming more widespread. The equitable distribution of entrepreneurial skills across various social backgrounds reflects the positive impact of inclusive educational policies and the efforts made to level the playing field for all students, regardless of caste or family background.

While caste and family occupation appear not to affect entrepreneurial skills, it is essential to consider other socio-economic factors that might influence entrepreneurial outcomes. For instance, family income and access to educational resources may create disparities in students' ability to capitalize on entrepreneurial opportunities. These factors could shape the skills students develop, particularly those related to accessing networks, capital, or mentorship. Future studies could explore how these socioeconomic elements affect entrepreneurial capabilities, particularly in marginalized groups who might face barriers to resource access. Understanding these barriers could help identify areas for targeted interventions to ensure that all students have equal opportunities to succeed in agricultural entrepreneurship.

This study will be helpful for the institutions to shape the syllabus of agriculture taught and the students will get proper need-based skill training programs. By which the students will be able to contribute not only to their family but also to society as well as the country in terms of finance. Search types of initiatives are important for rural growth and development in Odisha and beyond (Bosman, 2019).

Conclusion

The study on entrepreneurial skills of agriculture students in Odisha offers a deep insight into the current state of entrepreneurship education and competencies among students in the region. While students demonstrate moderate proficiency in entrepreneurial abilities, key areas like Credit and Finance and Marketing Skills show notable deficiencies, with none of the students reaching a high proficiency level. This finding points to an urgent need for specialized training in these fields, which are crucial for entrepreneurial success in agriculture. On the other hand, skills related to Planning and Enterprise Management are comparatively stronger, but a significant portion of students remain in the lower-skill category. This suggests that while students may have a foundational understanding, their ability to practically apply these skills is limited and requires further development. Interestingly, socio-economic factors such as caste, locality, and family size do not

appear to significantly impact the development of entrepreneurial skills. This challenges some common assumptions and highlights the importance of individual attributes like decision-making, leadership, and a proactive attitude toward seeking information. These personal qualities play a more decisive role in shaping entrepreneurial competencies, suggesting that entrepreneurship education must also focus on enhancing these traits. The lack of a gender divide in entrepreneurial skills is another critical finding, demonstrating that both male and female students have equal opportunities within the entrepreneurial education system. However, the study suggests that the existing education framework needs to be expanded with targeted interventions, particularly in financial literacy and marketing, to ensure students are well-prepared for the entrepreneurial demands in the agricultural sector. Moreover, programs that aim to boost leadership, decision-making, and problem-solving abilities are essential. These skills not only complement technical expertise but also empower students to adapt to challenges, make informed decisions, and lead their ventures successfully. In summary, the study underlines the importance of a more tailored and holistic approach to entrepreneurial education, one that strengthens both technical skills and personal attributes necessary for entrepreneurial success in agriculture.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	Yes
Editing of the article/paper	Yes	No
Supervision	No	Yes
Project Administration	Yes	No
Funding Acquisition	No	No
Overall Contribution Proportion (%)	60	40

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge

The author(s) solemnly declare(s) that this research has not involved Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

Research involving Plants

The author(s) solemnly declare(s) that this research has involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children

The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

Competing Interests/Conflict of Interest

Author(s) has/have no competing financial, professional, or personal interests from other parties or in publishing this manuscript. There is no conflict of interest with the publisher or the editorial team or the reviewers.

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The Practices of Peacebuilding in South Omo: A Qualitative Case Study in Hammer, Dassanech, Nyangatom Woreda and the Turkana Kenya Community

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Abstract

The study examined the practices of peacebuilding in the south Omo zone pastoralist and agro-pastoralist communities of Dassanech, Hamer, Nyangatom, Woreda of Ethiopia and the Kenya-Turkana cross-border resource-based conflicts. The study investigated internal and cross-border peacebuilding practices. To achieve the objective of the study, a qualitative research approach and case study research design were used. The study revealed that peace is the highest priority of the pastoral and agro-pastoral community who view conflict as synonymous with starvation, and poverty. The study also revealed that peacebuilding efforts between the two communities involve a range of actors and approaches. Key actors include: the Government, non-state actors, international organizations, public administrators, intergovernmental organizations and indigenous community-based institutions. They play a significant role in conflict management, prevention, and resolution as part of the broader peacebuilding process. While the outcomes of these practices have been less effective, these initiatives are recognized as valuable foundations for advancing peacebuilding efforts. The study also finds that there is relative peace in the study area and the trends of conflict are reduced. However, the objective of building peace is still not achieved because of the lack of government commitment to engage in peacebuilding and the complex nature of conflicts. Factors such as environmental changes, land disputes, resource scarcity, drought, the proliferation of small arms, livestock raiding, and killings are identified as key causes and triggers of conflict and violence between the two communities. The peacebuilding practices need to be done by various peace actors to create peace in the area. Moreover, developing new peace initiatives and peace leadership could play a vital role in the realization of peace in the area.

Keywords

Peacebuilding; Resources; Conflict; Cross-border conflict; Pastoralism; Agro-pastoralism; Land

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Introduction

Pastoralism is a livelihood mechanism and trans-human activity characterized by livestock herding and movement in the arid and semi-arid lands of East Africa. Pastoralists and agro-pastoralists move with their livestock and in most cases, raids, livestock theft, abduction, droughts, presence of illegal arms, inaccessibility of pasture land, water, epidemics, degradation, negative cultural practices instigate conflict and violence. Addressing these challenges requires implementing mechanisms that promote peace and development (IGAD, 2022). The nature of internal and cross-border pastoralist natural resource-based conflict is resource-driven. Furthermore, the salient triggers of conflict as a politically motivated, quest for maintaining livelihood and ethnic-based resource sharing and control within and across borders. It is frequently witnessed across the border with common signs seeming inevitable due to resource scarcity and environmental degradation (pers. Comm., Department Head of South Omo Zone Peace and Militia Office, 2023). The sources of the conflict are complex and multi-layered and need peaceful solutions because the multi-layered factors leading to conflict in the area are interconnected to the livelihood and survival of the community.

Conflict and peace have an impact on the relationship of the community. Peacebuilding processes vary depending on the context of the conflicts. Peacebuilding approaches can create an environment of positive community relationships (Karbo, 2008). Researchers classify the peacebuilding approaches into state-based and non-state-based traditional approaches (Murithi, 2008; Omeje, 2008). Peacebuilding practices need the role of state, and non-state actors with strategies to sustain peace in the control and utilization of resources like land, pasture, water points and water bodies. Creating peaceful utilization of these resources is vital for the survival, livelihood and development of the pastoral and semi-pastoral community. The conflict in the area is situational. Mostly the resource-based conflict is exacerbated during dry seasons. This is a time of resource shortage and the community is always in search of these resources anywhere across the boundary of the two countries (Pavanello and Levine, 2011). Land and water, in particular, can be structural drivers of pastoralist conflict and violence (Nilsson, n.d). Several interventions are being carried out by NGOs, international organizations, intergovernmental organizations and the governments in the study area to build peace and mitigate conflict and violence (European Union Emergency Trust Fund, 2016). The states are not the only actors in peacebuilding. It involves the participation of various non-state actors. Because the state centered approaches of peacebuilding are unable to address conflict and violence (Toru, 2010). Community-based peacebuilding approaches are an important part of conflict intervention. Public administrators and Indigenous community-based approaches to peacebuilding contribute to conflict resolution and resource sharing among the pastoral community. Indigenous conflict resolutions have been recognized by the states of Kenya and Ethiopia to create conditions of sustainable inter-ethnic peace based on their peace culture, norms and values (pers. Comm., Department Head of South Omo Zone Peace and Militia Office, 2023). Moreover, intergovernmental organizations like the European Union and IGAD, NGOs and civil society development institutions could be vital for peace.

This study argues that multiple approaches to peacebuilding are the most important mechanism for resolving cross-border resource-based conflict and creating sustainable

peace between the two countries' pastoralist communities. The specific objectives of this study are:

- 1) To identify the underlying cause of internal and cross-border conflicts among the Hamer, Dassanech and Nyangatom communities in Ethiopia, and the Turkana pastoralist and agro-pastoralists in Kenya;
- 2) To examine the practice of the peacebuilding system applied; and
- 3) To show the contributions of the system to conflict resolution and peacebuilding.

This article will contribute to existing literature on peacebuilding by analyzing and investigating the peacebuilding practice in internal and cross-border resource utilization conflicts. Based on the researcher's information and online sources, no prior studies have focused on the peacebuilding practices addressing internal and cross-border conflicts involving the Hamer, Dassanech, and Nyangatom Woredas of Ethiopia, as well as the Turkana communities in Kenya. This research aims to fill that gap and contribute to the development and enhancement of peacebuilding systems for managing internal and cross-border pastoral conflicts and violence.

Theoretical Framework of the Study

Lederach theory of grassroots peace-building is a comprehensive concept that encompasses, generates, and sustains the full array of processes, approaches, activities and stages needed to transform conflict towards more sustainable, peaceful relations. Peacebuilding practices need the transformation of conflict through various peacebuilding mechanisms like conflict resolution, management, negotiation, and prevention (Lederach, 1997). In addition, peacebuilding is a long-term, dynamic process, which aims to address relational, structural, attitudinal, and social issues through a vast array of mechanisms that co-create an infrastructure for peace. The peace infrastructures can influence the conflict situation to create sustainable peace among or between the conflicting groups (Ramcharan, 2009). Further, local community participation, capacity-building, institutional building, relationship-building, and cross-community dialogue are also required to address the root causes of conflict and its impacts (Jeong, 2005; Lederach, 1997; Zelizer, 2013).

Peacebuilding needs the long-term commitment to establishing an infrastructure of peace across the levels of a society, community and groups that empower the resources for reconciliation from within and maximize the contribution from others like NGOs, states, international organizations, inter-governmental organizations or peace actors from abroad (Lederach, 1997). The reconciliation of polarized communities is an important step within any peacebuilding process. Reconciliation prevents, once and for all, the use of the past as the seed of renewed conflict and violence. It also consolidates peace and breaks the cycle of violence in society (Mac Ginty and Williams, 2009).

As suggested by democratic peace theorists, democracy is the driving force of peace and economic development. Democracies do not take the path of war or violence rather they opt to work on the principles of cooperation, understanding and respect. Peace is also achievable through economic development-based cooperation (Patapan, 2012). As part of it, the economic peace theory, explains that the actors of government and civil society should cooperate economically, socially, and culturally on the ground with informants

like government officials, and NGOs, which can ensure stability and maintain peace. Solutions must be adopted by the top and middle leadership at the grassroots (Lederach, 1997). The political peace process must be strengthened by opening up opportunities to communicate across conflict lines, understanding the interests and desires of the other party confirming one's interests, and exploring viable alternative approaches that meet the needs of both parties. Peacebuilding initiatives include cross-cutting or inclusive relationships, such as people-to-people, business-to-business, and institution-to-institution initiatives. Economic peace theory suggests this economic interdependence promotes peace and prevents conflict. At the macro level, economic peace involves structural reforms to create an environment for peacebuilding (Galtung, 1975). Beyond the grassroots peacebuilding, the UN Agenda for Peace suggested that states conduct diplomatic negotiations and discussions for the peaceful settlement of disputes (Ghali, 1992). Diplomacy as a conflict and violence resolution mechanism is taken as a theoretical framework because it is important to analyze inter-state diplomatic engagement in cross-border resources-based and resource-sharing conflicts.

This study analyzed various governmental perspectives through the lens of peacebuilding theories, including the UN Agenda for Peace and the economic theory of peace, to explore the dynamics of internal and cross-border conflicts and peacebuilding efforts. It focused on the Dassanech, Hamar, and Nyangatom Woredas of Ethiopia, as well as the Turkana community of Kenya. The theoretical framework supports this analysis by examining the practices, approaches, and mechanisms of peacebuilding, highlighting its relevance to both positive and negative peace within the specific contexts of these conflicts.

By applying these theoretical approaches, particularly to resource-based internal and cross-border conflicts, the study emphasizes the critical role of grassroots governmental and non-governmental actors. These actors are shown to be particularly effective in addressing such conflicts and fostering reconciliation, offering contextually relevant mechanisms to heal the wounds of violence and build sustainable peace.

Methodology

This research employed qualitative research methods and multiple case study designs. The research was conducted through the analysis of primary and secondary data sources. Purposive sampling was used to identify key informants from among government officials, NGOs, elders' peace and militia officers, conflict prevention, early warning and early response experts on the Ethiopian side. The data related to the Kenyan side of the study were gathered indirectly, relying on secondary sources and primary data collected from Ethiopian participants. 107 individuals were selected to participate in interviews and focus group discussions. Six focus group discussions were used for the local peace committees, the Keble peace committee, community members, and public administrators comprising at least eight people in each group discussion on the Ethiopian side. The information about the Kenyan side depended on secondary data and was based on the primary data taken from Ethiopians. FGD, interview, and document analysis were employed to investigate the multiple approaches and practices of peacebuilding in cross-border resource-based conflicts. The purpose of all of the tools was to produce reliable data using data triangulation. The data obtained through unstructured interviews, and

FGDs and document analysis were organized based on themes, contents and analyzed qualitatively or inductively. In addition, direct quotes were used that described the views or opinions of interviewees about the study objectives. The study depends on secondary sources of data in the Kenyan side only and only qualitative approaches are used.

Results and Discussion

Causes of Conflicts

The conflicts in the region are both internal and cross-border. Internal conflict is the driver of cross-border conflicts as its base is a shortage of resources. Land, in particular, emerges as a critical source of contention due to its role in providing access to pasture, water, fishing grounds, and agricultural areas vital for livelihoods. According to Yntiso (2016), and Mwangi (2020), key resources like livestock, water, grazing land, flood retreat agricultural land and fish stocks are the main resources for the livelihood of local communities on both sides of the border areas. These resources are indispensable for the overall sustenance of the communities. Among them, water and pastureland stand out as the most crucial and contested resources, given their significance in supporting agro-pastoralist lifestyles. One major driver of conflict is the seasonal migration of agro-pastoralists in search of pasture and water for their livestock. This mobility often leads to disputes, particularly during dry seasons when resources become even scarcer. Informants noted that Ethiopian pastoralists frequently migrate to areas along the Kenyan border, while Kenyan communities also cross into Ethiopian territories. However, Ethiopian pastoralists' mobility is more pronounced during dry periods, further intensifying resource competition and conflict.

The Turkana area is the area for both Ethiopians and Kenyans and the competition over resources is often fierce across borders. Conflict over access to land, water and fishing rights is common between communities in the two countries. The resource scarcity and conflict are severely exacerbated by government or state development projects of the Gibe III dam through the transformation of communal lands into large-scale irrigated cash-crop schemes for sugar cane and cotton. These projects have displaced communities from their land without compensation and reduced the amount of water available to the Dassanech, Arbore and Turkana, who are downstream from the Omo and Wiyot rivers. Conflicts can also arise between upstream and downstream communities, particularly due to issues related to resource management and equity. One notable source of grievance is the lack of compensation provided by the Ethiopian government to pastoralists for their land (pers. Comm., Department Head of South Omo Zone Peace and Militia Office, 2023). This omission fosters resentment within the community and indirectly contributes to cross-border mobility and conflicts.

The conflicts are triggered by environmental and man-made factors like unpredictable weather conditions, environmental degradation, drought, and resource pressure caused by population large-scale development projects. These issues influence livelihoods and can result in conflict and instability between groups competing for access to land, pasture, water and fishing areas. Competition over resources is often fierce across borders. Conflict over access to land, water and fishing rights is common between the two countries (pers. Comm., Department Head of South Omo Zone Peace and Militia

Office, 2023). Resource scarcity and conflict are severely exacerbated by government or state development projects.

In addition, the informants explained the conflict in the following manner:

“The conflict takes the form of clan conflict as rival groups compete and fight over scarce resources like water points, cattle raiding (Plate 1) and lakes for fishing. Some conflicts are driven by historical clan rivalries. Internal conflicts can be seen between the Nyangatom and Suri, Dassanech and Nyangatom, Dassanech and Hamar, Dassanech and Turkana, Nyangatom and Turkana, Hamar and Mursi, and Hamar and Erbore over land. The internal conflicts exacerbate the external or cross-border resource-based conflicts. When we come to the cross-border conflicts, the Hamar also fights with the Gabra community and Turkana over fishing rights and range land. The increasing pressure on resources pushes the border area community to resort to violence to gain access to resources. The other cause of conflict in the study area is animal raiding as a cultural value and practice. Our culture promotes animal raiding (FGD 1 and interview with south Omo zone peace and militia office).”



Figure 1: Shows the return of looted cattle from Kenya to Ethiopia
The picture above shows the return of the looted cattle from Kenya to Ethiopia

The Role of Various Peacebuilding Actors, Dassanech, Nyangatom Woreda of Ethiopia and the Turkana of Kenya

The State as a Peacebuilding Actor

The governments of Ethiopia and Kenya have worked together to mitigate the conflict, build peace and facilitate the transformation of conflicts among pastoralists and agro-pastoralist communities in the Dassanech and Nyangatom Woreda of Ethiopia and their counterparts in Kenya. As (Lederach, 1997), stated, peacebuilding in a conflict can be done by the state security mechanisms. For instance, the state police force, the military and the local militia can manage conflict and violence by applying the state's early warning and response system can reduce further violence.

State-led diplomacy is one of the mechanisms to deal with cross-border conflict resolution, prevention, management and overall peacebuilding. Inter-state diplomacy is done for the reduction of conflict and violence together with other peacebuilding mechanisms in the study area (pers. Comm., Department Head of South Omo Zone Peace and Militia Office, 2023). The two states' security system also contributes too for communication and conflict prevention. Diplomatic practices are conducted as a mechanism for peace and largely include non-state and state actors. Public diplomacy is also the other approach to cross-border conflict prevention and peace done in the study area. Public diplomacy creates an opportunity for each to broaden the friendship relations between the two countries.

The two state governments conduct conflict resolution through elders, conflict management through the police offices and conflict prevention activities through the Woreda Conflict Early Warning and Response offices. The Dassanech, hammer and Nyangatom Woreda of Ethiopia administration work to enhance peace through established peace committees from the cattle keeper, elders, police and women. They have played a pivotal role in addressing community conflicts through the enhancement of communication understanding. The role of peace committees is primarily focused on conflict prevention and resolution. They try to communicate with the Woreda security offices to reduce conflict and violence. The Woreda governments have direct responsibilities for citizen security, peace and welfare. From the focus group discussion with the district government officials of the two sides, the study identified their roles to include working to share information and resolve conflict with the established peace committee, government bodies, elders and police officers. Even if the security officers are part of it, conflicts are resolved based on the culture of the two communities. There is a weak collaboration between Kenya and Ethiopia to engage in cross-border peacebuilding programs (FGD, 1, 3 and interview with the zonal peace and security office). As part of the governments of the two states, IGAD is also active in the border area to deal with conflict and peace. In the past, its main focus was on the collection, analysis and dissemination of conflict early warning information to the concerned bodies. It was also involved in two regional projects:

- (i) The Regional Pastoral Livelihoods Resilience Project (RPLRP)¹ and

¹ *Ethiopia - Regional Pastoral Livelihoods Resilience Project: environmental and social management framework (English)*. Washington, D.C.: World Bank Group.

- (ii) The Drought Resilience Sustainable Livelihoods Project (DRSLP)², which focuses on natural resource management, markets, livelihoods and disaster risk management contributing indirectly to conflict mitigation and peacebuilding. In spite of the regional focus of these projects, the present research suggests a weak collaboration between Kenya and Ethiopia, with little evidence of joint planning and consultation.

Recently fish represents a new livelihood for some communities living near Lake Turkana.³ The possibility of developing bilateral agreements between Kenya and Ethiopia may open up new options for Ethiopian pastoralists to move their herds into pastures that have the potential for additional production. Education and the opening up of wage employment opportunities for educated Nyangatom, and Dassanech may provide more diverse livelihoods that will contribute to resilience (USAID, 2021). These promote peace and improve community relationships. The government in collaboration with the EU, the Ethiopian Institute of Peace and the Ethiopian pastoralist association tries to create awareness about the culture of peace and the ways of peaceful co-existence.

The state police force, the military and the local militia can manage conflict and violence by applying the early warning, and response system can reduce further violence as seen in figure 2.



Figure 2: Public/community level Discussion between the police forces of two neighbouring states, engaging with communities from both countries to promote peacebuilding efforts

<http://documents.worldbank.org/curated/en/953271468202451582/Ethiopia-Regional-Pastoral-Livelihoods-Resilience-Project-environmental-and-social-management-framework>.

² Ethiopia - Drought Resilience and Sustainable Livelihoods Programme - Ethiopia Project (DRSLP-II) - IPR June 2021

³ Ethiopia: The Untapped Fishery Resources of Omo-Turkana Basin, 2020. The Ethiopian Herald, 2020. <https://allafrica.com/stories/202012160713.html>

Non-Governmental Organizations

Some NGOs are attempting to promote greater resource sharing to reduce conflict.⁴ International organizations have supported various peace efforts such as training, forums, peace clubs, peace radios, and peace committees as noted by The Federal Democratic Republic of Ethiopia (2015). In the study area except for peace committees and training, others are nonexistent (pers. comm. with Woreda Conflict Prevention and Early Response Office, 2022). Non-governmental organizations like FBOs, Riam Riam Peace Network, IOM, Mercy Corps, Oxfam GB, EpaRDA, and SAPCONE, commit the two communities peace help in the dissemination of information, providing training and participating in reconciliations. They provide education in the form of training to develop a culture of peace in the community (FGD 4). Based on the theory of culture of peace, the conflicting parties develop the attitude of nonviolence and fierce determination to defend human rights, justice and human dignity for the existence of peace in a community is expected from all members of a community. Peace will be a permanent feature of all social institutions, especially, the economic scene.

In both pre and post-conflict contexts, the involvement of intergovernmental organizations and civil society organizations, including NGOs, plays a crucial role as key drivers of peacebuilding and peace-related activities. The NGOs play an important role in advocacy to help the Woreda or districts to ensure peace and reduce conflict. NGOs are at the cutting edge of people-centred structural peace-building diplomacy practices between the two communities. In Ethiopia, international organizations and national Civil Society Organizations have had a crucial role in establishing local peace committees. CSOs have roles in the support of continuity of peace dialogues between the conflicting parties. They provide the skill of peacebuilding to leaders to enhance community-based peacebuilding (interview with Zonal and Woreda Peace, Conflict Prevention and Early Response Office, 2022).

There are many NGOs engaged in various activities. Specifically, 44 NGOs are working on cross-border issues. The 24 NGOs are on the Ethiopian side and 20 on the Kenya side. Within Ethiopia, most of their activities are focused on livelihoods and resilience, which include interventions such as rangeland management, agriculture and water.⁵

Local Peace Committees in Kebeles or Small Local Administrative Units

To address cross-border conflict harmonizing committees are established to reduce conflict and violence in the study area. For the success of peacebuilding, community participation is taken as the best strategy. In Dassanech, Nyangatom and Hammer Woreda of Ethiopia, peace committees were established to strengthen village peace, and border area peace. Conflict information sharing for concerned government bodies by cattle keepers and other community members is conducted to prevent violence. International organizations and National Civil Society Organizations have had a crucial role in establishing local peace committees around the borders. The Woreda peace committees have a mandate to facilitate the process of conflict resolution and to resolve conflicts. The

⁴ Pathway to peace, Pastoralist community Initiative and Development Assistance.

⁵ Cross-border analysis and mapping final report (2016).

committees meet irregularly to address any conflicts in the community and between the two communities. Conflicts are resolved especially by tribal leaders or elders.

Local administration representatives for women and youth, and elders are members of the committee. Kebele peace committees are more inclusive in establishments. The lack of active joint-Woreda district and cross-border peace committees hinders the timely resolution of conflicts and destructive violence that happened between the two states. The peace committees are one of the peacebuilding structures to facilitate people-to-people diplomacy in the part of Ethiopia and public diplomacy to the side of Kenya. To make public diplomacy or people-to-people diplomacy the south Omo zone government officials and the Woreda leaders play a significant role in using sport as an instrument of peace.

The Role of Indigenous Community-Based Institutions in Border Peacebuilding

The institution of traditional leadership has its origin from ancient times when communities sharing the same beliefs and kinship were allocated land for occupation and grazing, (Bennett and Murray, 1999). Indigenous institutions are used to address internal and external conflicts in pastoral communities of the study area. In the traditional institutions of the study area, tribal elders are engaged in conflict resolution and management. These institutions are effective in managing conflicts within their ethnic groups, and they also sometimes play a role in resolving conflict outside their ethnic group in cross-border conflicts as seen in figure 3. In each Woreda, there is a peace and security committee including tribal leaders or elders which is mandated to prevent, and settle conflicts in its area and also can participate in cross-border conflict resolution and prevention if they are selected by the community.



Figure 3: The picture shows a community discussion on resource conflict and its resolution [Source: Woreda government communication affairs]

Conflict resolution was identified as the primary priority by the community on shared resources like water and land for pasture. Community-based dialogue is also the way to address the root causes of conflict in the study area. The local community institutions are empowered to make their own decisions on conflicts and be part of the peace-making process. The Indigenous system provides better results when it comes to conflict resolution in the community of the study area. A large number of people who live in traditional communities subscribe to the principles of customary law and embrace the traditional court systems. They contribute tremendously to the dynamics of peace.



Figure 4: The approaches of peacebuilding in cross-border pastoral conflicts

Peacebuilding is multidimensional, the above-stated peacebuilding approaches in figure 4 are interconnected and the realization of one peacebuilding approach is dependent on the other to achieve the goal of peacebuilding. One peacebuilding approach can support the other approach to achieve the overall goal of cross-border peacebuilding. Achieving peace requires inclusive participation, and shared responsibility involving the state, civil society, and different international and local organizational structures. Multiple actors working in a coordinated manner as well as the use of multiple approaches are essential in conflict resolution in cross-border pastoral resource-based conflicts. The study highlights several

peacebuilding activities implemented in the area, which serve as systems to reduce conflict risks and threats and are considered key mitigation strategies (Figure 5).

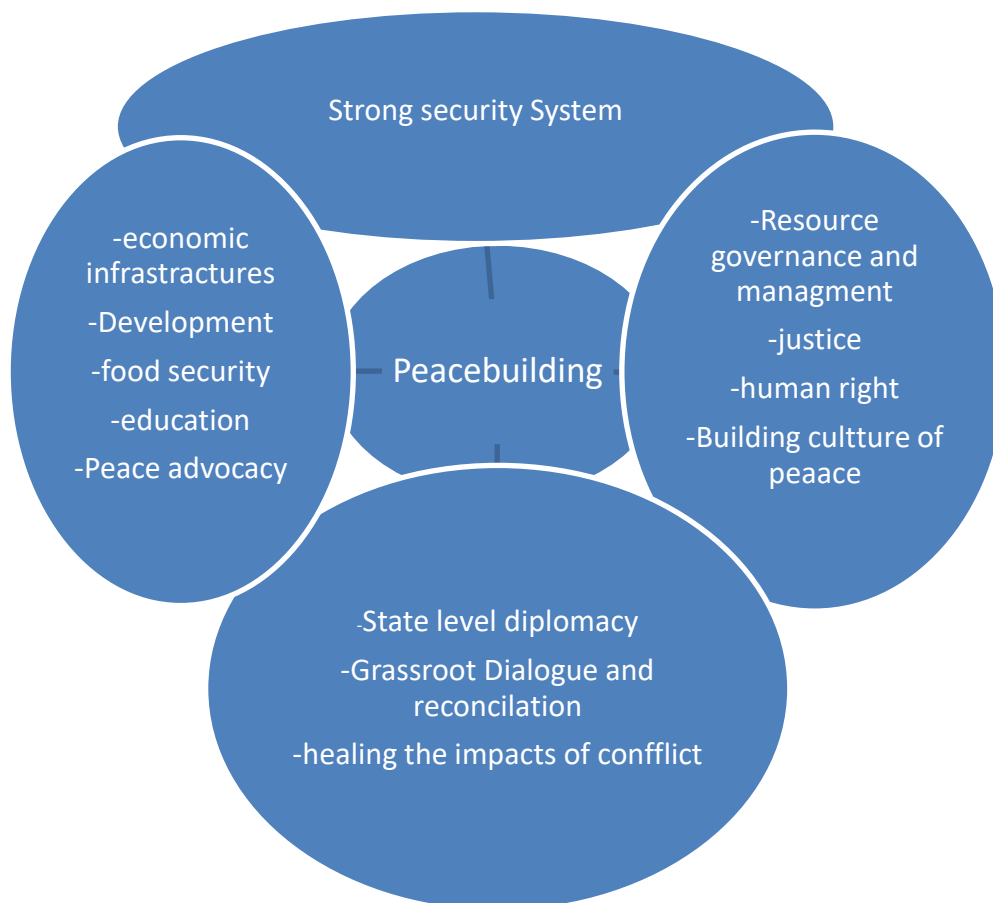


Figure 5: Framework of Peacebuilding

Weak resource governance, economic problems, population growth and environmental degradation are also drivers of conflict and violence (UN Environment Programme and UN Department for Political Affairs, 2015). Shortage of livelihoods and social-economic deprivation, particularly when coupled with a sense of historic marginalization, animate grievances. The study area community especially the Ethiopian side was marginalized from development like education and economic development but nowadays there are few improvements in such areas.

Peace needs to emerge organically from within society, addressing the multiple concerns and aspirations and seeking common ground so that all sectors feel invested in strategies, policies and mechanisms that offer the way forward to grassroots community peace (Chandran and Chari, 2015). When well-managed, natural resources can be a source of development, stability and peace. When mismanaged or misappropriated, they can have severely negative economic, social and environmental effects and constitute conflict and violence led a massive loss for peacebuilding and development. Development is critical

to preventing both lapse and relapse into conflict natural resource conflict. Human rights violations like killings of tribal members are also causes of conflict and must be addressed as early as possible so as not to trigger resource conflicts.

Pastoralist and Agro-pastoralist Women in Peacebuilding

Women are not always merely victims of conflict; their active participation in conflict resolution and peacebuilding is increasingly recognized. The UN Security Council Resolution 1325 (2000)⁶ emphasizes the importance of enhancing women's involvement in conflict resolution processes, highlighting their significant and transformative role in achieving sustainable peace. These have resulted in a worldwide call to involve women in issues of peace and conflict as active participants (2000). The activity of peace building among the pastoralist communities in the study area is given to the elders but nowadays there is an increasing involvement of other groups in the community such as women and youth in promoting peace among the conflicting community. The committee is established to deal with conflict resolution within the community. Women help their male counterparts to see things from a different peace perspective and the need to embrace dialogue in resolving inter and intra-ethnic conflicts. It shows that women are not the part and victims of conflict but also they are part of the solution. Women's peace leadership is important for conflict mitigation. Women are not always the victims of conflict as the UN Security Council Resolution 1325 (2000) calls for enhanced involvement of women in conflict resolution processes is an indication of the significant role women play in conflict resolution and peacebuilding.

Football Sport as a Pathway to Peacebuilding

Football sport is one sport used to create positive relationships in the study area community and it is the mechanism planned by the government to increase communication, and mutual understanding (pers. comm. with Woreda Peace and Militia office, 2022). Peacebuilding through football sports is practised by community members to liberate their minds and encourage mutual understanding as sports are not just physical activity but rather a system used to bring people together. Sports are not just physical activity regulated by norms and rules, rather, they are understood as a wider cultural expression that may bring people together by serving as a common denominator between communities who can, in the best case, actively mobilize in the name of peace and living together, and development of peace (Figure 6).

Conflict and Drought Early Warning System

The rural development Program in Ethiopia being implemented by the state did not give attention to the pastoralist and agro-pastoralist areas. The area is marginalized from development programs. Conflict and drought are common phenomena and the primary sources of vulnerability in the study area, with people being significantly affected by both. The conflict and drought early warning and response system is very weak. Having a functional drought and conflict early warning and response system will help reduce its

⁶ <https://www.un.org/shestandsforpeace/content/united-nations-security-council-resolution-1325-2000-sres1325-2000>

negative impacts on the community. Adopting drought and conflict early warning and response information gathering and rapid response mechanisms is useful to pastoralists and agro-pastoralists for conflict transformation. However, the system in the study area is not working. The existences of the system have long-term importance for livelihood change and diversification. Furthermore, it is good for grass adaptation to drought and water development.



Figure 6: Football sport held b/n the Kenyan and Ethiopian community in south Omo Ethiopia

Conflict early warning and response mechanisms are established at levels of government. However, the system in the study is incomplete and all of the structures of it are not institutionalized for the needed purpose. The mechanism lacks professionals in conflict analysis and interpretation. The conflict early warning information gatherings need to be done by professionals. Using field monitors, conflict data gatherers generate important conflict data for proper analysis and decision-making to prevent conflicts before they erupt and further escalation as it is part of the conflict transformation strategies. According to Lederach (1997), to transform the conflicts its structures, contexts and actors should be well studied. Based on the findings a study, state and non-state actors could collaborate with the community in alleviating resource scarcity and promote inter-dependence or resource sharing between communities.

According to key informants, strengthening institutions for Peace and development in the study area lacks the involvement of state and non-state actors. IGAD and USAID are trying to support to building the efficiency of the peace architecture at national, regional and Woreda levels. IGAD's CEWARN is also used to collect and analyze early warning information from the area, particularly the Dassanech and Nyangatom Woredas and Turkana areas. The Ethiopian Peace and Development Centre (PDC) completed a project on "Strengthening Local Cross-Border Conflict Management in Lake Turkana-South Omo Cross Border Area". The purpose of the project is the management of cross-border resources based conflicts. The security situation on the ground makes to run the project on the Ethiopian side. In addition to PDC, PACT Ethiopia is working on the peace of the community in the area. However, the number of potential implementing agencies on the Ethiopian side is limited. This indicated the issue of conflict transformation in the study area is not given the emphasis.

Water Resources Development and Management

According to key informants, the study area has rich ground and river water but the problem is development and management for use. To transform water-related conflicts, water resources development and management can play a significant role. The Ministry of Water, Pastoral Affairs, Irrigation and Energy did not do activities for conflict transformation. As water is an important and scarce resource in the area, much of the conflict and tension within and across borders is on it. At the local level, the presence of development projects such as sugar cane and cotton farms and the Gibe III dam have exacerbated water availability in downstream communities, such as the Dassenech, Erbore and Turkana communities but other areas did not have access to water. In this context, water management and development needs national and international relations to transform internal and cross-border water-related conflicts. The state's (Ethiopia and Kenya) cooperative interventions help to ensure fair and sustainable access to water sources strengthen livelihoods reduce instability and in the long time frame can transform cross-border conflicts. But the governments are negligent or maybe did not give attention to it.

The existence and access to good rangeland are crucial for a well-performing and stable agro-pastoral and pastoral system (IGAD, 2022). Deterioration of rangeland across the study area adds pressure to the livelihood of the community and instigates conflict in the search for pasture, bushes, and water. The cause of the rangeland's decline is due to the increase in pastoral households and their herd, climate change, withdrawal of rangelands from the pastoral area for commercial agriculture, and dams built upstream. Conflict and drought pose significant threats in Nyangatom and Turkana, serving as the main sources of vulnerability for the communities in these regions.

Informal community institutions of pastoralists and agro-pastoralists know the rangelands and how to rehabilitate them for use. The local knowledge is not promoted by state and non-state actors for the rehabilitation of rangeland. In the study area, the experience and lessons could be drawn from the Pastoral Community Development Program. It was working in this area on sustainable livelihood enhancement and pastoral risk management. PCDP activities are anchored on range management and supporting pastoral livelihoods, and in situations where there are already established villages, it supports the building of water facilities. NGOs such as AFD, Farm Africa, VITA, DRSL and RPLR were engaged in rangeland rehabilitation activities.

The Role of Public Administrators in Peacebuilding

Public administrators at the district/Woreda level played a vital role in fostering peace between the two countries and among the conflicting parties. They facilitate public peace meetings, public diplomatic relations, and leader-to-leader diplomatic discussions, and support various peace initiatives commenced by NGOs, and intergovernmental and governmental organizations. They are also working on finding pacific mechanisms of conflict mitigation, livelihood diversification, and improvement the governmentally designed projects on both sides.

The Opportunities of Peacebuilding in the Study Area

There are opportunities for peacebuilding in the study area, the following are the identified opportunities based on the collected data:

- Formal and informal education is also seen as an opportunity to contribute to the erosion of interest in conflict among pastoralists especially among the youth. There is little change in behaviours among the youth pastoralist community. Through time people develop a culture of peace because of the influence of education.
- Diversification of livelihoods in addition to pastoralism in some areas of the study area is observed to reduce conflict on pasture and water. Engaging in rainfed agriculture and using irrigation for crop production is the best opportunity to change the conflict situation in the study area.
- The existence of peace and militia offices for the promotion of peace and security in conflict-ridden areas is another opportunity for peacebuilding. The local and zonal offices are working together with the conflict early warning and response offices to prevent conflicts.
- The political development of self-administration is also a good opportunity to govern them in a way that participates in the decisions, and policy-making process of the government about the peacebuilding strategy of the state.
- Strengthening the indigenous system of conflict resolution in each ethnic group of the study area; community plays a significant role in the peacebuilding practices even if it never makes a lasting solution to peace. It creates a pathway for peacebuilding intervention.
- The last but not the least opportunity identified by the researcher is the indirect conflict intervention made by governmental, NGOs, and intergovernmental organizations. They contribute a lot in education and development which directly and indirectly creates a peaceful way of life in the community.

Conclusion

Multidimensional peacebuilding is applied in the study area. Peaceful co-existence for sharing or controlling resources is the dream of the pastoralist and agro-pastoralist community in the study area. The multiple actors of peacebuilding are practised to reduce conflict and to sustain peace among the community but are not fully effective in creating peace. The conflict dynamics are now reduced and there is relative peace but the conflict situation is sessional. The conflict increased in dry sessions when the amount of water and pasture were reduced. The role of the local government, peace committees, international organizations, intergovernmental organizations, NGOs and public administrators are significant to mitigate conflicts in the study area. Moreover, tribal leaders as part of the customary institutions played very important roles in preserving and building peace among the community and in cross-border conflicts. The resource-based conflict is still on and needs a new creative mechanism to reduce it, and to build peace. Turkana county leaders and the Dassanech, Hamar and Nyangatom Woreda of Ethiopia worked together to reduce conflict and violence but it lacks the coordination and cooperation to work together for peace. Governments and other bodies need to engage in conflict intervention mechanisms to create sustainable peace and reduce the negative impacts of conflict. Furthermore, the government of Ethiopia should realize the

formulated policy on peacebuilding, and focus on conflict sensitivity in development projects in the area. Realizing peace leadership in the local context is also recommended as part of the ongoing peacebuilding activities.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

This article is 100% contributed by the sole author. He conceived and designed the research or analysis, collected the data, contributed to data analysis & interpretation, wrote the article, performed critical revision of the article/paper, edited the article, and supervised and administered the field work.

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge

The author(s) solemnly declare(s) that this research has not involved Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

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The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee

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(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

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Problems and Prospects of Realizing the Bioenergy Potential of Ukraine

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Abstract

The article examines the key challenges facing the Ukrainian energy sector and explores global energy development trends in the 21st century, emphasizing the growing importance of bioenergy. It highlights Ukraine's significant bioenergy potential, driven by the availability of diverse biomass resources such as agricultural residues, forest biomass, energy crops, livestock waste, and industrial organic waste. A list of fast-growing energy crops suitable for cultivation in Ukraine is provided, alongside an analysis of key biomass-to-energy conversion technologies, including anaerobic fermentation, pyrolysis, gasification, combustion, fermentation, and esterification. The article underscores the strategic advantages of advancing bioenergy in Ukraine, including reduced dependence on imported energy, environmental benefits, rural development, job creation, increased investment attractiveness, and technological modernization of the energy sector. However, it also identifies significant barriers hindering the growth of the bioenergy industry, such as insufficient financing, outdated infrastructure, technological gaps, ineffective legislation, and competition from imported energy sources. To overcome these challenges, the article recommends adopting best practices from countries with successful bioenergy programs, including state and local budget subsidies, tax incentives, government investments, and grants for infrastructure development. It calls for a comprehensive strategy to support the industry, focusing on developing bioenergy infrastructure, simplifying licensing and regulatory processes, establishing national standards for bioenergy installations, and ensuring environmental compliance. Additionally, it emphasizes the need for research funding, support for startups and innovative companies, and attracting international investors and partners through participation in global technology exchange programs. These measures aim to unlock Ukraine's bioenergy potential and enhance its energy sustainability.

Keywords

Bioenergy; Ukraine; Energy infrastructure; Renewable energy; Biomass-to-energy technologies

Introduction

Energy is a fundamental component of modern society, ensuring the stable functioning of the economy, industry, transportation, and the daily lives of individuals. Reliable and accessible energy resources drive industrial growth, infrastructure modernization, investment activity, and job creation, and enhance the global competitiveness of nations. Moreover, energy significantly improves living standards by facilitating access to modern technologies and services.

The energy sector is also a key driver of innovation, particularly in the development of renewable energy sources, smart grids, energy storage systems, and energy-efficient solutions. However, challenges such as climate change, depletion of natural resources, and the increasing global demand for energy compel nations to seek sustainable approaches to energy development. In Ukraine, the energy sector plays a crucial role in ensuring the stability of the national economy. However, it faces numerous challenges, including high dependence on imported energy resources, outdated infrastructure, low energy efficiency, reliance on environmentally harmful coal, insufficient development of renewable energy sources, and systemic corruption. These issues have been exacerbated by the full-scale Russian invasion in 2022, which caused significant destruction to the energy infrastructure, the loss of generation capacity, and intensified the energy crisis. In this context, the development of bioenergy emerges as a critical and promising pathway to address Ukraine's energy challenges. Bioenergy sector refers to the industry and associated activities focused on the production, development, and utilization of energy derived from biological sources such as biomass, biogas, and biofuels. Bioenergy relies on the utilization of local resources, such as agricultural residues, forestry by-products, organic industrial waste, energy crops, and biogas. Harnessing these resources can significantly reduce Ukraine's dependence on imported natural gas and coal, lower greenhouse gas emissions, and enhance the stability of the energy system, particularly in times of crisis (Lisovyi, 2023).

The importance of bioenergy for Ukraine is multifaceted. Firstly, it strengthens energy independence by reducing reliance on external energy supplies. Secondly, bioenergy development stimulates the local economy by creating jobs in rural areas, enhancing infrastructure, and attracting investments. Thirdly, it has significant environmental benefits, including waste reduction and the mitigation of harmful emissions. Finally, bioenergy contributes to the modernization of the energy sector and facilitates Ukraine's integration into the European energy market. Furthermore, bioenergy plays a pivotal role in enhancing the resilience of Ukraine's energy system in the face of military and economic challenges. The use of local resources minimizes risks associated with disrupted imports and supports the recovery of regions affected by the war. Given its substantial potential and multifaceted impact, exploring effective strategies for bioenergy development is an urgent task for strengthening Ukraine's energy security, modernizing its energy infrastructure, and ensuring sustainable development in the face of contemporary challenges (Lutkovska and Zelenchuk, 2021). Energy is a fundamental driver of modern society, underpinning the stable operation of economies, industries, transportation systems, and daily life. Accessible and reliable energy resources fuel industrial growth, expand infrastructure, stimulate investment, create jobs, and enhance

the global competitiveness of nations. Additionally, energy plays a crucial role in improving living standards, providing essential services, and facilitating technological progress. In recent decades, the energy sector has become a catalyst for innovation, driving the development of renewable energy sources, smart grids, energy storage solutions, and energy-efficient technologies. These advancements aim to reduce dependence on traditional fossil fuels and support the global shift toward sustainability. However, this progress also demands new strategies to address environmental concerns and improve energy efficiency (Kostenko and Zghurovets, 2023).

According to Pryshliak (2021a), several key trends are shaping the 21st-century energy landscape: preference for high-quality fuels and efficient infrastructure; such as oil and gas pipelines and decentralized energy systems; growing reliance on established infrastructure, with increasing demands for expansion; development of adaptable energy systems equipped with flexible mechanisms; gradual reduction in dependence on oil and gas, with renewable energy sources playing a larger role in the energy mix; increased adoption of biofuels and renewable energy technologies and expansion of decentralized energy solutions, particularly in urban areas and agricultural regions.

Challenges in the Development of Ukraine's Energy Sector

In Ukraine, the energy sector plays a vital role in the national economy, but it faces numerous challenges that hinder its development and efficiency. These challenges span technical, economic, environmental, and political domains:

Dependence on Energy Imports. Ukraine relies heavily on imported energy resources, particularly natural gas and oil. Historically, the country sourced a significant portion of its gas from Russia, creating both energy and political dependencies. Despite efforts to diversify energy supplies and boost domestic production, reliance on imports remains a critical issue (Tyravskyi, 2021).

Outdated Infrastructure. Much of Ukraine's energy infrastructure is obsolete and in dire need of modernization. This results in low energy efficiency, high transmission losses, and frequent system failures. The reluctance of policymakers to implement necessary reforms and establish competitive energy markets has further exacerbated these issues. Additionally, corruption and mismanagement in state-owned enterprises continue to degrade the country's energy assets (Tyravskyi, 2021).

Low Energy Efficiency. Ukraine is one of the most energy-intensive economies globally, consuming significantly more energy per unit of GDP than developed nations. This inefficiency is linked to outdated technologies, poor insulation of buildings, and losses in electrical networks, making energy consumption in both industry and households highly inefficient (Huch-Denysenko, 2020).

Reliance on Coal. Coal-fired power plants generate a substantial portion of Ukraine's electricity, but this dependency is environmentally damaging and economically unsustainable. Many coal mines are located in conflict zones, particularly in the Donbas region, leading to unstable coal supplies and increased greenhouse gas emissions. The

war has further disrupted coal production, with less than half of Ukraine's state-owned mines operational as of 2024 (Demchenkov, 2023).

Slow Development of Renewable Energy. Despite significant potential in solar, wind, hydro, and bioenergy, Ukraine's renewable energy sector has developed slowly. After a brief period of growth, investment in renewables declined, partly due to high upfront costs, limited government support, and regulatory instability. The ongoing war with Russia has further hampered progress, destroyed infrastructure and created market uncertainties (Konechenkov, 2022).

Corruption and Inefficient Management. Corruption and poor governance are persistent issues in Ukraine's energy sector. Lack of transparency, exploitation of state resources, and mismanagement have led to significant financial losses that could have been used for modernization and innovation (Kurtiev, 2022).

Impact of Military Conflict and Political Instability. Russia's full-scale invasion of Ukraine has severely damaged the country's energy sector, with losses estimated at \$56.5 billion. Key infrastructure, including power plants, transmission lines, and oil and gas facilities, has been destroyed or occupied, further destabilizing the sector. The occupation of the Zaporizhzhya Nuclear Power Plant and the destruction of hydroelectric plants have compounded the crisis (Kyiv School of Economics, 2024).

Key Challenges in Ukraine's Energy Security

Biriukov (2024) highlights five critical challenges facing Ukraine's energy sector. These include 1) vulnerability of energy infrastructure to military attacks; 2) Dependence on imported energy resources; 3) Technological obsolescence within the industry; 4) Insufficient development of renewable energy; 5) Inefficient energy consumption; and 6) Promising Pathway: Bioenergy Development. One of the most promising solutions to Ukraine's energy challenges is the development of bioenergy. By utilizing local resources such as agricultural waste, forest residues, and biogas, Ukraine can reduce its dependence on imported energy, particularly natural gas and coal. Bioenergy offers a sustainable and resilient energy source, especially critical during periods of conflict and economic instability. Moreover, it aligns with global trends toward renewable energy and supports the country's transition to a green economy.

The main objectives of the study were:

- to assess the current state and development trends of the bioenergy sector in Ukraine;
- to evaluate the availability of raw materials used for bioenergy production in Ukraine;
- to analyze the efficiency and potential for improving biomass conversion technologies for energy production.

Methodology

This study is based on theoretical and methodological foundations rooted in the ecological and economic approach to renewable energy development, supported by

findings from prior scientific research in the field of bioenergy (Pecheniuk, 2024). A range of research methods was applied to achieve the study's objectives:

- *Logical Method*. The logical method was used to substantiate the benefits of effective bioenergy production for citizens, enterprises, regions, and the state. This involved summarizing global energy trends and addressing key challenges within Ukraine's energy sector, as outlined in Biriukov (2024).
- *Classification Method*. The classification of energy crops used in Ukraine's bioenergy production was based on the method used by Pryshliak (2021a), offering a structured understanding of the crops' role in the sector.
- *Systems Analysis of Energy Crop Advantages*. A systematization of the advantages of cultivating energy crops in Ukraine was conducted, incorporating forecasts developed by researchers at the Institute of Technical Thermophysics of the National Academy of Sciences of Ukraine (Heletukha, 2022).

By integrating these methods, the study provides a robust framework for understanding the current state, challenges, and opportunities within Ukraine's bioenergy sector and offers actionable recommendations for its sustainable development.

Results

Analysis of the Bioenergy Industry in Ukraine

Bioenergy, a crucial sector of renewable energy, harnesses biomass to generate power. Amidst global climate change, reliance on imported energy resources, and the pressing need to enhance energy efficiency, advancing bioenergy in Ukraine emerges as a strategic priority. Ukraine's bioenergy potential is significant, and its effective use can make a significant contribution to ensuring the country's energy independence.

Bioenergy projects can be implemented locally, which contributes to the decentralization of energy supply. This enhances the energy system's ability to withstand and adapt to disruptions in infrastructure and reduces reliance on large, centralized power plants that are easy targets for attacks. In addition, bioenergy production can stimulate the growth and strengthening of regional economies, especially in rural areas, by creating new jobs. This includes growing energy crops, collecting waste for recycling and operating bioenergy plants. Harnessing bioenergy helps to lower greenhouse gas emissions, which is important for improving the ecological situation and fulfilling Ukraine's international climate obligations. It significantly curtails reliance on coal, the dirtiest energy source. Investments in bioenergy can become part of broader reforms of Ukraine's energy infrastructure. This will open access to the latest technologies, attract investments and contribute to the diversification of the energy balance (Pecheniuk, 2024).

Ukraine boasts a robust agricultural industry, offering substantial potential as a source of biomass for energy generation. This makes it possible to use agricultural waste, which is now often simply burned or disposed of, to produce energy. Thus, advancing bioenergy in Ukraine will not only ensure a more stable and cleaner energy supply but also increase the country's energy security, promote economic growth and help solve environmental problems. Key sources driving bioenergy production in Ukraine include:

biomass of agricultural origin, forest biomass, energy crops, livestock waste, and industrial organic waste.

Agricultural biomass remains the main component of biomass energy potential in Ukraine. Ukraine is an agrarian country, which provides significant opportunities for the use of agricultural waste, such as straw, corn stalks, residues of grain and oil crops. This facilitates the substantial reduction of reliance on fossil fuels, especially gas and coal. The financial prospects of biomass of agricultural origin for energy production in Ukraine is almost 9 million tons of oil equivalent, which is equal to 43% of the total potential of biomass (20.9 million tons of oil equivalent). At the same time, the amount of available biomass tends to increase, which is important for ensuring the stability of the fuel supply in the energy complex (Agri-gator, 2019).

The statement highlights the significant role biomass can play in Ukraine's energy sector, emphasizing its potential contribution both to energy production and economic impact. Specifically:

- *Potential Energy Production.* The figure of 9 million tons of oil equivalent (toe) represents nearly half (43%) of the total biomass energy potential in Ukraine, which is estimated at 20.9 million toe. This indicates a substantial reserve of energy that can be harnessed from biomass, equivalent to approximately 9% of Ukraine's current total primary energy supply (based on pre-war energy consumption levels). Increasing the use of biomass could significantly enhance Ukraine's energy security by reducing its dependence on imported fuels such as natural gas and oil. It could also serve as a stable source of renewable energy, diversifying the energy mix and contributing to a more sustainable and resilient energy system (Lutkovska and Zelenchuk, 2021).
- *Economic Impact.* The growing availability of biomass resources underscores its capacity to support the development of a domestic bioenergy industry. This can lead to job creation in rural areas, stimulate local economies, and attract investment in energy crop cultivation, biomass processing, and related infrastructure. Leveraging this potential could generate significant cost savings by replacing imported fossil fuels with domestically produced biofuels. It also opens opportunities for exports of bioenergy products, such as pellets and biogas, to international markets, enhancing Ukraine's trade balance (Heletukha, 2022).
- *Stability of Fuel Supply.* The increasing availability of biomass ensures a reliable and scalable source of fuel, crucial for the stable operation of the energy complex. Unlike fossil fuels, biomass resources can be replenished continuously through agricultural and forestry activities, offering long-term sustainability. This stability is particularly important in the context of Ukraine's ongoing energy challenges, as it reduces vulnerabilities to geopolitical disruptions and supply chain uncertainties (Pryshliak, 2021a).

In summary, the figure highlights biomass as a key renewable energy resource for Ukraine, with the potential to contribute significantly to energy independence, environmental sustainability, and economic growth. One of the important sources of biomass in Ukraine is forest waste – branches, bark, and brush, which can be processed into fuel briquettes or pellets. The country's forested land covers more than 10 million hectares, which provides great opportunities for the use of wood and forest biomass.

However, the forest sector of Ukraine faces serious challenges that threaten its sustainable development. The worldwide shift towards eco-friendly energy highlights the urgency of addressing these issues to fully realize the sector's potential. According to estimates, Ukraine uses more wood for energy needs than it has time to regenerate. Thus, in 2023, the excess level of wood use amounted to 36%, which is an alarming trend for the future of the country's forest resources. Today, about 50-70% of forest biomass is harvested independently or illegally, and there is an imbalance in the market. Major types of biomasses, such as firewood and logging waste, are overused, while secondary resources such as wood chips and pellets are either not fully exploited or exported due to market distortions. Forest biomass is actively used by households, which consume about 55-60% of all resources, but the environment is significantly polluted due to outdated heating systems. This is a result of energy scarcity and the absence of alternative options (Budrin, 2023).

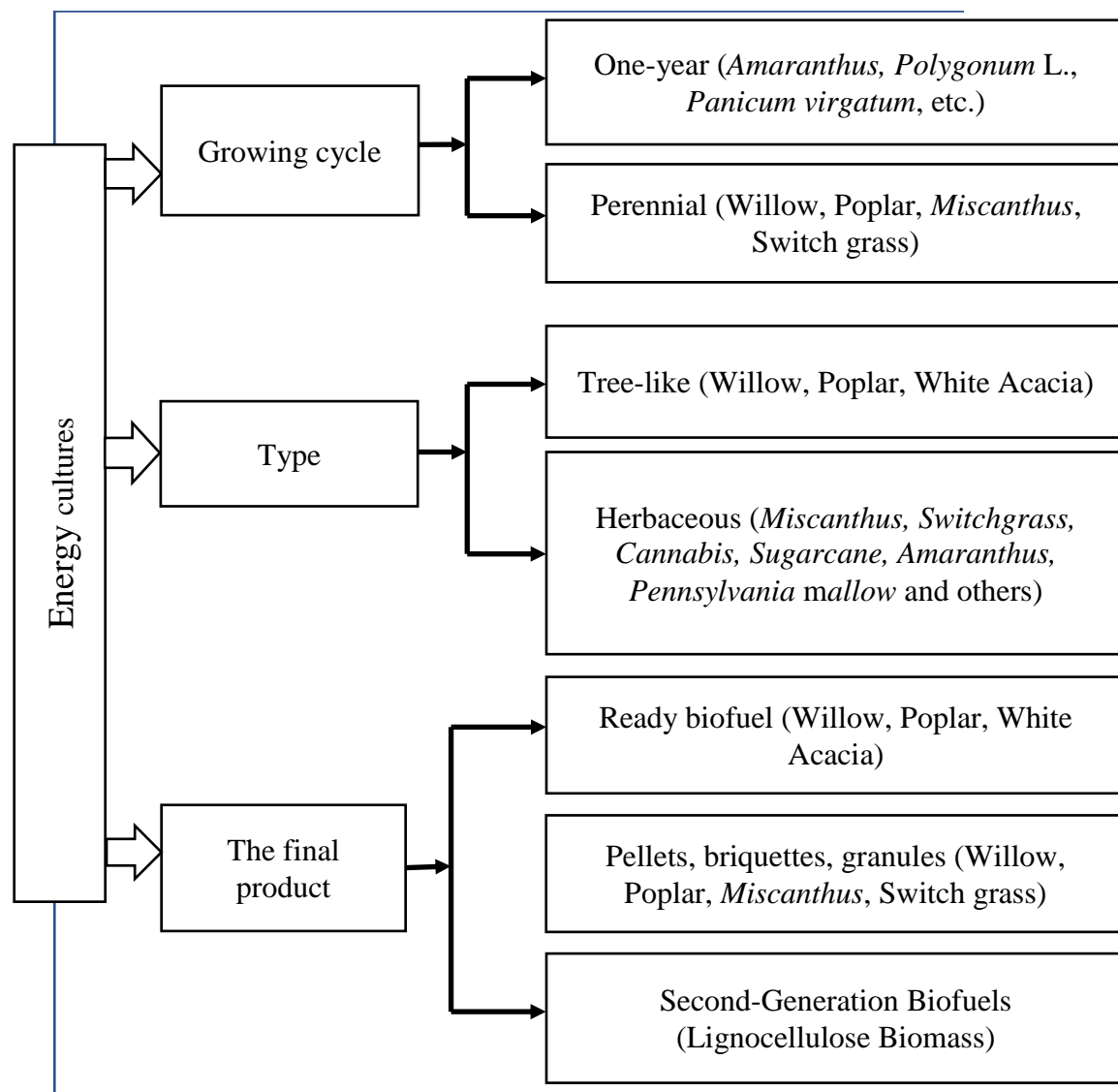


Figure 1. Characteristics of energy crops [Source: Pryshlyak, 2021a]

As noted by Hura (2024), Ukraine lacks a thorough regulatory framework for utilizing forest biomass for energy production. Existing regulations are fragmented, and their implementation is inconsistent. As of September 2024, sustainability criteria for biomass harvesting have not yet been implemented in the country, which limits the ability to meet EU standards and receive financial support. In addition, the process of forest and logging management remains time-consuming and poorly controlled, creating risks of abuse. Given the substantial potential of forest biomass to support national renewable energy targets, the sector requires extensive reforms, strategic planning, and the establishment of sustainability criteria for long-term development. Energy crops are plants that are specifically grown for use directly as fuel or for biofuel production. The general characteristics of energy crops for biofuel production are shown in figure 1.

Energy crops, unlike food crops, do not have special requirements for soil quality and can be grown on degraded lands. Among EU nations, Italy leads in land dedicated to energy plantations, covering 57,000 hectares, the highest in Europe. Following Italy are Poland with 13,000 hectares, Sweden with 12,000 hectares, Germany with 11,000 hectares, Denmark with 10,000 hectares, and Finland with 8,000 hectares (Eurostat, 2020).

The Raw Material Base of Ukrainian Bioenergy

Energy crops are usually low in chemical elements and high in lignin and cellulose, and some species are also rich in sugar and starch. This makes them an ideal resource for producing energy-efficient biofuels. The possibility of increasing the amount of cultivation of such crops depends to a large extent on the availability of land, as it is crucial to simultaneously address the rising global food demand, preserve the environment, ensure the sustainable use of soil and water resources, and also meet other requirements of sustainable development. Heletukha (2022) highlights the following advantages of growing energy crops in Ukraine:

- substitution of imported energy resources with own energy sources;
- improvement of the country's trade balance due to a decrease in imports;
- creation of new jobs, which contributes to the employment of the population;
- assistance in fostering the growth of the local economy;
- ensuring a stable and predictable source of biofuel;
- the potential of annual replacement of up to 8.9 billion m³ of gas at the expense of biofuel;
- reducing the level of greenhouse gas emissions;
- restoration of soil fertility thanks to the use of certain types of crops;
- a large stock of land resources for cultivation (up to 4 million hectares);
- the ability to accumulate solar energy (energy crops act as a kind of natural "accumulators" that collect and store solar energy, transforming it into a form that can be used to obtain energy for human needs) (Heletukha, 2022).

In Ukraine, more than 20 types of fast-growing energy crops, which are promising for growing to obtain plant biomass, are currently being studied. These crops include fast-growing trees, including varieties of willow and poplar, as well as annual and perennial grasses, such as sorghum, sugarcane, *Miscanthus*, amaranth, *Pennsylvania mallow*, *Rumex*, millet, hybrid tobacco, and others. Today, the area of energy plant plantations in Ukraine is about 6.4 thousand hectares, of which the largest areas are occupied by willow (about 3 thousand hectares) and *Miscanthus* (about 2 thousand hectares) (Pryshlyak, 2021b).

The Department of Selection and Sustainable Technologies for Growing and Processing Bioenergy Crops of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine is constantly working on the development of new varieties of bioenergy plants and implementing sustainable methods of their cultivation. The priority crops include: sugar and fodder beets, sugar and grain sorghum, *Miscanthus*, switchgrass (rod-like millet), willow, poplar, acacia and paulownia. In recent years, new *Miscanthus* varieties have been included in the State Register ("Osinniy Zoretsvit", "Snizhna Koroleva" ", "Misiachnyi Promin"), switchgrass ("Morozko", "Liadovske") and willow ("Zbruch") (Hanzhenko, 2020).

8 million hectares of Ukraine's agricultural land are deemed unproductive or marginal out of the total area suitable for cultivation (Heletukha, 2017; Savchuk, 2024). About 3.5 million hectares of these lands are excluded from crop rotation due to low fertility, susceptibility to erosion, excessive moisture and other unfavourable conditions (Blum, Geletukha & Grigoryuk, 2010). Cultivation of fast-growing, high-yielding energy crops on these lands will help protect soils from erosion, increase humus content, and generally contribute to improving the country's ecological and energy balance.

In Ukraine, there is great potential for energy production from livestock waste, such as manure and poultry droppings, by obtaining biogas. Biogas can be used to generate electricity and heat or as a substitute for natural gas. Currently, the large volumes of waste on the country's industrial farms are causing environmental problems that require solutions. Converting these wastes into biogas will not only help address environmental challenges but also enable the decentralized production of renewable energy and fuel. Livestock waste is particularly suitable for biogas production because, unlike energy crops, manure and droppings are by-products that require ecological disposal. Moreover, manure can be easily mixed with other substrates, such as plant silage, including corn.

Studies show that anaerobic fermentation of manure and droppings contributes to reducing the risks of soil and water pollution, lowering the volume of emissions released into the atmosphere, and reducing the negative impact on the climate. Thanks to such processing, the level of nitrogen and phosphorus pollution is reduced, which reduces threats to drinking water sources and wetlands. Also, anaerobic fermentation significantly reduces the intensity of the smell, minimizing its effect on the local community (Martsynkevych and Kolomiets, 2015). A promising raw material for bioenergy is the remains of food and agro-industrial production, in particular, waste from the processing of sugar beets and oil crops. These wastes can be utilized to produce biogas, bioethanol, and even solid fuel. Sugar beet pulp is rich in organic substances suitable for anaerobic fermentation. Extracts of oil crops, such as sunflower or soybean meal, are also high-calorie raw materials suitable for pyrolysis or gasification, which turns them into synthetic gas or biochar. Ukrainian breeders of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine are already carrying out selection work to create specially adapted types of sugar beet intended for the needs of the energy industry. Sugar beet biomass is saturated with sugars and can easily be processed into bioethanol. In addition, due to the increased content of dry matter, sugar beets can be processed into biogas (Kudril, 2019).

Biomass Conversion Technologies for Energy

Among the main technologies for converting biomass into energy, which allow for obtaining different types of fuel and energy, the following should be highlighted: anaerobic fermentation, pyrolysis, gasification, combustion, fermentation, and esterification. Anaerobic fermentation is used to process organic waste (manure, food waste, agricultural waste), which in the absence of oxygen is decomposed by bacteria with the formation of biogas. Biogas is generated through the process of methane fermentation, where organic materials derived from plants and animals are broken down in specialized biogas facilities. Based on Samoichuk (2020), 1 ton of dry organic raw

materials can be obtained from 350 to 400 m³ of biogas, which has a calorific value of 23-25 MJ/m³. In practical terms, 1 m³ of biogas has the potential to substitute 4 kWh of electrical energy or around 1.5 kg of solid coal.

The essence of pyrolysis consists of heating biomass at high temperatures without air access, which leads to its decomposition into solid residue (biochar), liquid products (pyrolytic oil) and synthetic gas. This process makes it possible to obtain high-calorie solid fuel (biochar) and liquid biofuel, which serves as a viable substitute for petroleum-based products (Daniuk and Boltianska, 2020). Gasification is the partial oxidation of biomass at high temperatures, which leads to the formation of synthesis gas (containing hydrogen, carbon monoxide and other combustible gases). Syngas can be used to produce electricity and heat or as a feedstock for the synthesis of liquid fuels (e.g. bioethanol or biodiesel). Syngas can be produced from almost any organic material, including biomass and organic waste. In recent decades, the global scientific and engineering community has achieved significant success in advancing cutting-edge approaches to the gasification of raw materials with carbon content. Modern technologies of thermochemical processing make it possible to transform waste and biomass into high-quality synthetic products, reducing the release of carbon emissions into the air and accumulation of waste in landfills. According to Kolisnyk (2023), this opens up great opportunities to advance the growth of Ukraine's chemical industry, especially taking into account the needs of post-war reconstruction.

Combustion (integrated production of heat and electricity) is the simplest and most widespread method in which biomass is burned to produce heat energy that can be used both for heating and for generating electricity within cogeneration systems that combine heat and power production. Cogeneration enhances overall energy efficiency and lowers fuel and energy resource costs compared to producing heat and electricity separately. In the countries of the European Union, there are various incentives to support the development of cogeneration technologies, which are quite flexible and regularly adapt to changes in the market situation (Heletukha, Zhelezna and Bashtovyi, 2019).

Fermentation is used to produce bioethanol from biomass containing sugars or starch (such as corn, sugar beets, and sugar cane). In this process, yeast converts sugars into ethanol. Based on the findings of experts from the Ukrainian technology company, bioethanol, which is used as a fuel for transport in the form of a mixture with gasoline, contributes to an increase in the total octane number, improves the efficiency of the engine, increases the oxygen content in the fuel to 3.7% and significantly reduces emissions of harmful substances, such as benzopyrenes, dioxins and carcinogens. Worldwide, 82% of ethanol is utilized as fuel, 9% serves industrial purposes, and the remaining 9% is used in the alcoholic beverage sector (Lukashevych, 2020).

The essence of esterification is the processing of vegetable oils and fats into biodiesel, which is obtained by the chemical reaction of fatty acid esters with methanol or ethanol, and it is used as an ecological alternative to diesel fuel. These biomass-to-energy technologies enable the utilization of diverse waste and agricultural by-products for producing eco-friendly fuel, reducing reliance on fossil fuels, and supporting greenhouse gas emission reductions and sustainable energy industry development. The growth of energy production from biomass will help reduce Ukraine's dependence on gas imports,

which is one of its main geopolitical and economic problems. According to Kyryliuk (2023), Ukraine has enough biomass to completely replace 10 billion cubic meters of imported natural gas by 2030 and promote energy self-sufficiency by advancing bioenergy initiatives. In addition, the country can substitute 22 million tons of coal imports and 1 million tons of gasoline. By replacing imported energy carriers, Ukraine will have the opportunity to make notable improvements to its trade balance and develop biofuel exports.

Substituting fossil fuels with biomass contributes to lowering greenhouse gas emissions and minimizes environmental harm. Among the main advantages of plant biomass as a source of energy are significantly lower emissions of harmful substances compared to traditional types of fuel and the prevention of any disruption to the carbon dioxide balance in the atmosphere. During the burning of biofuel from plant biomass, less CO₂ enters the atmosphere than plants absorb during photosynthesis, and 20-30 times less sulfur compounds and 3-4 times less ash are formed compared to coal (Roik, 2020).

Advantages of Bioenergy Development in Ukraine

Bioenergy can stimulate the development of rural areas and become an additional source of income for agricultural enterprises. The creation and utilization of biofuels can provide agriculture with its energy resources, reducing fuel costs. (Pryshliak, 2021b). As world experience shows, biofuel production is a profitable opportunity for the economy of any country, as it plays a role in generating new employment opportunities. According to Habrel's calculations, the production of 1,000 tons of biofuel in oil equivalent provides about 16 jobs, mostly in rural areas. In Ukraine, each percentage of biofuel in the total volume of fuel consumption can create from 45 to 75 thousand new jobs in rural regions (Habrel, 2011). The Bioenergy Association of Ukraine has developed the "Road Map for the Development of Bioenergy of Ukraine until 2050", which envisions a substantial rise in the energy utilization of agro-biomass (Heletukha, 2021). Implementation of the Roadmap will require investments in the amount of 21-33 billion euros and is expected to replace approximately 20 billion cubic meters of natural gas per year, while also generating over 160,000 jobs by 2050 (Table 1).

Table 1: Projections for key bioenergy development indicators in Ukraine through 2050

Year	Biofuel consumption, million tons of oil equivalent	Replacement of natural gas, bln. m ³	Displacement of gasoline and diesel fuel, mln. tons	Reduction of CO ₂ emissions, million tons/year	Investment, billion Euro		Creation of new jobs, units
					Min.	Max.	
2030	8.57	9.11	0.39	21.35	7.07	11.44	54300
2035	12.01	12.62	0.50	30.37	10.78	17.43	86200
2040	15.13	15.77	0.67	38.66	14.15	22.85	115400
2045	17.64	17.98	0.96	45.79	16.94	27.38	139000
2050	20.28	19.92	1.23	54.40	19.70	31.81	162700

Source: Heletukha (2021)

As reported by the International Renewable Energy Agency (IRENA), the global workforce in the renewable energy sector grows annually. Almost 66% of all employees in "green" energy are in Asian countries, where China's share is 42%. The USA and India each have 7% of jobs in this field, and the share of EU countries is 9.4% or 1.2 million jobs. In Europe, employment is distributed as follows: 314,000 people work in bioenergy, 298,000 in wind energy, and 235,000 in solar energy (Ukrainian Energy, 2023). Ukraine has demonstrated notable successes in implementing bioenergy projects, showcasing the potential of the sector to contribute to energy independence and sustainability. Key examples include:

- *Biogas Production*. Large-scale agricultural enterprises, such as MHP Eco Energy and Astarta-Kyiv, have established biogas plants utilizing agricultural residues and animal waste. These facilities not only generate electricity and heat but also reduce greenhouse gas emissions and provide organic fertilizers as a byproduct (Dombrovskiy, 2020).
- *Wood Biomass Utilization*. Municipalities, particularly in Western Ukraine, have replaced natural gas with wood chips and pellets for district heating. Projects like the bioenergy initiatives in Lviv and Ivano-Frankivsk regions demonstrate the cost-effectiveness and sustainability of using local biomass for energy needs (UNECE, 2023).
- *Industrial Bioenergy*. Ukrainian companies have integrated biomass boilers into their production processes, using wood residues to meet energy needs. This helps reduce waste and lower energy costs (Heletukha, 2017).
- *Energy Crops*. Pilot projects involving the cultivation of energy crops, such as willow and *Miscanthus*, have been successfully implemented in various regions. These crops are used as feedstock for biofuel production and have proven effective in rehabilitating degraded lands (Hanzhenko, 2020).

These projects highlight the economic, environmental, and energy security benefits of bioenergy, serving as a foundation for scaling up renewable energy initiatives in Ukraine. In addition, investments in bioenergy support the advancement of cutting-edge technologies and innovations, which stimulates overall technological progress. This, in turn, can benefit other sectors of the economy as well (Pecheniuk, 2024). A compelling reason to support the growth of bioenergy in Ukraine is the presence of almost 8 million hectares of unproductive land that can be used for growing perennial energy crops. According to experts' calculations, 2 million hectares of such land would be enough to completely replace gas in heat generation. To completely replace imported energy carriers with biofuels, approximately 3 million hectares need to be allocated for bioenergy crops, which is approximately 37% of all available low-productivity lands (Hadzalo, 2018).

It is important to highlight that the advancement of bioenergy in Ukraine is hampered by several objective and subjective reasons, among which we can highlight: insufficient level of financing of the industry, lack of effective stimulating legislative initiatives and limited technology, and lack of proper infrastructure. The absence of clear regulations governing the energy sector, along with intense competition from imported energy, also hinders the growth of the industry. The large-scale war initiated by the Russian Federation against Ukraine in 2022 led to a sharp decrease in the investment attractiveness of the bioenergy industry, and complex tax and regulatory conditions only

complicate the situation (Pecheniuk, 2024). In addition, Ukraine lacks modern technologies for optimal production and use of biomass, as well as infrastructure such as transport networks, state-of-the-art processing facilities and bioenergy plants. Some areas of bioenergy production can negatively affect the environment (for example, cutting down forests to obtain wood biofuel), which requires a balance between energy needs and environmental protection. The economic efficiency of bioenergy production in some cases is also inferior to traditional energy production (Pecheniuk, 2024). Projects that use biomass boilers or biogas plants for electricity generation often have high initial costs for equipment and infrastructure installation. The cost of biogas plants or biomass boilers can significantly exceed that of traditional thermal power plants that run on coal or natural gas. Furthermore, biomass as a raw material can be more expensive or less accessible compared to traditional energy sources like gas or coal, which can reduce the economic viability of bioenergy projects in the short term. For example, studies show that the cost of producing electricity from biomass can be 20-30% higher than from traditional energy sources due to high capital costs and expenses for transportation and processing of biomass. While traditional energy sources like gas or coal offer greater price stability and availability, bioenergy requires additional investments in technology development, raw material collection, and processing (Tsybul'ska, 2019). However, in the long term, bioenergy can become economically advantageous due to reduced costs for imported energy resources, the creation of new jobs in rural areas, and infrastructure development. Therefore, while bioenergy may initially lag behind traditional energy sources in terms of economic efficiency, its advantages become more evident over time, particularly in the context of energy security and sustainable development.

The development of bioenergy can create issues related to land use and food security. Specifically, extensive use of land for growing energy crops can reduce the area available for food production. This may lead to competition between energy production and food production, especially in the context of limited land resources. Additionally, monocultures of energy crops can deplete soils and worsen biodiversity. On the other hand, to maintain food security, bioenergy production must use agricultural waste (such as crop residues and organic waste), which reduces pressure on land while preserving its potential for food production.

Ways of Realizing Bioenergy Potential in Ukraine

To ensure the proper development of bioenergy, Ukraine should consider the best practices and experiences from around the world that implement state programs to support the industry. The primary methods for encouraging the growth of bioenergy production include:

- compensations from the state and local budgets to cover part of the capital costs associated with investments in bioenergy (capital subsidies, grants or discounts);
- tax credits (investment or production);
- reduction of tax rates on the acquisition or development of technologies for utilizing bioenergy solutions;

- state investments, loans or grants for infrastructure development and implementation of projects in bioenergy (Denysenko, 2020).

The outcome of fostering bioenergy development in Ukraine should be achieving a balance between the expected economic effect and the impact on the social and environmental situation in the regions of the country (Hryhoruk, 2020). In addition to financial support and tax incentives, an appropriate set of measures needs to be implemented:

- development of bioenergy infrastructure (funding the establishment and modernization of infrastructure for the collection, processing and transportation of biomass, creation of local biowaste processing hubs that will ensure the supply of raw materials to processing enterprises) (Pryshliak, 2021b);
- regulatory measures: Streamlining licensing and permitting procedures for bioenergy projects, developing and implementing national standards and technical requirements for bioenergy installations, and ensuring adherence to environmental regulations and standards;
- information support: Promoting the industry's growth through public and business outreach campaigns to raise awareness of bioenergy, and disseminating information on the best international practices and cutting-edge technologies in the bioenergy sector;
- scientific and innovative support: Funding research initiatives aimed at improving the efficiency of bioenergy technologies and providing support to startups and innovative companies within the bioenergy sector;
- enhancing global cooperation in the bioenergy sector: Attracting international investors and partners to advance bioenergy projects in Ukraine, participating in global exchange programs for sharing experiences and technologies, and leveraging global best practices to stimulate the development of the domestic bioenergy industry.

These measures will help speed up the advancement of bioenergy in Ukraine, and increase its economic efficiency (diversification of the resource base of energy, the substitution of imported media, production of stable and predictable energy, balancing of the energy system, diversification of agricultural production, development of innovations), promote ecological stability in the regions (decrease in human-induced environmental impact) and socio-economic development (creation of new jobs) (Stepanenko and Loktionov, 2024).

Conclusions

The research conducted highlights the potential of developing the bioenergy industry in Ukraine, which is due to the existing natural, resource, technological and human potential. The research highlights the significant potential of bioenergy development in Ukraine, underpinned by its natural, resource, technological, and human capital. Bioenergy can substantially reduce Ukraine's reliance on imported energy sources, particularly natural gas, which enhances the country's energy security and strengthens economic stability. By diversifying the energy mix and decreasing dependence on

traditional fossil fuels, bioenergy contributes to both national energy independence and environmental sustainability.

The development of the bioenergy sector brings socio-economic benefits, including job creation, especially in rural areas, and infrastructure growth. Biomass helps reduce greenhouse gas emissions and supports Ukraine's international CO₂ reduction commitments, aligning with global sustainability goals. However, advancing bioenergy in Ukraine requires legislative support, tax incentives, grants, and foreign investments. Additionally, improving biomass processing technologies and biofuel production efficiency will lower costs and expand market opportunities for bioenergy products. To fully unlock the potential of the bioenergy sector, Ukraine must continue to strengthen its legislative framework, invest in modern technological infrastructure, and build the necessary bioenergy supply chains. These efforts will ensure the sustainable and efficient development of bioenergy, establishing it as a key component of Ukraine's energy system and contributing to its long-term energy security. In summary, the strategic development of bioenergy holds immense promise for Ukraine, provided that the challenges related to legislation, technology, and infrastructure are effectively addressed.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>	<i>Author 6</i>	<i>Author 7</i>
Conceived and designed the research or analysis	Yes	Yes	No	No	No	No	No
Collected the data	Yes	Yes	No	Yes	Yes	No	No
Contributed to data analysis & interpretation	No	No	Yes	No	No	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Global Practices and Experiences in Developing a Green Economy amid Financial Crises

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Abstract

Currently, the global community confronts two pivotal challenges such as the rapid expansion of the world population and the consequential escalation of pressure on the environment. Swift and effective mitigation of these challenges necessitates the expeditious internalization of external effects as a primary preventive measure. Therefore, this article aims to analyze the strategies employed by the leading economies, including China, the United States, Korea, and the European Union, to advance their green economies amidst periods of financial downturns. By analyzing the cases of these countries, we explore the implementation of green economy policies and strategies during times of economic downturn, focusing on initiatives undertaken, investments made, and outcomes achieved. The study highlights the varying approaches and responses of different economies to promote green growth, including stimulus packages, policy frameworks, and investment priorities. The collected data underwent a comparative analysis to understand the dynamics of green economic development, such as policy frameworks, investment priorities, stimulus measures, and resultant outcomes. As a result, it is established that the green economy offers a strategic pathway for nations to address pressing challenges, such as economic downturns, by concurrently fostering environmental sustainability and social welfare. The integration of green practices aligns with the overarching goal of achieving sustainable development, wherein economic growth is harmonized with environmental preservation and social inclusivity.

Keywords

Green economy; International economic activity; International competitiveness; Economic security; Financial crisis

Introduction

The global community is confronted with two pivotal challenges, namely the rapid expansion of the world population and the consequential escalation of pressure on the natural environment. Swift and effective mitigation of these challenges necessitates the expeditious internalization of external effects as a primary preventive measure (Kasztelan, 2017). In the intricate landscape of economic dynamics, the intersection of green development and financial crises represents a critical juncture, which demands thoughtful consideration. For example, the rise in temperatures and diseases caused by pollution leads to a deterioration of human capital and a decrease in productivity levels, resulting in economic decline (Bossone *et al.*, 2022).

The economic crisis of 2008 catalyzed green growth, prompting governments to swiftly implement 'green' stimulus and recovery plans. For example, in 2009, the American Recovery and Reinvestment Act (hereinafter - ARRA) allocated approximately \$90 billion specifically for green investments, including renewable energy, energy efficiency, and clean technology research in the United States (Federal Communications Commission, 2009). This funding helped advance initiatives like weatherizing homes, improving energy grids, and investing in electric vehicles, setting a precedent for green stimulus efforts in the U.S. According to the Department of Energy, ARRA's investments were crucial in increasing wind energy capacity by 60% and solar capacity by nearly 20% from 2009 to 2011. Furthermore, South Korea's Green New Deal allocated around 80% of its \$38 billion stimulus package to green projects, making it one of the most environmentally focused recovery plans globally. These investments targeted green transportation, energy efficiency, water management, and the development of green industries. This initiative helped South Korea emerge as a global leader in green technology and significantly increased renewable energy use, aiming to create over 1.5 million jobs by 2020 through green sectors (Technopolis Group, 2016).

These initiatives aimed to tackle environmental concerns while simultaneously fostering green economic growth and employment opportunities. This intersection prompts an exploration into strategies that align environmental sustainability with economic resilience, seeking a harmonious balance between mitigating ecological challenges and addressing the economic ramifications of crises. In this way, economic growth can be enhanced while taking care of natural and human capital and being respectful of the planet's limits. However, it challenged the validity of economic models and policies that had evolved in recent decades (Fedrigo-Fazio and Ten Brink, 2012).

Thus, when compared to the "brown" (or traditional) economy, the green economy does not guarantee higher levels of output and employment (United Nations, 2011). Green economy is defined as the results of improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities (Economic Commission for Europe, 2011). Although the term "green growth" is similar to the concept of a green economy, these terms are different in their implementation. The OECD Green Growth Report defines green growth as "promoting economic growth and development while ensuring that natural assets continue to provide resources and environmental services essential to our well-being" (Fedrigo-Fazio and Ten Brink, 2012). Meanwhile, the concept of green growth highlights the significant value placed

on expanding economies quantitatively to support increasing populations, evolving development goals, and poverty alleviation efforts (UNEP, 2011).

Consequently, the green economy and green growth are based on the principle of advancing economic development worldwide. The emphasis lies on the ecologically responsible approach to growth that preserves the delicate balance of planetary ecosystems. At the same time, the concept of the green economy encompasses several paramount challenges that confront contemporary society, including the eradication of poverty, fostering a more harmonious relationship with the environment, mitigating the potential adverse effects of global climate change, and charting a course towards sustainable development (United Nations, 2011).

As articulated by the United Nations Conference on Trade and Development (UNCTAD), the successful transition to a green economy necessitates a concerted effort to address at least four key elements (United Nations, 2011). The first one is the identification of funds for transitional initiatives in developing countries. Second, the establishment of an enabling environment, conducive to private investment, emerges as a crucial factor in providing support to these endeavours. Thirdly, leveraging trade as a supportive instrument for sustainable development is essential, coupled with the imperative to resist the allure of green protectionism. Lastly, the design and implementation of innovative mechanisms for the transfer of green technologies to developing nations stand out as the fourth imperative in navigating this transition effectively.

However, industrialized economies are better equipped to transition to a green economy as compared to developing economies. In other words, they possess more technological, financial, and human resources to realize a low-cost transition to a green economy. Conversely, transition expenses are likely to be higher in developing economies. It is challenging to foresee a transition period where the internalization of social and environmental costs does not, at least initially, result in a decline in real income (Polishchuk *et al.*, 2019).

Furthermore, crises of various kinds frequently share similar roots: the accumulation of unsustainable economic imbalances and discrepancies in asset prices or exchange rates, typically within a framework of financial sector distortions and structural inflexibilities that often reveal the unsustainable aspects of the existing economic system (Kuzheliev and Britchenko, 2016). For example, the 2008 global financial crisis was caused by the collapse of the U.S. housing market. Years of unsustainable lending practices, including subprime mortgages, created an economic imbalance in the form of a housing bubble. Distorted asset prices in real estate within a loosely regulated financial sector led to the global economic collapse. Moreover, the Eurozone Debt Crisis of 2010-2012 provides another example. Unsustainable debt accumulation in countries like Greece, Portugal, and Spain led to a crisis when the financial sector's ability to lend was damaged by high public debt levels. The economic imbalances between stronger economies (e.g., Germany) and indebted economies exposed the structural weaknesses of the Eurozone in terms of the inability to adjust currency values or manage debt independently within the currency union.

At the same time, crises can be a catalyst for change, prompting a rethinking of current economic models and policies (Barbier, 2010). In its turn, the green economy, as a paradigm, places sustainability at its core, encompassing diverse sectors such as renewable energy, eco-friendly technologies, sustainable agriculture, and circular economy practices (McKenna *et al.*, 2016). Henceforth, directing investments towards the establishment and fortification of a green economy emerges as a strategic approach, considering its explicit emphasis on sustainability and resilience. This approach is discerned as a methodological means to not only reconstruct societies following crises (Knight, 2021), but also to systematically address the inherent vulnerabilities that underpin socio-economic systems (Environment Management Group, 2018).

Learning from past experiences is vital for enhancing resilience in the face of future economic crises or environmental challenges. Analyzing how countries navigated the intersection of economic recovery and green development during the 2008 crisis can contribute to the formulation of more resilient and adaptive strategies for future uncertainties. As the global economy struggled to recover after the financial crisis of 2008-2009, it became increasingly clear that the global economy is in the midst of an economic slowdown. Both the demand and supply sides of the economy were significantly affected by this disruption (Bossone *et al.*, 2022). In this regard, this article aims to analyze the strategies employed by the leading economies, including China, the United States, Korea, and the European Union, to advance their green economies amidst periods of financial downturns. This aim stipulated the following research questions:

- 1) How do the strategies for advancing green economies differ among leading economies, such as China, the United States, Korea, and the European Union, during periods of financial downturn?
- 2) What specific green economy policies, initiatives, and investment priorities have been implemented by these leading economies to sustain green growth during economic downturns, and what outcomes have they achieved?
- 3) What key lessons and best practices can be identified from the comparative analysis of green economy responses to financial challenges in different countries?

Materials and Methods

This study adopts a comparative and analytical approach to examine the development of the green economy in the context of financial crises using the example of China, the USA, South Korea, and the European Union. It seeks to understand the dynamics of green economic development, such as policy frameworks, investment priorities, stimulus measures, and resultant outcomes. By systematically comparing these factors across the selected countries, this research seeks to provide a comprehensive outline of the diverse approaches adopted in fostering green economic resilience during times of financial uncertainty.

An in-depth review of scholarly papers, reports from international organizations (OECD, World Bank, UN) and analytical documents on the strategy and policies of the green economy was carried out in order to highlight the impact of financial crises on the implementation of environmentally sustainable economic practices. The study uses data from official sources, such as government reports, economic indicators, national action

plans and initiatives adopted by governments during financial crises. Moreover, incentive packages, investments in green technologies, and environmentally oriented programs are assessed in terms of their impact on employment and economic growth.

Regarding the scope of the analysis, government-related information constituted a vital component of the data collection process. Official government websites and repositories were accessed to gather comprehensive data on green economy policies, stimulus packages, and initiatives implemented by countries such as China, the United States, Korea, and the EU. The information sourced from these official channels encompassed a range of documents, including reports from government agencies, policy briefs, and legislative documents. It is acknowledged, however, that the availability of such data may exhibit variability across countries, and certain information may be confined to official government sources or published reports, potentially influencing the comprehensiveness of the subsequent analysis. Furthermore, to enrich the understanding of green economic development strategies amidst financial crises, this study also incorporated insights from case studies and reports published by reputable international organizations. Papers and research papers from reputable organizations, such as the United Nations Environment Programme (UNEP), World Bank, and International Monetary Fund (IMF) were meticulously reviewed.

The comparative method was used to assess the approaches of different countries to the green economy development during economic downturns. This method facilitates identifying key success factors, barriers, and differences in these approaches. Key aspects such as funding, sectoral priorities, impact on economic sustainability, and environmental outcomes were compared.

Specific cases were analyzed to study successful green economy initiatives during financial crises in each country. In particular, the implemented state policies, innovative approaches to investing in renewable energy sources, effective management of resources, and the response to the challenges of climate change were considered.

On the basis of the obtained results, a set of recommendations is provided for politicians and researchers on the sustainable development of economies during crises, using the experience of leading countries in green economy implementation. The purpose of this review is to extract valuable insights into the diverse experiences of different countries in advancing green growth during periods of financial crises. By leveraging the wealth of knowledge provided by these international sources, this research aims to analyze the multifaceted dynamics associated with the promotion of green economies in the aftermath of financial challenges.

Results

Analysis of the environmental consequences of financial downturns

The global financial crisis of 2008-2009, which was characterized by a confluence of systemic failures in financial markets and a pervasive credit crunch, ushered a profound economic recession that reverberated across the international landscape. The crisis not only underscored vulnerabilities in the global financial system but also brought about a

period of economic contraction that affected a variety of industries (Nazarova *et al.*, 2021).

During this tumultuous economic period, marked by fragile financial markets and constrained credit access, a parallel and noteworthy phenomenon unfolded in the realm of environmental consciousness. Public concerns regarding climate change grew significantly. The juxtaposition of these two phenomena, the global financial crisis and the intensification of climate change concerns, defined the socio-economic landscape during that period. On one front, financial market grappled with the aftermath of systemic failures, leading to a significant economic downturn. Simultaneously, an increasing awareness and sense of urgency surrounding climate change issues permeated public discourse, highlighting the interconnectedness of economic and environmental considerations on the global stage (Melnyk *et al.*, 2019).

The upsurge in environmental concerns was especially pronounced in the run-up to the 15th Conference of the Parties to the UNFCCC in Copenhagen in 2009. This period witnessed a marked increase in discussions surrounding climate-related issues, with stakeholders from diverse sectors converging to deliberate on strategies to address the impending environmental challenges. The impending COP15 summit served as a catalyst, galvanizing international attention and prompting a reevaluation of global priorities. The discourse surrounding the conference extended beyond traditional environmental circles, permeating political, economic, and societal spheres (Khastagir, 2015).

Hence, the recognition of the interconnectedness between economic recovery and environmental sustainability gained traction during this pre-COP15 period (Nazarova *et al.*, 2021). Policymakers and global leaders were compelled to navigate the dual imperatives of mitigating the immediate economic fallout from the financial crisis and charting a course toward a more sustainable, resilient, and environmentally responsible future.

The Copenhagen summit became a crucial juncture where nations convened to negotiate and deliberate on strategies to combat climate change. At the forefront of this significant diplomatic undertaking were key figures including the President of COP15 and Danish Prime Minister, Lars Lokke Rasmussen, the UN Secretary-General, Ban Ki-moon, and the President of the United States, Barack Obama (Khastagir, 2015). Collaboratively, they played instrumental roles in shaping the trajectory of discussions and facilitating the preparatory work that culminated in the crafting of a three-page draft agreement. Drafting was entrusted to a group of national ministers known collectively as the Circle of Commitment. This assembly comprised representatives from diverse geographical regions and included Colombia, Indonesia, Ethiopia, the United Kingdom, Maldives, Grenada, Lesotho, Algeria, Bangladesh, India, China, South Africa, Mexico, and South Korea. It set a foundation for ongoing global dialogue and action to address climate change collectively and comprehensively (Khastagir, 2015).

As we delve into the experiences of different countries in navigating the complexities of implementing green economy measures during times of crisis, it becomes evident that the intersection of economic recovery and sustainable development is both nuanced and dynamic. The following paragraphs illuminate distinctive cases, drawn from the

information discussed, showcasing how diverse nations have approached the integration of green economy principles in response to crises. These cases underscore the pivotal role of sustainability in shaping recovery trajectories and offer valuable insights into the diverse approaches adopted by countries across the globe. Significant green stimulus initiatives were implemented in response to the 2008-2009 financial crisis by several major economies, including the China, US, Korea, Japan, and several member states of the European Union (Jaeger *et al.*, 2020).

China experience of green economy

The adoption of green economy principles by China is rooted in its economic development since the early 1970s. Over the past four decades, China's approach to environmental conservation has transitioned from basic “end-of-pipe” environmental protection measures to the integration of sustainable development principles into its overarching strategic development policies (Weng *et al.*, 2015).

China was among the early responders to the crisis, unveiling a \$586 billion (or 4 trillion yuan) stimulus package in September 2008, with approximately \$200 billion allocated for green initiatives (Jaeger *et al.*, 2020). The effectiveness of China's 2008-2009 economic stimulus package appears to have been positive, given its appropriate size, well-selected components, and timely implementation. Investments in urban infrastructure, green economy, and improved and targeted social services played a vital role in China's efforts to reduce income inequality and foster a more inclusive growth trajectory (Fardoust *et al.*, 2012).

From a fiscal standpoint, China initially benefited from low public debt and a large state budget surplus, allowing for significant fiscal flexibility in implementing an extensive stimulus package. A significant portion of the stimulus package focused on additional infrastructure expenditures, particularly in transportation and energy sectors. Additionally, funding was provided for social projects, especially in the health sector and environmental protection, which were considered to be critical for sustainable growth (Melnyk *et al.*, 2019).

Accordingly, China's fiscal stimulus in 2008 amounted to 4 trillion yuan, approximately 12.5% of the country's GDP (Table 1). Over a period of 27 months, the stimulus initiatives and programs were implemented, with about 1.2 trillion yuan coming from the government and nearly 3 trillion yuan directed towards projects led by local governments and the private sector. These efforts were largely financed through loans from state-owned and commercial banks.

Thus, China's stimulus package had two main elements, focusing on infrastructure projects such as railways, roads and urban transport. In the first 8 months of 2009, the total investment in rail, road and mass transit in China reached RMB 1,410 billion, a record high. However, despite being environmentally friendly, some railways were built to facilitate interregional coal transportation.

Following the implementation of these infrastructure projects, both coal and power output in China surpassed their previous peak levels in 2008, starting from June 2009.

Consequently, the country's energy consumption witnessed rapid growth in the second quarter of 2009. This surge in energy consumption can be attributed to the substantial allocation of funds towards infrastructure projects, with approximately 81% of the stimulus funds dedicated to such endeavors. These infrastructure projects, characterized by their heavy reliance on materials such as nonferrous metals, steel, iron, and cement, significantly contributed to increased energy consumption in the country.

Table 1: China's fiscal stimulus in 2008

<i>RMB 4 trillion stimulus package composition</i>	<i>Total allocation*</i>
Housing guarantees	0.4 trillion
Rural construction	37 million
Saving energy and reducing emissions	21 million
Infrastructure development	1.5 trillion
Social services	15 million
Industrial restructuring	37 million
Rebuilding Wenchuan after a disaster	1 trillion
Total (in RMB)	4 trillion

*All currency units in RMB [Source: Yang *et al.* (2024)]

A total of RMB210 billion was earmarked for energy-saving, emission-reducing and environmental engineering projects. This direct investment was anticipated to yield significant benefits, including an estimated saving of approximately 19 million tons of coal annually, equivalent to around 14% of China's total energy conservation in 2010. Furthermore, a portion of the stimulus package, amounting to RMB 80-100 billion, was directed towards nuclear power projects, which were expected to deliver an annual saving of nearly 14 million tons of coal upon their completion. As the sustainability of heavy investment in energy-intensive industries is limited, it was anticipated that the stimulus package would shift its impact on energy consumption in China from negative to positive by 2014.

However, its focus on saving energy, reducing pollution and restructuring industry has indirectly influenced investments in alternative energy. Consequently, there has been a notable increase in investment in large-scale renewable energy power generation projects, alongside a marked rise in investment in the manufacturing of wind and solar power generation equipment. These developments reflect a shift toward greater emphasis on alternative energy sources, spurred by the broader objectives to save energy and reduce emissions as outlined in the stimulus package.

China's stimulus program produced positive results in stimulating and restoring growth. In the first half of 2009, China's urban fixed asset investment increased by 26.5%, up 0.4% year-on-year. Notably, from the second quarter of 2009, China's GDP growth stopped declining and began to rise again. GDP grew by 6.1%, 7.9%, and 8.9% in the second quarter, third quarter, and fourth quarter, respectively (Yang *et al.*, 2024). Furthermore, through 2019, China's high-speed rail network, built during the ten years following the financial crisis, displaced about 500,000 barrels of jet fuel per day that would have otherwise been consumed in domestic aviation (Varro *et al.*, 2020). This

underscores the impact of China's ambitious and infrastructure-focused stimulus in swiftly restoring the country to a dynamic, green growth trajectory.

China is moving towards holistic and integrated approaches to environmental sustainability in its economic development. In China's green economy concept, eco-industry refers to many environmentally friendly industries. Besides water treatment, air purification, energy monitoring and waste recovery, the Chinese environmental industry has expanded to include environmental protection and ecological conservation goods and services. The environmental industry has become an all-encompassing industry (Weng *et al.*, 2015). This evolution reflects a maturation of environmental consciousness and a recognition of the interconnectedness between environmental preservation, social progress, and economic prosperity. As China continues to navigate the complexities of sustainable development, green economy is poised to remain a pivotal driver shaping the country's developmental trajectory and policy landscape in the coming years.

Green stimulus initiatives in the United States

In numerous instances, green stimulus initiatives have demonstrated equal or greater effectiveness in job creation compared to spending on fossil fuels or traditional stimulus measures. The ARRA (Federal Communications Commission, 2009) was created to boost renewable energy and energy efficiency jobs. ARRA, which was passed as an economic stimulus package following 2008-2009 global financial crisis, provided about \$800 billion (Varro *et al.*, 2020).

The administration of President Obama referred to the ARRA (2009) as an extraordinary response to a crisis unparalleled since the Great Depression. The ARRA was a multi-pronged approach aimed at modernizing the country's infrastructure, promote energy independence, expand education, provide affordable healthcare, give tax relief, and protect vulnerable people. The specified actions in the act included (U.S. Government, 2009):

- Saving and creating jobs and help the economy recover;
- Provide assistance to those most impacted by the recession;
- Encouraging technological advances in science and health to provide the investments needed to increase economic efficiency;
- Investing in infrastructure that provides long-term economic benefits, such as transportation and environmental protection;
- Stabilizing state and local government budgets to avoid cuts in critical services or tax growth at the state and local level.

During 2008–2009, the United States devoted 12% of its total economic stimulus to green initiatives (Jaeger, 2020), leading global investments in renewable energy at that time. The ARRA allocated approximately \$90 billion to the clean energy sector, which was distributed to various sectors through both direct funding and tax-related measures. As shown in Figure 6, under the ARRA, a significant portion of clean energy funding, accounting for 51%, was designated for renewable energy and energy efficiency initiatives. Significant resources have also been allocated to public transport (20 %) and upgrading the electricity grid (12%). Direct spending through 45 investment provisions targeting high-value investment areas to promote a sustainable economy accounted for nearly two-thirds of clean energy funding.

Support for renewable energy under the ARRA entailed the expansion of existing incentives and the establishment of new programs. In particular, it extended the production tax credit for wind and the investment tax credit for solar. A post-implementation assessment of the ARRA by the Obama administration found that the initiative supported approximately 900,000 job-years (the equivalent of full-time, year-round employment) in the clean energy sector from 2009 to 2015. A significant portion of jobs were created in the first few years after the stimulus.

According to the World Resources Institute (WRI), grants totaling \$25 billion created an estimated 44,000–66,000 jobs in the wind energy sector and 8,300–9,700 jobs in the solar photovoltaic sector between 2009 and 2013 (Jaeger *et al.*, 2020). These grants also supported 4,500–4,900 permanent wind energy jobs and 610–630 permanent solar jobs over a 20–30 year operational lifespan. Additionally, an estimated 8,000 short-term construction jobs and 500 permanent jobs were created. Additionally, loans worth \$2.5 billion financed five commercial-scale solar plants and one of the world's largest wind farms, creating 8,000 short-term construction jobs and 500 permanent jobs. In 2010, the Weatherization Assistance Program (WAP) also played a significant role in supporting 28,000 jobs. In this way, it contributed to a reduction of 7.4 million metric tons of carbon emissions, as the ARRA increased funding for the Weatherization Assistance Program by USD 5 billion.

The State Energy Program, backed by a financial allocation of \$3.1 billion, significantly impacted employment by supporting 51,000 job-years from 2009 to 2013. This initiative anticipated to yield substantial long-term benefits, as it is expected to result in greenhouse gas (GHG) emissions reduction by 164 million metric tons of carbon dioxide from 2009 to 2050. These reductions are equivalent to the environmental impact of taking 35 million cars off the roads for an entire year. Moreover, the program achieved \$7.7 billion in energy bill savings, contributing to both environmental sustainability and economic efficiency. However, an assessment (Popp *et al.*, 2020) concluded that the ARRA contributed to an overall increase in total employment, albeit at a slower pace compared to other stimulus investments. The findings fall in the middle of previous estimations, suggesting just under 15 jobs for every \$1m of ARRA environmental investment over time.

A notable outcome of ARRA's green fiscal stimulus was its persistent job creation effects, in contrast to the short-term gains observed in other sectors. However, the most significant benefits were observed among manual workers with higher education levels. There was no increase in the wages for other manual laborers, possibly due to the modest size of the green stimulus, insufficient to counteract the long-term decline in the negotiating power of employees, or possibly low-quality jobs.

The Republic of Korea's integrated approach to green growth

Through a comprehensive approach and the establishment of a central governing body solely dedicated to overseeing green growth initiatives, the Republic of Korea has systematically pursued green growth. The joint initiative mobilized various government departments and engaged stakeholders from various sectors of society. The objective was to effectively execute a multifaceted strategy that aligned with environmental

sustainability goals. In 2009, South Korea's adoption of the National Strategy for Green Growth and the concurrent enactment of the Five-Year Plan for Green Growth were key responses to the global financial downturn. These strategic frameworks served as foundational pillars for South Korea's commitment to integrating green principles into its national development agenda.

The Presidential Committee on Green Growth (PCGG) oversees the national green growth strategy and 5-year plan implementation and exercise an overall guidance of green growth programs at national level. It was formed by merging three organizations: the Presidential Commission on Sustainable Development, the Presidential Commission on Energy, and the Special Task Force on Climate Change. This committee plays a pivotal role in shaping and coordinating the green growth agenda of the nation.

From January 2009 to October 2012, the PCGG has been a proactive force in advancing environmental sustainability in the Republic of Korea. It has diligently organized and conducted a total of 21 regular meetings and 11 policy implementation review sessions. These gatherings have served as dedicated forums for focused discussions, strategic deliberations, and comprehensive assessments. Within its ambit of responsibilities, the committee plays a pivotal role in deliberating on the overarching green growth policies and initiatives put forth by the government. Furthermore, it actively engages with the execution and performance of these plans and policies.

Moreover, a significant facet of the PCGG's mandate involves effective coordination with pertinent central administrative agencies and local governments. This collaborative effort ensures a synchronized approach to green growth initiatives, fostering cohesion and alignment across various administrative levels within the national governance structure. Thus, the PCGG assumes a global perspective by actively participating in the global dialogue on green growth. By engaging with international counterparts and contributing to global discussions on sustainable development, the committee facilitates the exchange of best practices, fosters international collaboration, and positions South Korea as a proactive participant in the global green growth agenda. While the PCGG holds the pivotal role of coordinating and deliberating on green growth policies, its influence on the allocation of financial resources remains indirect. The Ministry of Strategy and Finance retains the authority to determine budgetary allocations, which impact the PCGG's ability to implement and scale its envisioned green growth initiatives.

The government's strategic roadmap for advancing its vision in the realm of green technologies materialized in the form of the Green Technology R&D Master Plan, published in January 2009. In formulating strategic goals, presented in Figure 1, the government meticulously examined prevailing trends and anticipated future trajectories within the field of green technologies. An in-depth analysis encompassed an assessment of global trends, insights into the status of forerunners in the global eco-industry, as well as an evaluation of the domestic capacities and the availability of skilled human resources.

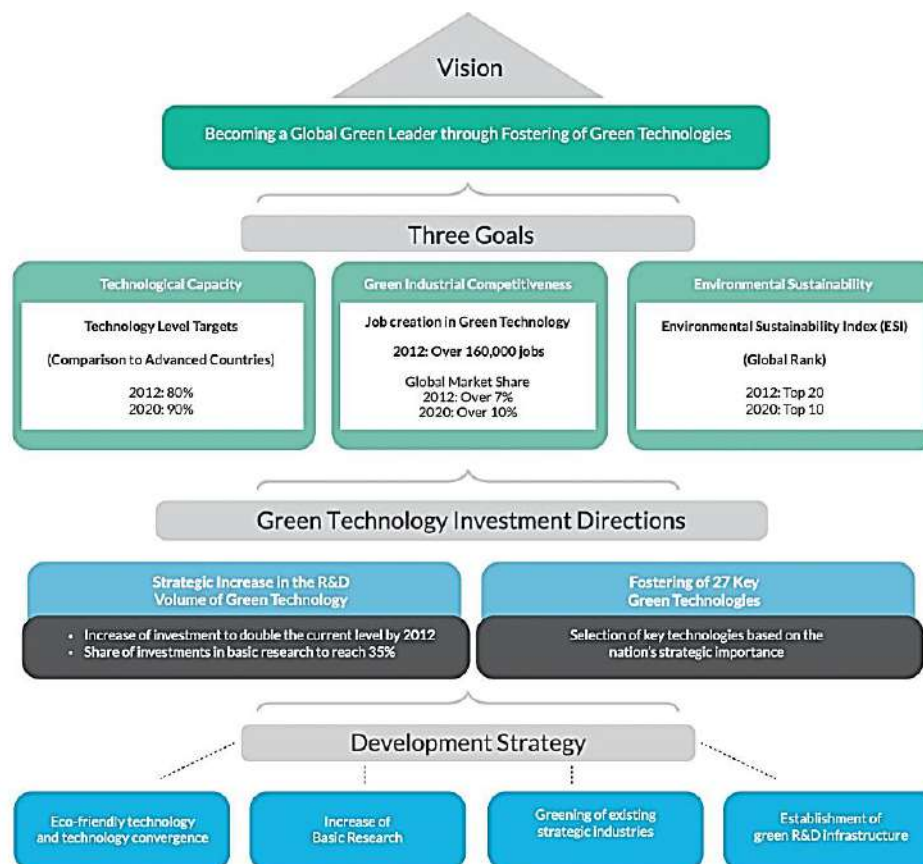


Figure 1: Korea's green technology research and development vision and objectives [Source: Global Green Growth Institute (2015)]

Accordingly, in the formulation of the national GHG reduction targets, the government undertook a meticulous process involving extensive assessments, consultations with relevant experts, and public discussions. This approach aimed to establish a robust social consensus and garner widespread support for the ensuing initiatives. Following the president's announcement in July 2008, signaling the intention to disclose quantified mid-term GHG reduction targets for the period leading up to 2024, an ad hoc team of researchers was assembled. This team, composed of experts from national research institutions specializing in climate science, energy, and economic modeling, was tasked with projecting the Republic of Korea's (ROK) future GHG emissions under various policy scenarios.

The government systematically formulated and presented three distinct scenarios to the public. These scenarios were developed as projections of GHG emissions, taking into account various influential factors. The Business-As-Usual (BAU) emissions projection, a central component of this process, is typically derived from a comprehensive assessment encompassing key variables such as the oil prices, population growth rate, economic growth rate, energy demand, and industrial structure.

These scenarios outlined proposed emission reduction targets: a 21% reduction (Scenario-1), a 27% reduction (Scenario-2), and a 30% reduction (Scenario-3) from BAU levels by the year 2020. Notably, a poll conducted by the PCGG immediately following the announcement indicated that the public demonstrated a favorable inclination towards Scenario 1, whereas experts in fields associated with climate change exhibited a preference for Scenario 2. Meanwhile, an assessment conducted in October 2009, following the successful hosting of the G-20 Summit by the Republic of Korea (ROK), revealed a shift in public sentiment. The majority of the general public now favored Scenario 3, signaling a nuanced evolution in public opinion regarding the preferred GHG reduction trajectory for the nation. Table 2 illustrates the intricate interplay of public perception, expert input, and external events in shaping the trajectory of environmental policies within the Republic of Korea.

Table 2: Scenarios for reducing GHG emissions

<i>Scenario</i>	<i>Target</i>	<i>Criteria</i>	<i>Public consultation-based group support</i>
1	21% (171 million tons reduction from BAU)	Cost efficiency	Industry sector
2	27% (223 million tons reduction from BAU)	International standards	Academic or research institutions
3	30% (244 million tons reduction from BAU)	Developing countries	Environmental and civil organizations

Source: Special Committee on Climate Change (2012)

As depicted by the Global Green Growth Institute (2015) in the Republic of Korea encountered challenges in achieving substantial progress in developing and commercializing green technologies, hindering the realization of planned emissions reductions from the selected measures. Despite having committed to ambitious targets, the inherent limitations of regulatory measures became apparent, with substantive gains being difficult to attain within a compressed timeframe. It is crucial to conduct a thorough examination to determine the appropriateness of the GHG mitigation measures selected by the government and their calculated impacts, given their pivotal role as the basis for setting national reduction targets.

In response to dynamic circumstances, the government has noted rapid transformations within the energy market, particularly concerning technological advancements. The Republic of Korea, designated as one of the most resource-deprived nations, consistently prioritized addressing energy security as a key component of its economic growth plan. Due to resource constraints, the Republic of Korea was compelled to rely heavily on imported energy to meet the ever-increasing energy demands of its economic activity. This reliance on energy imports underscores the critical role energy security plays in shaping the economic strategy and underscores the necessity for strategic planning in managing its energy portfolio. The Republic of Korea adopted the concept of New and Renewable Energies (NRE), which includes a broad range of eight renewables and three new energies:

- Renewable Energy: biomass, solar thermal, wind, small hydro, ocean, photovoltaic, geothermal, and waste;
- New Energy: coal liquefaction and gasification, fuel cell, and hydrogen energy.

Amid an economic slowdown and energy challenges, the Republic of Korea encountered a volatile global renewable energy market after the 2008 financial crisis. In response, adopting the low-carbon, green growth paradigm was seen not as an option but as a national imperative. The energy dilemma carries noteworthy ramifications for other countries, underlining how developing economies must address environmental challenges early in development. Thus, the experience of Korea serves as a pertinent example of the imperative for developing economies to proactively address environmental challenges from the outset of their development trajectories. This necessitates a shift towards sustainable practices and the consideration of long-term resource constraints. In an era dominated by the specter of climate change, the conventional approach of overcoming poverty solely through economic growth rooted in resource-intensive activities and technologies is perceived to have diminished prospects for sustained success.

The successful adoption of green economy as a national agenda is contingent upon robust public support. Recognizing this, the Republic of Korea government strategically emphasized the economic advantages associated with green growth, concurrently highlighting its potential to increase the quality of life through the GHG emissions reduction. This approach aimed to secure public approval by illustrating the tangible benefits and positive impacts associated with embracing a green growth paradigm. A remarkable ideational shift was facilitated by the shift to proactive governance in directly addressing climate change, effectively countering criticisms and fostering a paradigm where green growth has evolved into an immutable political ideology. During this transformative period, low-carbon and clean energy initiatives have gained widespread acceptance, being recognized not merely as suitable policies but exemplifying as a best practice.

Moreover, the explicit articulation of the agenda item related to the promotion of a green lifestyle within the Republic of Korea's Five-Year Plan for Green Growth, termed as the "green revolution of life practices" in Korean, underscores a deliberate and strategic approach towards encouraging transformative changes in individuals' lifestyles. The choice of the term "revolution" carries a profound connotation, signifying a call for transformative changes in people's lifestyles. This deliberate framing challenges conventional unsustainable practices, emphasizing the need for a fundamental shift towards a sustainable lifestyle. In order to extend its reach to a broader audience, it is imperative to promote the sense of social responsibility and personal fulfillment driven by it as a social trend.

Despite having a favorable foundation upon which to cultivate robust societal momentum, the government has encountered challenges in fully realizing its initial expectations concerning the promotion of a green lifestyle. A persistent obstacle in this endeavor is the deficiency in effective promotion and communication with the public, impeding the implementation of various government policies and programs in the Republic of Korea. Addressing this deficiency is paramount for ensuring the effective uptake of environmentally conscious behaviors and facilitating the attainment of the government's objectives in fostering a sustainable and eco-friendly way of life.

Integration of economic, environmental, and social considerations in the EU's countries

The crisis that commenced in 2008 exerted widespread impacts on many countries. In response, nations directed their policy efforts to cope with the crisis and develop incentive programs to revitalize their financial systems. The EU initiated the Economic Recovery Plan in November 2008 with the objective of stimulating demand, restoring shattered confidence, and promoting employment. In conjunction with this plan, the EU proposed smart investment proposals focusing on skills enhancement and technological advancements aimed at fostering long-term economic development.

In this context, the EU policies and actions for the period of 2009–2010 were formulated, taking into account not only the economic dimensions of the crisis but also its environmental and social ramifications. These initiatives aimed to tackle the multifaceted problems posed by the crisis and chart a course towards comprehensive recovery, ensuring the integration of economic, environmental, and social considerations in the EU's strategic response.

The European Economic Recovery Plan was built around two primary pillars, underpinned by a fundamental guiding principle (Commission of the European Communities, 2008). The first pillar is designed to stimulate demand and boost confidence by injecting a substantial amount of purchasing power into the economy. The Commission proposes an immediate budgetary impulse totaling €200 billion (being equivalent to 1.5% of GDP), emphasizing the urgency of this measure to bolster demand while adhering to the principles of the Stability and Growth Pact. The second pillar emphasized the need to focus short-term actions on improving Europe's long-term competitiveness. The Plan delineates a comprehensive program focusing on smart investment strategies. These smart investments encompassed targeted allocations towards developing requisite skills for future demands, investing in energy efficiency initiatives to create jobs and conserve energy, clean technologies, and infrastructure to promote sustainability. Of the €200 billion earmarked, 13.2% was allocated to making the world greener. Of this, 75% was directed toward improving the energy efficiency of buildings, 20% to railways, and 5% to vehicles. Moreover, more than two-thirds of the 200 billion euros earmarked for climate action in the economic stimulus plan were allocated to energy efficiency. As shown in Figure 2, the largest share was invested in developing energy-efficient buildings, followed by networks and low-carbon vehicles.

Similarly to Korea, the EU's eco-investments are part of a well-developed strategy to become a leader in clean energy technologies, despite relatively modest green stimulus spending (Ladislav and Goldberger, 2010). Europe's green stimulus may appear modest compared to the substantial stimulus projects undertaken by China, the United States, and South Korea. However, this discrepancy largely stems from Europe's significant prior renewable and energy efficiency investments, as well as its well-established clean energy technology manufacturing sector. Consequently, the impact of green investment policies has been notable, with each dollar invested in green initiatives yielding significant returns in terms of GDP growth. At the national level, every \$1 in green investment is estimated to boost GDP by approximately \$0.60 to \$1.10, while at the European level, this impact has been even more pronounced, reaching up to \$1.50 (Jaeger *et al.*, 2020).

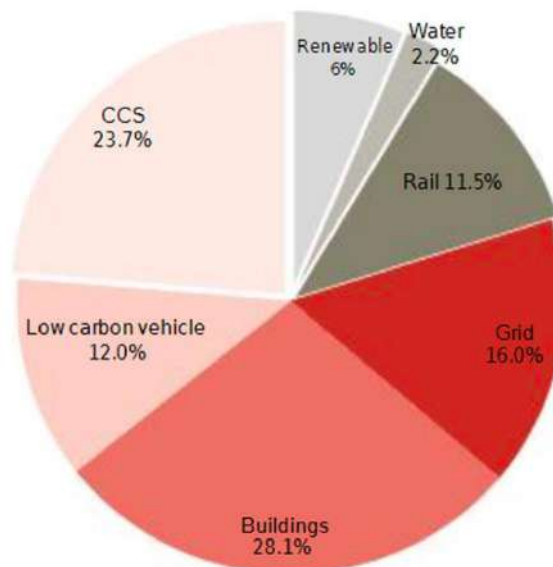


Figure 2: EU green incentive expenditures distribution [Source: Mentés (2023)]

The focus on green initiatives varied across countries, with distinct strategies adopted by individual Member States. For instance, Germany incentivized the purchase of lower emissions vehicles, whereas France prioritized investments in energy efficiency and public transport infrastructure (Ladislaw and Goldberger, 2010). Among the Member States, Germany implemented the largest fiscal recovery program within the EU. Roughly 13% of the \$105 billion stimulus package in Germany went toward green investments (Barbier, 2015). The ambitious EUR 81 billion (equivalent to USD 104.8 billion) plan comprised a combination of tax reductions and strategic investments in infrastructure and climate change initiatives (Energy Tracker Asia, 2020).

The building refurbishment initiative, with an allocation of €3.3 billion (equivalent to \$4.6 billion), emerged as one of the most substantial programs within the stimulus framework. An analysis conducted prior to the implementation of this initiative projected that the investment in building refurbishment would be recouped through reduced energy costs while simultaneously generating an estimated 25,000 jobs within the manufacturing and construction sectors (Meyer-Ohlendorf *et al.*, 2009). Furthermore, Germany introduced a €5 billion (approximately \$7 billion) vehicle scrappage scheme as part of its stimulus measures. While this initiative successfully stimulated the automobile industry, it also resulted in an unintended consequence of increased emissions.

The allocation of France's stimulus plan towards green measures has been debated, with estimates ranging from 8 to 20 percent of its total €26 billion (equivalent to \$34 billion) French Economic Revival Plan (Jaeger *et al.*, 2020). Within this stimulus framework, investments in green initiatives encompassed a range of sectors including solar photovoltaic (PV) technology, building efficiency enhancements, and railway infrastructure improvements. However, alongside these green investments, a portion of the stimulus was directed toward upgrades of fossil fuel plants and road infrastructure projects.

Furthermore, in response to the economic downturn, the EU introduced three distinct initiatives targeting sectors significantly impacted by the crisis, namely the construction, automotive, and manufacturing sectors. These programs, namely the Green Vehicle Initiative, the Energy-efficient Buildings Initiative, and the Future Factories Initiative, were specifically tailored to address the challenges faced by these sectors. The overarching objective of these initiatives was to promote the adoption and integration of green technologies, enhance energy efficiency standards, and mitigate carbon emissions across the targeted sectors. By fostering the deployment of sustainable practices and innovative solutions, the EU sought not only to bolster the resilience of these industries but also to advance its broader environmental sustainability agenda.

In this regard, the EU's emphasis on green growth has continued in recent years, with the adoption of the European Green Deal in 2019, which aims to transform the EU's economy into a more sustainable and eco-friendlier one by 2050 (Hedberg and Šipka, 2022). Moreover, the EU established ambitious objectives aimed at curbing greenhouse gas (GHG) emissions and accelerating the adoption of renewable energies. The EU's ambitious target to reduce GHG emissions by at least 55% by 2030 underscores its steadfast commitment to combating climate change and fostering the movement towards a more sustainable and environmentally conscious economy.

Discussion

Our study highlights the critical implementing green stimulus measures is insufficient for achieving comprehensive economic recovery. Each nation incorporated within its stimulus package a diverse range of incentives aimed at fostering short-term growth, encompassing initiatives such as tax reductions, expanded unemployment compensation and outright grants to states and municipalities (Ivashchenko *et al.*, 2018). However, the efficacy of green investments in driving economic growth varies significantly, necessitating careful prioritization of initiatives that deliver optimal environmental and economic benefits.

Certain allocations towards green investments exhibit a greater capacity to stimulate economic growth compared to others. Therefore, it is imperative for policymakers to discern and prioritize those green investment avenues that offer optimal potential for bolstering economic recovery and fostering sustainable growth trajectories. By strategically allocating resources towards the most impactful green initiatives, countries can effectively leverage their stimulus packages to achieve both environmental and economic goals.

However, the definition of "green" is subjective and varies by interpretation. Green stimulus projects encompass a broad spectrum of initiatives, from clear investments in renewable energy and infrastructure to more subtle categories such as expenditures on waste and water infrastructure, modernizing the electric grid, and improving transportation. However, there exists criticism regarding the allocation of stimulus funds, with concerns raised about the insufficient allocation towards green investments.

Therefore, to expedite green investments, some countries have opted to relax environmental restrictions and guidelines, prompting debates over the prioritization of

environmental sustainability versus short-term economic gains. It is essential to discern that not all green investments are created equal, and critical evaluation is necessary to ascertain their efficacy. For instance, transportation infrastructure projects can only be deemed "green" if they demonstrably improve upon the environmental impact of alternative transportation options.

Beyond transportation, it is crucial to evaluate the long-term lifecycle impacts of such projects, including emissions from construction, maintenance, and eventual decommissioning. Similarly, renewable energy initiatives should be assessed not only for their immediate benefits in reducing carbon footprints but also for their resource use, such as the mining and disposal of rare earth elements required for solar panels and batteries. Urban development plans branded as "green" should undergo scrutiny to ensure they incorporate sustainable design principles that minimize energy consumption and foster biodiversity. Furthermore, the social equity aspects of green investments demand careful consideration, as projects should provide inclusive benefits without disproportionately disadvantaging marginalized communities.

Moreover, the environmental damage caused by other facets of the stimulus package may offset the benefits of green investments (Polishchuk *et al.*, 2019). Therefore, a detailed approach is imperative in evaluating the overall environmental benefits and efficacy of stimulus spending, ensuring that green investments are strategically prioritized and harmonized with broader environmental objectives.

Thus, the introduction of economic incentives aimed at developing green economy has proven to be effective. Just as during the financial crisis of 2008, many countries attempted to stimulate economic recovery through green stimulus measures, similarly, governments imposed a scope of restrictions as a result of the COVID-19 outbreak, aimed at containing the spread of the virus and alleviating its socio-economic impact. Consequently, the implementation of green economy during the 2008 financial crisis and the introduction of restrictions amid the COVID-19 pandemic exhibit notable similarities in their approaches, despite the differing contexts of these crises. As the World Resources Institute (WRI) noted, the Great Recession of 2008 was triggered by domestic financial situation (Jaeger *et al.*, 2020). At that time, the economy had an "output gap" between what the economy could produce and what the economy produced; the economy remained healthy, but the credit markets froze. By contrast, the COVID-19 crisis was both health and economic. It was triggered by the pandemic, which in turn caused a significant reduction in supply and demand.

Both periods witnessed a concerted effort by governments and policymakers to address the economic downturn while simultaneously advancing environmental sustainability objectives (Jaeger, 2020). During 2008-2009, the United States, South Korea, and China allocated significant funds towards green stimulus initiatives, yet their commitments in response to COVID-19 have been comparatively lower. Conversely, the EU economies, such as Germany and France, signaled intentions to allocate substantially more towards green stimulus efforts than during the financial crisis 12 years ago.

However, even in the leading countries, the green stimulus response to COVID-19 has been lower as a percentage of total stimulus compared to the Great Recession. Of

particular concern are the responses of the United States and Japan, where governments have not prioritized sustainability to the same extent. During the 2008-09 financial crisis, the US spent 12 percent of the overall stimulus package on green initiatives, including significant investments in renewable energy. However, as of November 2020, less than 1 percent of the \$3trn coronavirus economic stimulus package went to green initiatives. Likewise, Japan spent 6 percent of their financial crisis stimulus on green measures, but essentially none of their \$2trn economic stimulus package (Jaeger, 2020).

Accordingly, countries have varying degrees of success in implementing their fiscal stimulus plans. The most successful are likely to be the ones with effective policy incentives and economic structures that will keep driving future green investment when the stimulus programs end. Improving both economic and environmental policies and programs are required to promote economic growth and address climate change through increased transparency on stimulus packages and further analysis of country policies (Levchenko *et al.*, 2021).

The concepts of green economy and green growth are considered central to the sustainable development plans. While green growth describes economic expansion that is consistent with environmental protection and social inclusion, green economy describes an economic framework that prioritizes environmental sustainability and social well-being (Ovsak *et al.*, 2024). Together, these principles emphasize social equity and environmental resilience, such as adapting to climate challenges while advocating for a transition to more sustainable production and consumption. The adoption of policies aligned with green economy and green growth can be vital in advancing sustainable development objectives, concurrently fostering the emergence of novel employment prospects and enhancing societal well-being.

Hence, green economy offers a strategic pathway for nations to address pressing challenges, such as economic downturns, by concurrently fostering environmental sustainability and social welfare. The integration of green practices serves as a pragmatic response to the dual challenges of economic recovery and environmental stewardship. During crises, the pursuit of green economy components aligns with the overarching goal of achieving sustainable development, wherein economic growth is harmonized with environmental preservation and social inclusivity. Resilience and adaptability in the context of green practices are evident in the ability of ecosystems, communities, and technologies to withstand crises and adapt to changes. For instance, renewable energy sources such as solar panels and wind turbines provide electricity even during natural disasters, ensuring the continuity of critical infrastructure. In agriculture, sustainable practices like crop rotation and agroforestry protect soil from degradation and reduce dependency on favorable weather conditions. Urban environments benefit from green roofs and parks, which mitigate flood risks during heavy rainfall and reduce urban heat island effects. Adaptability is showcased through innovations such as energy-efficient retrofitting of buildings, enabling them to respond to climate challenges, or circular economy models, where waste becomes a resource, easing the impact of supply chain disruptions. Even transportation systems, including electric vehicles and bike-sharing programs, evolve to meet the demands of growing cities (Levchenko *et al.*, 2021). These approaches create a robust foundation for long-term sustainable development and the capacity to address unforeseen challenges.

In recent years, several of leading economies implemented significant stimulus packages in response to the global financial crisis. Many of them included a significant green component. Approximately 90 percent of the stimulus expenditures during the global financial crisis was allocated by the following five economies: China, the US, South Korea, Japan, and the EU. In 2008, China initiated a substantial stimulus package totaling 4 trillion yuan (approximately \$586 billion USD) to mitigate the adverse impacts of the financial crisis. A significant segment of China's stimulus funds was designated for green investments, encompassing infrastructure development, including the construction of railways, highways, and transportation. Significant resources were also allocated to energy-saving, emission-reducing and environmental projects (Melynk *et al.*, 2019).

Similarly, in the US, the ARRA was the primary economic stimulus package in response to the global financial crisis of 2008-2009. Its total budget was approximately USD 800 billion. The ARRA included substantial investments in green sectors such as renewable energy, energy efficiency, and environmental conservation. Funds were allocated for various initiatives, including renewable energy projects, weatherization programs, green infrastructure development, and research and development in clean energy technologies. Specifically, the ARRA supported approximately 900,000 person-years of employment in the clean energy sector between 2009 and 2015, with a significant portion of the jobs created in the early years after the stimulus (Jaeger, 2020).

In parallel, South Korea responded to the financial crisis by adopting the 5-Year Plan for Green Growth and the National Strategy for Green Growth in 2009. The country prioritized investments in renewable energy, energy-efficient technologies, eco-friendly infrastructure, and green innovation to foster economic recovery and sustainable development. Since its establishment in January 2009, the PCGG was instrumental in driving environmental sustainability initiatives in South Korea (Fedrigo-Fazio and Ten Brink, 2012).

Furthermore, the EU also launched the Economic Recovery Plan in 2008 to help stimulate demand, restore trust and bolster employment following the financial crisis. A notable portion, equivalent to 13.2% of the earmarked €200 billion budget, went for green investments. 75% of them were channeled towards enhancing the energy efficiency in the building sector, with 20% allocated to railways, and the remaining 5% allocated to vehicles. These initiatives underscored the commitment of these nations and regions to prioritize economic recovery through green investment strategies during the 2008 financial crisis (Commission of the European Communities, 2008).

Indeed, while green stimulus measures can provide a considerable increase in the economy and environmentally sustainable projects, they alone cannot address the complex economic and ecological challenges facing the world. Although they can offer momentum during times of weak financial markets and limited private investment. It involves investments in clean energy industries to bring about an overall recovery. Transitioning to a low-carbon economy demands a comprehensive, long-term approach supported by the right policy framework and sustained investment. While green stimulus initiatives play a crucial role, they are just one component of the broader strategy needed to address environmental challenges effectively (Mazaraki *et al.*, 2023).

Like other aspects of stimulus bills or the green movement, green stimulus measures face challenges and controversies. However, the urgent necessity to create jobs, stimulate economic revival, and develop promising eco-friendly industries, while tackling burning environmental issues has elevated the importance of green stimulus as a strategic political aim. Nevertheless, it is essential to acknowledge that it is still early to fully evaluate the success of green stimulus spending. More comprehensive transparency and analysis of these initiatives are necessary to assess their true effect on the environment and the economy.

Finally, public perception plays a crucial role in developing green economy strategies during crises. Thus, when public support for environmental action is high, governments are more likely to include green initiatives in economic stimulus packages. For example, during the 2008 financial crisis, strong public awareness of climate change led many governments to prioritize green projects in recovery plans as a dual solution to economic and environmental issues. Hence, public support can drive policies toward investment in renewables, energy efficiency, and sustainable infrastructure as part of recovery efforts. Moreover, public perception that emphasizes environmental responsibility pressures companies to align with green practices. For instance, during recent crises, investors have directed funds toward green bonds and sustainable companies, driving green growth when traditional sectors are struggling. In addition, public support can be crucial in driving the structural changes necessary for developing green economy. For example, the use of low-emission transportation and renewable energy infrastructure requires substantial shifts. Public support of these initiatives makes it politically viable for governments to invest in long-term sustainable growth solutions rather than reverting to traditional high-carbon industries.

Conclusion

Green economy and green growth are key elements of sustainable development strategies as they combine economic growth with environmental sustainability and social inclusion. The world's leading economies, such as China, the United States, South Korea and the EU, have made significant investments in green projects during global financial crises, which prompted economic recovery and environmental transformation.

Moreover, green stimulation has demonstrated effectiveness in creating jobs and developing new technologies. However, its full impact needs further analysis. Thus, key lessons learned from the analysis of this experience can help governments and researchers develop more adaptive and sustainable approaches to addressing economic and environmental challenges in the future. Future studies could focus on developing metrics to evaluate the effectiveness of green stimulus programs in achieving low-carbon transitions and their impact on reducing economic vulnerabilities. Analyzing the role of international cooperation in financing and implementing green initiatives, particularly in developing economies, would also contribute to understanding how global partnerships can drive sustainable development. By addressing these research areas, scholars and policymakers can work together to refine strategies for leveraging the green economy as a tool for overcoming economic crises and achieving long-term sustainability.

Therefore, green economy can be a long-term strategy to overcome economic crises because it ensures sustainability by integrating environmental and social goals. While financing green initiatives is an important component of stimulus programs, there is a need to continue developing policies and supporting investments to transition to a low-carbon economy, which will be the basis for sustainable economic development in the future.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	Yes	No	No	No
Collected the data	Yes	Yes	No	Yes	Yes
Contributed to data analysis & interpretation	No	No	Yes	No	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	Yes	No	No
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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

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Green Growth in Jordan: Leveraging Waste Management for Sustainability, Poverty Reduction, and Social Development

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Abstract

This paper examines Jordan's social development in the context of ecology and waste recycling through an analysis of the Hashemite Kingdom of Jordan's 2021-2025 National Green Growth Plan, which prioritizes green growth. The study addresses Jordan's environmental challenges, including high waste generation, limited recycling infrastructure, and the socio-economic impacts of the Syrian refugee crisis, emphasizing the need for strategic waste management to achieve national development goals. The methodology employed involved a comprehensive review of recent literature, a detailed analysis of waste generation and recycling data, and an evaluation of green growth strategies outlined in Jordan's national plans. To enrich the study, global best practices and case studies were incorporated to propose actionable solutions. The findings of the study highlight several barriers, including inadequate infrastructure, limited public awareness, and poor private sector involvement. The study identifies waste collection and recycling as potential avenues for poverty reduction, economic innovation, and reducing reliance on imported materials. The study recommends the implementation of Extended Producer Responsibility (EPR) initiatives, the enhancement of public awareness, and the leveraging of technologies such as the Internet of Things (IoT) for the efficient management of waste. The promotion of private sector partnerships and the engagement of vulnerable communities can drive sustainable growth, positioning Jordan for a greener economy.

Keywords

Green growth; Wastewater management; Poverty reduction; Sustainability; Resource efficiency

Introduction

One of the most pressing threats facing humanity and modern civilization is the environmental catastrophe, which has various facets, such as soil and water pollution from industrial waste and human waste, drinking water shortages, and global climate change.

Addressing such disasters is critical for environmental and societal sustainability. While international organizations play a crucial role in promoting environmental conservation and sustainable development, the primary responsibility lies with national governments. Although various international organizations help protect nature and the sustainable development of society, the primary responsibility lies with the national government. Governments are at the forefront of efforts to achieve harmonious development, and poverty reduction and the introduction of waste recycling systems is played by the governments of national states, which can also be seen in the example of the activities of the Jordanian government (Danthurebandara *et al.*, 2012). Globally, one-third of all solid waste generated still ends up in open landfills, and only one fifth is recycled (Aldayyat *et al.*, 2019). This underscores the untapped potential of waste as a resource that could transform from an environmental burden into an economic asset. Improving the waste management system is recognized today as the main problem in the field of environmental protection. Key steps to address this issue were identified at the International Conference on Sustainable Development in Johannesburg in September 2002. These include waste prevention and minimization, maximum reuse, recycling of resources, use of alternative environmentally friendly materials, involving governments and all stakeholders, to minimize adverse environmental impacts and increase the efficiency of resource use (Lozano, 2024).

A green growth framework and sector-specific activities are included in the Waste Sector Green Growth Action National Action Plan 2021–2025 (GG-NAP), which is in line with the National Green Growth Plan (NGGP), Jordan Vision 2025, and Nationally Determined Contributions (NDCs) under the Paris Agreement (Alam and Ahmade, 2013). Leveraging the sector's resilience through ecologically and socially inclusive economic growth is the cornerstone of the green growth concept. A total of 91% of Jordanians were urban dwellers in 2018, a historically high percentage of urbanization that reflects both the special demands on services brought on by the Syrian refugee crisis and the "typical" difficulties associated with rapid and unplanned growth (MacArthur, Waughray and Stuchtey, 2016). According to Statista (2018), Jordanians generate 0.81 kg of municipal waste per person per day on average, which is 26% more than their counterparts in other upper-middle-income nations (GIZ, 2014). A major focus of the green growth plan in Jordan is the garbage problem, which offers both socioeconomic and environmental opportunities. Regarding the makeup of Jordan's municipal solid trash, food waste accounts for more than half of the waste produced by Jordanian homes (Statista, 2015) In addition, the 7% recycling rate for municipal garbage is poor, even when contrasted with the 10% average for all states in the Gulf Cooperation Council (GCC). Inadequate treatment and disposal facilities, coupled with tax enforcement measures, result in the significant or increasing generation of several forms of waste in Jordan, including hazardous, medical, electronic, construction, and demolition trash, among others. With 10% of GHG emissions coming from landfilled garbage, landfilled waste has a significant environmental impact on Jordan. (Government of the Hashemite Kingdom of Jordan, 2015), a number that is anticipated to rise in tandem with population growth. The waste management industry serves as an example of the opportunities and challenges associated with moving toward a more circular economy and, eventually, a more efficient and safe form of urbanization, which are the primary objectives of the Kingdom of Jordan's green growth plan. For example, investments in the separation of waste at the stage of its collection and campaigns to change the behavior of the

population, as well as promoting recycling and resource reuse habits foster opportunities for the growth of small and medium-sized enterprises (Zighan *et al.*, 2024). Technological innovation, creating incentives for investment and increasing the efficiency of the use of resources in the processes of consumption and production can reduce the burden on the state budget, while supporting both economic growth and a high level of ecology, which allows nature to facilitate ecological recovery and supports long-term public health.

In light of the above knowledge and research gaps, this study addresses environmental and socio-economic challenges in Jordan, particularly in the area of waste recycling. The country's waste disposal methods remain underdeveloped, which exacerbates environmental degradation and hinders sustainable development. Additionally, the limited collaboration between government bodies and private sector entities in waste management highlights a critical gap in achieving efficient and sustainable recycling practices. The main objectives of the study are defined:

1. Identification of the main goal and ways of green development in Jordan.
2. Description of the main threats of plastic to flora and fauna.
3. Identification of the main threats to Jordan's economic growth.
4. Analysis of ways to reduce poverty and the role of women in this process.
5. Determination of the factors of interaction between state and private initiatives in the field of waste management in the context of poverty reduction.
6. Description of the basics of responsible production through the efficient use of resources.
7. Providing recommendations to the Jordanian government for more efficient waste collection and recycling.

Literature Review

Several articles have been addressed to this subject over the last ten years. Pervez and Ahmade (2013) in their article revealed that the unregulated disposal of waste and pollution from various sources creates significant obstacles to nature conservation, which as a result, worsens the overall condition of the ecosystem, negatively affects the health of the population and interferes with the stable development of the economy and society. The findings of the current study align closely with the results presented in the referenced article, confirming its conclusions, therefore, one of its main issues was the implementation and improvement of the waste disposal management process. MacArthur, Waughray and Stuchtey (2016) found that more than 95% of plastic packaging that enters production and sale ends up as waste, and 32% of that waste in the future, does not enter the municipal waste management system. This problem is especially relevant for Jordan, as the existing waste collection practices in Jordan reflect significant room for improvement.

Beaumont *et al.* (2019) in their article have researched how ingested plastic may affect marine life and they come up with a conclusion that the chemicals contained in plastic can cause generational and population-level impacts on marine life, which travel up the food chain. Since Jordan has two seas, the Red and the Dead, the study of the impact of plastic particles on the pollution of water bodies and the state of marine flora and fauna is relevant for this state, besides, the Red Sea is now an ecological disaster due to the

war with the Yemeni Houthis. GGNAP in their report, Waste Sector (2020), analyzed the role of Jordanian municipalities and the required expenses. This role will be further explored in the current research paper. Danthurebandara *et al.* (2012) described the cost drivers for emissions of harmful greenhouse gases GHGs. It turned out that it is cheaper and safer to introduce systems of control and management of landfills than to overcome the consequences of soil and water pollution with heavy metals and dangerous chemical compounds.

Wilson, Velis and Cheeseman (2006) proposed a solution for waste management – integrating the informal sector into the waste management planning process, building on his practice and experience while working to increase efficiency and improve the living and working conditions of those involved in this process. All this correlates with the fact that many people living in cities depend on waste recycling processes in the context of making a profit from it. Assayed *et al.* (2023) suggest using the concept and tools of the Internet of Things to collect data related to resource-efficient and cleaner production at the industry level, which can help to accurately control the carbon footprint that appears in the production process. Monitoring of emission data is usually carried out with the help of sensors that can estimate the number of harmful substances in the air or on the ground, based on which the level of pollution is then analyzed and measures are developed to neutralize the danger. Zighan *et al.* (2024) focused on the role of international food retailers in Jordan in implementing 4 specific dimensions of sustainable supply chains (responsible packaging, reduction, redistribution and recycling) and the impact of this implementation on food security in Jordan. All of these aspects of supply chains reduce the negative impact on the environment, as responsible packaging requires the retailer to use the most environmentally friendly packaging possible, and recycling will reduce the volume of landfills required and provide Jordan with cheap and clean energy.

Al-Bawwat *et al.* (2023) in their scientific paper considered two options for using residues, namely thermal treatment and their conversion into biogas. Based on this, they evaluated the inclusion of biomass processing in the Jordanian energy network. Jordan's need for cheap and clean energy is critical, as the population of this country feels a lack of it. Therefore, this research is extremely important, as it shows new ways of obtaining electricity, which, in addition, will allow to disposal of a significant part of waste. The article by Abu-Qdais, Shatnawi and Al-Shahrabi (2023) contains a set of recommendations for more municipalities in Jordan, the main of which is the need to create an effective mechanism for collecting solid waste for further processing, rather than using the practice of increasing electricity bills. The effect of the recommendations given in this scientific article is difficult to overestimate since the constant increase in electricity tariffs only increases poverty, which, in turn, prevents the building of a developed society that lives in harmony and provokes discontent among the poorest sections of Jordanian society. Aldayyat *et al.* (2019) determined that one of the main negative factors of insufficient waste recycling is the lack of awareness of refugees from Syria about waste management. Their research allowed us to capture another component of insufficient waste recycling, namely the lack of effective information for refugees. Hajar *et al.* (2020) assessed the sustainability of the solid waste management sector in Jordan using the Sustainability Window tool. This allowed us to identify examples of the use of modern technologies for the specifics of solid waste management in Jordan.

Thorne (2021) examined a skills development program in northern Jordan that significantly contributed to the well-being and personal development of the women involved. This scientific work allowed us to identify the importance of involving women in economic processes in Jordan. Al-Sharif, Geldermans and Rinke (2024) investigated the practicality of concrete recycling in the context of construction waste management in a cyclical economy in Jordan. This study allowed us to determine the relevance of construction waste recycling in Jordan.

Methodology

It is necessary to present the methodology for selecting literature on the chosen topic for analysis. The main criterion for selecting literature was its relevance (not older than twenty years) and diversity (works by different groups of researchers). The search was carried out using the search engines Google and Google Scholar (a specialized system for searching for scientific publications). Among the search keywords and phrases, the following were used: “waste”, “pollution”, “chemicals”, “ecological disaster”, “greenhouse gases”, “waste management”, “carbon footprint”, “food supply”, “use of residues”, “refugees”, and “women's development”. After forming the methodology for literature selection, it was decided to proceed to the analysis of the selected literature. In the course of this analysis, it will be shown what it gave for writing the current article.

In the course of the research, thematic literature, monographs, scientific-analytical publications of foreign scientists on the studied issues, and the results of independent observations were used. The selection criteria for all sources are the same as those used for the literature analysis in the previous section. All research methods were selected by the created algorithm, which first collects information; identifies the central key concepts; identifies the stages and factors of the object's development; performs calculations and draws intermediate and general conclusions. For ethical reasons, interviews with Jordanian residents and refugees were not used among the methods used to collect information. All information was obtained by analyzing existing literature. A number of the following general scientific methods were used following Pyvovarov and Chepur (2020) to solve the research tasks:

1. Monitoring technique: used to gather, organize, and evaluate data on resource efficiency, social development, poverty alleviation, and environmental sustainability;
2. Method of abstraction: used in the course of the study to highlight the main concepts and categories;
3. Methods of analysis and synthesis: used in the process of identifying the stages and factors of development, as well as the most influential elements of the researched object;
4. Abstract-logical and dialectical methods of scientific knowledge, as well as the method of scientific abstraction, were used in the research to form theoretical generalizations, clarify the conceptual apparatus, and formulate conclusions;
5. Method of quantitative data processing: allowed to express in numerical values different aspects of the investigated issues.

Such groups of special methods were used to solve individual research tasks, such as information collection methods; information processing methods; methods of analytical work; and justification methods.

Results

Enhancing natural capital for green development in Jordan

The first goal of Jordan's green development is to increase the country's natural capital, which the government of this country can help with various solutions. This strategy is aimed at permanently improving the quality of natural resources used for economic growth through their processing and production and providing ecosystem services that support the activities of Jordan's economic sectors.

Natural capital is defined as the “stock of natural assets, including geology, soil, air, water, and all living things” (NSW Environment and Heritage, 2024). These natural capitals are typically used to drive economic growth in the countries that own them by stimulating business through their use in production and supporting livelihoods. They are also used to manage ecosystem services, such as providing people with clean water and good quality soil and air, which undoubtedly have high economic value.

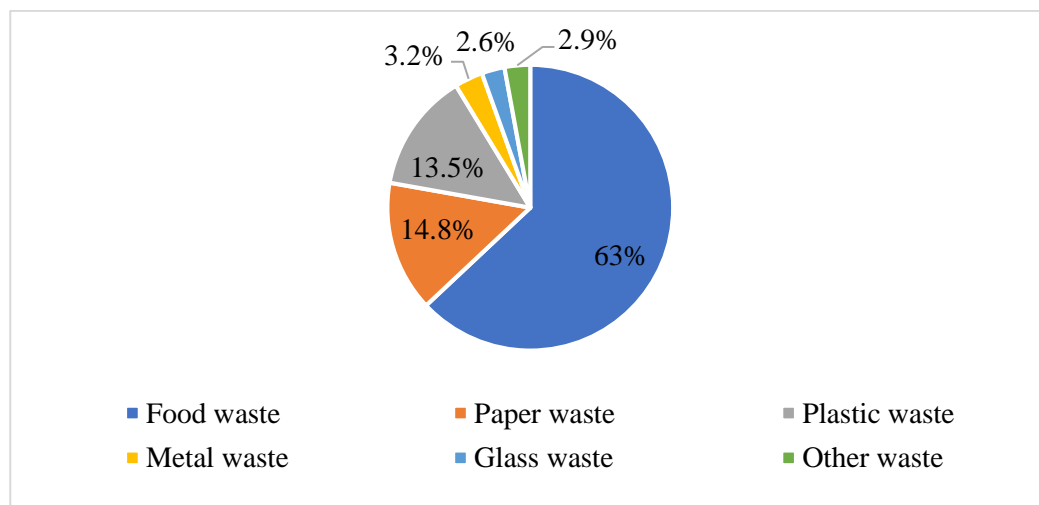


Figure 1: Percentage distribution of waste generated in the capital of Jordan by its origin (Awad, 2024)

Uncontrolled dumping of waste or pollution from industrial, commercial, agricultural and residential sources creates significant obstacles to the conservation of natural capital. Improper handling of household and production waste can lead to the leakage of toxic, corrosive, reactive or other dangerous substances into the soil and water bodies, which will make them unsuitable for further use (Alam and Ahmade, 2013). Untreated hazardous materials, such as industrial or medical waste, can lead to the release of heavy metals (such as zinc or lead) and toxic chemicals into the air, soil, surface or groundwater, affecting the health of newborns and causing numerous plant diseases and fauna. After all, pollution worsens the health of the ecosystem as a whole, negatively

affects the health of the entire country's population and their livelihoods, and also prevents the economy from developing stably. The country's ecological system is also impacted by the refugee crisis due to pollution, deforestation, soil erosion, and increased water use. Population growth affects the amount of water consumed. When it comes to water resources, Jordan is the fourth-poorest country on earth. The distribution of waste generated in the capital of Jordan by type is shown in figure 1.

Although the percentage of waste generated in the Jordanian capital cannot be extrapolated to all of Jordan, analyzing figure 1, we found the following patterns:

1. Among the waste, food waste prevails, which means a potentially large presence of organic matter in the waste structure. This determines the high prospects for processing waste into biogas.
2. The next type of waste, by the largest share in the total amount, is paper waste. This highlights the potential for waste processing as an income-generating opportunity for marginalized populations, particularly through the collection and recycling of paper waste.
3. Notably, plastic waste represents the third-largest share of total waste. While recyclable, it poses significant dangers to both flora and fauna.
4. The share of metal waste is insignificant, it can also become a way of earning money for the poorest segments of the population, but is also dangerous in terms of soil contamination with heavy metals.

The kingdom is experiencing a greater shortage of water as a result of the refugee crisis, and there is a discernible gap between the amount of water that is needed and what is available. According to Jordan's Ministry of Planning and International Cooperation, 70% of Jordanians and refugees do not have access to enough water per day to meet the national standard of 100 liters per person. This assessment was made in connection with the migratory issue. Due to poverty, population increase, and the country's declining economic standing as a result of the refugee crisis, Jordanians are being compelled to exploit their natural resources, which has resulted in illegal logging to make up for the country's high fuel and oil prices. The problem of solid waste management in Jordan is aggravated by the presence of a large number of Syrian refugees, reaching 600,000 people, 80% of whom have settled in municipal jurisdictions (Aldayyat *et al.*, 2019). It is evident that following a sizable refugee inflow, there has been a rise in environmental infractions (Salameh, 2023). One of the projects to preserve Jordan's natural capital is the project to save the Dead Sea, for the implementation of which the governments of Jordan and Israel signed an agreement to replenish the Dead Sea with water from the Red Sea - a canal will be laid through which 300 m³ of water will enter the reservoir annually (Statista, 2018).

Waste can have long-term environmental and societal impacts, even in communities located far from disposal sites. Also, it can have long-term effects on the environment and people. 95% of plastic packaging that enters the economy is thought to be thrown away as waste, with 32% of this rubbish evading municipal waste collection (MacArthur, Waughray and Stuchtey, 2016). The annual amount of plastic garbage poured into the world's oceans is approximately 8 million tons when combined with waste from fishing and ocean-based leisure. Marine animals may become entangled in these polymers or suffer other serious harm. Marine life, which consumes marine plastics and associated

chemicals to move up the food chain, can be negatively impacted by ingested plastics and the chemicals they carry at the generational and population levels. It is predicted that the annual cost of the multi-level effects of plastics' deterioration of ecosystems is USD 2.5 trillion (Beaumont *et al.*, 2019).

Municipalities are in charge of paying for all waste collection expenses as well as, on occasion, the costs associated with disposal locations, such as small landfills and waste separation facilities. It can divert attention from thinking about the indirect costs by straining already scarce financial resources to pay for these expenses. Solid waste (SW) collection, separation, transportation, storage, and treatment are extensive processes. Depending on the particular situation, the environmental costs of waste management can be challenging to estimate and might differ significantly (European Commission, 2024). Emissions of harmful greenhouse gases (such as methane and carbon dioxide) and pollution from landfill leachate are important cost drivers (Danthurebandara *et al.*, 2012). Similar to plastic in the ocean, leachate continuously seeps into soil and water in the absence of effective sanitation procedures. Substances like metals or other chemical compounds linger in the ecosystem, affecting plants as well as the health of animals and humans who come in touch with these dangerous compounds. Leachate pollution cleanup from landfills is a far more time-consuming and costly procedure than sanitary control upgrades for landfills that are already operational.

Sustainable economic growth through effective waste management

The second objective of the national green growth plan of the Kingdom of Jordan is defined as the process of ensuring sustainable economic growth. Effective management of the waste management sector is an important factor in ensuring sustainable economic growth in Jordan. A predictable consequence of economic growth is an increase in the total amount of household and industrial waste, which makes their collection and disposal an increasingly difficult process (Kaza *et al.*, 2018). For sustainable management of this situation, improved technical skills, involvement and use of innovations, a high level of social awareness and a change in the behavior of the population are required. However, many developing countries struggle with both the technical and financial burden of waste management, which accounts for as much as 20 to 50% of municipal budgets worldwide (Aleluia and Ferrao, 2017).

To understand the importance of the relationship between sustainable economic growth and waste processing, it is worth remembering that Jordan generates more than 12,000 kilotons of waste and residues every year, of which approximately 42% can be used as a source of biogas, which will overcome Jordan's energy dependence (Al-Bawwat *et al.*, 2023). The effectiveness of the waste sector and incentive structures are equally important and for these incentives to be implemented the dialogue between the public and civil society is required.

To achieve sustainability, active engagement of the private sector is essential, leveraging its financial resources, including investments and revenue-generation capabilities, to support and drive sustainable initiatives effectively. The government can shift the obligation of managing post-consumer waste to the producers and generate the required income through the introduction of Extended Producer obligation (EPR) initiatives. The

EPR principle states that producers (developers and manufacturers included) must minimize the environmental effects of their work and account for the expenses of the product's end-of-life (or its packaging) (Ministry of Local Administration, 2014). EPR initiatives work to improve waste avoidance, reduction, reuse, recycling, and recovery to carry out the «polluter pays» principle. Innovation may result from this process, improving the capacity to use garbage as a resource and divert it from landfills (European Commission, 2024).

EPR schemes may help businesses to reevaluate their business models, and future business perspectives, extend the product life cycle, and provide packaging buyback programs. These could be achieved by efficient waste management via R&D plans in the waste sector. Moreover, the government can invest in capacity-building programs and encourage medium-sized enterprises (SMEs) to improve waste recovery systems.

Lack of qualified management of waste disposal systems can lead to negative economic consequences in the long term. It has been proven that there are significant indirect costs associated with poor solid waste management which often leads to fatal externalities such as disease and increased human mortality, water and soil pollution, damage to municipal drainage systems and high greenhouse gas emissions. A further effect of poor solid waste management is a low quality of life for the local population, high recovery costs and low numbers of visitors to the country (for tourism or business), the spread of crime and terrorism (Office of the Federal Chief Sustainability Officer, 2020b). Mechanical biological treatment plants are an alternative to sustainable solid waste management (Hajar *et al.*, 2020). It was found that the average cost of processing solid waste in a modelled plant in Jordan over 30 years would be about US\$39 per ton (Thabit, Nassour and Nelles, 2020).

Discussion

Social development, gender equality, and poverty reduction

Social development and poverty reduction is a third national green growth objective and the main part of Jordan's long-term development plan. This objective is a predominant element of green growth inclusiveness. To achieve this, the government is focusing on poverty reduction by reducing inequality in society such as women's empowerment and gender equality, which are the critical part of economic growth. According to a 2015 McKinsey study, women only contribute 37% of the GDP, However, closing this gender gap could significantly boost the global economy, with potential gains estimated between USD 12 and USD 28 trillion (McKinsey Global Institute, 2015). Given that women only contribute 18% of GDP to the Middle East and North Africa (MENA) area, there is a clear potential for economic growth through increased female participation. Unfortunately, women in Jordan, as well as in other countries of the Global South, often do not have the opportunity to participate in the formal labor market (Thorne, 2021). However, a recent positive signal emerged in the first quarter of 2024, when the female labor force participation rate reached 15.5%, the highest level since the third quarter of 2018 (World Bank Group, 2024). Since 2021, the employment rate among refugees in camps has also decreased. Household responsibilities are preventing many women from finding employment. And, the refugees living in camps who do find jobs are much more

vulnerable to workplace hazards and abuses. The reduction in employment opportunities has contributed to rising poverty levels in Jordanian refugee camps (Figure 2).

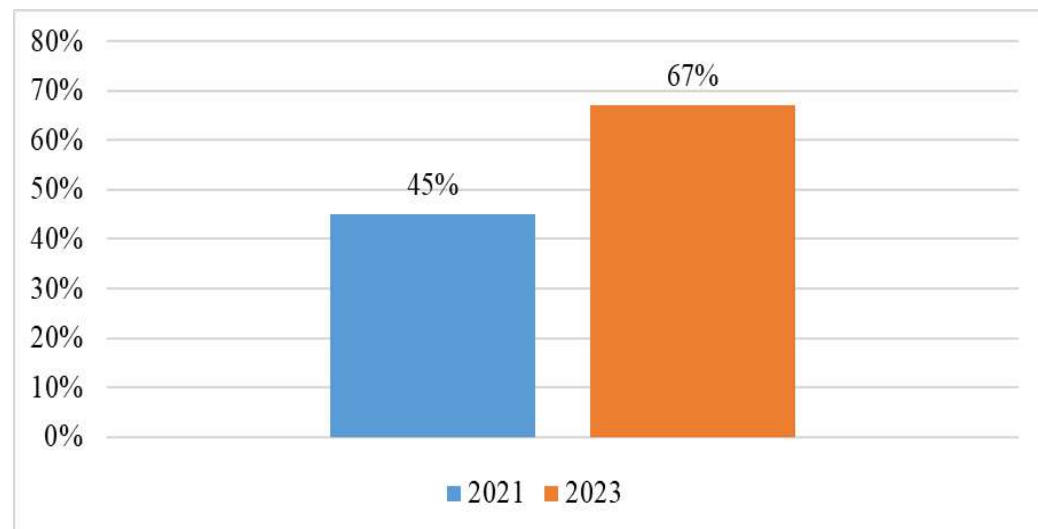


Figure 2: Percentage of poor in refugee camps in 2021 and 2023 (Anera, 2024)

Analyzing figure 2, we found an increase in the poverty level of refugees living in Jordanian camps by 22 per cent, which is a serious concern, as it may cause an increase in the criminal background and the emergence of social unrest. Although the number of Syrian refugees may tend to decrease due to the end of the civil war in Syria, as a result of the overthrow of the Bashar Assad government, to reduce the poverty level of refugees, it is necessary to provide them with effective tools for earning money, one of which may be waste collection and subsequent recycling.

Waste management as a driver of sustainable growth

Gender parity and the recognition of the impoverished and marginalized as proactive agents of change towards more sustainable growth are prerequisites for green growth (European Commission, 2024). With almost 40 million workers worldwide, the trash industry contributes significantly to social development, poverty alleviation, and livelihood ((Antonis and Costas, 2015). Research suggests that around 15 million people, or 1% of the urban population in developing nations, make their living by picking up waste (Taher, Abu Safe and Perrin 2021).

Jordanians who want to become waste pickers, if given the right job opportunities, can turn their profession into a means of poverty reduction by collecting recyclable and recyclable waste as raw materials for the production of new products, thereby reducing the need for imported secondary raw materials, which will allow to save on materials for production and provide the inhabitants of the Kingdom with affordable and simple work (Wilson, Velis and Cheeseman, 2006).

In developing nations, waste picking gives many impoverished people a means of subsistence, but it also contributes to a high degree of informality in all facets of the waste system and instability due to shifting market values for recovered commodities.

Further impediments to achieving economies of scale include restricted transportation options and storage capacity for collected garbage. Informal waste pickers have the potential to decrease the time and resources that the government needs to allocate towards the collection, transportation, and handling of solid waste (SW). They can also prolong the lifespan of SW management facilities and prevent recyclable materials from ending up in landfills (European Commission, 2024).

Municipalities play a key role in leveraging community-driven waste management, they are obligated to consult communities and spread awareness. Unfortunately, all municipalities in Jordan suffer from low reimbursement, where at best it reaches 50% (Abu-Qdais, Shatnawi and Al-Shahrabi, 2023). The Jordanian government can introduce new waste management schemes based on the gender roles of women and men in Jordan. The main areas of activity within these strategies will be the purchase and sale of household waste, the reuse and recycling of solid waste, as well as the maintenance of cleanliness on the streets (Kasimba, Choguya and Muqayi, 2023). International food retailers also play an important role in ensuring social development and poverty reduction in Jordan, as they help achieve food security by implementing sustainable supply chains that include waste recycling (Zighan *et al.*, 2024).

The shift toward a more formal and transparent system for waste collection, processing, and material recovery offers the Jordanian government and businesses socio-economic opportunities. This transition can help maintain landfill infrastructure, provide livelihoods for many poor and marginalized workers, and create decent, well-paying jobs for all residents. The work of extracting material from the waste stream improves the processes of cyclical resources, at the same time, increasing social sustainability. Only government support for occupational health and safety in the waste disposal sector, the ability of its structures to involve Jordanian local communities in investment and political decision-making, as well as the opportunity to organize waste and material disposal markets can also cultivate successful private sector enterprises, and throughout the world, including Jordan, contribute to the main goal of the waste disposal sector – achieving inclusive green growth (European Commission, 2024).

The solid waste management initiatives undertaken by municipalities, MOLA, and MoEnv are the primary focus of the waste management industry in the Kingdom of Jordan, which is overseen by multiple public bodies. Priorities for promoting sustainable management of municipal solid waste, construction and demolition (C&D) waste, electrical and electronic waste (e-waste), and other waste streams are included in the action plan. Other important types of waste, such as wastewater (addressed in the water sector action plan), manure and compost (addressed in the agriculture sector action plan), as well as various measures related to the efficient use of resources (in the hospitality sector in the Plan actions in the tourism sector), are in other sectoral action plans (European Commission, 2024). Jordan can achieve its fourth national green growth goal through responsible production and consumption, improving resource efficiency. Resource efficiency can be achieved by two elements: producing the same economic output with lower environmental inputs and lower levels of pollution, and reducing the levels of pollution associated with or embedded in consumption.

Sustainable consumption and production means producing more goods of better quality with lower production costs. It is also about separating permanent economic growth and environmental degradation, increasing the efficiency of natural resource use and promoting sustainable lifestyles. Resource-efficient and clean production is a practical example of breaking the link between permanent economic growth and environmental degradation and, thus, contributes to the transition to zero emissions (Assayed *et al.*, 2023).

Sustainable consumption and production can also become key factors in poverty reduction and the transition to a low-carbon and green economy (UNESCAP, 2016). Achieving responsible consumption and production may require the cooperation of producers, the government, retailers and an active part of society.

Conclusion

Social development and poverty reduction are the main goals of Jordan's long-term development plan. This goal is an important element of inclusive green growth. To achieve these goals, the Jordanian government must focus on reducing poverty by reducing inequality in society, such as women's empowerment and gender equality, which are critical factors in the economic growth of any modern state. Thus, the process of collecting and recycling waste can be a driver for poverty reduction and many innovations, as recyclable waste can be used as a resource for product manufacturers and reduce their need for imported secondary raw materials. The Jordanian government is recommended to coordinate consumption and production waste reduction processes by providing reliable infrastructure and working with the private sector to develop regulations that can prevent the use of harmful materials in production processes. Such cooperation should be of a permanent and contractual nature, which will allow business representatives to participate in Jordan's development processes as equal partners of the government, whose opinions will be taken into account when making important decisions. In addition, public awareness campaigns about the importance of recycling and sustainable practices can play a significant role in changing consumer behavior. Educating the public about the environmental and economic benefits of recycling can lead to greater community involvement and support for government initiatives. Schools, media, and community organizations can be powerful allies in spreading this message and encouraging a culture of sustainability. By integrating these efforts, Jordan can make significant strides toward its goals of social development and poverty reduction, while also protecting the environment for future generations.

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Author's Contributions (in accordance with ICMJE criteria for authorship)

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Striving for Sustainable Development of Ukraine: Guest Editorial

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Abstract

The special issue on the Sustainable Development of Ukraine aims to study the multidimensional nature of ensuring Ukraine's sustainable development and develop practical recommendations for overcoming challenges by integrating scientific achievements, technological innovations, and management strategies. The objectives of the special issue are to study the role and analyse the prospects for the introduction of innovative technologies and digitalization in ensuring the sustainability of the Ukrainian economy; to analyze the regulatory framework and political mechanisms aimed at shaping a sustainable development strategy in Ukraine; to study environmental approaches and analyse the state and key stages of the implementation of the circular economy; to identify social aspects and develop practical solutions for priority areas of social impact, in particular, education, emotional intelligence and social inclusion.

The rapid expansion of industry and the ongoing exploitation of natural resources to meet humanity's growing needs have highlighted the urgent need for a qualitative shift in the international order. This new approach should focus on transforming the global ecosystem into a framework where humanity and the environment coexist harmoniously, ensuring that human priorities do not compromise the preservation, renewal, and sustainable use of limited natural resources. Consequently, environmental protection has become a critical issue not only in the political arena but also as an existential challenge intertwined with regional and national interests, ultimately carrying significant global implications. Sustainable development represents a balanced interaction between society and nature, safeguarding the survival of humanity while preserving the environment. It aims to meet the needs of the present generation without jeopardizing the ability of future generations to meet their own needs. This principle now underpins policymaking in the United States, Canada, Japan, the European Union, and numerous other countries, including those in the developing world.

The sustainable development paradigm emerged in response to widespread environmental degradation and the urgent need to address global threats to ecosystems and human health at the close of the 20th century. In modern Ukraine, the implementation of this paradigm is influenced not only by global environmental and social challenges but also by the profound consequences of the full-scale invasion by the Russian Federation in early 2022. Since the drafting of the initial *Law on the Concept of Sustainable Development of Ukraine* (No. 3234, dated April 25, 2001), numerous efforts and extensive consultations have sought to define key priorities for sustainable development, establish a national framework, create a legal basis for transitioning to sustainable development principles, and develop relevant indicators. However, the first comprehensive document outlining Ukraine's strategic approach to long-term development was the *Decree of the President of Ukraine* "On the Strategy of Sustainable Development 'Ukraine - 2020'" (No. 5/2015, January 12, 2015), followed by the *Decree of the President of Ukraine* "On the Sustainable Development Goals of Ukraine for the

Period up to 2030” (No. 722/2019, September 30, 2019). Despite these efforts, a lack of an effective state regulatory model persists—one that integrates economic growth, social equity, and sustainable use of natural resources. This gap is highlighted in subsection 2.1 of Section 2 of the ISES Analytical Report, *Analysis of State Strategic Documents on the Adaptation to Global Challenges*. Additionally, ongoing scientific discourse and international experience underscore the absence of universal approaches and tools for achieving sustainable development. This further emphasizes the need for continued research and the development of innovative strategies to refine and implement the sustainable development paradigm, both in Ukraine and globally.

The special issue on the Sustainable Development of Ukraine aims to study the multidimensional nature of ensuring Ukraine's sustainable development and develop practical recommendations for overcoming challenges by integrating scientific achievements, technological innovations, and management strategies. The objectives of the special issue are to study the role and analyse the prospects for the introduction of innovative technologies and digitalization in ensuring the sustainability of the Ukrainian economy; to analyze the regulatory framework and political mechanisms aimed at shaping a sustainable development strategy in Ukraine; to study environmental approaches and analyse the state and key stages of the implementation of the circular economy; to identify social aspects and develop practical solutions for priority areas of social impact, in particular, education, emotional intelligence and social inclusion.

The relevance of the special issue is to identify strategic directions for achieving sustainable development in Ukraine in the face of the extraordinary challenges of our time. The beginning of Russia's full-scale invasion of Ukraine has led to several significant negative factors, including a decrease in the level of security for the population, destruction of infrastructure, loss of human resources, and the performance of business entities in a changing business environment. The foremost opportunity for a rapid and high-quality recovery of the business sector is the implementation of sustainable development measures. Ukraine's sustainable economic development in the context of the war and the subsequent post-war period is primarily determined by the availability of the country's internal resources and the ability of government agencies to influence the cohesion of society, effectively apply financial and economic levers to regulate development, timely identify threats and ensure the implementation of changes to prevent or mitigate their negative consequences. Therefore, the articles presented in the special issue cover various aspects of sustainable development, which allow us to systematize challenges, identify key priorities and ensure a comprehensive approach to their solution.

The legal aspect of the article on the topic "Using Renewable Energy for Sustainable Economic Growth and Environmental Sustainability" indicates the need to eliminate the consequences of climate change by strengthening the legislative support for the implementation of renewable energy. In this context, the authors identify a clear and effective legal framework as a prerequisite for improving the stability of the energy sector, along with balanced public policy and investment attractiveness. The article "Regulatory and Institutional Frameworks for Ensuring Financial Security in Ukraine's Energy Sector: Challenges and Future Outlook" examines the regulatory and institutional aspects necessary to ensure Ukraine's energy security. It also emphasizes

Ukraine's integration into the European Energy Space for infrastructure modernization and financial security in the energy sector. The article on the topic "Policy and Legal Framework for the Formation of Effective Sustainable Development Management Strategies in a Geographical Context" assesses the policy and legal mechanisms for activating green technologies and sustainable development. Based on the article's results, the authors propose ways to eliminate inequality in access to resources and global crises by involving the public in achieving the Sustainable Development Goals. In the document "The Role of the Circular Economy in Promoting Environmentally Sustainable Industrial Production", the authors propose solutions to strengthen the regulatory policy of resource efficiency and sustainable development to eliminate the shortcomings of the current legislative framework in Ukraine. The article "Social Integration in Stimulating Sustainable Development of United Territorial Communities" examines solutions for strengthening joint governance in united territorial communities. The article "Legal Protection of the Environment in Wartime: Theoretical and Practical Analysis" analyses mechanisms for compensation for damage caused by military actions and recommendations for post-war environmental policy, including compliance with EU standards on environmental safety.

The economic aspect is traced in the paper "Assessing the Impact of Green Taxation Policies on Sustainable Growth", which assesses the impact of environmental taxation policies on sustainable economic practices. The authors of this article emphasize the ability of the leading EU companies to boost investments in renewable energy and environmental taxes to promote sustainability in the context of globalization and the aggravation of environmental problems. The study "Agricultural Technologies as a Tool for Integrating Artificial Intelligence into the Agricultural Infrastructure of Ukraine" considers IoT, robotics and precision farming as key drivers of economic growth and environmental balance. The article's authors contribute to the scientific debate on resource efficiency and the economy's global competitiveness through agricultural technologies. Another innovation is artificial intelligence, which is analyzed in the article "Artificial Intelligence in Waste Management in the Context of Implementing Circular Economy". The authors of this article argue that the current state of the processing industry in Ukraine is unsatisfactory. However, reducing waste incineration and operating expenses makes it possible to achieve rapid growth in this sector, thus advancing the national waste management strategy. The paper "The Role of Innovation Parks in Stimulating Digital Achievements and Promoting Energy Efficiency" examines the role of innovation parks in providing a platform for implementing such innovations. In addition to fostering innovation, it is important to mitigate risks related to climate change and adapt business processes to its impacts, as highlighted in the article "Developing strategies for adapting business processes to climate change: minimizing risks in the context of global climate challenges". The article focuses on issues of flexibility and planning and outlines the main strategies that contribute to the coherence of corporate operations with current environmental uncertainty. Therefore, the authors argue that risk reduction initiatives' resource potential and investment planning should be assessed to ensure business resilience. The article "Ensuring Sustainable Development of the Agricultural Sector through Financial Instruments in the Context of Climate Change" demonstrates the effectiveness of financial instruments in increasing the resilience of the agricultural sector to climate change and promoting the productivity of companies. The authors of the article "Ukraine's Role in Ensuring Global Food

Security: Current Challenges and Prospects" examined Ukraine's experience as a key global food supplier in the context of the need to increase the productivity of the agricultural sector and resilience to geopolitical challenges.

The environmental aspect is evident in the study "Review of Innovative Approaches to Sustainable Use of Ukraine's Natural Resources". The article analyses Ukraine's energy sector, emphasizing the role of renewable sources in decarbonization and ecosystem preservation during post-war reconstruction. However, in another article, "Development of Renewable Energy Sources: Impact on Sustainability and the Environment", the authors focused on the benefits of renewable energy in solving global energy problems. The article "Advancing Waste Reduction and Resource Conservation through Circular Economy Practices: A Rational Review" aims to study the circular economy regarding waste minimization and conservation of natural resources.

The social aspect is also considered in several papers in this issue. The article "Leveraging Media and Public Relations Strategies to Advance Sustainable Development: Approaches, Frameworks, Tactics in Modern Conditions" examines innovative methods of communication, the dynamics of trust in the media, and the characteristics of the formation of environmental awareness and corporate responsibility. The article "The Role of Communication in Developing Environmental Awareness and Concern for Environmental Problems" demonstrates the potential of communication to increase public awareness of environmental problems. The research found that digital platforms possess a distinct advantage over traditional media, making them more effective in promoting environmental consciousness. The findings of the work "Typological Model of How Civil Servants Develop Emotional Intelligence in Ukraine" offer recommendations for improving emotional resilience and decision-making by civil servants. The article "Pedagogical Approaches to Educating Environmental Awareness of Students of Higher Educational Institutions" discusses environmental awareness. It aims to convey the values of sustainable development to students and prepare them for the professional role of environmentally conscious citizens.

The special issue highlights the challenges confronting Ukraine's sustainable development, which is currently mired in a prolonged armed conflict. This issue presents research on social components, economic instability, legal assistance, and environmental awareness. The findings presented in this special issue aim to provide novel prospects for implementing novel technologies, enhance the legal framework, and enhance public support for sustainable development. The authors present systemic resolutions for resolving and adapting contemporary issues in the specialized issue. This special issue of GJNR offers various scientific strategies and valuable suggestions for boosting public awareness, bolstering the legal framework, and implementing fresh concepts. This issue contributes significantly to the scientific discourse aimed at ensuring the sustainable functioning of Ukraine during times of war and its postwar recovery and ensuring the quality of the Sustainable Development Goals.

- Prof. Dr. Zoriana Buryk
Guest Editor for Special Issue

Legal Protection of Environment in Conditions of War: Theoretical and Practical Analysis

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Abstract

The paper investigates the issues of international legal regulation of environmental protection and ensuring environmental security during armed conflict. It is substantiated that environmental protection during armed conflict should be based not only on the application to the environment of the rules for the protection of civilian objects but also on the recognition of the need to ensure special protection of the environment as such. An important point of the research is the search for a legal mechanism for the proper provision of compensation for damage caused to the environment, the calculation of the amount of damage and an effective procedure for such compensation. The article outlines the main problems, results, and prospects of the newest legal mechanism being formed in Ukraine to ensure compensation for the damage caused to the environment by Russia's military actions. In this article, attention is paid to the following key issues: types and features of the activities of subjects (state authorities and civil society organisations) in ensuring compensation for damage to the environment; problems of collecting, analysing, recording, and verifying evidence of damage caused; regulatory mechanisms for determining the amount of compensation for damage; problems of achieving real compensation for damage. The study also defines the prospects of Ukraine's post-war environmental policy from the perspective of ensuring environmental security. For this purpose, the provisions of the Law of Ukraine "On Environmental Protection" were analysed on the matter of guaranteeing environmental security in wartime. It is concluded that the post-war restoration of the Ukrainian environment should be multifunctional because, in addition to eliminating the consequences of military actions, it should also meet the new standards of the European community.

Keywords

Armed conflict; Right to the natural environment; Damage to the environment; Compensation for damage; Environmental security

Introduction

History has many examples of armed aggression, the consequences of which are catastrophic for the environment. Modern military technologies (use of chemical, biological, and other weapons of mass destruction) make this threat even more serious than ever before, leading to long-term recovery and in some cases irreversible environmental consequences. The scale of environmental damage (usually, it results in transboundary pollution) and hidden environmental threats (pollution of water bodies, degradation of forests, extinction of certain species of flora and fauna in the future) emphasises the need to study national and international problems of legal regulation of environmental protection and ensuring environmental security during armed conflict. It is especially important during the full-scale war between Russia and Ukraine.

The environment is the biggest casualty as a consequence of the Russian war imposed on Ukraine. Mass destruction of the industrial and civil infrastructure, chemical and air pollution, radioactive pollution, ammunition, and missiles caused fires, forest and agriculture damage, wildlife and biodiversity loss, and contamination of waters and soil will make Ukrainian lands uninhabitable during and after the war (Khrushch *et al.*, 2023).

The purpose of this publication is an integrated analysis of issues related to environmental protection in wartime, starting with the study of the fundamental principles of international law, which regulates the issue of environmental protection during armed conflicts, exploring the problems of adequate compensation for damage caused to the environment during the war, calculating the number of losses and finding an effective procedure for such compensation. As a result, we propose further main priorities of post-war environmental restoration of Ukraine and directions of key environmental reforms.

Such a multi-faceted analysis will contribute to a comprehensive understanding of environmental problems and the scale of the consequences of the war not only for Ukraine and will serve to determine further steps in establishing an effective mechanism for preventive environmental protection and compensation for damage caused by the formation of a coherent state policy, cooperation at the international level, and the creation of an effective system of environmental monitoring and means of environmental restoration.

The following methods are the methodological basis of the research: *historical legal* – was used in the study of the environment as an object of legal protection in wartime; *comparative law* – helped in the search for effective mechanisms to hold Russia accountable for environmental damage; *systemic structural* – was used in the study of problems of compensation for environmental damage caused by Russia to Ukraine as a result of the war; *formal legal* – helped to determine the priorities of post-war environmental policy of Ukraine. The application of these methods made it possible to reach the aim of the study.

The Environment as an Object of Legal Protection in Wartime

Environmental protection during armed aggression is a rather complex issue caused primarily by a lack of specific legal regulation of this issue in wartime.

First of all, this issue is regulated by at least two branches of international law – international environmental law and international humanitarian law (the law of armed conflict). International environmental law is a relatively young branch of law. Nevertheless, given the urgency of the protection of the environment as a possibility for the further existence of humanity, environmental law quickly gained its significance, and its principle of sustainable development became universal law, fundamental for the harmonious and balanced development of all spheres of social life. The World Charter for Nature, approved by the UN General Assembly on 28 October 1982, proclaims the general principles of nature conservation, according to which any human activity related to nature should be guided and judged, and cl. 5 defines the principle of protecting nature from degradation caused by warfare or other hostile activities.¹ The Stockholm Declaration of 1972 contains the provision that humanity and the environment should be freed from the use of nuclear and other types of weapons of mass destruction (principle 26).² The Rio Declaration of 1992, in principle 24, declares that war inevitably has a destructive effect on the process of sustainable development, and therefore states must respect international law by ensuring environmental protection in the event of armed conflict. Principle 25 of the Rio Declaration emphasises that peace, development, and environmental protection are interdependent and inseparable.³ Agenda 21 stresses the need to consider the issue of compliance with the norms of international law of measures to prevent large-scale destruction of the environment during armed conflict.⁴

The norms of international environmental law are predominantly preventive in nature and provide for the protection and preservation of the natural environment, but they do not define a mechanism for environmental protection during armed conflict. The only two exceptions that directly define the principles of environmental protection in wartime are, firstly, the UN Convention on the Law of the Non-navigational Uses of International Watercourses of 1997, which in Art. 29 establishes that ‘international watercourses and related installations, facilities and other works shall enjoy the protection accorded by the principles and rules of international law applicable in international and non-international armed conflict’;⁵ secondly, the UNESCO

¹ World Charter for Nature. (1982). Available online at:

<https://digitallibrary.un.org/record/39295?ln=en&v=pdf> (accessed on 14 August 2024).

² Declaration on the Human Environment (1972). Available online at:

<https://wedocs.unep.org/bitstream/handle/20.500.11822/29567/ELGP1StockD.pdf> (accessed on 14 August 2024).

³ The Rio Declaration on Environment and Development (1992). Available online at:

https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_CONF.151_26_Vol.I_Declaration.pdf (accessed on 14 August 2024).

⁴ Agenda 21. United Nations Conference on Environment and Development Rio de Janeiro (1992).

Available online at: <https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf> (accessed on 14 August 2024).

⁵ Convention on the Law of the Non-navigational Uses of International Watercourses (1997). Available online at: https://legal.un.org/ilc/texts/instruments/english/conventions/8_3_1997.pdf (accessed on 14 August 2024).

Convention on the Protection of the World Cultural and Natural Heritage of 1972, which in Art. 11(4) provides for the creation of a List of World Heritage in Danger while identifying among the threats the danger of armed conflict.⁶

It can thus be concluded that international environmental law is not adapted to wartime, and it is understandable and quite logical because military goals and the goals of environmental protection are mutually exclusive. International environmental law is peacetime law and does not provide for environmental protection mechanisms during armed conflict.

Therefore, international humanitarian law (IHL) is applicable – the branch of law that is applied during armed conflict. Furthermore, during armed conflict, in the event of contradictions between the norms of IHL and the norms of other branches of international law, the norms of IHL will prevail (Medvedeva *et al.*, 2016).

The environment under IHL includes the natural environment, civilian objects and objects indispensable to the survival of the civilian population. The core principles of IHL that may be considered to have a bearing on environmental protection include – distinction, proportionality, precaution, military necessity and humanity (Akpoghome and Worluh-Okolie, 2024).

International humanitarian law aims primarily to protect victims of armed conflict and to regulate the conduct of hostilities. This reflects the need to establish a regulatory framework to mitigate the inevitable consequences inflicted on people, property and the environment during times of war (Kovalenko *et al.*, 2024).

Despite the long history of the formation of this field, the norms related to environmental protection during armed conflict began to be formed not so long ago, and today they cannot adequately respond to environmental threats. In international humanitarian law, there are several international treaties whose provisions are directly or indirectly aimed at protecting the environment during armed conflict. A certain degree of environmental protection during armed conflict is provided by the 1972 Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxic Weapons and on their Destruction (Art. 2);⁷ the 1993 Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and their Destruction (Art. 4, 5 and 7);⁸ the 1997 Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of

⁶ Convention concerning the Protection of the World Cultural and Natural Heritage (1972). Available online at: <https://whc.unesco.org/archive/convention-en.pdf> (accessed on 14 August 2024).

⁷ Convention on the Prohibition of the Development, Production and Stockpiling of Bacteriological (Biological) and Toxic Weapons and on their Destruction (1972). Available online at: https://www.un.org/en/genocideprevention/documents/atrocities-crimes/Doc.37_conv%20biological%20weapons.pdf (accessed on 14 August 2024).

⁸ Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction (1993). Available online at: https://www.un.org/en/genocideprevention/documents/atrocities-crimes/Doc.42_Conv%20Chemical%20weapons.pdf (accessed on 14 August 2024).

Anti-Personnel Mines and their Destruction (Art. 5(4)(c) and 7(1)(f));⁹ the Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons Which May Be Deemed to Be Excessively Injurious or to Have Indiscriminate Effects;¹⁰ etc.

A special act in the field of environmental protection in the event of armed conflict is the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques of 1977 (ENMOD), according to which the participating states undertake not to resort to military or any other hostile use of environmental modification techniques having wide-ranging, long-lasting or severe effects as means of destroying, damaging or harming any other State Party (Art. 1).¹¹

Additional Protocol I to the Geneva Conventions (AP I) relating to the Protection of Victims of International Armed Conflicts of 8 June 1977 contains norms directly aimed at environmental protection during armed conflict (Art. 35 and 55). Accordingly, cl. 3 of Art. 35 prohibits the use of ‘methods or means of warfare which are intended, or may be expected, to cause widespread, long-term and severe damage to the natural environment’. Art. 55 indicates:

1. Care shall be taken in warfare to protect the natural environment against widespread, long-term and severe damage. This protection includes a prohibition of the use of methods or means of warfare which are intended or may be expected to cause such damage to the natural environment and thereby prejudice the health or survival of the population.
2. Attacks against the natural environment by way of reprisals are prohibited.¹²

As can be seen from the above, the provisions of international treaties operate with the evaluation categories such as “widespread, long-lasting, severe damage” and do not regulate in sufficient detail the issue of how the achievement of military goals correlates with damage to the natural environment that will have long-lasting serious consequences of destruction. For understanding and implementing norms, customary international law is useful, which, according to the Statute of the International Court of Justice of the United Nations, is defined as “general practice accepted as law”.¹³

It is generally accepted that a norm in customary international law requires two elements: state practice (*usus*) and the conviction that such practice is mandatory,

⁹ Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti-Personnel Mines and on their Destruction (1997). Available online at: https://www.un.org/en/genocideprevention/documents/atrocity-crimes/Doc.44_convention%20antipersonnel%20mines.pdf (accessed on 14 August 2024).

¹⁰ Convention on Certain Conventional Weapons and its Protocols (1980). Available online at: https://www.icrc.org/en/download/file/166960/dp_consult_8_1980_convention_on_ccw.pdf (accessed on 14 August 2024).

¹¹ Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (1977). Available online at: https://treaties.un.org/doc/Treaties/1978/10/19781005%2000-39%20AM/Ch_XXVI_01p.pdf (accessed on 14 August 2024).

¹² Protocol Additional to the Geneva Conventions of 12 August 1949, and relating to the Protection of Victims of International Armed Conflicts (Protocol I) (1977). Available online at: https://www.un.org/en/genocideprevention/documents/atrocity-crimes/Doc.34_AP-I-EN.pdf (accessed on 14 August 2024).

¹³ Statute of the International Court of Justice. (1945). Available online at: https://legal.un.org/avl/pdf/ha/sicj/icj_statute_e.pdf (accessed on 14 August 2024).

prohibited or permitted, based on the nature of the norm as a matter of law (*opinio juris sive necessitatis*). In the meantime, the norms of international treaties quite often acquire the meaning of customary law, which makes it possible to extend their effect to armed conflict whose parties are not parties to the treaties, e.g., attacking any part of the natural environment if it is not a military objective is based on the general requirement to distinguish between military and civilian objects (the so-called principle of distinction). This principle is directly reflected in Protocol III to the UN Convention on Certain Conventional Weapons stipulating that ‘it is prohibited to make forests or other kinds of plants cover the object of attack by incendiary weapons except when such natural elements are used to cover, conceal or camouflage combatants or other military objectives, or are themselves military objectives’.¹⁴

The UN General Assembly suggested that all states apply this principle, and the practice of states (reflected in official statements, military manuals and court decisions – *authors’ note*) established this rule as a norm of customary international law expanding the boundaries of international treaty law.

This universality of customary international law is also confirmed by the practice of international judicial and quasi-judicial institutions, which are often required to apply customary norms. Therefore, regarding nuclear weapons in 1996, the International Court of Justice of the United Nations recognised that the obligation of states to ensure that activities under their jurisdiction and control respect the environment of other states or territories outside national control is part of customary international law.¹⁵

In a generalised form, customary norms in international humanitarian law were consolidated in the Report of the International Committee of the Red Cross on customary norms of IHL applicable to armed conflicts of an international and non-international nature. Chapter 14 – “The Natural Environment”, which contains three norms, is devoted to direct environmental protection. Rule 43 defines the application of general principles of conducting military operations to the natural environment, including: ‘(a) no part of the natural environment may be attacked unless it is a military objective; (b) destruction of any part of the natural environment is prohibited unless required by imperative military necessity; (c) launching an attack against a military objective which may be expected to cause incidental damage to the environment which would be excessive about the concrete and direct military advantage anticipated is prohibited’.¹⁶

Rule 44 imposes restrictions on the methods and means of warfare and requires the adoption of all feasible precautions during military operations to avoid and, in any event, to minimise incidental damage to the environment. Rule 45 prohibits the use of methods or means of warfare that are intended, or may be expected, to cause widespread, long-term and severe damage to the natural environment.

¹⁴ Ibid, n.10.

¹⁵ Summaries of Judgments, Advisory Opinions and Orders in Legality of the threat or use of nuclear weapons. Available online at: <https://www.icj-cij.org/public/files/case-related/95/7497.pdf> (accessed on 14 August 2024).

¹⁶ International humanitarian law databases. Available online at: <https://ihl-databases.icrc.org/en/customary-ihl/v1> (accessed on 14 August 2024).

Analysis of these norms demonstrates the application of such general principles of customary international law as the principles of: (a) distinction (the natural environment cannot be the direct target in a military objective), (b) necessity (prohibition of actions that cause harm not justified by military necessity and the obligation, whenever possible, to choose the least harmful means of achieving the military objective) and (c) proportionality (the obligation to observe proportionality between the expected military advantage and the incidental damage to the environment). It is these principles of customary law that make it possible to correctly qualify and establish whether the parties in armed conflict violate the contractual norms of IHL. In practice, the application of these international acts indicates the fact that environmental protection is subordinate to the existing laws of war. The Guidelines on the Protection of the Environment in Armed Conflict specify that international environmental law may continue to apply during armed conflicts insofar as it does not conflict with the applicable law of armed conflict.¹⁷ The UN International Court of Justice, in its Advisory Opinion on the Legality of the Threat or Use of Nuclear Weapons, ruled that environmental obligations – in particular, the obligation of states to ensure that activities within their jurisdiction or control do not adversely affect the environment of other states – apply in the context of armed conflict, at least if they do not conflict with military law. The Resolution of the General Assembly emphasised that ‘the destruction of the environment, not justified by military necessity and carried out wantonly, is contrary to the existing international norms’.¹⁸

The study, specially prepared by the United Nations Environment Program (UNEP) on the topic of environmental protection during armed conflict, presents the main errors and gaps in the application of the relevant norms of IHL, e.g.:

- Art. 35 and 55 of Additional Protocol I to the Geneva Conventions do not provide effective protection to the environment during an armed conflict due to the narrow and imprecise threshold level required to prove damage;
- the provisions of IHL, which regulate the means and methods of warfare or provide for the protection of civilian property or objects, provide only indirect protection of the environment; furthermore, these provisions have rarely been applied with the stated purpose;
- most provisions of IHL are designed to protect the environment in the context of international armed conflict and are not necessarily applied in the context of armed conflicts of a non-international nature;
- due to the lack of judicial practice regarding this issue, there is a lack of law enforcement activity in this area;
- there is no permanent international mechanism for monitoring violations and ensuring adequate compensation for environmental damage caused during armed conflict;
- customary principles of distinction, necessity and proportionality are insufficiently effective means of ensuring environmental protection in conditions of armed conflict (Blaha *et al.*, 2016).

¹⁷ Guidelines on protection of natural environment in armed conflict. Available online at: <https://www.icrc.org/en/document/guidelines-protection-natural-environment-armed-conflict-rules-and-recommendations-relating> (accessed on 14 August 2024).

¹⁸ *Ibid.*, n.15.

One example is the recent situation with Russia's blowing up of the Kakhovska Dam (Nazarchuk, 2023). This is the most serious international crime that has caused man-made, ecological, and humanitarian catastrophes of an unprecedented scale since the Second World War. The environmental situation resulting from the destruction of the Kakhovka hydroelectric power station by the occupying forces falls squarely within the concept of the crime of ecocide. This concept exists in the legal framework of Ukraine, Russia, and a dozen other countries. However, international law does not yet recognise the concept of ecocide, does not provide a legal definition of it, and does not provide for the criminal responsibility of subjects of international law for this crime (Malysheva and Hurova, 2024). At the same time analysis of the norms of international humanitarian law demonstrates that dams and power plants have the highest levels of legal protection. Additional Protocol I to the Geneva Conventions (Art. 35) expressly prohibits the use of methods of warfare that cause serious damage to the natural environment. Although the Geneva Conventions stipulate prohibitions, they do not contain a mechanism for the prosecution. The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques contains a specific response plan. According to Art. 5 Ukraine can appeal to the UN Security Council with a complaint against Russia for an investigation. Each State Party can send a request to the UN Secretary General to convene a Consultative Committee of Experts to clarify and assess the situation. Nevertheless, the participation of the UN Security Council is ineffective as long as the Russian Federation has the right to veto.

To summarise, the current international mechanisms for resolving armed conflicts and managing their consequences are insufficient to protect the environment. Even a superficial analysis of the norms of international law demonstrates what principles are used to balance the interests of society in an environment safe for life and health and the military goals of the participants in an armed conflict – military necessity justifies the damage caused to the environment. It should be the other way around: what limitations of military necessity should be applied to achieve an acceptable degree of environmental protection? In other words, environmental damage must be minimised by establishing strict sanctions so that belligerents avoid any use of force that may cause excessive environmental damage. The path to harmonisation will lie in the cooperation between the norms of international environmental law and international humanitarian law and the search for a balance between the environmental policy of society, and the policy of the participants in an armed conflict to achieve the goals of the war. The norms of international humanitarian law should be strengthened by the norms of environmental or eco-humanitarian law.

Environmental protection during armed conflict should be based not only on the application to the environment of the rules for the protection of civilian objects but also on the recognition of the need to ensure special protection of the environment as such. The environment as a silent victim of war needs more effective protection during armed conflict. As noted by W. Verwey, a new approach to regulating legal issues of environmental protection in wartime is needed. The priority should be to make the environment an independent object of legal protection and not to differentiate between issues of environmental protection during martial law and peacetime. This approach will contribute to sustainable development and environmental protection in the face of modern challenges and to the creation of effective norms of international

environmental law that would be effective regardless of political, economic or social circumstances (Verwey, 1995).

The first manifestations of such an approach already exist. In particular, in the already mentioned Advisory Opinion on the Legality of the Threat or Use of Nuclear Weapons, the International Court of Justice of the United Nations stated that environmental law indicates important factors that are to be properly taken into account in the context of the implementation of the principles and rules of the law applicable in armed conflict.¹⁹ In addition, the UN General Assembly Resolution ES-11/5 “Promoting legal protection and providing reparations for aggression against Ukraine” of 14 November 2022 directly provides for compensation for the damage caused to the natural environment of Ukraine.²⁰ Therefore, stipulating the principle of respect for the natural environment during armed conflict in the norms of customary and contractual IHL would contribute to the fact that the environment would be defined not only as an object of the protection of human habitat but also as an independent object of protection during armed conflict.

Problems of Compensation for Environmental Damage Caused by Russia to Ukraine as a Result of the War

As a result of insufficient legal regulation of environmental protection during armed conflict, there is a problem regarding the proper provision of compensation for damage caused to the environment, the calculation of the amount of damage and an effective procedure for such compensation.

Russia’s military aggression against Ukraine causes huge losses every day, associated with both the death of people and the destruction of industrial and social infrastructure. Ongoing hostilities, rocket launches, and thousands of artillery shells lead to irreparable damage not only to the humanitarian and economic spheres but also to the natural environment, the safe condition of which is a necessary condition for normal human activity. Today, it is too early to talk about the real extent of the damage. The current estimates do not objectively cover all cases; they change daily. According to the estimates of the State Environmental Inspectorate of Ukraine, the armed aggression of the Russian Federation led to the following serious environmental consequences: air pollution (explosions and fires in the conflict zone caused emissions of harmful substances, such as nitrogen and sulfur oxides, hurting air quality and public health); water pollution (destruction of infrastructure and pollution by oil and chemicals led to serious pollution of rivers and reservoirs, threatening aquatic ecosystems and provision of drinking water for the local population); soil pollution.²¹

In general, the estimated losses calculated by the State Environmental Inspectorate by the approved methods amount to UAH 2,183 billion; 2,636 cases of damage and losses

¹⁹ Ibid, n.15.

²⁰ Furtherance of remedy and reparation for aggression against Ukraine: resolution adopted by the General Assembly (2022). Available online at: <https://digitallibrary.un.org/record/3994481?ln=en&v=pdf> (accessed on 14 August 2024).

²¹ The latest estimates show new data on the scale of damage caused to the environment. Available online at: <https://www.dei.gov.ua/post/2734> (accessed on 14 August 2024).

as a result of Russian armed aggression were recorded, and 1,478 cases were documented by the employees of the State Environmental Inspectorate of Ukraine.²² As a general rule, damage caused to natural objects and natural systems must be compensated. Under Art. 68 of the Law of Ukraine “On Environmental Protection”, damage caused as a result of violation of the legislation on environmental protection is subject to compensation in full.²³ This definition demonstrates the shortcomings of the national legislation: the definition of damage as a violation of the law does not provide an understanding of the concept of “environmental damage”.

Legal responsibility, which is provided for in the corresponding legislative acts on natural resources, is an important factor for compensation for damage caused to the environment as well as achieving the conditions for ensuring rational nature use, environmental protection and environmental security (Hetman, 2019). In the meantime, the Ukrainian environmental legislation did not stipulate the grounds, procedures and mechanisms for compensation for damage to the environment in a situation of full-scale military operations. Requirements and procedures valid until 24 February 2022, concerned environmental offences related, in particular, to exceeding emission or discharge standards by industrial enterprises; non-compliance by individuals and legal entities with requirements, obligations, prohibitions regarding the protection and use of natural resources, etc. Damage to the environment as a result of hostilities made it necessary to change both the legislation and the legal forms of the economic activity of entities in this area.

Analysis of the amount of damage to the environment, and individual natural objects and, on this basis, holding Russia accountable for the damage caused have become the primary tasks for competent state bodies and civil society as a whole. It is worth quoting the conclusion regarding the understanding of environmental damage, substantiated by M. V. Krasnova in her dissertation study devoted to the problems of compensation for damage under the environmental legislation of Ukraine. Environmental damage is the deterioration of the state of the environment, natural resources and complexes, and other natural objects that do not affect the private interests of individuals in a generally accepted sense. Therefore, in the event of such damage, no person can have a proprietary interest, on which a claim against the offender for compensation of damage would be based since the damage is caused to objects that do not belong to anyone, or to objects that belong to the whole society (Krasnova, 2010). Therefore, the main burden of work related to the collection, recording, and verification of evidence of the damage caused, development of methods, and calculation of compensation amounts is assigned to the Ministry of Environmental Protection and Natural Resources of Ukraine and the State Environmental Inspectorate of Ukraine. No less important is the activity of the Specialised Environmental Prosecutor’s Office and its units on the ground. According to the Regulation on the Specialised Environmental Prosecutor’s Office (under the authority of the Department) of the Prosecutor General’s Office one of the main tasks of this unit is: the administration and procedural oversight of pre-trial investigations, the resolution of

²² Consequences of military actions and impact on the environment. Available online at: <https://ecozagroza.gov.ua/> (accessed on 14 August 2024).

²³ On environmental protection. Law of Ukraine (1991). No. 1264-XII. Available online at: <https://zakon.rada.gov.ua/laws/show/1264-12#Text> (accessed on 14 August 2024).

various legal issues during criminal proceedings, and the maintenance of public accusations in criminal cases related to offences in environmental protection.²⁴

Civil society organisations also do a lot of work – environmental public organisations, international organisations, joint public initiatives that express and defend public ecological interest in a safe natural environment. For instance, the charity organisation “Environment-People-Law” began recording environmental crimes from the first weeks of the war and in July launched a regranting program, as part of which seven organisations were selected on a competitive basis: NGO “Ekosphere”, NGO “Ekosotsium”, NGO “Ukrainian Nature Conservation Group”, NGO “Kherson Regional Department of Sociological Association of Ukraine”, NGO “Merry Dolphin”, NGO “Black Sea/Odesa/Regional Branch of the Ukrainian Environmental Academy of Sciences”, NGO “Institute of Econology”, whose work involves documenting environmental crimes of war, improving methods of assessment of environmental damage, assessment of ecosystem services not received as a result of the war and recording data for the further formation of lawsuits in the international courts demanding compensation for damage to the environment of Ukraine.²⁵

It is valuable and effective to combine the efforts of various entities to develop an evidence base, because the available technical, organisational, and personnel resources of specialised state bodies are clearly insufficient. In March 2022, the Ministry of Environment of Ukraine created a working group on documenting crimes against the environment. It included representatives of public organisations and public environmental initiatives, such as “Ekoaction”, “SaveDnipro” and others (Oberenko, 2022). In the beginning of March 2022, the Operational Headquarters were established at the State Environmental Inspectorate to create a single register of the damage caused to the environment as a result of the invasion of the Russian Federation into the territory of Ukraine.²⁶ The general tasks of the Headquarters are to compile a list of all violations in the field of environmental protection and to hold Russia accountable. It includes experts from the State Environmental Inspectorate, representatives of the Committee of the Verkhovna Rada of Ukraine on Environmental Policy and Nature Management, the Ministry of Environmental Protection and Natural Resources of Ukraine as well as experts – representatives of public environmental organisations and scientific institutions.

What damage caused to the natural environment and its elements is subject to compensation? There are various types of legal responsibility in the field of environmental protection, namely: first, responsibility for violations of legislation in the field of environmental protection and the protection of the environmental rights and interests of individuals; secondly, responsibility for damage caused to the environment and environmental rights and interests by activities not prohibited by international or

²⁴ On the approval of the Regulation on the Specialized environmental prosecutor’s office (under the authority of the Department) of the Prosecutor General’s Office. Order of the Prosecutor General. (2023). No. 185. Available online at: <https://zakon.rada.gov.ua/laws/show/v0185905-23#Text> (accessed on 14 August 2024).

²⁵ The environment as a silent victim of war. Available online at: <http://epl.org.ua/announces/dovkillya-movchazna-zhertva-vijny/> (accessed on 14 August 2024).

²⁶ Operational headquarters at the State Environmental Inspectorate of Ukraine. Available online at: <https://shtab.gov.ua/> (accessed on 14 August 2024).

national law. These types of responsibility in international law are considered as different international legal categories. They are recognised by the UN International Law Commission which developed separate provisions for each type of responsibility. They are also defined differently in international law. In the meantime, international responsibility for breach of duty under the norms of international law is defined by the term “responsibility”, and responsibility for the harmful consequences of illegal actions that caused damage is defined by the term “liability” (Bazov, 2019).

As regards the prospects of consideration of relevant claims in international institutions, it is worth referring to the concept officially defined at the level of the European Union. A comprehensive normative understanding of “environmental damage” is contained in cl. 1, Art. 2 of Directive 2004/35/EU of the European Parliament and the European Council “On environmental liability with regard to the prevention and remedying of environmental damage” of 21 April 2004.²⁷

The concept of “damage” in the same Directive is interpreted as a measurable adverse change in a natural resource or measurable impairment of a natural resource service, which may occur directly or indirectly (cl. 2, Art. 2).

Undoubtedly, the ongoing war significantly complicates the collection and recording of evidence, documenting the cases of the damage caused. The main difficulties of data collection are related to the intensity and large-scale impact of the war, the destruction of monitoring observation points, the lack of a sufficient number of specialists, etc. Since the first days of the war, the Government of Ukraine and non-governmental organisations (NGOs) have introduced several tools for documenting environmental damage. For example, today the “EkoZagroza” monitoring panel works online with daily updated data on the impact of the war on the environment.²⁸ Such information must be properly documented and verified. The collection and recording of evidence must be based on recognised international practices to be considered by international institutions. It is of particular importance to observe the principles of objectivity and independence when forming the evidence base. Experts say that Kuwait (after Iraq’s military aggression) filed 168 environmental lawsuits for a total amount of \$85 billion but received only \$5.26 billion, i.e., 6.19% of the desired amount (Metyk, 2022).

Therefore, of considerable importance is the Resolution of the Verkhovna Rada of Ukraine of 20 September 2022 on the Address of the Verkhovna Rada of Ukraine to the General Assembly of the United Nations, the United Nations Environment Program, the European Parliament, the European Commission, the parliaments and governments of states that are members of the United Nations General Assembly regarding the formation of a special environmental monitoring mission to record environmental damage on the territory of Ukraine.²⁹ A working group was created to

²⁷ Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage // Official Journal of the European Union, 2004, L 143. pp. 56–75. Available online at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02004L0035-20190626> (accessed on 14 August, 2024).

²⁸ Ibid, n.22.

²⁹ On the address of the Verkhovna Rada of Ukraine to the General Assembly of the United Nations, the United Nations Environment Program, the European Parliament, the European Commission, the

develop legal instruments for compensation for damage and losses caused to Ukraine as a result of the military aggression of the Russian Federation, including reparations, confiscation, contributions as well as steps for their implementation with regard to international legal mechanisms, international experience and judicial practice.³⁰

Specific forms, methods, and sources of a destructive impact on the environment in a situation of military operations necessitate a revision of the existing methods of determining the amount of damage caused to natural objects. Current methods do not establish a procedure for calculating damages in emergencies. For instance, by cl. 3 of the Methodology for calculating the amount of compensation for damage caused to the state as a result of above-standard emissions of pollutants into atmospheric air, it is not applied when violations of the legislation on the protection of atmospheric air are committed by business entities as a result of emissions of pollutants from unorganised stationary and mobile sources or related to the influence of physical and biological factors or caused by the irresistible forces of nature or military actions.³¹ In the meantime, from a doctrinal point of view, the general criteria that determine the legal characteristics of liability (compensation for damage), deserve attention: a) changes in the state of the natural environment that can be considered adverse only if they are caused by physical, biological or chemical factors, to which it is possible to apply regulations; b) the severity of the consequences that must be determined against the environmental quality standards defined in the law or technical regulations; c) scope of liability (Krasnova, 2010).

On 29 April 2022, the Cabinet of Ministers of Ukraine amended cl. 2 of the Procedure for determining damage and losses caused to Ukraine as a result of the military aggression of the Russian Federation and supplemented the directions for determining damage and losses with those related to the natural environment.³² Today, a calculation of damage should be made on the basis of the following environmental indicators: losses of the forest fund; subsoil losses; losses of the water area, losses of the natural reserve fund; damage caused to land resources; damage caused to atmospheric air; damage caused to water resources. For each of these indicators, as specified in the Resolution, the corresponding Methodologies have been approved.³³

parliaments and governments of states that are members of the United Nations General Assembly regarding the formation of a special environmental monitoring mission to record environmental damage, caused by the armed aggression of the Russian Federation on the territory of Ukraine. Resolution of the Verkhovna Rada of Ukraine. (2022). No. 2594-IX. Available online at: <https://zakon.rada.gov.ua/laws/show/2594-IX#Text> (accessed on 14 August 2024).

³⁰ On the working group on the development and implementation of international legal mechanisms for compensation for damage caused to Ukraine as a result of the military aggression of the Russian Federation. Decree of the President of Ukraine (2022). No. 346/2022. Available online at: <https://zakon.rada.gov.ua/laws/show/346/2022#Text> (accessed on 14 August 2024).

³¹ On the adoption of the Methodology for calculating the amount of compensation for damage caused to the state as a result of above-standard emissions of pollutants into atmospheric air. Order of the Ministry of Energy (2020). No. 227. Available online at: <https://zakon.rada.gov.ua/laws/show/z0414-20#Text> (accessed on 14 August 2024).

³² On Amendments to clause 2 the Procedure for determining damage and losses caused to Ukraine as a result of the military aggression of the Russian Federation. Resolution of the Cabinet of Ministers of Ukraine (2022). No. 551. Available online at: <https://zakon.rada.gov.ua/laws/show/551-2022-%D0%BF#Text> (accessed on 14 August 2024).

³³ On the adoption of the Methodology for determining the amount of damage caused to land and soil as a result of emergency situations and/or armed aggression and hostilities during martial law. Order of

These Methodologies introduce new concepts, methods and calculations of losses arising as a result of emergencies and/or military aggression and hostilities during martial law. The Methodology for calculating unorganised emissions of polluting substances or a mixture of such substances into atmospheric air as a result of emergencies and/or during the operation of martial law and determining the amount of the damage caused defines a new concept of “unorganised emissions” – emissions that enter atmospheric air in the form of undirected flows of a gas-dust mixture from pollution sources not equipped with special facilities for the removal of gases through gas ducts, pipes, and other facilities.

Nevertheless, to receive reparations, the national methods of calculating damages must correspond to international ones since the process of bringing the aggressor country to justice will be carried out at the international level. Analysts are noticing the fact that the introduced methods do not fully meet international standards. This opinion was expressed by A. Demydenko, a member of the Working Group at the Operational Headquarters of the State Environmental Inspectorate of Ukraine. The basis of the current methodology for atmospheric air is a calculation of the unpaid environmental tax on these emissions. This approach is wrong since this is damage to the budget, not to a natural resource, and compensation is given for damage to the resource (Lystopad, 2023).

the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 167. Available online at: <https://zakon.rada.gov.ua/laws/show/z0406-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for calculating unorganised emissions of polluting substances or mixtures of such substances into atmospheric air as a result of emergency situations and/or during martial law and determining the amount of damage caused. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 175. Available online at: <https://zakon.rada.gov.ua/laws/show/z0433-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for determining damage and losses caused to the land fund of Ukraine as a result of the military aggression of the Russian Federation. Order of the Ministry of Agrarian Policy and Food of Ukraine (2022). No. 295. Available online at: <https://zakon.rada.gov.ua/laws/show/z0586-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for determining the damage caused as a result of water pollution and/or clogging, arbitrary use of water resources. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 252. Available online at: <https://zakon.rada.gov.ua/laws/show/z0900-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for determining damage caused to the natural environment within the territorial sea, exclusive maritime (economic) zone and internal sea waters of Ukraine, in the Azov and Black Seas. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 309. Available online at: <https://zakon.rada.gov.ua/laws/show/z1253-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for determining the damage and losses caused to the natural environment due to arbitrary use of the subsoil as a result of the military aggression of the Russian Federation. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 366. Available online at: <https://zakon.rada.gov.ua/laws/show/z1337-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for determining the damage and losses caused to the forest fund as a result of the military aggression of the Russian Federation. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 414. Available online at: <https://zakon.rada.gov.ua/laws/show/z1308-22#Text> (accessed on 14 August 2024); On the adoption of the Methodology for determining damage and losses caused to the territories and objects of the nature reserve fund as a result of the military aggression of the Russian Federation. Order of the Ministry of Environmental Protection and Natural Resources of Ukraine (2022). No. 424. Available online at: <https://zakon.rada.gov.ua/laws/show/z1416-22#Text> (accessed on 14 August 2024).

The Search for Effective Mechanisms to Hold Russia Accountable for Environmental Damage

The next step in reparations for environmental damage caused by the war is to find effective institutions to decide and implement future reparations.

There is no real possibility of bringing the culprits to justice and receiving compensation for the damage caused to natural objects within the national judicial system. According to experts: the most progressive domestic legislation on the assessment of environmental losses as a result of Russian aggression will not work without implementing appropriate procedures for the seizure of Russian assets, resolving the issue of the removal of immunity from Russian property and the actual recovery of the assets of the Russian Federation and persons directly involved in starting the war against Ukraine (Ripenko, 2022).

International law allows for different forms of paying compensation for damage caused by the military aggression of another state through judicial or quasi-judicial mechanisms, which are usually not mutually exclusive or mutually dependent. The main indicator for choosing one or another compensation mechanism is its effectiveness, i.e., the decision of the court or other competent authority must be implemented and fair compensation received. Currently, there is no universal effective mechanism for real compensation for environmental damage caused by the military aggression against Ukraine.

Let us consider the UN International Court of Justice. According to Art. 92 of the Charter of the United Nations: ‘The International Court of Justice shall be the principal judicial organ of the United Nations. It shall function by the annexed Statute, which is based upon the Statute of the Permanent Court of International Justice and forms an integral part of the present Charter.’³⁴

Scholars confirm the jurisdiction of the UN International Court regarding acts of aggression, in particular, in terms of violating the principle of the non-use of force in interstate relations (Kasyaniuk, 2018). It should also be noted that on 16 March 2022, this Court issued a decision on the request for interim relief in the genocide case *Ukraine v. Russia*, requiring Russia to immediately cease all hostilities in Ukraine and withdraw all military and irregular military forces under its control or influence. However, according to Art. 94 of the UN Charter, the main problem is the lack of enforcement mechanisms.³⁵

As noted by international experts, the Court’s order: Will not have much practical significance for current efforts to gather evidence for use in future prosecutions of war crimes. The Security Council will remain paralysed when it comes to adopting resolutions under Chapter VII of the UN Charter for the foreseeable future (Keitner *et al.*, 2022).

³⁴ Charter of the United Nations (1945). Available online at: <https://www.un.org/en/about-us/un-charter> (accessed on 14 August, 2024).

³⁵ *Ibid*, n.34.

The next body is the International Criminal Court, guided in its activities by an international multilateral treaty – the Rome Statute. Having jurisdiction over the most serious crimes of concern to the entire international community – crimes of genocide, crimes against humanity, war crimes and a crime of aggression, the International Criminal Court can exercise its functions and powers on the territory of any participating state, and, by a special agreement, on the territory of any other state that is not a party to the Rome Statute (Bazov, 2019). Nevertheless, the Rome Statute does not provide for such a crime as ecocide, despite the fact that corresponding proposals have been extensively developed by international experts in recent years.³⁶ Even if the International Criminal Court recognises the damage to the environment as large-scale, long-lasting and severe, ie a war crime within the meaning of Art. 5 of the Rome Statute, will it be possible to award compensation to Ukraine for environmental damage if the ICC considers such a case? According to the practice of the court, compensation for damage is not its main task; however, it is noted that compensation for material and moral damage can be received by victims.

The European Court of Human Rights can be considered ineffective today, because the implementation of the decisions of the European Court of Human Rights against Russia is currently unlikely or almost impossible since the Russian parliament adopted a law on non-implementation of the decisions of the European Court of Human Rights issued after 15 March 2022. In addition, on 16 March 2022, Russia left the Council of Europe, and the possibility of filing a complaint against Russia to the European Court of Human Rights was available until 16 September 2022. Another international quasi-judicial, or rather a political body, is the UN Compensation Commission, whose creation is known regarding compensation by Iraq for the damage caused to Kuwait. It was established under Security Council Resolution 692 (1991) to compensate successful claimants. The commission received a percentage of the revenues from the export sales of Iraqi oil and petroleum products. The United Nations Compensation Commission has awarded \$52.4 billion in compensation to more than 1.5 million successful claimants. The mandate of the Compensation Commission included consideration of claims for direct environmental damage and depletion of natural resources, including damage or expenses for: mitigation and prevention of environmental damage, including expenses for fighting oil fires and cleaning coastal and international waters from oil; adequate measures have already been taken for cleaning and restoration of the environment or future measures that have documentary evidence of their necessity for cleaning and restoration of the environment; adequate monitoring and assessment of damage to the environment to assess and mitigate damage and restoring the environment and others.³⁷ However, the creation of such a body in Ukraine's situation is hardly realistic, considering that the decision is made at the level of the UN Security Council, of which Russia is a member with the right of veto. Therefore, the most important task of the Ukrainian state today is, using the experience of relevant international institutions, to establish a separate specialised

³⁶ Is it time for “ecocide” to become an international crime? Available online at: <https://www.economist.com/international/2021/02/28/is-it-time-for-ecocide-to-become-an-international-crime> (accessed on 14 August, 2024).

³⁷ The UN Compensation Commission – the prospect of financing environmental restoration in Ukraine after the war with the Russian Federation. Available online at: <http://epl.org.ua/wp-content/uploads/2022/05/Kompensatsijna-komisiya-OON.pdf> (accessed on 14 August, 2024).

court based on the Ad Hoc principle as well as a fund to guarantee payments at the expense of, among other things, the confiscated assets of the aggressor state. In our opinion, the only effective mechanism is establishing a special compensation commission that should become the platform for consideration of a wide range of possible claims under international law filed by various groups of injured parties, including states, international organisations, individuals and legal entities.

The working group of Ukraine proposed concluding an international agreement on establishing a compensation mechanism for the damage caused by Russian aggression. It is assumed that strategic partners will be involved in the agreement, on whose territory most of the frozen assets of the Russian Federation are located. Based on the agreement, a permanent commission will be created to consider lawsuits or applications for compensation of losses. In addition, the agreement will stipulate the obligations of the states that are parties to such an agreement regarding the blocking, confiscation and transfer of Russian assets under their jurisdiction to the compensation fund (Mudra, 2022). To withdraw the sovereign assets of the Russian Federation in favour of Ukraine, the partner countries must have legal opportunities. This model of the compensation mechanism raises questions without answers.

A completely different approach was proposed by the Minister of Justice of Ukraine, D. Maliuska. In his opinion, the process of concluding an international agreement with many states can be long and unpredictable. Signing bilateral agreements with countries where Russian assets are located is thought to accelerate this process. Such a preliminary agreement exists with Latvia (Maliuska, 2022). It provides for the seizure of Russian assets in favour of Ukraine based on national legislation, not the creation of a multilateral international mechanism for compensation or an International Claims Commission. Therefore, finding mechanisms and gaining experience in compensating for damage to the environment of our state is a difficult and long-term task (Churylova and Strelnyk, 2022).

There are three problems accompanying any compensation commission that will be created to compensate for the damage to Ukraine, which are common to many reparations programs and which require an urgent solution to effectively compensate for the damage to the environment: institutional capacity (properly defining the jurisdiction of this commission, prescribing a clear procedure for consideration of claims and decision-making), funding (the provision of the commission's activities by a special fund that will be financed from Russian assets and its related legal entities and individuals, which are frozen/removed by states; direct contributions from Russia and other organisations) and timeliness (absence of a lengthy procedure for considering the case, the possibility of implementing decisions at the expense of the special fund).

Ensuring Environmental Security as the Goal of the Post-War Environmental Policy of Ukraine

Even in the conditions of the war, the future main priorities of a comprehensive policy of response to the environmental consequences of the war should be considered. In particular, following the results of the meeting of the International Working Group on

the Environmental Consequences of War,³⁸ the framework document of the International Working Group on the Environmental Consequences of War was adopted (15 September 2023) that stipulates that the main directions of work in overcoming the adverse environmental consequences of war are:

- 1) damage assessment: the government of Ukraine should continue to collect information about the damage on an ongoing basis, involving the Ukrainian society;
- 2) criminal prosecution for committing crimes against the environment: attacks during armed conflict that intentionally cause serious damage to the environment are a clear violation of international humanitarian law and constitute a war crime under the Rome Statute of the International Criminal Court. In Ukrainian legislation actions causing an ecological disaster are specifically defined as ecocide;
- 3) green recovery: while recovering from the devastation caused by the war, Ukraine also has the very difficult task of fully transitioning to a green economy. To date, the independent assessment has identified guiding principles for recovery, but more specificity is needed to implement the best policies and priorities across all environmental and economic sectors.³⁹

A safe state of the environment means that it does not adversely affect human health and the functioning of living organisms and has chemical, physical, biological, and other elements that do not disturb a natural balance between humans and the environment and do not exceed the safety standards established by legislation. In practice, to ensure the right to an environment safe for life and health, it is important to develop clear criteria on the basis of which it would be possible to determine the safety or danger to the environment. The main requirements for the quality of the environment are contained in environmental standards and regulations. Today, such basic criteria in Ukraine are environmental security standards (standards of maximum permissible concentrations of pollutants in the natural environment, maximum permissible levels of harmful physical and biological effects on it). Exceeding these standards will be a violation of the right to a safe environment (Kobetska, 2008).

However, the understanding and meaning of environmental security is much broader and is not limited to interpreting it as the right to the natural environment that is safe for life and health.

The concept of environmental security is multifaceted, and even within the framework of the Law of Ukraine “On Environmental Protection” scholars interpret it in several ways: 1) as the intention to ensure the environmental security of human activities (Part 1 of the Preamble to the Law); 2) as a component of the state’s environmental policy aimed at preserving the environment safe for the existence of living and non-living

³⁸ Ruslan Strilets took part in the second meeting of the International working group on the environmental consequences of the war. Available online at: <https://mepr.gov.ua/ruslan-strilets-vzyav-uchast-u-drugomu-zasidanni-mizhnarodnoyi-robochoyi-grupy-shhodo-ekologichnyh-naslidkiv-vijny/> (accessed on 14 August, 2024).

³⁹ Framework document: High-level working group on environmental consequences of war. Available online at: https://www.president.gov.ua/storage/j-files-storage/01/20/45/e763357d648c04ac25db118120df330d_1694848461.pdf (accessed on 14 August, 2024).

nature, protecting the life and health of the population from the adverse impact caused by environmental pollution (Part 2 of the Preamble to the Law); 3) as one of the tasks of the legislation on environmental protection (Art. 1 of the Law); 4) as the main principle of environmental protection (cl. a and b of Art. 3 of the Law); 5) as a subjective environmental right of citizens (cl. a, Art. 9 of the Law); 6) as a duty of citizens in the field of environmental protection (cl. b of Art. 12 of the Law); 7) as the goal of management in the field of environmental protection (part 5, p. 16 of the Law); 8) as a separate area of environmental protection activity (Chapter XI of the Law) (Krasnova, 2019).

By Part 1 of Art. 50 of the Law, environmental security should be understood as a state of the natural environment that prevents the deterioration of the ecological situation and the occurrence of danger to people's health. Environmental security is guaranteed to the citizens of Ukraine by implementing a wide range of interconnected political, economic, technical, organisational, and other measures (Part 2, Art. 50 of the Law). Analysis of Chapter XI "Measures to ensure environmental security" of the Law demonstrates that this system of measures also includes compliance with environmental security requirements for military and defence facilities, and military activities, as stated in Art. 58 of the Law. Under Part 2 of Art. 58 of the Law, environmental security requirements must also be observed during the deployment of military units, military exercises, manoeuvres, movement of troops and military equipment, except for special situations declared in accordance with the legislation of Ukraine. This exception constitutes the conditions for waging a full-scale war on the territory of the state. After all, in the realities of martial law, when the priority goals are the defence of the country, and the preservation of the lives of citizens and their property, compliance with the requirements of environmental security becomes an extremely difficult task. In this case, the environment turns into a silent victim of military operations, as the state of natural objects and their resources deteriorates significantly. This, in turn, not only adversely affects the ecosystem but can also cause danger to the health and lives of people.

In 2014, with the signing of the Association Agreement, Ukraine announced its European integration intentions, and in June 2022, received the status of a candidate for EU membership.⁴⁰ In 2019, the European Union adopted the so-called "green" approach in its policy and activities, which, as stipulated by the European Green Deal, aims to achieve climate neutrality on the European continent by 2050. Several new EU strategies were revised and developed to fulfil the tasks of the European Green Deal.⁴¹ Accordingly, Ukraine's gradual implementation of the goals of the European Green Agreement and all derivative documents is an inevitable task. Therefore, the post-war restoration of the Ukrainian environment should be multifunctional, because, in

⁴⁰ Association Agreement between the European Union and the European Atomic Energy Community and their Member States, of the one part, and Ukraine, of the other part // Official Journal of the European Union, 2014, L 161. pp. 3–2137. Available online at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02014A0529%2801%29-20231201> (accessed on 14 August, 2024).

⁴¹ The European Green Deal. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. (2019). COM/2019/640 final. Available online at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN> (accessed on 14 August, 2024).

addition to eliminating the consequences of military actions, it should also meet the new standards of the European community. In July 2022, on the website of the Cabinet of Ministers of Ukraine, the National Council for the Recovery of Ukraine from the Consequences of the War published the Draft Plan for the Recovery of Ukraine.⁴² According to the Project, the strategic goal of the post-war reconstruction is a clean and safe environment: the integration of climate goals into all sectors of the economy and social life; minimisation of environmental security risks (chemical and radiation security); reduction and prevention of industrial pollution and introduction of the “polluter pays” principle; effective waste management; balanced use of natural resources and ensuring their proper quality; restoration and development of nature conservation areas, preservation of biodiversity, expanding the area of natural ecosystems and balancing of landscapes; achieving European standards of public administration in the field of environmental protection.

To achieve these goals, it is necessary to implement key reforms: an integrated climate policy; environmental security (chemical and radiation); reform of industrial pollution regulation; effective waste management; balanced use of natural resources; management of nature conservation areas to preserve landscape and biological diversity; effective state management in the field of environmental protection; environmental control and legal responsibility; comprehensive environmental monitoring.

Conclusion

The environment, as a silent victim of war, needs more effective protection during armed conflict, as well as the development of powerful international mechanisms for determining and compensating for damage caused by the consequences of war. Environmental protection should not only apply the rules for civilian objects but also recognize the need for special protection of the environment as such. Introducing the principle of respect for the natural environment into the norms of customary and contractual IHL would redefine the environment as not only part of human habitat protection but as an independent object requiring protection during armed conflict. The path to harmonisation will lie in rapprochement and cooperation between the norms of international environmental law and international humanitarian law, and the search for a balance between the environmental policy of society and the policy of the participants in armed conflict in achieving the goals of the war.

An important issue of the research is the search for a legal mechanism for the proper provision of compensation for damage caused to the environment, a calculation of the amount of damage, and an effective procedure for such compensation. The article outlines the main problems, results and prospects of the newest mechanism being formed in Ukraine to ensure compensation for the damage caused to the environment by Russia’s military actions.

In the process of the research attention is focused on the following key issues:

⁴² Project of the recovery plan of Ukraine. Materials of the working group “Environmental security”. Available online at: <https://www.kmu.gov.ua/storage/app/sites/1/recoveryrada/ua/environmental-safety-assembly.pdf> (accessed on 14 August, 2024).

- Types and features of the activity of subjects (state authorities and civil society organisations) in ensuring compensation for the damage to the environment caused by military actions.
- Problems of collection, analysis, recording and verification of evidence of the damage caused. The importance of ensuring objective and independent formation of the evidence base and the involvement of representatives of foreign states and international organisations in this process is emphasised.
- Normative mechanisms for determining the amount of compensation for damage. The latest legal prescriptions regulating directions and types of compensation are indicated.
- Prospects and problems of achieving real compensation for damage. A list of international judicial and quasi-judicial bodies that can extend their competence to consider such categories of cases and problematic aspects of the involvement of each of them are identified. The need to create a separate specialised court based on the Ad Hoc principle.

This study also defines the prospects of Ukraine's post-war environmental policy from the perspective of ensuring environmental security. For this purpose, the definition of a safe environment and the concept of environmental security are analysed as well as the provisions of the Law of Ukraine "On Environmental Protection" on the subject of guaranteeing environmental security in wartime. It is concluded that Ukraine's gradual implementation of the goals of the European Green Agreement and all derivative documents is an inevitable task. Therefore, the post-war restoration of the Ukrainian environment should address both the consequences of military actions and the new European standards. The goals of the post-war restoration of Ukraine's environment and the directions of key environmental reforms are determined.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>
Conceived and designed the research or analysis	No	No	Yes
Collected the data	Yes	Yes	Yes
Contributed to data analysis & interpretation	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes
Critical revision of the article/paper	No	No	Yes
Editing of the article/paper	No	Yes	No
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Agricultural Technologies as a Tool for Integrating Artificial Intelligence into the Agricultural Infrastructure of Ukraine

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Abstract

This study evaluates the potential of artificial intelligence (AI) and agritech solutions to drive sustainable development in Ukraine's agricultural sector during the post-war recovery period. Emphasizing high-potential technologies such as IoT-enabled precision farming and robotics, the research highlights their technical and commercial viability, as well as investment opportunities, in alignment with global trends. By employing systems analysis, formalization, and logical abstraction, the study identifies innovative solutions to enhance resource efficiency, minimize environmental impact, and promote economic growth. Key findings reveal that agritech serves as a critical enabler for rebuilding Ukraine's agricultural infrastructure, creating a post-war model that balances economic and environmental priorities. Strengthening the integration of AI and advanced technologies will enhance the efficiency and productivity of farms, bolster Ukraine's global competitiveness, and deliver positive social outcomes, including fostering digital adoption in rural communities. These insights provide a roadmap for leveraging agritech to align with sustainable development goals while addressing local challenges.

Keywords

Sustainable development; Innovative technologies; Agridrones; Smart farming; Automation

Introduction

The global climate crisis, population growth, and food security challenges demand modern and innovative management approaches. Globally, efforts are being made to develop and implement environmentally friendly technologies and products. In

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today's agricultural landscape, the agrotechnology industry has become a key driver of sustainable development and a crucial factor in the economic growth of agricultural production (Shabatura, Nikoliuk and Gryshova, 2020). Digital technologies and AI are increasingly integrated into agribusiness, supporting agricultural production strategies, complementing traditional business models, and contributing to the evolution of production chains and value-creation processes. AI technologies are already widely used in agriculture, facilitating automation through machines and mechanisms equipped with GPS navigation and other advanced smart technologies, digitalization, and an ecologically balanced approach to farm management. The agricultural technology sector offers innovative solutions that redefine traditional farming methods, including process digitalization and farm automation. The agri-industrial sector is set to become an even more essential component of the global economy, as it will need to meet the demands of a population projected to reach 9.7 billion by 2050 (Neto, Brewer and Gray, 2023). This sector is poised to reduce costs, optimize time and resource use, and enhance crop yields and livestock quality. Simultaneously, the gradual transformation of the global agro-industrial sector and the adoption of new technologies are expected to increase global agricultural production by 69% from 2010 to 2050 (European Commission, n.d.).

There is an ongoing and lively discussion within the scientific community about the specific aspects of digital transformation in global agriculture. Klerkx, Jakku and Labarthe (2019) highlighted several key themes in the socio-scientific literature on agricultural digitalization. These include the adoption, use, and adaptation of digital technologies on farms; the influence of digitalization on farmers' identities, skillsets, and work processes; concerns surrounding power dynamics, ownership, privacy, and ethical considerations in digitalized agricultural production and value chains; the role of digitalization within Agricultural Knowledge and Innovation Systems (AKIS); and the economic and managerial dimensions of digital systems in agricultural production and value chains. The authors emphasize that managing the digital transformation of agriculture should carefully consider social factors and work to minimize potential negative impacts. Although studies emphasize the need for social aspects of the introduction of digital technologies, there is insufficient information on how exactly to adapt global technological solutions to the local conditions of Ukraine, especially in the context of post-war reconstruction.

Ingram *et al.* (2022) argue that digital agriculture policies require a broader evidence base. Khaustova *et al.* (2021) highlight issues within state policy on technology transfer in the agribusiness sector, particularly in the context of its legal support. Tielkiniena *et al.* (2020) emphasize the advancement of agricultural lobbying at the legislative level, enabling a more responsive approach to global market dynamics. MacPherson *et al.* (2022) examine high-level policy and legislation in Germany and Europe, identifying the key institutional, social, and legal prerequisites for implementing digital agriculture, which supports various sustainable development goals. They propose specific measures, such as financial support, training, and advisory services, to help small farmers overcome barriers to implementing these initiatives effectively.

In their study, Garske, Bau and Ekardt (2021) present a somewhat contrasting perspective to that of MacPherson *et al.* (2022). They argue that digital innovation and artificial intelligence can significantly contribute to the sustainable advancement of

agriculture and the achievement of climate and environmental goals. Garske, Bau and Ekardt (2021) highlight that precision farming technologies can reduce nutrient surpluses and water pollution, while digital technologies can monitor emissions and support environmental protection efforts. Additionally, MacPherson *et al.* (2022) examine digital transformation processes that facilitate the transition to renewable energy sources. Garske, Bau and Ekardt (2021) emphasize that key prerequisites for agricultural digitalization include the advancement of power grids, data transmission infrastructure, and public investment. Although studies consider the potential of digital innovations for the sustainable advancement of agriculture, they do not take into account the specifics of the economic challenges of the post-war period.

The study by Neto, Brewer and Gray (2023) on data collection and usage across the agricultural supply chain reveals significant heterogeneity in data collection and analysis practices. Increased customer satisfaction and improved decision-making were identified as the primary benefits of data utilization. However, the anticipated benefits and challenges of implementing these efforts vary, with companies at the initial stages of the supply chain often differing in their views on the perceived advantages and obstacles. Ehlers *et al.* (2022) suggest that digitalization scenarios in the agricultural infrastructure should incorporate diverse perspectives, particularly focusing on transparency, data management, efficiency, workflow automation, privacy, and control. The authors highlight the need to consider uncertainties and the variety of long-term policy strategies, as well as to define the roles of governments, agribusinesses, non-governmental organizations, and other stakeholders in shaping effective strategies. They conclude that successful digitalization in agriculture requires accessible digital infrastructure, flexible strategies, and the integration of responsible research and innovation into agricultural policy. The digitalization processes in the agricultural infrastructure vary significantly based on the specific circumstances and context of each country. Countries may be Internet of Things (IoT) in various phases of development and show varying levels of efficiency based on available resources, infrastructure, and technological maturity.

In Ukraine, the potential for digitalization in the agricultural infrastructure is expanding even during wartime, as highlighted in scientific studies focused on rapid agricultural innovations and the use of artificial intelligence (Balian *et al.*, 2023). Agriculture in Ukraine is increasingly adopting "smart" characteristics, driven by the strong motivation of domestic farmers for post-war recovery and restoration of land resources, particularly in heavily impacted areas. These studies provide valuable insights into the opportunities and challenges of Ukraine's agricultural digital transformation and help identify strategic directions for further development. The purpose of this study was to establish agricultural technologies as key enablers of AI in Ukraine's agricultural sector. Consequently, this research highlights the potential of AI to support the sustainable development of Ukraine's agricultural industry in the post-war period.

According to research by ICL Group (2024), modern agrotechnologies play a key role in enhancing the efficiency and sustainability of agriculture. The primary technologies highlighted in this study include precision agriculture, the Internet of Things (IoT), artificial intelligence and machine learning, robotics and automation (e.g., the use of robots to perform various agricultural tasks, from sowing to harvesting), vertical farming, and biotechnology. These technologies have significant potential for

application in the post-war reconstruction of Ukraine's agricultural sector. For example, precision agriculture and IoT can help optimize resource use on restored agricultural lands, while robotics can mitigate labour shortages in rural areas. The ICL Group study emphasizes that implementing these technologies requires not only technical knowledge but also changes in farm management approaches and farmer training. This aligns with Klerkx, Jakku and Labarthe (2019), who highlighted the importance of social factors in adopting digital technologies in agriculture.

This research aims to analyze the potential and prospects of integrating artificial intelligence technologies into Ukraine's agricultural sector, specifically to: Identify the key areas of application for AI technologies in agriculture. Assess the impact of implementing innovative technologies on the efficiency and productivity of agricultural production in Ukraine. Explore current trends in the advancement of the Internet of Things (IoT) and other AI solutions in the global agricultural infrastructure and their relevance to Ukraine. Identify opportunities, obstacles, and challenges on the path to digital transformation of Ukrainian agriculture. Develop recommendations for the effective integration of artificial intelligence technologies into Ukraine's agricultural sector, taking into account local specifics.

Materials and Methods

This study was conducted as a comprehensive analytical review focused on examining the role of agrotechnologies as tools for integrating artificial intelligence (AI) into Ukraine's agricultural sector. It was based on secondary data analysis and the application of various analytical methods. The selection of methods was adapted to the multifaceted nature of the research problem, prioritizing approaches that ensure a holistic and detailed understanding. This study was conducted as a comprehensive analytical review to explore the role of agricultural technologies as tools for integrating artificial intelligence (AI) into Ukraine's agricultural sector. A combination of qualitative and analytical approaches was employed to address the multifaceted nature of the research problem, ensuring both a holistic and detailed understanding of the subject matter.

To examine the interconnections among various components of agricultural technology implementation, a systems analysis approach was adopted. This method allowed for the identification of systemic links between technology adoption and its impact on productivity, sustainability, and economic outcomes. Frameworks such as SWOT were utilized to evaluate the strengths, weaknesses, opportunities, and threats associated with AI-driven agricultural innovations. The holistic perspective offered by systems analysis was critical for understanding the complex dynamics of technology integration in the context of post-war reconstruction.

Formalization was another key methodological tool, used to systematically structure and categorize data. This approach provided a clear representation of the current state and future potential of agricultural technologies in Ukraine. The use of formalization ensured that the analysis remained focused and precise, allowing the study to distill actionable insights from a diverse range of data sources. To generalize trends and conceptualize key aspects of Ukraine's agricultural development, abstract analysis was employed. This method facilitated the identification of patterns critical for the successful implementation

of agricultural technologies. Complementing this, logical analysis was used to establish connections between technological adoption and environmental sustainability, supporting the study's argument regarding the role of agricultural technologies as drivers of AI integration and post-war agricultural recovery. These methods were chosen for their ability to effectively interpret secondary data while addressing the complexity of the problem.

The study relied heavily on secondary data sources, including reports from Data Bridge and Mordor Intelligence, as well as statistical data from the Ministry of Agrarian Policy and Food of Ukraine. Reports by Data Bridge and Mordor Intelligence provided valuable insights into global market trends and technological advancements, known for their rigour and relevance. These reports were critically evaluated to mitigate potential biases and ensure their applicability to the Ukrainian agricultural context. Statistical data from the Ministry encompassed key indicators such as production volumes, cultivated areas, and labour productivity, which were essential for assessing the current state of the sector. These data were collected and processed using standardized international methodologies, ensuring reliability and relevance. However, it is important to acknowledge that the exclusive use of secondary data may limit the study's originality and depth. Commercial reports and industry forecasts, while valuable, may carry inherent biases due to their market-oriented perspectives. Although efforts were made to critically assess these sources and cross-reference findings with other datasets, the absence of primary data collection restricts the ability to directly validate conclusions. Incorporating primary data, such as interviews, surveys, or field studies, in future research would provide richer insights and strengthen the empirical foundation of the analysis. To assess the investment potential and integration opportunities for agricultural technologies in Ukraine, the study applied a systematic evaluation framework. Key indicators such as market size, growth projections, and adoption rates were analyzed to determine the feasibility and attractiveness of agritech investments. The analysis incorporated comparative benchmarking, where Ukraine's performance was measured against leading agritech markets, and scenario analysis to project the long-term impact of integrating advanced technologies. These methods provided a structured evaluation of both the economic viability and scalability of innovations, addressing specific challenges such as labour shortages and resource optimization.

By integrating these approaches and acknowledging the study's limitations, the research ensured a comprehensive yet transparent analysis of how agricultural technologies can drive sustainable development and economic recovery in Ukraine. This methodology provided a robust foundation for understanding the interplay between technology and sustainability, while also offering actionable insights to guide future strategies.

Results and Discussion

Overview of Modern Agricultural Technologies

One of the key areas of modern agricultural technology is precision farming, which implements the Internet of Things (IoT), computer vision, and artificial intelligence (AI). Technologies such as drones and robots are actively used to automate agricultural processes, reducing the need for physical labour. For example, the global IoT market in

agriculture, according to Data Bridge Market Research (2024), reached \$6.95 billion in 2023 and is projected to grow to \$22.45 billion by 2031 (Figure 1).

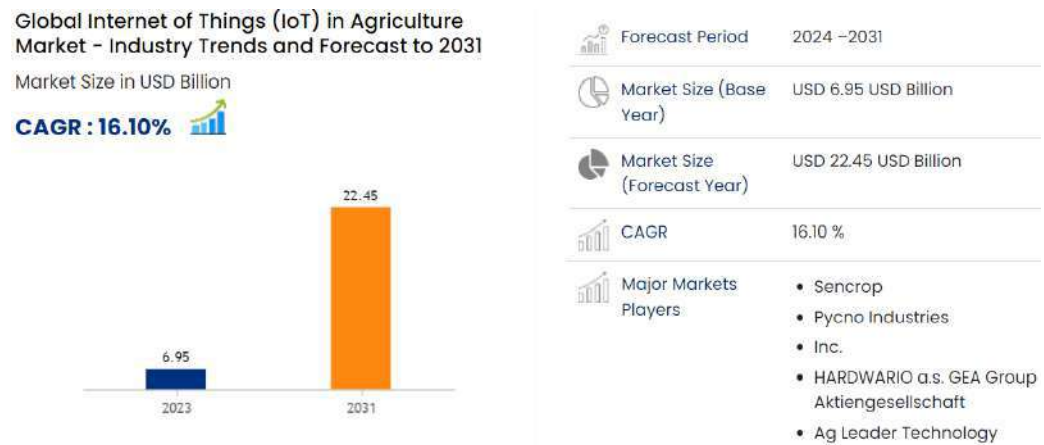


Figure 1: Global Internet of Things (IoT) Trends and Forecast in the Agriculture Market to 2031

This forecast highlights the growing interest in IoT technologies; however, the report primarily focuses on global market trends, which may only be partially relevant for Ukraine due to its specific context. The implementation of these technologies in Ukraine requires adaptation to local conditions, including limited infrastructure and a lack of financial resources for farmers. The report "Global IoT in Agriculture Market – Industry Trends and Forecast to 2031"¹ states that IoT enables precise monitoring of soil and crop conditions, optimizes resource usage, and automates processes. For Ukraine, this holds particular value in restoring agricultural lands damaged during the war. However, the report does not account for the challenges related to the low technological readiness of farmers in post-conflict regions, which may hinder the adoption of even proven solutions.

Introduction of Agricultural Technologies in Ukraine

The introduction of IoT sensors in Ukrainian farms could reduce water and fertilizer usage by 20–30% and increase yields by 15–20% (Shabaturova, Nikoliuk and Gryshova, 2020). However, as Garske, Bau and Ekardt (2021) point out, the high costs of installing and maintaining IoT infrastructure remain a significant barrier, especially for smallholder farms. According to forecasts, the AI market in the agricultural sector is expected to grow from \$1.7 billion in 2023 to \$4.7 billion by 2028, with a compound annual growth rate (CAGR) of 22.5% (AI in Agriculture Market Size).² While these figures demonstrate the potential of AI for global agriculture, they do not account for Ukraine's local challenges, such as the lack of infrastructure and skilled specialists. Companies like Microsoft Corporation and Prospera Technologies Ltd. are investing in partnerships and innovations to secure competitive advantages. For Ukraine, this

¹ Global Internet of Things (IoT) in Agriculture Market – Industry Trends and Forecast to 2031. (2024). Available online at: <https://shorturl.at/gnDD6> [Accessed on 23 October 2024].

² AI in Agriculture Market Size & Share Analysis - Growth Trends & Forecasts (2024 - 2029) (2024). Available online at: Source: <https://www.mordorintelligence.com/industry-reports/ai-in-agriculture-market> [Accessed on 23 October 2024].

presents an opportunity to attract foreign investments, but only if global solutions are adapted to local needs. For example, AI can be effectively used to monitor soil conditions in regions that have undergone significant anthropogenic impact, particularly due to military actions.

This underscores the potential for leveraging advanced technologies to address both environmental and economic challenges. Global examples, such as the use of drones for crop monitoring by John Deere, show a 25% reduction in field treatment costs and a 20% increase in efficiency. In Ukraine, a similar approach is being applied by "Astra-Kyiv," which introduced drones for crop monitoring in 2023, enabling timely detection of diseases and optimization of field treatment costs. However, as noted by Neto, Brewer and Gray (2023), the effectiveness of technology implementation depends not only on its technical feasibility but also on social and economic conditions, such as access to financing and farmer training. Ukraine faces the challenge of a low level of farmer readiness for digital transformations, which may hinder the pace of AI and IoT adoption.

Economic Impact of Agricultural Technologies

The agricultural technology sector has several advantages, including increased efficiency and productivity, water conservation, cost reduction, improved safety, and enhanced sustainability. It is important to note the following growth factors: labour shortages, high labour costs, advancements in artificial intelligence and the Internet of Things, limited supply, and global dependence on advanced technologies. In this direction sources such as Data Bridge Market Research (2024) and Agriteka (2023) highlight the key benefits of agricultural technologies, including increased efficiency, resource savings, and cost reduction. However, many of these reports have a global focus and may insufficiently address the specific market conditions of countries like Ukraine. For instance, while the integration of IoT is noted to enhance water conservation and resource management, its implementation in Ukraine may be constrained by the limited availability of infrastructure and the high cost of equipment.

Despite these challenges, there are agricultural enterprises in Ukraine actively adopting IoT technologies, computer vision, and artificial intelligence (AI) to improve efficiency and automate processes. Notable examples include agricultural holdings such as "Ukrlandfarming," "Industrial Milk Company" (IMC), "Astra-Kyiv," and "Myronivsky Hliboproduct" (MHP). For instance, "Ukrlandfarming" employs a telemetry system consisting of external sensors to automatically collect data on irrigation, fertilizer application, and harvesting. This system optimizes resource use and improves production efficiency. The company "Astra-Kyiv" has introduced drones for monitoring crop conditions, enabling timely adjustments to growing conditions and reducing processing costs.

These examples demonstrate the potential of advanced technologies to transform agricultural practices in Ukraine. However, scaling such solutions to a national level requires addressing systemic challenges. Global estimates of the IoT and AI markets indicate significant growth potential, but their adaptation to local conditions remains a key challenge. For instance, the cost savings of up to 30% and the profitability increase of 15–20% mentioned in Table 1 from IoT implementation can only be achieved if

proper infrastructure is established and access to financing is provided for small and medium-sized farms (Table 1).

Table 1: Successful projects of integration of AI and agricultural technologies into agricultural sectors of Ukraine

<i>Project/Technology</i>	<i>Application Area</i>	<i>Impact</i>	<i>Increase in Profitability (%)</i>	<i>Cost Savings (%)</i>
IoT for Soil Monitoring	Precision farming	Improved resource allocation	15–20	30
AI for Yield Prediction	Forecasting crop yields	Enhanced decision-making accuracy	10–15	20
Robotics in Harvesting	Automation of harvesting	Reduced labour costs and efficiency	25-30	40
Drones for Crop Scouting	Monitoring crop health	Early detection of diseases	12-18	25
Smart Irrigation Systems	Water management	Optimized water usage	8-12	35

This gap highlights the importance of localized strategies for technology adoption, which are often overlooked in global analyses. Many sources, such as Drach (2024) and Garske, Bau and Ekardt (2021), pay insufficient attention to the methodology of technology implementation in the context of individual countries. For example, while cases of drone and robot deployment in the U.S. and EU countries are described, there is a lack of detailed information on adapting these practices to Ukraine's conditions, where farmers often face challenges such as limited access to training, resource constraints, and underdeveloped digital infrastructure. A more accurate analysis would require consideration of factors such as farm size, farmers' readiness for digitalization, and state support. Specifically, the metrics mentioned in the table, such as water savings or reductions in labour costs, may vary significantly depending on the type of farming operation and regional specifics.

For medium and small agricultural enterprises, the implementation of agrotechnologies requires significant capital investments. The introduction of IoT technologies in agriculture is associated with certain financial challenges. Initial costs for purchasing modern devices, sensors, and infrastructure can be quite high, especially for small farms or those located in regions with limited resources. Additionally, ongoing costs for maintenance, storage, and equipment connectivity further increase the overall expense of implementing IoT solutions. To overcome financial barriers, small and medium-sized enterprises in Ukraine's agricultural infrastructure need to utilize various financial models and actively engage with government support. Successful strategies for collaboration, cooperation, and training can significantly enhance the chances of successfully integrating new technologies and ensuring the sustainable development of agribusiness in Ukraine.

Social and Environmental Impacts

However, the implementation of innovative farming technologies is hindered by farmers' low technological readiness, limited awareness, restricted learning opportunities, and distrust of innovations. Problems with internet connectivity and inadequate digital infrastructure further constrain farmers' capabilities. Moreover, many modern technological solutions are not adapted for small farms, creating challenges in integrating innovations with traditional practices.

The reduced demand for physical labour may lead to population migration from rural areas to cities in search of work. This trend can cause demographic shifts and an ageing population in rural communities.

1. Social inequality. Farmers with greater resources may implement new technologies more quickly, potentially exacerbating social inequality between large agricultural companies and small farmers. Small farmers may struggle to access financing and training.
2. Changing the role of farmers. Farmers are evolving from being mere producers to becoming managers of technological processes. This transformation alters their role in society and imposes new educational and professional training requirements.

Research on farmers' readiness for digitalization is critical for understanding their training needs. Many farmers may be insufficiently prepared to use new technologies as a result of a lack of access to education or resources. It is necessary to develop specialized training programs for farmers that cover the basics of digital technologies, data management, and the use of modern agricultural practices. This will help farmers adapt to changes and enhance their competitiveness. Government support programs and funding can assist small farmers in implementing new technologies and receiving training. Collaboration between agribusiness and educational institutions can also contribute to fostering essential skill development in rural communities. Thus, the digitalization of the farming infrastructure holds the capacity to reshape employment and the social structure of rural communities in Ukraine. However, for the successful integration of new technologies, it is essential to increase farmers' readiness for change and address their training needs. Developing effective support and training strategies is key to ensuring the sustainable development of the agricultural infrastructure and improving living conditions in rural communities.

Building on this, the practical application of digital technologies by Ukrainian agricultural enterprises offers valuable insights into the potential benefits of innovation. The examples of Ukrainian companies, such as "Ukrlandfarming" and "Astra-Kyiv," demonstrate positive outcomes from implementing innovations; however, their impact on the sector requires further quantitative evaluation. For instance, while "Ukrlandfarming" successfully uses a telemetry system for irrigation monitoring, there is a lack of information regarding the long-term effectiveness of these innovations and their impact on the sustainability of farming enterprises. The studies by Ingram *et al.* (2022) and MacPherson *et al.* (2022) emphasize the importance of the social aspects of digitalization, such as its effects on employment and the evolving requirements for qualifications. In the Ukrainian context, these challenges become even more significant

due to rural population migration and inequalities between small-scale farmers and large agricultural holdings. While global trends in agrotechnologies show significant potential, their implementation in Ukraine requires adaptation to local conditions. Most studies focus on the technical aspects of innovations but insufficiently address the social, economic, and infrastructural challenges. Future research should concentrate on developing localized strategies that integrate successful global practices while accounting for the realities of Ukraine.

Investment Opportunities and International Cooperation

At the same time, Ukraine's vast agricultural land areas and the significant role of agriculture in the national economy present substantial investment opportunities. Among the most promising areas is the development of land demining technologies, which are essential for restoring agricultural productivity in regions affected by military activities. Modern agricultural technologies, like autonomous aerial vehicles (drones) and artificial intelligence systems, can be used for effective monitoring of contaminated areas. For instance, the combination of drone reconnaissance with mechanized demining tools allows for faster and safer clearing of large agricultural fields from mines and shells. This accelerates the return of land to agricultural use, which is critical for food security. For example, the Ukrainian UAV SKIF, developed by Culver Aviation, is used for field measurements and crop monitoring. With high image accuracy (up to 1 cm per pixel), SKIF helps farmers obtain detailed outlines of their plots, enabling optimized planting and disease prevention. Mordor Intelligence (2024) highlights that global trends, such as the development of data analytics and the accessibility of precision agriculture technologies, are key drivers of investment. However, these reports focus on general global trends and often fail to account for the specific conditions of the Ukrainian market, including limited infrastructure and unequal access to technologies for smallholder farms.

The agreement between Ukraine's Ministry of Economy and Palantir for implementing technologies for humanitarian demining serves as a successful example of collaboration with international partners. The use of data analysis platforms like Palantir enhances the efficiency of demining processes, but the practical application of such technologies is constrained by their high cost and the need for specialized training. This underscores the necessity of developing programs that provide local companies with access to similar solutions. On the other hand, the use of SKIF drones and THEMIS ground robots for demining agricultural lands is a significant achievement in the development of agricultural technologies. However, further research is needed to understand the long-term impact of these technologies on productivity and land restoration. These factors collectively create a favourable environment for investments in agricultural technologies, stimulating innovation and contributing to the growth of the Ukrainian economy. Thus, investors can consider Ukraine's agricultural technologies as a promising sector, especially amid the ongoing development of technologies and the increasing global demand for agricultural products. The creation of such collaborative platforms indicates a readiness to invest in agricultural technologies in Ukraine. Foreign investors' interest in agricultural technologies is explained by the fact that Ukraine is a powerful agricultural player. Given the significant potential of Ukrainian agriculture, investors can expect substantial opportunities for development and innovation in the agritech sector. This underscores the importance of collaboration between local

developers and international investors, fostering further technology development and improving the efficiency of Ukraine's agro-industrial complex. It is also worth noting that Ukrainian agritech startups have opportunities to attract investments and receive support through various forms of funding, including grants from public or private funds, as well as through accelerators, incubators, and ecosystems. AgTech Ukraine, a company founded in 2015 to promote the development of a high-tech market for Ukraine's agricultural sector and advance Ukrainian technologies on the international stage, has already invested over \$1 million in promoting agritech in Ukraine. Tielkinienė *et al.* (2020) indicate that the scalability of agricultural technologies for small farms remains a critical barrier. This is also true for Ukraine, where small farmers face challenges in accessing financing and digital infrastructure. Despite support from organizations like AgTech Ukraine, which has invested over \$1 million in agritech development, these efforts need to be expanded to address systemic issues.

The Global Innovation Mission for Ukraine until 2030 identifies agritech as one of its priorities, providing a positive signal for investors (Ministry of Digital Transformation of Ukraine, n.d.). MacPherson *et al.* (2022) highlight that the creation of subsidies and financial incentives is key to overcoming barriers to technology adoption. For Ukraine, this necessitates the development of targeted support programs aimed at infrastructure development and farmer training. However, while these high-level initiatives provide a roadmap for progress, many sources, such as Wang (2024) and Mordor Intelligence (2024), focus on macroeconomic data and global trends, often overlooking the unique challenges faced at the local level. For instance, market estimates for IoT and agritech often do not account for specific conditions faced by small farmers in Ukraine, such as limited financing or access to specialized training. This creates gaps in understanding how these technologies can be adapted to the Ukrainian context. The investment potential of agritech in Ukraine remains high, but its realization requires overcoming several barriers, including limited infrastructure, high technology costs, and unequal access to innovations for small farmers. A critical analysis of the sources highlights the need to localize global solutions and develop targeted government support programs. Successful collaboration between international and local partners, such as the agreement with Palantir, demonstrates the potential of investments in the agritech sector while emphasizing the importance of institutional support and adapting innovations to local conditions.

Advancing Agricultural Robotics in Ukraine

Building on this foundation, agricultural technologies are increasingly recognized as essential tools for addressing global challenges related to sustainable development and employment in agriculture. Rising labour costs and declining availability, exacerbated by border closures, economic instability following the COVID-19 pandemic, and Russia's military aggression against Ukraine, have placed significant strain on farmer incomes. Over the past decade, the implementation of agricultural technologies in Ukraine has been vital not only for reviving its economy after the war but also for contributing to global food security. To effectively address these challenges, Ukraine must prioritize investments in innovative agricultural solutions that ensure a stable level of production and sustainable practices. Automation can help alleviate these problems. Advancements in robotics and artificial intelligence have made the use of agricultural robots a more realistic option. Around the world, many startups and established

companies have developed ready-made solutions for various agricultural tasks such as weeding, planting, and harvesting.

Agricultural robotics is rapidly evolving due to modern technologies. Everyday tasks on the farm are often repetitive, time-consuming, and dangerous, making them ideal for automation using robotic systems. In Ukraine, robotic systems are actively being implemented in agricultural enterprises, significantly improving the effectiveness of agricultural production. Companies like Ecorobotix have developed robots that can automatically detect weeds and spray them with a small dose of herbicides. This reduces the use of chemicals by 2-3 times, representing an environmentally safe approach. John Deere has introduced the electric tractor robot Sesam 2, which can perform tasks such as soil cultivation and harvesting. This tractor can work in synergy with other robots, ensuring overall productivity. The use of drones for the early identification of diseases in fields allows agronomists to conduct timely treatments. Drones are equipped with high-definition cameras and GPS, providing detailed images of crops. The Aquarius robot is used for automated irrigation of plants in greenhouses. It can operate in two modes: a fixed mode, where the agronomist sets the irrigation rate, and a proportional mode, where the robot independently determines the necessary amount of water using sensors. Robots are also used in automated livestock management systems, enabling farmers to effectively monitor the health of livestock and provide proper care. Robots for tillage can perform various tasks, such as soil cultivation and planting. They free farmers from hard labour and enhance the efficiency of crop production. However, regulatory restrictions still hinder the widespread adoption of agricultural robotics, and the level of autonomy of these systems remains relatively limited. Despite this, the market for agricultural drones is expected to continue to grow actively for the foreseeable future. Other areas of robotic applications in agriculture are still developing. Field robots that perform tasks such as weeding and planting are in the early stages of commercialization. Unlike milking robots, which are stationary and typically operate indoors, the advancement of autonomous field robots faces several technical challenges that have historically restricted progress in this area.

In Ukraine, the implementation of field robots that perform tasks such as weeding and planting is still in the early stages of commercialization. However, unlike stationary milking robots that operate indoors, autonomous field robots face several technical challenges that limit their development. Some agricultural companies in Ukraine are testing robots for automated weed removal. These machines utilize machine vision and AI-based technologies to accurately identify and remove weeds without harming the crops. Ukrainian farmers are beginning to implement automated planting robots capable of precisely placing seeds in the fields. This helps reduce resource usage and increases planting efficiency. The use of drones for monitoring fields and applying fertilizers is becoming increasingly popular. Drones can quickly cover large areas, providing agronomists with crucial information about plant conditions. Companies like John Deere are developing electric robotic tractors capable of executing tasks related to soil cultivation and harvesting. These robots help reduce the physical burden on farmers and enhance productivity. Some agricultural enterprises are implementing automated irrigation systems that can autonomously determine the water needs of plants and supply them according to environmental conditions. Thus, while field robots in Ukraine may

not achieve widespread commercialization yet, their implementation can significantly improve the effectiveness of agricultural production in the country.

The agricultural environment has its unique challenges, such as unpredictable terrain, unknown obstacles, and changing weather conditions, which can complicate autonomous navigation and operation, as well as reduce the reliability of these systems. Furthermore, many agricultural regions are located in rural areas where access to communications, as well as repair and maintenance services, may be limited. Despite these challenges, significant progress has been made in computer vision and AI technologies, bringing field robotics closer to commercial use. Startups like Naïo Technologies, ecoRobotix, and TerraClear are actively commercializing robots for various agricultural tasks. Meanwhile, major equipment manufacturers like John Deere, AGCO, and Kubota are working on developing autonomous tractors. The Fendt MARS project offers a glimpse into the future of agricultural robotics by utilizing small autonomous robots to perform tasks traditionally carried out by piloted tractors. The results of this project have laid the groundwork to further the development of the Xaver agricultural robot lineup. Companies such as Octinion, Harvest CROO, and FF Robotics are investing in the progression of robotics for harvesting fresh fruits, as this is an important agricultural activity that remains a significant challenge for automation. This work requires a precise balance of using computer vision to determine fruit ripeness, accurate positioning for precise harvesting, and soft-grasp technology to avoid damaging the fruit during collection. These companies are developing innovative solutions aimed at improving the efficiency and quality of the fruit harvesting process, which can positively impact overall agricultural production, as the progression of agricultural robotics leads to the emergence of new value-added chains (Figure 2).

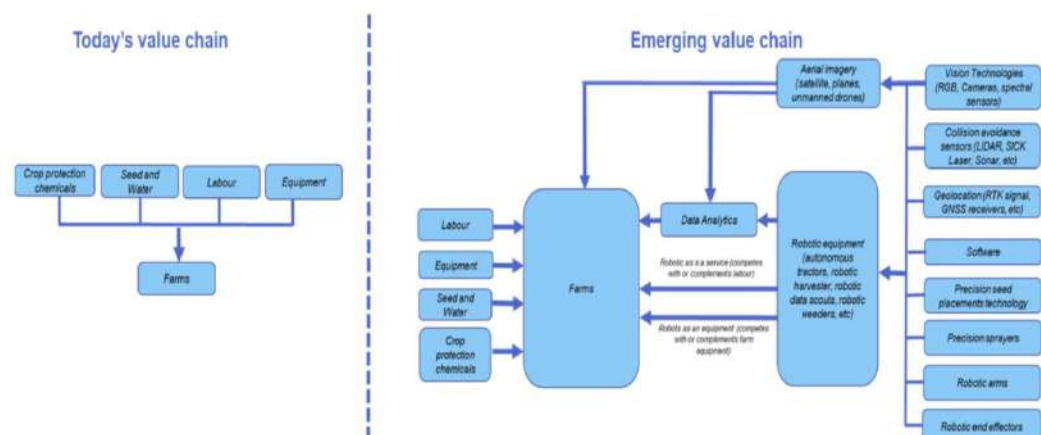


Figure 2: The advancement of agricultural robotics leads to the emergence of new value chains

Wang (2024) highlights the growing use of agricultural robots and their potential to automate complex processes, such as fruit harvesting. However, challenges related to adapting these technologies to the conditions of Ukrainian farms remain underexplored. For instance, field robots face technical obstacles, such as uneven terrain and unstable weather, which can limit their applicability. Moreover, startups like Naïo Technologies

and ecoRobotix focus on developing environmentally friendly solutions, such as robots for weed control. However, these solutions require significant initial investments, which can pose challenges for Ukrainian farmers who lack access to subsidies or grants. Therefore, while global advancements in agricultural robotics offer promising solutions, their successful implementation in Ukraine necessitates tailored approaches that consider local challenges and provide adequate financial and infrastructural support to farmers. Building on this, smart farming in Ukraine is indeed becoming an increasingly important area of agricultural development. The application of modern technologies, such as sensors and data collection systems. Automation in growing various crops helps optimize production processes, reducing labour and resource costs.

The incorporation of diverse technological solutions opens new opportunities for farmers, helping to enhance their productivity and profitability. The advancement of this direction in agriculture is a key factor in supporting sustainable and efficient food production. Ehlers *et al.* (2022) and Neto, Brewer and Gray (2023) highlight the significant potential of precision farming technologies to reduce resource losses, lower emissions, and improve biodiversity. These findings are particularly relevant for Ukraine, where environmental issues have become increasingly critical due to the consequences of war. However, these studies primarily focus on developed countries with advanced infrastructure. Adapting these practices to Ukraine's realities requires additional analysis, especially considering the country's limited digital infrastructure and insufficient funding for small-scale farms. Projections from sources like "TOP-5 Reasons..."³ indicate significant growth in the IoT market in agriculture by 2029. However, most studies, including these, fail to account for regional differences, such as the lack of internet access and infrastructure in rural Ukraine. To adapt these technologies in Ukraine, targeted funding programs and technical support initiatives are necessary. Moreover, while sensor technologies promise resource conservation and efficiency gains, the costs of installation and maintenance remain substantial barriers for Ukrainian farmers. This underscores the need for financial instruments, such as government subsidies and grants, to support farmers in adopting these innovations. In parallel, the projected growth of the AI market in agriculture by 2028 highlights a growing interest in the integration of advanced technologies into farming practices. Artificial intelligence offers significant benefits over traditional farming methods, including precision farming, drone analytics, and the use of agro robots. These advantages include increased efficiency, accuracy, and reduced resource costs.

The Ukrainian context underscores the importance of adapting global technologies. For example, Borrero and Mariscal (2022) highlight that the use of IoT and drones enhances water resource and nutrient management. However, their study does not address the economic barriers, such as the high cost of implementing these technologies, which may hinder their adoption among Ukrainian farmers. The high cost of IoT and drone technologies presents a significant challenge, particularly for small-scale farmers who comprise a large portion of Ukraine's agricultural sector. Artificial intelligence, as noted by Agriteka (2023) and Ehlers *et al.* (2022), holds great potential for optimizing production processes, such as monitoring plant and livestock health. However,

³ TOP-5 reasons why you need to use touch agtech technology in 2023 (2023). Available online at: <https://agriteka.com/2405-top-5-prichin-chomu-potrnbno-vikristovuvati-sensorn-agtech-tehnologiyi-u-2023-roc.html> (Accessed on 1 February 2024).

implementing these technologies in Ukraine faces challenges related to a lack of specialists and limited access to high-tech equipment. Addressing these challenges requires comprehensive training programs tailored to farmers and agronomists. Additionally, Borisova *et al.* (2020) emphasize the importance of engaging young specialists in managing technological systems but fail to consider the issues of workforce migration and demographic challenges in rural areas. Successful implementation of these solutions necessitates accounting for social factors, including worker motivation and the development of educational programs. While global studies emphasize the potential of agricultural technologies, their implementation in Ukraine faces various challenges, including technical, financial, and social barriers. Adapting global solutions to local conditions requires a comprehensive approach that includes infrastructure development, educational programs, and financial support mechanisms. Combining global innovations with local adaptations will be key to the sustainable development of Ukraine's agricultural sector.

Innovative Agrotech Solutions for Ukraine

Building on this foundation, the post-war recovery of Ukraine's agricultural infrastructure should be underpinned by smart Agrotech models that dynamically enhance resilience and facilitate the restoration of devastated areas. The strengthening of the integration process of advanced farming technologies into Ukraine's agriculture can significantly modernize the agricultural infrastructure with innovative solutions, increase the investment attractiveness of the industry and the efficiency of agricultural businesses, and reduce risks associated with the extreme conditions of restoring land resources. This includes the following key aspects:

1. **Water Quality Monitoring via Semtech Long-Range Wide-Area Network (LoRaWAN) Standard:** This will allow for effective and reliable large-scale water quality monitoring, which is particularly important for agriculture in dispersed and expansive areas. The information obtained from such monitoring will enable farmers to make informed decisions about water resource management and reduce environmental impact.
2. **Use of ExactRate Technology for Optimizing Fertilizer Use:** This will enhance the efficiency of fertilizer application and reduce costs, which may lead to increased yields and minimize negative effects on soil resources and the environment.
3. **Application of IoT for Managing Weather-Related Risks:** Through IoT-based weather monitoring and forecasting systems, farmers can receive early warnings about potentially hazardous weather conditions, such as droughts or floods, and take timely measures to protect their crops and property.
4. **Increasing Awareness and Investment in Europe for IoT in Agriculture:** Encouraging farmers to adopt IoT technologies in agriculture is a crucial step toward creating a sustainable and efficient agricultural system. European experience can serve as a model for Ukraine in implementing cutting-edge solutions in this area.

All these measures improve risk management, enhance the efficiency and resilience of Ukrainian agriculture, and rejuvenate the environment.

The Ukrainian agricultural infrastructure is indeed one of the key industries in the economy, and its significance is increasing in the context of the war. The development and implementation of modern agrotechnologies can play a significant role in ensuring the resilience and productivity of this sector. The adoption of agrotechnologies, such as process automation and precision agriculture, can substantially increase crop yields. For instance, technologies that use data to optimize production enable farmers to reduce resource costs and enhance land use efficiency. This is especially important in wartime conditions, where resources may be limited. The agricultural infrastructure in Ukraine is facing significant losses due to negative impacts such as weather conditions and economic difficulties. The use of agrotechnologies can help mitigate the effects of these factors. For example, monitoring and forecasting systems can assist farmers in adapting their strategies to changing climate and market conditions. This ensures greater resilience of agricultural enterprises to risks, which is critical under the current circumstances. Ukraine has significant potential in utilizing water resources and land. Modern technologies can contribute to their rational use. For example, precision agriculture systems can optimize water and fertilizer usage, achieving not only productivity but also reducing detrimental effects on the environment. The advancement of agricultural technologies also stimulates innovative activities in agriculture. This can involve the creation of innovative plant varieties and the implementation of drones for field monitoring. Investments in agrotechnologies facilitate the attraction of both domestic and foreign investments, modernizing the infrastructure of the agricultural infrastructure and achieving competitiveness in the global market. Thus, modern agrotechnologies possess the capability to significantly enhance the resilience and productivity of Ukraine's agricultural infrastructure in wartime. They not only help reduce vulnerability to external factors but also promote rational resource use and the advancement of innovative activities.

The combination of technical innovations with social aspects creates a comprehensive approach to the advancement of the agricultural sector, which can significantly improve farmers' lives through increased production efficiency, improved decision-making, social adaptation, and environmental sustainability.

The study by Klerkx, Jakku and Labarthe (2019) emphasizes the social aspects of digitalizing agriculture, highlighting that the adaptation of technologies must take local conditions into account. This is particularly relevant for Ukraine, where the implementation of innovative solutions faces challenges such as a lack of skilled personnel and limited financial resources. While global trends showcase the advantages of agrotechnologies, such as reducing resource use and increasing yields, their effectiveness in Ukraine depends on adapting to the country's specific conditions. Findings of Garske, Bau and Ekardt (2021) confirms that artificial intelligence and precision farming can contribute to achieving environmental goals. However, in the Ukrainian context, these technologies must account for local climatic conditions and the types of crops being cultivated. For example, the experience of companies like "Ukrlandfarming" demonstrates that telemetry systems can significantly optimize the use of water and fertilizers, but their implementation requires substantial investments and staff training.

The adaptation of technologies also involves educating farmers and raising their awareness of new tools. Successful projects demonstrate that without proper training and support, farmers may encounter difficulties in adopting new technologies. For example, companies implement training programs for their employees, which promote better understanding and utilization of AI. The adoption of AI demands substantial capital investments, posing challenges for small and medium-sized enterprises. Local market characteristics, such as the availability of financing and investments, affect the pace of technology adoption. For example, projects may be adapted according to the financial capabilities of farmers, allowing for the avoidance of excessive financial burdens. Specific examples of successful projects in Ukraine, such as the telemetry collection system for the agroholding "Ukrlandfarming," demonstrate how AI can be integrated into existing processes. This system not only automates processes but also enables farmers to obtain data for task execution in real time, which is critical for enhancing productivity. Water quality monitoring technologies, particularly the use of the LoRaWAN standard, can play a crucial role in restoring lands contaminated as a result of the war. Research by Ingram *et al.* (2022) highlights the effectiveness of such technologies in reducing the environmental impact of agriculture. However, large-scale implementation in Ukraine faces challenges, such as insufficient infrastructure and the high cost of equipment.

The implementation of ExactRate for fertilizer optimization represents a critical step toward cost reduction and yield improvement. However, research by MacPherson *et al.* (2022) emphasizes that the successful adoption of such technologies requires financial support for small-scale farms. For Ukraine's agricultural sector, this underscores the necessity of subsidy and grant programs. Research by Borrero and Mariscal (2022) underlines the importance of IoT in mitigating risks associated with weather conditions. However, in Ukraine, limited internet access in rural areas may hinder IoT adoption in agriculture. Addressing this barrier requires government initiatives to improve infrastructure. The experience of companies such as "Ukrlandfarming" demonstrates the significant potential of AI solutions to enhance agricultural efficiency. However, Ingram *et al.* (2022) note that without government support and educational programs, farmers may struggle to adapt to these technologies. For instance, the development of tailored training programs is a vital prerequisite for the successful integration of AI into the agricultural sector. Research by Borisova *et al.* (2020) emphasizes the importance of engaging young specialists in the agricultural sector through the development of modern educational programs. This is particularly relevant for Ukraine, where a significant portion of rural youth migrates to cities in search of employment. Creating modern working conditions in the agricultural sector can encourage the return of young specialists and drive the modernization of the industry. European experiences with IoT in agriculture, as noted by Klerkx, Jakku and Labarthe (2019), could be adapted for Ukraine. However, it is crucial to consider that most European solutions are designed for high-tech farms and require modification to suit Ukraine's less developed infrastructure.

Thus, modern agricultural technologies hold significant potential for restoring Ukraine's agricultural sector. However, their implementation requires adaptation to local conditions, including financial barriers, limited infrastructure, and the need for farmer education. Global examples, such as the use of IoT and AI, can serve as models for creating innovative solutions that contribute to the sustainable development of Ukraine's agricultural sector.

Achieving success will necessitate the development of a national strategy to support farmers, incorporating funding, education, and infrastructure development.

Conclusions

This study highlights the significant potential of agricultural technologies in transforming Ukraine's agricultural sector by improving efficiency, sustainability, and resilience. Key findings include:

- **Main Benefits of Agricultural Technology:** Technologies such as IoT, AI, and robotics can reduce resource use by up to 30% and increase yields by 15–20%. Crop monitoring drones improve processing efficiency by 20% and reduce costs by 25%.
 - **Barriers to Adoption:** Limited infrastructure, high upfront costs, and low digital readiness among farmers, especially smallholders, remain critical concerns. For example, IoT adoption costs can exceed \$10,000 per farm, posing a significant financial barrier for small businesses.
 - **Role of Education and Support:** More than 70% of farmers lack sufficient training in digital technologies, highlighting the need for tailored programs to equip them with the necessary skills to adopt these technologies. Public-private partnerships and international collaborations are critical for addressing these gaps.
 - **Investment Opportunities:** The global IoT market for agriculture is projected to grow from \$6.95 billion in 2023 to \$22.45 billion by 2031. Ukraine's agritech sector, supported by 41.5 million hectares of arable land, is well-positioned to attract significant investment, particularly in precision agriculture and robotics.
- Strategic Recommendations:** Adapting global technologies to local conditions, expanding subsidy programs, and improving digital infrastructure can promote adoption. For example, government-supported initiatives could enable small farms to achieve a 15–20% increase in profitability through precision farming.

By addressing these challenges and harnessing its agricultural potential, Ukraine can unlock the transformative power of agricultural technologies, contributing not only to its economic recovery but also to global food security.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>	<i>Author 6</i>
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes	Yes
Collected the data	No	No	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	No	Yes	Yes	Yes	Yes
Wrote the article/paper	No	No	Yes	Yes	No	No
Critical revision of the article/paper	Yes	Yes	No	No	Yes	Yes
Editing of the article/paper	No	Yes	Yes	No	No	No
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Harnessing Renewable Energy for Sustainable Economic Growth and Environmental Resilience

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Abstract

Renewable energy sources are a crucial element of the overall sustainable global economic development system due to climate change, depletion of fossil fuel sources, and the need to reduce the negative impact on the environment. Additionally, in modern geopolitical challenges, escalating economic pressures, and regional disparities in renewable energy development further complicate the global transition to sustainable energy. This article aims to define the role of renewable energy sources in ensuring sustainable economic development and analyze the influence of key factors on their implementation in sustainable development. We analyzed literature sources, and statistical data, followed by comparative analysis, systematization, and generalization, to identify the key factors influencing the implementation of renewable energy sources. The expert assessment method revealed the impact of internal and external factors on the development of the energy sector. These factors include Politics (P), Economy (E), Social sphere (S), Technology (T), Ecology (E) and Law (L) pillars that influence the implementation of renewable energy sources in ensuring sustainable economic development. The findings suggest that political instability (P1 - -2.7) and the destruction of energy infrastructure (P2 - -3.0), as well as economic factors (Total E - 5.05 / -8.33), are currently the main negative factors affecting the renewable energy sector in Ukraine. Additionally, social (Total S - 4.63 / -8.67) and environmental aspects (Total E - 3.9 / -8.125) still lack adequate management by the government and public perception, negatively impacting the further development of renewable energy sources. At the same time, technological innovations (Total T - 9.1 / -9.1) and the legal environment (Total L - 9.16 / -9.16) show potential for further sectoral development. The implementation of alternative energy sources and the overall support of the energy sector mainly depend on balanced policies in the electricity sector, the sector's investment attractiveness, social support, and the availability of technological innovations.

Keywords

Waste; Fiscal policy; Macro-financial stability; Renewable energy sources; Alternative energy sources

Introduction

Renewable energy sources (RES) are currently an alternative to traditional energy systems, allowing the avoidance of natural resource shortages and the reduction of adverse environmental impacts. Using renewable energy sources, such as solar, wind, geothermal, hydro, and bioenergy, reduces greenhouse gas emissions, decreases dependence on fossil fuels, and increases countries' energy security. Globally, 36,469 solar photovoltaic farms (Global Energy Monitor, 2024c), 17,292 wind farms (Global Energy Monitor, 2024d), 2,689 hydroelectric power stations (Global Energy Monitor, 2024b), and 353 geothermal stations (Global Energy Monitor, 2024a) are currently in operation (Figure 1). It should be noted that renewable energy sources are expected to account for more than 42% of global electricity production by 2028, with the share of wind and solar photovoltaic energy doubling to 25% (IEA50, 2024). However, it should be noted that the current development of RES is accompanied by uneven technological advancement in this area across different countries and geographical regions of the world. For example, such disparity is illustrated by the significant gap between Western European countries, such as Germany, Denmark, and Austria, which are leaders in the implementation of wind and solar technologies, and developing countries, particularly in Africa or Southeast Asia, where the field of renewable energy sources is developing much more slowly. The reasons for this gap primarily include different levels of economic development, the availability of investments, political support, and the existence of the necessary infrastructure to integrate renewable energy sources into national energy systems.

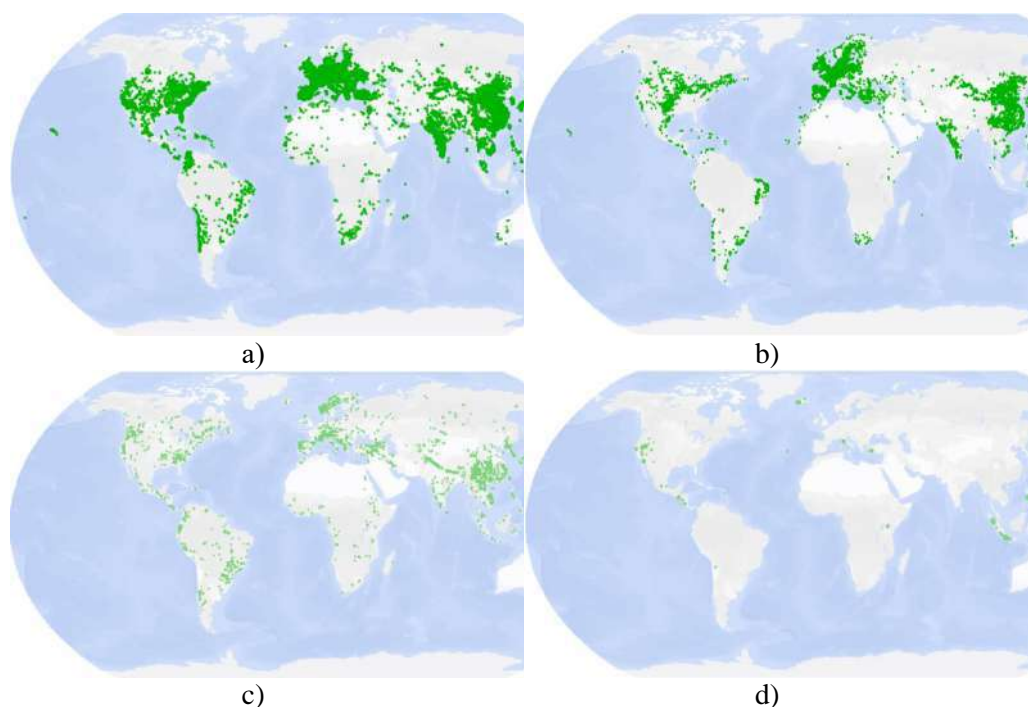


Figure 1: Global renewable energy infrastructure status showing a) map of operating solar photovoltaic farms; b) map of operating wind power plants; c) map of operating hydroelectric power plants; and d) map of geothermal energy use

Source: Global Energy Monitor (2024a; 2024b; 2024c; 2024d)

Among the European Union (EU) member states, Germany is making significant efforts to implement renewable energy sources (RES), mainly through the Energiewende programme, which aims to transition to a low-carbon, environmentally responsible, reliable, and economical energy supply. A balanced policy results in the shift from nuclear energy to green energy, reducing CO₂ emissions and gradually eliminating dependence on imported resources. Renewable energy accounts for 49% of Germany's electricity, leading to a high concentration of new projects in the solar energy sector. Therefore, Germany is one of the leading EU countries actively contributing to enhancing energy security, improving energy efficiency, and decarbonizing the economy (Edo, 2023). Denmark's case is like Germany's but more market-oriented and decentralized. Denmark has successfully reduced its high dependence on imported fossil fuels to partial self-sufficiency due to its high share of RES, which accounted for 68.4% of domestic electricity production in 2018 (Wang, Moreno-Casas and Huerta de Soto, 2021). Austria is also advanced regarding RES, with its climate policy, based on the "Mission 2030" strategy, aimed at significantly reducing greenhouse gas emissions by 36% by 2030 compared to 2005 levels. The combination of Austria's strategic initiatives primarily directs investments into the energy sector, in line with Austria's broader decarbonization goals, demonstrating its commitment to global environmental sustainability, which has led to an increase in the number of solar photovoltaic and wind energy systems in the country (da Silva *et al.*, 2024).

In contrast, in Nigeria, the focus is not on the widespread adoption of RES, although the country has a plan for further integration under the Renewable Energy Master Plan (REMP). Instead, it is on rural electrification, where most areas do not have access to electricity. Given Nigeria's economic problems, political instability, and dependence on the oil industry, it is essential to develop measures and ensure coordination between the government, industry, civil society, and international partners to move forward and realize Nigeria's clean energy ambitions (Idoko *et al.*, 2024; Oduro, Simpa and Ekechukwu, 2024). An analogous situation is observed in South Sudan, where the population has the lowest access to electricity due to security risks and political instability — only 7.7% as of 2021; over 90% of rural areas do not have electricity. This situation prompts the government to develop policies to implement RES but also hinders investment opportunities in this area (Thiak and Hira, 2024).

Another example of insufficient RES development is Ukraine's energy sector amid Russia's full-scale invasion. However, despite Ukraine's macroeconomic, geopolitical problems, and supply chain challenges, global investments in energy transition technologies, including RES and energy efficiency, reached USD 1.3 trillion in 2022 (Polyanska *et al.*, 2023). For Ukraine, the prospects of using RES are primarily concerned with ensuring energy security and independence in the context of Russia's destruction of energy infrastructure and a significant electricity deficit caused by the war.

Thus, the relevance of studying the prospects for using RES to ensure the sustainable development of economies in different geographical regions of the world is determined by the opportunities to reduce dependence on fossil fuels, decrease greenhouse gas emissions, and ensure energy security. Additionally, the study allows for considering regional characteristics, including natural and climatic conditions, economic

development, and political will, in assessing the effectiveness of RES implementation, which is a determining factor in the global transition to sustainable development and combating climate change.

The aim of authoring the scientific article is to determine the role of RES in ensuring sustainable economic development. The article aims to analyze current trends in the development of the energy sector in countries with various levels of development. The study of political, economic, social, technological, environmental, and legal factors influencing the implementation of RES in ensuring sustainable economic development allowed for an analysis of Ukraine's potential as a developing country to expand its renewable energy capacity, create new and restore destroyed energy infrastructure amid the ongoing Russia-Ukraine war and political instability.

Literature Review

Currently, the issue of developing renewable energy sources in the context of ensuring environmental sustainability and economic growth is particularly pressing, considering the depletion of fossil fuels and climate change, which can be mitigated through green energy and the rational use of energy (Sotnyk *et al.*, 2023). Sustainable development involves conserving natural resources, reducing the negative impact on the environment, and ensuring economic growth through environmentally safe solutions (Mikhno *et al.*, 2021). In this context, green energy, based on renewable sources such as solar, wind, hydro, geothermal, and bioenergy, allows a transition to an energy-efficient economy by reducing dependence on fossil fuels (Kansongue, Njuguna and Vertigans, 2023). The implementation and efficient use of renewable energy sources contribute to the reduction of greenhouse gas emissions (Al-Ghouti *et al.*, 2021), improvement of air quality (Do Thi *et al.*, 2021), and enhancement of energy security (Thiak and Hira, 2024). According to the International Energy Agency (IEA), the deployment of renewables in the power, heat and transport sectors is one of the main enablers of keeping the rise in average global temperatures below 1.5°C. In the Net Zero Emissions by 2050 scenario, renewables allow electricity generation to be almost completely decarbonized. Meanwhile, renewable transport fuels and renewable heat contribute to significant emissions reductions in transport, buildings and industry (IEA50, 2024).

It is essential to consider the current scientific discourse on the circular economy and environmental transformation concept to determine the critical trends in developing renewable energy sources to ensure sustainable economic development. For example, Koval *et al.* (2023) argue that the potential for transitioning to a circular economy and promoting sustainable consumption contributes to the conservation of natural resources and increased energy efficiency. In this context, implementing and developing renewable energy sources, as one of the components of the circular economy, also positively affects the national economy, including reducing the use of fossil fuels and promoting environmentally responsible consumer behaviour (Yakovenko, 2023). At the same time, the need to use circular management models to achieve a sustainable business process, as discussed by Arsawan *et al.* (2024), is related to the need to increase the resilience of enterprises in the context of their adaptation to climate change, optimization of natural resource use, and potential transition to renewable energy sources.

Furthermore, for many countries, the issue of reducing the gap in access to and the quality of energy resources across different regions remains relevant (Igliński *et al.*, 2016). Moreover, to support the renewable energy sector and, as a result, ensure sustainable economic development, a balanced investment policy in the energy sector is necessary. This promotes the implementation of next-generation technologies and reduces environmental risks (Nikonenko *et al.*, 2022); the introduction of an environmental risk system based on sustainable development principles (Sumets *et al.*, 2022); and the eco-transformation of energy services to support the low-carbon transition (Kovalko, Eutukhova and Novoseltsev, 2022).

Methodology

The following methods were employed in the research:

Literature Review: Literature was used to study current trends in the development of renewable energy sources for sustainable economic development, a literature review was conducted, drawing from a wide range of sources. Of these, 25 scientific articles of the most scientifically significant articles published in the period from 2021 to 2024 were selected for inclusion in the analysis. Reports from the International Energy Agency (IEA), the Global Energy Monitor, and peer-reviewed journals such as Renewable and Sustainable Energy Reviews were also analyzed to obtain statistical data to support the identified trends. This body of literature provided insights into the adoption of RES technologies across the solar, wind, hydro, and geothermal energy sectors.

Statistical Analysis: Data from 2024 Global Energy Monitor and IEA reports were used to determine the state of the global renewable energy infrastructure. During the study, 4 data sets covering the number of operating solar photovoltaic power plants, wind turbines, hydroelectric power stations, and geothermal energy were analyzed to assess the global infrastructure of renewable energy, emphasizing the trends of their development in different regions and countries.

Comparative and Systematic Analysis: Comparative analysis was used to compare strategies and the level of RES development in different countries. In particular, the sample included documents, energy strategies, such as Germany's Energiewende, and investment reports from 2005 to 2024 from countries such as Germany, Denmark, Austria, Nigeria, and Ukraine. This method is used to study international experience in the development of the alternative energy sector and to identify the uneven development of technological solutions in this area across different countries and geographical regions of the world. Using the systematization method, the previously identified factors contributing to the development of renewable energy are classified by analyzing relevant government reports, climate strategies, and scientific studies published in the period 2021–2024. Thus, we have outlined the politics (P), economy (E), social sphere (S), technology (T), ecology (E), and law (L) factors influencing the implementation of renewable energy sources in ensuring sustainable economic development. The degree of influence of each factor on implementing renewable energy sources was determined using expert assessments on a ten-point scale. The study involved 25 researchers conducting ecology, sustainable development, and environmental management studies. A high score indicates a strong impact and a serious threat, while a low score indicates

no impact or threat. For each factor, the weight score was calculated by multiplying its importance by the degree of influence. The result of the analysis is the calculation of the total weighted score (Total), which allowed for assessing the impact of individual factors on the economic security of the regions. Additionally, the values assigned to the relevant factors were determined by experts based on their experience and the contextual relevance of each factor to the development of renewable energy sources. Positive values (+) indicate opportunities, while negative values (-) reflect threats arising from the impact of the specified factors on this process. Instead, the generalization method was used to formulate the features of the factors and their manifestation by synthesizing data from more than 25 sources of literature, including climate strategies, Reports from the International Energy Agency (IEA), the Global Energy Monitor, etc. This allowed us to draw comprehensive conclusions about the role of renewable energy in ensuring sustainable development.

Expert Evaluation and Assessment: The expert assessment method is applied to investigate the impact of internal and external environmental factors on implementing renewable energy sources in ensuring sustainable economic development. The criteria for expert selection included academic qualifications (PhD or equivalent in ecology, energy management, or related fields) and professional experience in renewable energy. Selection criteria that emphasize academic and professional expertise were necessary to ensure that the assessments are expert, although experiences and areas of specialization may skew the assessment towards certain factors (e.g., political or technological factors) over others. As a rule, priority was given to experts with the highest number of publications among others and who are involved in national or international environmental and energy initiatives. Instead, the criteria for conducting the research included several political, economic, social, technological, environmental, and legal factors related to the sector's development. The study involved 25 researchers, 7 of whom are professors aged 40 to 60 who focus their research on developing preventive measures to overcome threats to the energy sector's development; 8 are professors aged 45 to 55 who, in their scientific work, develop strategies and measures to ensure sustainable economic development; and 10 are lecturers in the departments of ecology and environmental management. Based on the data obtained, a weighted assessment of each factor was calculated, reflecting the extent of their influence on the development of Ukraine's energy sector in the context of Russia's full-scale invasion of Ukraine, the destruction of critical infrastructure, including the energy infrastructure of the country, and political instability.

Thus, the outlined methods provided a solid basis for further research for assessing the current state of renewable energy development and its potential for sustainable economic growth. In this context, the analysis of relevant scientific sources, the analysis of secondary statistical data, and the comparative analysis of various state development strategies contributed to the efficiency and objectivity of developing our system of factors influencing the introduction of renewable energy sources in ensuring sustainable economic development, which is discussed in the next section.

Results

Implementing renewable energy sources (RES) plays a crucial role in sustainable development, primarily by reducing dependence on coal and other non-renewable energy sources, which increases the country's energy security and reduces its vulnerability to price fluctuations and supply disruptions. Given that many countries are still directly dependent on fossil fuels (coal, oil, natural gas), there is a need for a gradual and measured transition to RES to ensure the resilience of the energy system through risk distribution and energy source diversification (Oduro, Simpa and Ekechukwu, 2024). To achieve zero fossil fuel use by 2050, renewable energy production needs to increase 6 to 8 times if energy demand remains constant or increases by 50% from the 2020 energy demand level. In this context, the aggressive application of energy-saving policies, including land use and taxation, could reduce global energy consumption by 10% or more by 2050. The likelihood of achieving independence from fossil fuels also increased by limiting global energy demand growth by 25% by 2050 compared to 2020 (Holechek *et al.*, 2022).

The market orientation and decentralized nature of renewable energy sources—solar, wind, geothermal, hydro, and bioenergy — minimize energy losses during transportation, contributing to the efficient use of resources. The opportunity to transition to green energy encourages many businesses to develop and implement eco-efficiency, green production, and environmentally friendly management practices to reduce their environmental impact. To maintain public interest in green production and consumption, governments of various countries are working to make renewable energy more accessible and efficient by developing a new conceptual model primarily based on a network of distributed energy systems (Gawusu *et al.*, 2022).

Moreover, the implementation of RES offers broad opportunities to reduce carbon dioxide (CO₂) emissions and other pollutants, resulting in improved air quality and reduced negative impacts on climate change. Dependence on unstable energy resources and global air quality deterioration is driven by dirty coal and oil products. In contrast, implementing renewable energy sources in this context effectively reduces emissions and the amount of solid waste (ash and slag from coal processing), oil waste, and waste from burning fossil fuels. This reduces pollution and enhances energy security (Al-Ghouti *et al.*, 2021).

Table 1 presents the main factors influencing the implementation of renewable energy sources in ensuring sustainable economic development. An impact assessment of individual parameters was conducted using a PESTEL analysis to assess the significance of the identified factors.

The first factor influencing the implementation of renewable energy sources is the political factor (P), which includes political instability, the consequences of military actions, and state regulation of the energy sector. Table 2 presents the results of assessing the impact of political factors on the implementation of renewable energy sources.

Table 1: Factors influencing the implementation of renewable energy sources in ensuring sustainable economic development

<i>Group of factors</i>	<i>Factors with the most significant impact</i>	<i>Features and their manifestation</i>
Politics (P)	Political instability (P1)	Uncoordinated political decisions on the development of the renewable energy sector
	Destruction or neglect of energy infrastructure (P2)	Destruction of energy facilities, including power plants, substations, and networks, which hinders energy supply and integration of renewable energy sources
	Availability of a state strategy for the development of renewable energy sources (P3)	Clarity and effectiveness or inconsistency of renewable energy policies
	State support for the development of renewable energy sources (P4)	Implementation of feed-in tariffs, grants, grant programs and subsidies for renewable energy projects
Economy (E)	Impact on the sustainable development of the national economy (E1)	Level of dependence of the energy sector on fossil fuel imports
	The volume of attraction and general availability of investments in renewable energy sources (E2)	Clear rules and facilitation of financing of renewable energy projects by public and private investors
	Cost of alternative energy production (E3)	High cost of renewable energy technologies, their implementation and provision of appropriate infrastructure
	Level of availability of the latest technologies (E4)	High cost or lack of access to new technologies
Social sphere (S)	Environmental awareness of the population (S1)	Low level of interest and awareness of the benefits of implementing renewable energy sources
	New jobs in the renewable energy sector (S2)	Insufficient development of the industry, which may limit job creation, and the availability and quality of educational training programs
	Availability of alternative energy in rural and remote areas (S3)	Lack of access to electricity in remote regions or high cost for residents of rural areas
	Impact of renewable energy sources on the quality of life and health of the population (S4)	Spread of chronic diseases among the population due to air, water and soil pollution from traditional energy sources
Technology (T)	Level of technological infrastructure (T1)	Lack of or outdated grid and systems for integrating renewable energy sources

<i>Group of factors</i>	<i>Factors with the most significant impact</i>	<i>Features and their manifestation</i>
	Level of maintenance and management of energy systems (T2)	Low efficiency of management and control of new energy systems
	Integration of decentralized systems into the national energy grid (T3)	Difficulties with the integration of decentralized energy solutions due to lack of appropriate infrastructure
Ecology (E)	Impact on greenhouse gas emissions (E1)	Reduction of CO ₂ and other greenhouse gas emissions
	Impact on biodiversity (E2)	Loss of natural environment due to the construction of new energy facilities
	Impact on waste management (E3)	Level of control over industrial waste
	Impact on water consumption (E4)	Impact of hydropower plants on water resources and ecosystems
	Impact on land use (E5)	Impact of renewable energy infrastructure construction on agricultural land and natural landscapes
Law (L)	Efficiency of the legal and regulatory framework for renewable energy sources (L1)	Existence or absence of institutions, laws and regulatory instruments that support the development of renewable energy sources
	Efficiency of state regulation of renewable energy sources (L2)	Establishment of clear rules and requirements for certification, licensing, and compliance of renewable energy technologies
	Availability of international environmental agreements (L3)	Speed and quality of implementation of international climate and environmental agreements

Table 2: Assessing political factors on renewable energy sources implementation

<i>Events/f actors</i>	<i>Threats (-) / Opportunities (+)</i>	<i>Manifestation capability</i>	<i>Significance</i>	<i>Impact on the renewable energy sector</i>
P1	-	0.3	9	-2.70
P2	-	0.3	10	-3.00
P3	+ / -	0.25 / 0.25	8	+2.00 / -2.00
P4	+	0.15	7	+1.05
Total P	2 (+) / 3 (-)	1	34 of 40	+3.05 / -7.70

Political factors impact the implementation of renewable energy sources to ensure sustainable economic development. In particular, the consequences of the full-scale invasion include political instability (P1 = -2.7) and Russia's destruction of energy infrastructure (P2 = -3.0), which cause chaotic decision-making and inconsistency in the

actions of governing institutions regarding the development of the energy sector under conditions of the destruction of crucial energy infrastructure facilities. The need for a clear strategy for developing the renewable energy sector ($P3 = 2.0 / -2.0$) is due to the importance of effectively integrating sustainable development principles to eliminate inconsistencies in policy related to alternative energy sources. A positive factor influencing the implementation of renewable energy is the possibility of state support for the sector ($P4 = 1.05$) by introducing green tariffs, subsidies, grant programs, and funding.

Economic factors (E) include the cost of securing essential resources and the technological and investment attractiveness of introducing renewable energy sources into the country's energy sector. Table 3 presents an assessment of the impact of this group of factors.

Table 3: Assessing economic factors on renewable energy sources implementation

<i>Events/ factors</i>	<i>Threats (-) / Opportunities (+)</i>	<i>Manifestation capability</i>	<i>Significance</i>	<i>Impact on the renewable energy sector</i>
E1	+ / -	0.25 / 0.27	9	+2.25 / -2.43
E2	+ / -	0.28 / 0.26	10	+2.8 / -2.60
E3	-	0.24	8	-1.92
E4	-	0.23	6	-1.38
Total E	2 (+) / 4 (-)	1	33 of 40	+5.05 / -8.33

Expanding renewable energy sources ($E1 = 2.25 / -2.43$) reduces the national economy's dependence on fossil fuel imports. However, it is essential to ensure the investment attractiveness of the sector ($E2 = 2.8 / -2.6$) to cover the high costs of production technologies ($E4 = -1.92$) and the construction and provision of appropriate infrastructure ($E3 = -1.38$) as negative influencing factors. Table 4 presents an assessment of the impact of social factors on the implementation of renewable energy sources.

Table 4: Assessing social factors on renewable energy sources implementation

<i>Events/ factors</i>	<i>Threats (-) / Opportunities (+)</i>	<i>Manifestation capability</i>	<i>Significance</i>	<i>Impact on the renewable energy sector</i>
S1	+ / -	0.3 / 0.32	9	+2.70 / -2.88
S2	+ / -	0.27 / 0.25	7	+1.89 / -1.75
S3	-	0.22	9	-1.98
S4	-	0.21	10	-2.10
Total S	2 (+) / 4 (-)	1	35 of 40	+4.63 / -8.67

The assessment of the impact of social factors on the implementation of renewable energy sources showed that the most significant factors for sustainable economic development are the increase in eco-consciousness among the population ($S1 = 2.7 / -2.88$) and the creation of new jobs in the alternative energy sector ($S2 = 1.89 / -1.75$). However, the inefficiency of related measures may hurt the further implementation of

environmental initiatives in the country's energy sector. Additionally, it is essential to ensure the availability of alternative energy in rural and remote areas ($S3 = -1.98$) and to improve the population's quality of life and health ($S4 = -2.1$), as currently, no practical results have been achieved in these areas. The results of the evaluation of the impact of technological factors on economic security are presented in table 5.

Table 5: Assessing technological factors on renewable energy sources implementation

<i>Events/factors</i>	<i>Threats (-) / Opportunities (+)</i>	<i>Manifestation capability</i>	<i>Significance</i>	<i>Impact on the renewable energy sector</i>
T1	+ / -	0.29 / 0.3	8	+2.32 / -2.40
T2	+ / -	0.32 / 0.3	9	+2.88 / -2.70
T3	+ / -	0.39 / 0.4	10	+3.90 / -4.00
Total T	3 (+) / 3 (-)	1	27 of 30	+9.10 / -9.10

Technological factors in the current conditions are a negative phenomenon that requires improvements to the energy grid and systems for the integration of renewable energy sources ($T1 = 2.32 / -2.4$), increasing the efficiency of management and control over new energy systems ($T2 = 2.88 / -2.7$), and the systemic integration of decentralized systems into the national energy grid ($T3 = 3.9 / -4.0$). This will contribute to optimizing technological infrastructure, improving maintenance and management, and eliminating integration challenges due to the lack of appropriate infrastructure. In turn, the results of calculating the degrees of influence of environmental factors on the implementation of renewable energy sources are presented in table 6.

Table 6: Assessing environmental impact on renewable energy sources implementation

<i>Events/factors</i>	<i>Threats (-) / Opportunities (+)</i>	<i>Manifestation capability</i>	<i>Significance</i>	<i>Impact on the renewable energy sector</i>
E1	-	0.2	8	-1.60
E2	-	0.15	6	-0.90
E3	-	0.25	10	-2.50
E4	+ / -	0.2 / 0.2	7	+1.40 / -1.40
E5	-	0.2	9	-1.80
Total E	1 (+) / 5 (-)	1	40 of 50	+8.20 / -8.20

The most significant negative impact on the implementation of renewable energy sources currently comes from the significant volumes of greenhouse gas emissions ($E1 = -1.6$), excessive consumption of water resources ($E4 = -2.5$), destruction of natural habitats ($E2 = -0.9$), agricultural lands, and natural landscapes ($E5 = -1.80$). These existing threats can be overcome by improving the efficiency of the waste management system ($E3 = 1.4 / -1.4$), which will ensure the sustainable development of the energy sector and the economy. In addition, it is essential to highlight the impact of legal factors on implementing renewable energy, as shown in table 7.

Table 7: Assessing legal factors' impact on renewable energy sources implementation

<i>Events/factors</i>	<i>Threats (-) / Opportunities (+)</i>	<i>Manifestation capability</i>	<i>Significance</i>	<i>Impact on the renewable energy sector</i>
L1	+ / -	0.37 / 0,36	10	+3.70 / -3.60
L2	+ / -	0.35 / 0,36	10	+3.50 / -3.60
L3	-	0.28	7	-1.96
Total L	2 (+) / 3 (-)	1	27 of 30	+9.16 / -9.16

The presence of a regulatory and legal framework (L1 = 3.7 / -3.6) and state regulatory instruments (L2 = 3.5 / -3.6) regarding renewable energy sources creates favourable opportunities for the sector's development and ensures the sustainable development of the economy. However, the absence or non-fulfilment of conditions in international environmental agreements (L3 = -1.96) hinders the development of the country's energy sector and the potential for attracting foreign investments, expertise, and technologies.

As a result of assessing the impact of various aspects of the internal and external environment on implementing renewable energy sources to ensure sustainable economic development, cumulative weighted assessments (Total) were calculated for each factor. The summarized results for each impact factor are presented in figure 2.

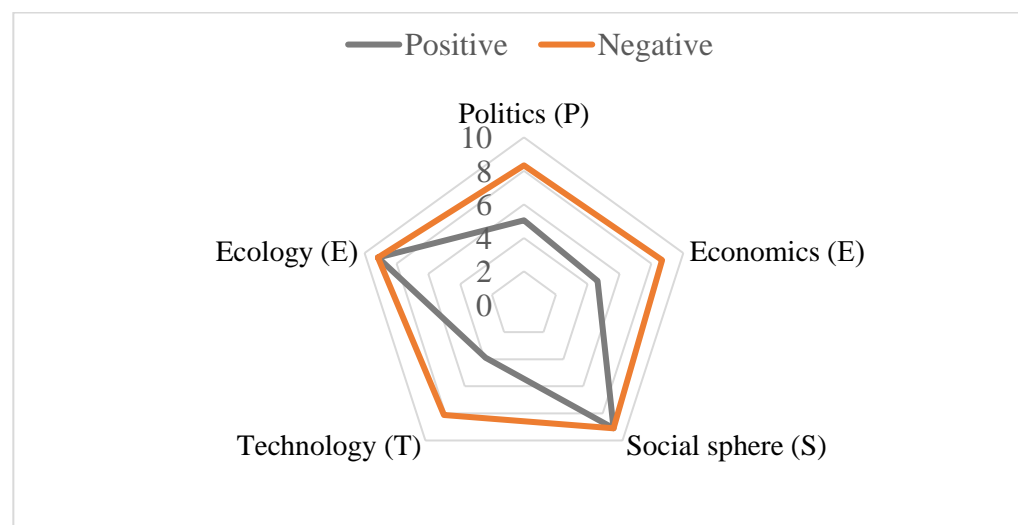


Figure 2. General assessment of factors influencing the implementation of renewable energy sources in sustainable economic development

Thus, the overall impact of political factors indicates that their negative influence (Total P = -7.70) significantly outweighs the positive opportunities (Total P = 3.05), due to political instability and the destruction of energy infrastructure. Additionally, economic factors (Total E = 5.05 / -8.33) hurt the development of the renewable energy sector, including the prohibitive costs of implementing renewable energy sources and the difficulty of accessing financial resources, which significantly limits the growth of this sector. In turn, low public awareness, and insufficient public support (Total S = -8.67) are the main barriers to the effective implementation of renewable energy, despite

positive social attitudes in some regions (Total S = 4.63). Technological factors demonstrated a balance between opportunities and threats (Total T = 9.1 / -9.1), as they can have both positive and negative consequences in the case of insufficient technological capacity. The main environmental threat to implementing renewable energy sources (Total E = 3.9 / -8.125) is the increased pressure on ecosystems due to inefficient management systems. The most significant favourable influence on the implementation of renewable energy comes from legal factors (Total L = 9.16 / -9.16), as a clear legislative framework creates stable conditions for the sustainable development of the national economy. Therefore, the slowdown in the development of renewable energy sources is caused by political instability and economic and social barriers. In contrast, technological innovations and balanced legal policies are critical tools for reducing negative impacts and stimulating further growth in the energy sector.

Discussion

The present study analyzed the influence of external and internal environmental factors on adopting renewable energy sources to achieve sustainable economic development, employing PESTEL analysis supported by expert assessments. Nonetheless, the study possesses certain limitations. Social factors, specifically public awareness of renewable energy sources, exhibit significant variations across regions, which were not captured in the study and may have an impact on the interpretation of social perception factors. However, this avoids significant fragmentation of the results and allows for a focus on more general trends and challenges. The study has a certain time frame (2021-2024), which may limit the applicability of the results in the long term if socioeconomic conditions, technological advances, or political situations change. Also, the focus on certain countries (e.g. Germany, Denmark, Austria, Nigeria, Ukraine) may limit the generalizability of the study's findings to other regions. This approach distinguishes our study from others. For instance, Igliński *et al.* (2016) conducted a PEST analysis of renewable energy sources in the Łódź Voivodeship, Poland, which primarily relied on a literature review without integrating statistical or empirical data. Similarly, Kansongue, Njuguna and Vertigans (2023) examined internal and external factors in renewable energy development in Togo, based on framework approaches, including PESTEL and SWOT analysis. Although this study includes current statistical data on the functionality of renewable energy sources, it does not assess the opportunities and threats to their development. Compared to prior studies, such as Igliński *et al.* (2016) and Kansongue, Njuguna and Vertigans (2023), our research integrates both expert assessments and statistical insights, providing a multifaceted perspective on the barriers and enablers of renewable energy adoption. Unlike Do Thi *et al.* (2021), which is based on applying PESTLE analysis, multi-criteria decision analysis, and life cycle assessment (LCA) methods for comparing desalination technologies using renewable energy sources, our study uniquely combines PESTEL analysis with expert input to highlight actionable recommendations. Their study presented a scientific discussion on fossil fuels and alternative energy sources by processing a large amount of statistical data from Saudi Arabia and creating a normalized decision matrix. However, the results of our study on the factors influencing the implementation of renewable energy sources in ensuring sustainable economic development are based on the collection of expert assessments, which provide unique results regarding political, economic, social, technological, legal, and environmental factors. Thus, recommendations for stakeholders based on: identified

policy challenges (Total P = 3.05 / -7.70) include ensuring coordination and consistency of strategies and strengthening government support for the renewable energy sector through clear incentives (green tariffs, subsidies, etc.); economic challenges (Total E = 5.05 / -8.33), which involves the implementation of measures to increase investments in renewable energy sources by intensifying public-private partnerships and simplifying bureaucratic barriers; social issues (Total S = 4.63 / -8.67) that can be addressed by expanding training programs for green jobs and increasing public awareness and confidence in renewable energy; technological barriers (Total T = 9.1 / -9.1), which require increasing the availability of renewable energy in rural and remote regions with the help of decentralized local government systems; environmental problems (Total E = 3.9 / -8.125), which require qualitative regulation of the impact of RES infrastructure on the environment; legal barriers (Total L = 9.16 / -9.16) require authorities to regulate the legal framework to facilitate the certification and licensing of RES infrastructure. Moreover, a large amount of scientific literature was analyzed, and our conclusions were made regarding the role of alternative energy in ensuring sustainable economic development. This study was also adapted to the conditions of the current Russia-Ukraine war and the need to restore energy infrastructure. However, future research should explore the integration of digital innovations, such as blockchain and IoT, into renewable energy systems to address technological and operational inefficiencies.

Conclusion

The modern concept of the energy sector, based on the use of alternative energy sources, aims to reduce dependence on fossil fuels, minimize greenhouse gas emissions, and improve air quality. At the same time, creating favourable conditions for the development of renewable energy sources stimulates innovation, energy efficiency, and sustainable consumption and generates new economic opportunities. In addition, collaboration between governments, private entities, and local communities is essential to overcoming sectoral barriers and realizing the full potential of renewable energy technologies. However, the effectiveness of implementing renewable energy sources is directly dependent on several political, economic, social, technological, environmental, and legal factors that determine the development of this sector and present potential risks. Given the current geopolitical tensions and energy crises, renewable energy adoption is more critical than ever to ensure energy security and environmental sustainability. Thus, renewable energy sources play a crucial role in ensuring the economy's sustainable development, combining sustainability principles with the country's overall economic growth. With continued investment and innovation, renewable energy can serve as a cornerstone for global climate action and energy independence, fostering resilience in the face of future challenges.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	Yes
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis and interpretation	Yes	Yes	No	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Typology Model of Emotional Intelligence Development in Civil Servants Engaged in Implementing Sustainable Development in Ukraine

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Abstract

In the contemporary context of global crises, such as the COVID-19 pandemic and the Russian-Ukrainian conflict, public servants' efficacy in managing natural resources critically depends on their emotional intelligence (EI). This study examines the critical role of EI in public servants managing natural resources during the COVID-19 pandemic and the Russian-Ukrainian conflict. These crises underscore the necessity of understanding public servants' emotional resilience, anxiety levels, and social competence to enhance their effectiveness and adaptability. The research explores whether public servants can be categorized into more than three typologies of EI development. It hypothesizes four distinct types: "Child", "Student/Pupil", "Specialist/Worker", and "Professional/Manager" characterized by unique combinations of emotional intelligence, anxiety, and social competence. A structured survey was administered on 150 public servants across Ukraine via Google Forms, covering demographic and professional variables. A refined sample of 30 participants, balanced by gender, geographic region, and service category, was subjected to cluster analysis. The findings revealed clear distinctions among the proposed typologies. The "Child" type represents individuals with low EI, high anxiety, and limited social competence, while the "Professional/Manager" type includes those with advanced EI, minimal anxiety, and strong social skills. Intermediate types, "Student/Pupil" and "Specialist/Worker," exhibit developmental trajectories toward higher emotional intelligence and professional competence. This typology provides a practical framework for designing tailored interventions aimed at improving the emotional intelligence of public servants. Recommended strategies include stress management techniques, mentoring, and continuous professional development programs. This study offers a novel approach to understanding and addressing the emotional and professional needs of public servants during periods of uncertainty.

Keywords

Civil servants; Emotional intelligence; Covid period; Typology models; Public administration; Sustainable development

Introduction

The relevance of emotional intelligence (EI) in public administration has significantly increased, particularly during the COVID-19 pandemic and ongoing conflicts (Ilichok *et al.*, 2023). These challenges have placed immense pressure on public servants, requiring innovative approaches to decision-making and sustainable management of resources. In this context, the development of emotional intelligence has emerged as a key factor in enhancing the adaptability and effectiveness of public servants. Global trends are driving substantial transformations in public administration, particularly in the integration of advanced technologies and the intellectualization of processes (Masyk *et al.*, 2023; Podolchak, 2022). Such changes are vital for improving collaboration between administrative authorities and stakeholders, especially under conditions of uncertainty. Emotional intelligence serves as a crucial competency for ensuring effective communication, decision-making, and resilience among public servants, which directly impacts organizational performance and sustainability.

Emotional intelligence plays a pivotal role in professional achievements, contributing to team cohesion and organizational success. Understanding and developing EI are especially relevant in modern public administration, where the ability to manage emotions, reduce anxiety, and enhance social competence is crucial. Despite the growing importance of this competency, research on its role in public administration remains limited, particularly regarding its application in crisis management and sustainable resource governance. By focusing on emotional intelligence, this study addresses a critical gap in the literature, offering insights into its impact on public servants' ability to navigate complex challenges. This investigation underscores the need for public management systems to incorporate EI development into training programs, thereby fostering more resilient and effective personnel capable of adapting to rapidly changing circumstances. The development of one's potential for emotional intelligence, and the acquisition of new emotional competencies is becoming an increasingly common phenomenon. The question of emotional intelligence is of interest to many researchers and theoreticians, and it is especially relevant to the field of public administration. Scientists distinguish the components of this human ability in different ways and offer different possible explanations for its functioning (Boruc, 2019). Among the most common theories is Meyer and Salovey's model (Meyer and Salovey, 1990), which distinguishes skills that support emotional functioning: evaluating and regulating emotions, as well as using emotions in action. The second important model is Goleman's (1997) model, which presents five main elements that form emotional intelligence: the ability to recognize and name one's own and others' emotions, manage emotions, the ability to motivate oneself, and the ability to maintain relationships with people. Bar-On's (2000) model of emotional intelligence, which includes stress control, individual elements of mood – optimism and happiness – and reality check, is another theoretical construct of the discussed topic that has gained relevance. In this model, the ability to control one's reactions is important, which is called the impulse control component (Gayathri and Meenakshi, 2013). Discussion of the concept of emotional intelligence obliges us to define its two components: emotions and intelligence. Psychology, which has emotions as one of its main objects of interest, has divided the mind into three parts since the 18th century: cognitive, affective, and motivational (Mayer and Salovey, 1999).

The development of emotional intelligence is a multiphase process consisting of the previously mentioned competencies, from the recognition of emotions to their effective control and management (Piotrowski, Gulla and Jaskułowski, 2011). A deficit of emotional intelligence is associated with consequences, which include: limited or impossible understanding of one's own emotional experiences; incompetent expression of emotions, which can lead to rumination, weakening of control over emotional manifestations or violation of the influence of emotions on the actions taken. Emotions cause difficulties in effective mobilization and in choosing the right course of action, as well as in choosing its direction (Podolchak, Tsygylyk and Dziurakh, 2022; Shpak *et al.*, 2021; Sribna *et al.*, 2023). Perhaps we are dealing here with the concept introduced by Goleman (1997), which is emotional illiteracy, which consists of the lack of ability to understand complex interpersonal contexts.

Despite the numerous empirical studies conducted on the very concept of emotional intelligence, little can be found in the literature on its determinants. The development of emotional intelligence occurs under the influence of the individual's experiences, which are recorded in the autobiographical memory, that is, in the one that refers to the past. Behavioural models studied by Lazarus and Folkman (1987) and Rongińska and Gaida (2001) underscore the significance of individual capabilities and interpersonal relationships in managing professional demands. The theoretical and methodological basis of the development of a typology model of emotional intelligence development is the presence of three levels of general emotional intelligence in all known models for its assessment. In particular, its levels are defined as: low, medium and high. However, the components of emotional intelligence are different in all models. Mayer and Salovey conceptualized emotional intelligence as the ability to perceive, understand, utilize, and manage emotions, a framework operationalized through the Mayer-Salovey-Caruso Emotional Intelligence Test (MSCEIT) (Mayer *et al.*, 2004). Goleman (1997) created a model that considers emotional intelligence as a set of skills that can be developed separately, which are self-awareness, self-management, social awareness and relationship management. His view of emotional intelligence stems from his inability to accept a narrow, biological definition of intelligence in which intelligence quotients are inherited and invariant over life experience (Goleman, 2007). He also defines a person's potential ability to acquire practical skills based on self-awareness, motivation, self-direction, empathy, and good relationships with other people (Goleman, 2007). According to Yelkikalan *et al.*, (2012), its level increases with age. This is because it is largely acquired and thus develops throughout life through experience (Goleman, 2007). Emotional intelligence affects task performance as well as achievement (including academic performance (Yelkikalan *et al.*, 2012).

The role of emotions in human life is extremely important, especially when it comes to significant events (Lazarus, 1991). Emotions are an expression of how a person relates to a certain reality, and how they perceive and interpret this reality. It is emotions that guide human choices and behaviour (Gasiul, 2007). They can be defined as a direct reaction of the organism to environmental stimuli (Podolchak, Tsygylyk and Dziurakh, 2022). They are the generator of further reactions on the physiological, physical, psychological and, accordingly, social levels. Emotions determine the way or style of communication (both verbal and non-verbal) and its perception and therefore play a role in the formation of relationships. Especially in the formation of significant, close ones, but also - they also

protect against the formation of some. The genesis of primary emotions, such as fear or disgust, is related to the survival instinct. Both fear and disgust in their primary form are designed to warn of danger (TenHouten, 2006; Podolchak *et al.*, 2023; Podolchak *et al.*, 2022). The biological aspect of this phenomenon is to protect the life and survival of the species. Its psychosocial dimension, on the other hand, consists of preventing entry into risky relationships or interactions that may become a burden. It is important to accurately interpret your own emotions, as well as to correctly assess the emotional state of people with whom you interact. The ability to recognize one's own emotions and the emotions of other people is a component of emotional intelligence.

In addition to managing emotions and the level of emotional intelligence, social competence also determines effective social functioning. Matczak and Knopp (2013) consider emotional intelligence as a basis for the formation of social competence. Like emotional intelligence, social competencies are also developed to a large extent through social activity, and contacts with other people and are correlated with each other. Social competence is an acquired skill that can be effectively applied in various social situations. Social competencies include the following skills: adaptability (ability to adapt and be flexible in different situational contexts); emotional connection (ability to form satisfactory emotional relationships and receive social support); effective communication (ability to read other people's intentions, interpret their messages and adequately respond to them); the ability to achieve one's own goals (dexterity in actions and interpersonal relations) (Henne, 2003). They are useful for improving collaboration and problem-solving. They contribute to one's development and overcoming difficulties, the ability to get along with people, to get to know and support them. Due to them, a person is accepted by others (Otrębski and Rutkowska, 2006). Along with emotional intelligence social competencies also determine effective social functioning. Matczak and Knopp (2013) consider emotional intelligence as a basis for the formation of social competencies. Like emotional intelligence, social competencies are also developed to a large extent through social activity, and contacts with other people and are correlated with each other. The connection of emotional intelligence with self-awareness, self-control, motivation, empathy, social skills, and communication skills causes its direct impact on the effectiveness and efficiency of the performance of tasks (Podolchak, Prokopyshyn-Rashkevych and Karkovska, 2019; Yelkikalan *et al.*, 2012). However, to date, there are no scientific works that would assess the degree of impact of COVID-19 on the level of emotional intelligence and, therefore, the model of levels of emotional intelligence.

In light of the above knowledge, this study aims to develop a typological model for the development of emotional intelligence, which involves the specification of types for the possibility of developing emotional intelligence in the workplace for public servants. We hypothesize that there are more than three distinct types of emotional intelligence models among public servants during the COVID-19 pandemic, characterized by their levels of emotional intelligence, anxiety, and social responsibility. Establishing a clear number of types of the model of emotional intelligence will make it possible to recommend specific methods of developing their soft skills and build reasonable career plans with a high degree of probability of implementation in practice due to a more accurate knowledge of their types of the model of emotional intelligence. To test this hypothesis, the study was guided by the following objectives:

- (1) to form a country-wide sample of public servants, ensuring even gender distribution and a manageable size (30 participants) for effective statistical analysis;
- (2) to identify types of emotional intelligence models based on levels of emotional intelligence, anxiety, and social competence during the COVID-19 pandemic, using quantitative data derived from validated surveys;
- (3) to use cluster analysis to distinguish different types of emotional intelligence development models;
- (4) to validate the classification of public servants into specific emotional intelligence types through statistical evaluation.

Methodology

Design of Survey and Sampling

The study employed a survey designed in Google Forms, comprising three sections. The first section collected demographic and professional data, including age, gender, territorial residence (North, South, West, East, or Center of Ukraine), affiliation to the public service category (A, B, or C), and length of service. The second section evaluated emotional intelligence using the Hall test, measuring components such as self-awareness, emotional regulation, empathy, and interpersonal skills. The third section assessed anxiety using the GAD-7 test and social competence through a validated set of questions targeting adaptability, emotional connection, and communication abilities.

From the total sample of 150 public servants, 30 were selected for detailed analysis. The research group included 10 respondents from each public service category (A, B, and C), with an even distribution by gender and territorial residence across Ukraine. Specifically, two participants from each region (North, South, West, East, and Center) were selected per category to ensure geographic and professional representation. This categorization was applied to minimize sampling bias and provide balanced data for subsequent cluster analysis.

The selected group had an average age of 35 years, with a standard deviation of ± 10 years. While approximately half of the respondents were aged 24–30, about a third were aged 40–60, ensuring representation across different experience levels. Social competence was assessed using the 360° feedback method, a multidimensional approach that incorporates evaluations from supervisors, peers, and self-assessments (Nowack, 2009) (Figure 1). This method provided a comprehensive view of interpersonal and professional skills, with results scaled from 0 to 1 for use in cluster analysis.

Figure 1 illustrates the typology model of emotional intelligence development, according to which the emotional intelligence of personnel was analyzed at different levels of development. In particular, the type of development “Professional/manager” corresponds to a high level of emotional intelligence, “Specialist/worker” and “Student/pupil” corresponds to an average level, and “Child” corresponds to a low level.

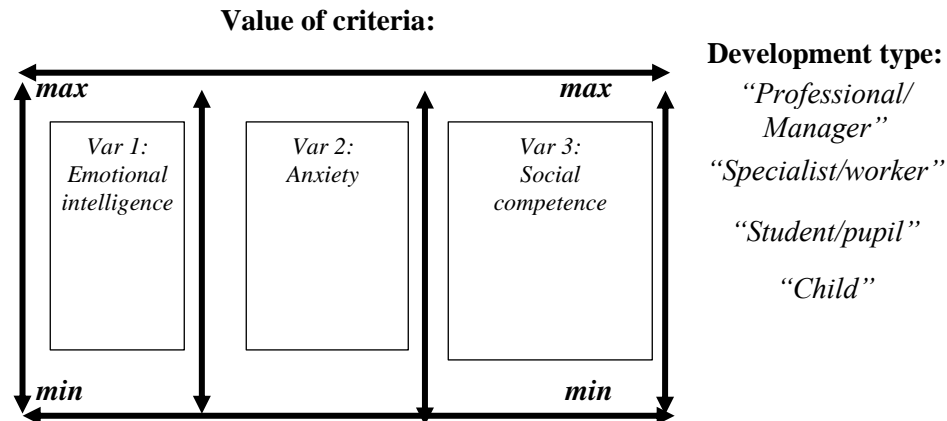


Figure 1: Typology model of emotional intelligence development
 * formed by the authors based on Caruso (2008), and Goleman (1997).

Statistical Analysis

For clustering, three key parameters were used: emotional intelligence (measured using the Hall test), anxiety (assessed through the GAD-7 test), and social competence (evaluated from survey responses). The clustering process involved constructing a similarity dendrogram using Ward’s method with Euclidean distances as the measure of similarity or dissimilarity. Based on the dendrogram, the optimal number of clusters was determined using the “elbow method” and analysis of significant jumps in cluster formation. The identified clusters were further refined using the k-means method to allocate the studied criteria to specific types. Finally, average values of classification features within each cluster were analyzed, and the clustering results were interpreted to identify dependencies between the selected criteria.

Levels of Emotional Intelligence and Their Evaluation

The study classified emotional intelligence (EI) into three levels: low, medium, and high. These levels were derived from the Hall test, a validated instrument widely used to measure EI. The test evaluates self-awareness, emotional regulation, interpersonal skills, and empathy, which are critical components of emotional intelligence (Mayer and Salovey, 1997). Public servants were categorized into distinct EI levels based on their test scores, scaled between 0 and 1 for analysis. Low EI corresponds to challenges in recognizing and managing emotions, medium EI reflects moderate proficiency and high EI indicates advanced emotional competence, including the ability to empathize and maintain effective social interactions. These levels provided a framework for cluster analysis, enabling the identification of developmental typologies. The classification into EI levels was essential for understanding the variability in public servants' emotional and social competencies. Emotional intelligence significantly impacts decision-making, stress management, and professional interactions, making it a critical factor in assessing public servants' effectiveness during crises. By categorizing participants into distinct levels, the study aimed to provide actionable insights for targeted interventions and professional development strategies.

Results

Overview of Emotional Intelligence Typology

The formation of social competence is critical in modern society, as it determines an individual's success in daily life, enabling adaptation, influence over life events, and the development of personality orientations (Shpak *et al.*, 2022). Globalization and societal progress further emphasize the need for such qualities to establish universal principles and support personal growth. Globalization and societal progress increase the need for qualities that uphold universal principles and foster personal development.

The characteristics of the model of the typology of the development of emotional intelligence provide for the formation of a specific type of development of the emotional intelligence of an individual, in particular:

Developmental type “Child”:

This developmental type includes 16% of the respondents, and was the least prevalent among the public servants. In the cluster analysis, public servants identified as the “Child” type exhibited lower scores in emotional intelligence and social competence, alongside higher anxiety levels. This group requires targeted interventions to foster emotional growth, including training in emotional regulation and social skills. The high level of intelligence of the parents is a kind of potential for the development of this intelligence in the child. In turn, such parental guidelines as a high level of activity, availability, flexibility and a positive attitude are also positively correlated with the level of emotional intelligence of children. The most important role in the formation of emotional competence is played by the process of socialization of the child in the family environment. The social conditions in which the child develops, and the upbringing to which this child is exposed, make up a complex of social determinants of emotional intelligence.

As for psychological affiliation, the level of the “child” cycle characterizes a mature person who feels, thinks, acts, speaks and reacts as in childhood. Such a person is in constant doubt and complex. A person lives in tension and is afraid to take unnecessary or wrong steps. The person has a constant struggle with herself for anything. In this state, a person will always adapt to others, it is difficult for him/her to adapt to the environment in which he/she is, such people, are often offended and make claims to others. As a result of such considerations, the person becomes disappointed in life and neglects the opportunity to use the experience gained to exclude similar mistakes in the future.

Development type “Pupil/Student”:

This group included 27% of the respondents, highlighting its prevalence among public servants. At this level of the cycle of emotional intelligence, there is an opportunity to acquire appropriate social competencies, the ability to manage emotions and develop emotional intelligence. All this is possible in the case of the positive influence of educators, in particular parents, and teachers. At this level, there are many opportunities for purposeful development and learning. For an adult, the level of the “Pupil” cycle is

characterized by the opportunity to acquire knowledge, skills and competence to a greater extent, which corresponds to a professional direction. In addition, this level of the emotional intelligence development cycle is characterized by a lack of stability in the perception of the situation. The so-called emotional illiteracy is also associated with the growth of adolescent problems (Piotrowski, Gulla and Jaskułowski, 2011), in particular: impaired self-control and emotional expression, lack of ability to recognize and name experienced emotions, cognitive disorders of self-control, low self-esteem, lack of ability to predict consequences own actions, a negative image of the world, lack of a sense of the meaning of life, lack of empathy, etc. Problems in these areas usually begin in childhood, and if timely measures are not taken to rehabilitate a person, – his/her deficit will begin to affect more and more broad areas of his/her functioning. This will contribute to irreversible damage to the emotional and social sphere of the personality, which will not function properly in adulthood (Boruc, 2019). Both a deficiency of emotional intelligence and a low sense of quality of life.

At the “Student” level of development emotional intelligence and social competence develop to a large extent through social activity, and contacts with other people and are positively correlated with each other. At this stage a wide range of opportunities for acquiring skills in various directions and self-improvement are present, however, the general environment is an important factor in the development of students’ emotional intelligence. If this level is low, it is likely to hurt the student, lead to behavioural and emotional maladjustment, and problems at this age and, as a result, may affect his/her academic performance and success in adulthood. Therefore, this level of the cycle can also be characterized as such that the control of emotions, social competence and emotional intelligence is expressed by the perception of the “Student” by the environment.

Development Type “Specialist/Worker”:

This developmental type includes 37 % of the respondents and was most prevalent among the public servants. High emotional intelligence in itself does not guarantee that a person with it will be able to use emotional skills at work. However, it is a lever to achieve the opportunities included in its mandate. For example, excellent customer service is the result of highly developed empathy. The same applies to trust in a person, which is an expression of competence based on the ability to manage oneself (self-regulation), i.e. to control impulses and emotions. Emotional intelligence is extremely important when it comes to communication. Key elements of effective communication depend on the ability to “put yourself in the shoes” of the recipients of messages. Highly emotional people, as it were, unconsciously pay attention not only to external factors, such as the tone of voice or facial expression of the interlocutor, but, above all, they subjectively perceive, analyze and evaluate the perceived stimuli.

It’s hard to overstate the importance of emotional intelligence in the workplace. Having a high level of emotional intelligence and social competence in combination with a low level of anxiety, that is, the ability to manage emotions will positively affect the professional career of employees at all levels: from better communication to increased productivity and leadership skills. In addition, with the increasing globalization of many companies, emotional intelligence plays an especially important role at work. Multicultural teams must learn to understand each other, express their opinions and

views, and adapt to their differences. Employees also have to deal with increasingly complex relationships with consumers and colleagues. Thus, having the emotional ability to empathize, interact, and collaborate with people from other social groups will improve work performance and effectiveness. A distinctive feature of those who have reached the highest positions in their careers is persistence, the ability to build partnerships, the willingness to make efforts and the ability to seek help from more experienced people.

Development Type “Professional/Manager”:

This developmental type includes 20 % of the respondents, highlighting its prevalence among public servants. The type of development “Professional/manager” is characterized by high social competence, in particular, an acquired skill that can be effectively applied in various social situations. Social competencies include the following skills: adaptability (ability to adapt and be flexible in different situational contexts); emotional connection (ability to form satisfactory emotional relationships and receive social support); effective communication (ability to read other people’s intentions, interpret their messages and respond appropriately to them); the ability to achieve one’s own goals (dexterity in actions and interpersonal relationships) (Henne, 2003). They are useful for improving collaboration and problem-solving. They contribute to one’s development and overcoming difficulties, the ability to get along with people, to get to know and support them. They make a person acceptable to others (Otrębski and Rutkowska, 2006). Therefore, the level of the cycle “Professional / manager” can still be interpreted as a formed effective leader. A leader’s lack of interpersonal communication skills negatively affects the work of all his subordinates – it leads to wasting time, causes bitterness, weakens motivation and commitment, and causes anger, hostility and apathy. A leader’s high emotional intelligence, or lack of it, can be measured by the organization’s gains or losses in using the talents of subordinates.

Broadly speaking, emotional intelligence is the ability to recognize, manage, and use one’s own emotions and the emotions of others. This means that people with high emotional intelligence can easily recognize the emotions that they and others feel. They can also regulate their emotions and use them to accomplish a variety of tasks and responsibilities while helping others achieve the same. Public servants are a group consisting primarily of heads of departments, services, departments, etc. The second, more numerous part of the staff consists of specialists in various fields of activity.

The specifics of the work of heads/managers in the field of public administration consists in the management of subordinate personnel, i.e. it is a process consisting of three elements: power, leadership and management. This function of the manager is reduced to finding and applying the best way to transform resources into planned results; the manager’s function is to enter into two-way relations, as a head and as a subordinate (Stępień, 2002), and the function of a leader is to rally followers, exert influence, create a vision of development and motivate people to action (Kanarski, 2002). The appropriate level of a managerial position requires from the head/manager (public servant) not only knowledge of management and practice, but also relevant social skills, in particular, this awareness and desire to satisfy the basic needs of the team, and not only material or official, but also emotional, as they are clearly defined addictions and official relations

significantly narrow the individual's opportunities for action. In addition, the created image of a public servant as a mentally strong person makes it difficult to overcome difficulties and, as a result, can lead to emotional disorders (Florkowski, 2000). Therefore, the skills he/she possesses in terms of managing his/her emotions will certainly be useful in his day-to-day work as a public servant. A modern public servant, in addition to mastering and using specialized knowledge, must also be good at social skills, which is undoubtedly facilitated by a high level of emotional intelligence (Jaworowska and Matczak, 2001). Based on this, three key categories were chosen, which served as the basis for conducting cluster analysis.

Data and Cluster Formation

The data in table 1 was derived from a structured survey conducted among a sample of 30 public servants, selected from a larger pool of 150 respondents. The survey collected information on three key variables: emotional intelligence (Var 1), anxiety (Var 2), and social competence (Var 3). These variables were assessed using validated tools: the Hall test for emotional intelligence, the GAD-7 test for anxiety, and a set of survey questions to evaluate social competence.

Additionally, demographic and professional details were recorded, including age, gender, place of residence (North, South, West, East, or Center of Ukraine), and public service category (A, B, or C). The 30 respondents were selected to ensure a balanced representation across these categories, with even gender distribution and geographic representation. The collected data was then scaled between 0 and 1 to standardize it for further statistical analysis, including clustering.

Table 1: Input data for cluster analysis of the formation of types of emotional intelligence development

No.	Var 1: Emotional intelligence	Var 2: Anxiety	Var 3: Social competence	Age	Gender	Place of residence	Public service category
1	0.90	0.10	0.80	49	F	Center	A
2	0.95	0.0	1.00	60	M	East	A
3	0.78	0.10	0.80	43	M	North	A
4	0.98	0.05	1.00	47	M	West	A
5	0.60	0.30	0.55	36	M	East	B
6	0.72	0.20	0.64	25	F	North	C
7	0.82	0.15	0.76	43	F	West	A
8	0.64	0.26	0.70	32	M	North	B
9	0.75	0.12	0.74	53	M	South	A
10	0.93	0.10	0.90	40	F	North	A
11	0.81	0.20	0.75	28	F	North	B
12	0.54	0.40	0.49	24	F	Center	C
13	0.63	0.34	0.50	25	M	Center	C
14	0.48	0.60	0.63	31	M	South	B
15	0.73	0.21	0.65	30	F	Center	B
16	0.37	0.41	0.36	28	F	West	C

No.	Var 1: Emotional intelligence	Var 2: Anxiety	Var 3: Social competence	Age	Gender	Place of residence	Public service category
17	0.70	0.19	0.73	51	M	Center	A
18	0.86	0.10	0.89	43	F	East	A
19	0.34	0.71	0.33	26	F	East	C
20	0.91	0.07	0.90	40	F	South	A
21	0.67	0.54	0.61	27	F	West	B
22	0.84	0.23	0.79	29	M	West	B
23	0.25	0.85	0.19	25	F	South	C
24	0.31	0.76	0.29	29	M	Center	B
25	0.52	0.48	0.43	27	M	East	C
26	0.29	0.93	0.15	24	M	North	C
27	0.66	0.25	0.63	25	M	West	C
28	0.73	0.19	0.78	33	F	South	B
29	0.33	0.74	0.35	48	F	East	B
30	0.49	0.58	0.67	41	M	South	C

Based on table 1, a similarity dendrogram based on Euclidean distances was constructed, shown in figure 2.

The most significant associations, which correspond to the “jumps” of the Ward graph, are characteristic of the optimal number of clusters, which is determined by calculating the difference between the number of examined criteria and the step corresponding to an obvious “jump”. Therefore, it is possible to combine into four clusters.

The results obtained using the analysis of the union graph (Figure 2) coincide with the results using the conglomerative method. The criterion for further selection from among the options for the number of classification groups, in particular four, is the maximum number of indicators that will be significant for this multifactor grouping (Figure 3). The advantage of this method is the ability to check the statistical significance of differences between selected clusters.

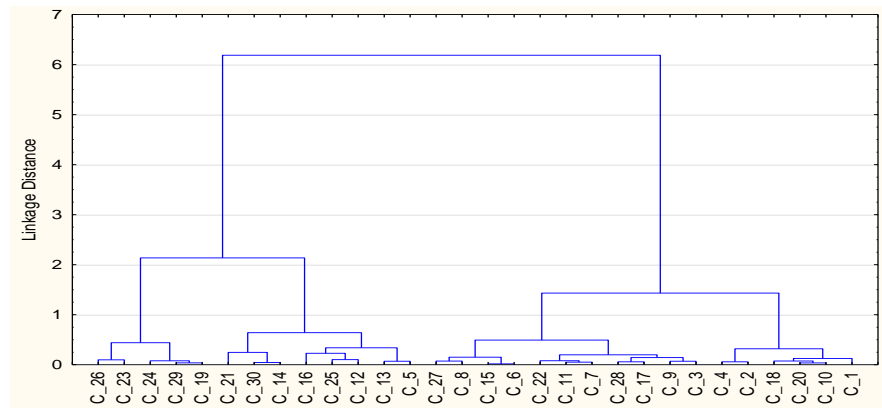
The variability of the formed clusters is described by values from 0 to 1 and the following characteristics:

Cluster – 1: type “pupil/student” criteria Var 1: Emotional intelligence, Var2: Anxiety, Var3: Social competence is within the average level;

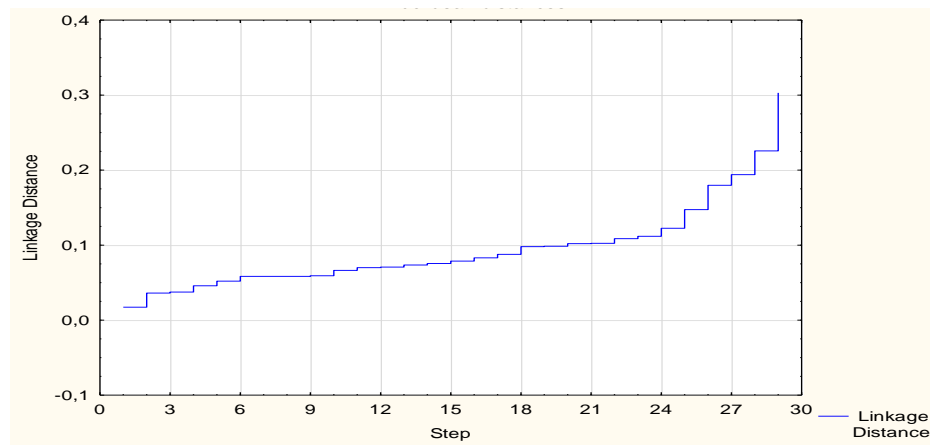
Cluster – 2: type “child” criterion Var 1: Emotional intelligence, Var3: Social competence - the lowest, Var2: Anxiety – the highest.

Cluster – 3: type “specialist/worker” criteria values Var 1: Emotional intelligence, Var3: Social competence – above average, Var2: Anxiety – below average.

Cluster – 4: type “professional/manager (leader)” criterion Var 1: Emotional intelligence, Var3: Social competence – the highest, Var2: Anxiety – the lowest.



(a)



(b)

Figure 2: Dendrogram of the formation of clusters and the graph of unification of the types of development of emotional intelligence: a) Tree Diagram for 30 Cases Ward's method Euclidean Distances; b) plot of Linkage Distances across Steps Euclidean Distances

Validation of Hypothesis

Table 2: Averaged values of criteria for clustering types of emotional intelligence development (*k*-means clustering results dialogue)

Criterion	The average value of cluster formation	Standard deviation	Dispersion	Number of surveyed respondents in the Covid-19 period
Cluster – 1: type “pupil/student”				
Var 1	0.537	0.095	0.009	8
Var 2	0.456	0.111	0.012	
Var 3	0.530	0.105	0.011	
Cluster – 2: type “child”				
Var 1	0.304	0.035	0.001	5
Var 2	0.798	0.090	0.008	
Var 3	0.262	0.087	0.007	

Criterion	The average value of cluster formation	Standard deviation	Dispersion	Number of surveyed respondents in the Covid-19 period		
Cluster – 3: type “specialist/worker”						
Var 1	0.743	0.064	0.004	11		
Var 2	0.190	0.050	0.002			
Var 3	0.724	0.061	0.003			
Cluster – 4: type “professional/manager (leader)”						
Var 1	0.921	0.041	0.001	6		
Var 2	0.070	0.040	0.001			
Var 3	0.915	0.075	0.005			
Variable	Analysis of Variance					
	Between SS	df	Within SS	df	F	Signig f. p <
Var 1	1.239	3	0.119	26	90.082	0.001
Var 2	1.838	3	0.152	26	104.322	0.001
Var 3	1.342	3	0.174	26	66.517	0.001

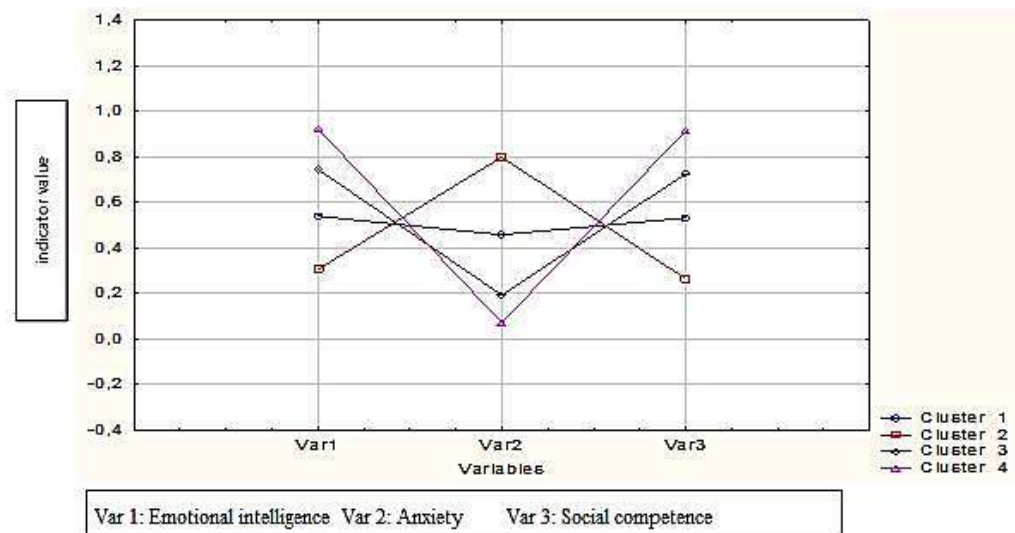


Figure 3: Variability of formed clusters of types of emotional intelligence development

As can be seen from table 2, 37% of the surveyed public servants belong to the “specialist/worker” type of emotional intelligence development, 27% correspond to the “pupil/student” type, 20% of public servants belong to the “professional/manager (leader)” type, and 16 % – corresponding to the “child” type. These findings support our hypothesis that there is a presence of more than three types of emotional intelligence models in the hierarchy of the division of public servants during the COVID-19 pandemic according to indicators of emotional intelligence, anxiety and social responsibility.

Discussion

Our findings identified four distinct clusters - “Child,” “Pupil/Student,” “Specialist/Worker,” and “Professional/Manager”— each representing unique combinations of emotional intelligence, anxiety, and social competence levels. Notably, public servants in the “Child” cluster displayed low emotional intelligence and high anxiety, which significantly impeded their professional growth and adversely affected the overall psychological climate within their teams. Such individuals necessitate interventions to enhance their emotional intelligence through training, mentoring, and work-life balance initiatives. These results align with existing literature that emphasizes the impact of emotional intelligence on professional effectiveness and team dynamics (Goleman, 1997; Podolchak, Tsygylyk and Dziurakh, 2022; Popadynets *et al.*, 2021; Prykhodko *et al.*, 2021). However, our study faces limitations due to its small sample size and the self-reported nature of data, which may not capture the full complexity of emotional intelligence dynamics in workplace settings. Future studies could expand the sample size and explore the integration of behavioural assessments to corroborate self-reported data.

Our findings contribute to the understanding of emotional intelligence in public administration, suggesting that enhanced emotional intelligence can significantly improve public servants' effectiveness and adaptability. This research underscores the necessity for ongoing professional development programs tailored to different emotional intelligence levels, particularly in challenging contexts like the pandemic. Additionally, considering the global relevance of emotional intelligence in diverse professional settings, further research could explore comparative studies across different cultures and administrative frameworks to enhance the generalizability of these findings.

Increasing the level of emotional intelligence is associated with decreased anxiety and enhanced social competence, facilitating progression from the “Child” developmental type to the “Pupil/Student” stage and potentially onward to “Specialist/Worker” and “Professional/Manager” levels. This progression reflects a dynamic where enhanced emotional management capabilities lead to improved interpersonal and professional outcomes (Goleman, 1997). Continuous effort in developing emotional intelligence is crucial for transitioning through these stages, highlighting the transformative impact of emotional intelligence on personal and professional growth (Salovey and Mayer, 1990). The “Pupil/Student” type cluster consists of public servants who exhibit balanced emotional intelligence, emotion management, and social competence, generally at a moderate level. This group is characterized by a positive orientation towards professional development, demonstrating openness to learning and adapting through educational opportunities, professional training, and mentoring (Podolchak *et al.*, 2022). While this development stage is promising, these individuals are still influenced significantly by their environmental context, which can lead to variability in their performance and task handling (Prykhodko *et al.*, 2021).

Those in the “Specialist/Worker” cluster display an average ability to manage emotions, corresponding to moderate levels of anxiety and social competence. They are generally effective in their roles and contribute positively to the team's psychological climate. However, there is room for further development in emotional intelligence and social skills to achieve optimal effectiveness and adaptability in their professional roles

(Popadynets *et al.*, 2021). Implementing targeted training and continuous professional development can significantly enhance the capabilities of public servants, leading to improved individual performance and overall organizational health (Mayer, Salovey and Caruso, 2008). These findings suggest that fostering emotional intelligence in public administration is not only beneficial but essential for professional success and a positive workplace environment. Future studies should focus on longitudinal assessments to better understand the long-term impacts of emotional intelligence development on public service efficiency and effectiveness.

Based on the above, the following methods should be used for the development of emotional intelligence, reduction of anxiety and improvement of social competence for public servants who belong to the type of “pupil/student” and “specialist/worker”: communication training, stress management techniques, work on social skills, feedback, maintaining a positive working atmosphere, development of leadership skills, healthy balance of work and life, learning throughout life. These findings are consistent with established research in the field of emotional intelligence and its impact on workplace behaviour and performance. Key contributions by Goleman (2007), Yelkikalan *et al.* (2012), Lazarus (1991), Gasiul (2007), and Podolchak *et al.* (2022) underline the significant role that emotional intelligence plays in enhancing individual adaptability and overall organizational effectiveness. Their research supports the notion that increased emotional intelligence is crucial for reducing anxiety, improving social competence, and facilitating progression through various developmental stages within the public service sector.

Public servants who belong to the “professional/manager” cluster in terms of the level of emotional intelligence development have a high value of managing emotions (ie, low anxiety), social competence, and a high level of emotional intelligence. They perform tasks as efficiently as possible and contribute to maintaining a healthy psychological climate in the team. Moreover, these public servants can be mentors for the development of emotional intelligence for the types of “child”, “student/pupil”, and “specialist/worker” and are the driving force in the performance of assigned tasks. These public servants can reduce the negative impact of COVID-19 on the personnel of the organization through their activities. However, they should also not forget about the principle of lifelong learning to maintain their skills and abilities at a high level. These findings are consistent with established research in the field of emotional intelligence and its impact on workplace behaviour and performance. Key contributions by Goleman (2007), Yelkikalan *et al.* (2012), Lazarus (1991), Gasiul (2007), and Podolchak *et al.* (2022) underline the significant role that emotional intelligence plays in enhancing individual adaptability and overall organizational effectiveness. Their research supports the notion that increased emotional intelligence is crucial for reducing anxiety, improving social competence, and facilitating progression through various developmental stages within the public service sector.

Research on the level of emotional intelligence and its impact on the effectiveness of assigned tasks remains an ongoing area of inquiry. Enhancing emotional intelligence is crucial not only for personal growth and organizational effectiveness but also plays a significant role in sustainable natural resource management. By fostering an emotionally intelligent workforce, public organizations are better equipped to adapt to

environmental, social, and economic challenges, thereby contributing significantly to the United Nations Sustainable Development Goals. For instance, emotionally intelligent leaders in public agencies can manage resources more effectively, make informed decisions that promote sustainability, and ensure that development strategies prioritize ecological balance and social equity. A study by Smith and Lazarus (2018) demonstrated that organizations with higher levels of emotional intelligence among their staff were more successful in implementing sustainable practices. These organizations tended to have better teamwork and communication, leading to more innovative solutions for environmental management. Moreover, integrating emotional intelligence into the training programs of public servants can enhance their responsiveness to the complex dynamics of climate change, economic shifts, and social inequalities. This integration aligns with findings from Jones *et al.* (2020), who found that public sector employees with high emotional intelligence were more adept at navigating the complexities of policy implementation related to sustainable development, particularly in multi-stakeholder environments.

Thus, the ongoing research underlines the importance of emotional intelligence in fostering a public sector that is not only effective in its immediate tasks but also competent in advancing broader sustainability objectives. This strategic approach ensures that development strategies are not only effective but also inclusive and equitable, further enhancing the long-term sustainability of natural resources and community livelihoods. Enhancing emotional intelligence in public organizations supports their adaptability to environmental, social, and economic challenges, thereby contributing significantly to the United Nations Sustainable Development Goals (SDGs). This alignment is crucial as emotionally intelligent leaders are better equipped to manage the complexities of sustainable resource management and policy implementation. For instance, their ability to handle stress and engage stakeholders effectively facilitates progress toward climate action (SDG 13), promotes sustainable cities and communities (SDG 11), supports good health and well-being (SDG 3), and fosters partnerships (SDG 17). Research on the level of emotional intelligence and its impact on the effectiveness of assigned tasks is ongoing, highlighting that higher emotional intelligence not only aids in personal and organizational effectiveness but also ensures that development strategies consider ecological balance and social equity. This ongoing inquiry underscores the role of emotional intelligence in making informed decisions that promote sustainability, manage resources more effectively, and advance broader sustainability objectives. The study has broader implications for targeted interventions for the "Child" group - training programs to foster emotional regulation and social competence; for the "Pupil/Student" group: Support for professional skill-building and emotional stability; for the "Specialist/Worker" group - enhancements to empathy and leadership skills; and for the "Professional/Manager" group - strategies to sustain high performance and minimize stress.

Conclusion

In this study, we developed a typology model of emotional intelligence using cluster analysis to explore how emotional intelligence can influence the performance of public servants during the COVID-19 pandemic. Our hypothesis questioned whether different levels of emotional intelligence affect their capability to handle workplace demands

effectively. The analysis categorized public servants into four developmental types: "child", "pupil/student", "specialist/worker", and "professional/manager". Each category demonstrates distinct levels of emotional intelligence, anxiety, and social competence. Implementing this model can enhance decision-making, stress management, and interpersonal skills, crucial for addressing the complex challenges of sustainable natural resource management. By improving emotional intelligence, public servants can more effectively implement sustainable practices, contributing to the broader goals of the Sustainable Development Goals by promoting ecological balance and social equity. For ongoing professional enhancement, targeted training and educational programs are essential. These should focus on communication training, stress management, and developing leadership skills to continuously improve the emotional and social competencies of public servants. Future studies should investigate the applicability of this emotional intelligence development model in the post-COVID-19 era and perform a comparative analysis to validate the current findings. While the results are recommendatory and provide a basis for informed decision-making, they should not be seen as conclusive for evaluating the overall effectiveness and efficiency of public servants. By integrating emotional intelligence frameworks within public administration, we can foster a more resilient and adaptive workforce, capable of managing both current and future environmental and social challenges effectively.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4
Conceived and designed the research or analysis	Yes	No	Yes	Yes
Collected the data	Yes	No	Yes	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Green Entrepreneurship Strategies: Integrating Eco-Friendly Energy Technologies with the Digital Economy

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Abstract

Integrating innovation, energy-saving technologies, and the digital economy is crucial for achieving sustainable development, increasing competitiveness and ensuring a high quality of life. Addressing this issue requires a comprehensive approach involving cooperation between governments, businesses and society to achieve shared goals. This study evaluates the interaction between energy-saving technologies and the digital economy in green business and offers practical recommendations for entrepreneurs and government agencies to support green businesses through political and economic measures. Research employed methods such as literature review, monographic, analytical, graphical, content analysis, comparison, synthesis and analysis, and generalisation. The article highlights the leading positions of scholars from different countries on the issues under study in recent years. A comparative analysis of the Top 10 countries of the world based on the 2023 Human Development Index and the Innovation Development Index is presented. This study shows that trends in global investment in energy efficiency (2015-2022), the growth of gross value added in the environmental goods and services sector in the EU-27 (2001-2021), and the growth of green bonds (2019-2022) within the EU-27 demonstrate the effectiveness of green entrepreneurship through innovation and digitalisation. Leading digital platforms for transferring innovations to green businesses were identified. The article also provides practical recommendations for the transfer of innovations to promote green business development in the context of digital transformation for entrepreneurs and government agencies.

Keywords

Green entrepreneurship; Energy-saving technologies; Green economy; Innovation; Digital economy

Introduction

Climate change, environmental pollution and depletion of natural resources necessitate finding new solutions to reduce the negative impact on the environment. Climate change has become one of the most critical and hotly debated issues of the twenty-first century, threatening to destroy the world. One of the main causes of climate change is greenhouse gas emissions, which are wreaking havoc on the earth (Shang *et al.*, 2022). Energy-saving technologies and digital innovations can significantly reduce greenhouse gas emissions and resource consumption. Society, investors, and consumers increasingly demand that businesses adhere to the principles of sustainable development. Green businesses that integrate energy-saving technologies with the digital economy meet these requirements and create competitive advantages (Zhu *et al.*, 2023). The development of digital technologies, such as the Internet of Things (IoT), artificial intelligence, blockchain, and big data, opens up new opportunities for optimizing business processes and improving energy efficiency (Kalla *et al.*, 2024). Integrating these technologies into green businesses can significantly increase their efficiency and sustainability. Using energy-saving technologies and digital solutions can reduce energy and resource costs, increase productivity and reduce operating expenses. This helps enhance profitability and create new economic opportunities.

Many countries are adopting policies and international agreements to support green entrepreneurship and reduce greenhouse gas emissions (OECD, 2022). Research into innovative approaches can help develop effective policies and strategies to implement these commitments. Traditional business models often do not meet the requirements of modern challenges (Hina *et al.*, 2022). Innovative approaches to green entrepreneurship which integrate energy-saving technologies and the digital economy contribute to creating new, more sustainable business models. Green entrepreneurship supports job creation, improves the quality of life, and preserves environmental balance (INNO GREEN, 2018). This is especially important in sustainable development and preservation of natural resources for future generations. The combination of green technologies and the digital economy opens up new opportunities for innovation, the development of new markets, and investment. This helps to reduce and alleviate the environmental burden, optimize resources, and increase energy stability. However, the strategy requires significant investment, the development of digital skills, and government support. Overall, this approach has great potential for Ukraine's sustainable development but requires a comprehensive approach with innovation, investment, and training.

The purpose of this study is to assess the interaction of energy-saving technologies and the digital economy in the context of green entrepreneurship development and offer practical recommendations for entrepreneurs to implement innovative approaches, as well as for government agencies to support green entrepreneurship through political and economic measures. The following research objectives were set to guide this study: 1) to perform a literature review of the problems of forming green entrepreneurship in the context of digitalization to ensure sustainable development; 2) to identify trends in global energy efficiency investments; 3) to analyse the impact of green business on the sustainability of economic development and value-added; 4) to identify the practical recommendations for the transfer of innovations to ensure the development of green business in the context of digital transformation.

Literature Review

Sustainable development is the central paradigm of future social development, and developing a circular economy through globalisation and digitalisation will contribute to achieving these goals. The study's practical significance is to deepen the theory and practice of circular economy development. Sustainable development is the central paradigm of future social development, and the development of the circular economy through globalization and digitalization will contribute to achieving these goals. The practical significance of the study (Gavkalova *et al.*, 2024) is to deepen the theory and practice of circular economy development. The depletion of natural resources poses threats to industrial development, provision of material goods, and quality of life. The authors believe that irrational use of natural resources and inefficient resource management worsen the environmental situation and reduce the efficiency of enterprises. The analysis shows that sustainable development has become a key paradigm of the future, and the development of the circular economy is one of the mechanisms for achieving this goal through its links to globalization, digitalization, innovation, and digital distribution. The findings contribute to the development of the theory and practice of the circular economy.

Globalisation challenges and threats highlight the need for countries to strengthen financial security through systemic measures and adaptation of strategies to new economic realities. The need to integrate digital technologies into the financial and economic sectors is emphasised significantly by Desyatnyuk (2024), who also presents the principal elements and tools of entrepreneurial innovation systems that allow the commercialisation of scientific projects and research. The practical significance lies in the fact that the proposed model of interaction between businesses, the state, and universities is an effective mechanism for solving the issue of forming a system of entrepreneurial innovation initiatives (Krysovaty and Ptashchenko, 2023). Semenenko (2016) shows the connection between energy sources and energy security with sustainable development, reveals the dependence on energy security, and indicates its main threats and ways out, as shown in the example of Ukraine. A new typology of business models for green technologies is proposed, illustrated by various environmental technological solutions (Trapp and Kanbach, 2021). Scientists believe environmental responsibility is essential to regulate at the national, regional and corporate levels (Bobkova *et al.*, 2021). It has been determined that green entrepreneurship is essential for creating new business opportunities in the circular economy, sustainable development, and overcoming the socio-economic and environmental challenges humanity faces (Mondal, Singh and Gupta, 2023a).

Challenges in the study of green entrepreneurship include the development of adequate definitions, the choice between qualitative and quantitative approaches, and the fact that most studies focus on existing businesses, leaving out new and disappeared businesses (Schaper, 2016). As the digital economy has developed, its impact on green innovation and energy efficiency has become a current research focus. Results show that running a business based on green technologies or positioning it in the green sector does not significantly impact the likelihood of receiving venture capital. However, it can serve as a reliable signal for investors (Mrkajic, Murtinu and Scalera, 2017). To fully utilise the potential of promoting energy efficiency, the sustainability of the green innovation system

needs to be strengthened. A policy focus on “digital greening-energy efficiency” should support the development of the digital economy (Shevchenko *et al.*, 2023). The rational allocation of resources and the implementation of green standards should be strengthened during the development of the digital economy, and the constraints that hinder energy efficiency in the early stage of digitalisation should be overcome by accelerating the digitalisation process (Ma and Lin, 2023; Wu, Zhu and Wang, 2024). Econometric studies of entrepreneurship show that the environmental orientation of new businesses is a critical factor for sustainable development (Neumann, 2022). Currently, more and more attention is being paid to teaching students about green entrepreneurship and their interest in implementing business ideas in green entrepreneurship (Alekseieva *et al.*, 2023).

It has been concluded that concern for green entrepreneurship among students positively correlates with entrepreneurial education and environmental knowledge (Anghel and Anghel, 2022). The impact of intellectual capital on supply chain circular economy (SCCE) systems, consisting of a closed supply chain (CLSC) and a reverse omnichannel, is studied (Zheng *et al.*, 2024). Evidence of the impact of the digital economy on carbon emissions at the household level has been analysed, which helps to understand the interaction between production and consumption in achieving carbon neutrality and identify ways to reduce emissions from consumption (Du, 2024). It has been proven that digital transformation should be considered not only in the context of business models but also in terms of economic effects and their feasibility (Gorokhova, 2021), with state audits playing a crucial role in improving energy efficiency and promoting green and low-carbon economic development (Liu, Nie and Lin, 2024).

There are different views on the role of the digital economy in green entrepreneurship. Some researchers believe that energy efficiency and natural resources contribute to reducing the ecological footprint (Sotnyk *et al.*, 2023). The digital economy has a detrimental effect on reducing the ecological footprint with the development of renewable energy (Zhao, Lin and Bashir, 2024), noting that the actual impact of the digital economy on sustainable development can be more accurately determined through better construction of the digital economy index (Huang and Lin, 2024). Other studies have shown that improving digital infrastructure significantly improves industrial energy efficiency (Wang and Shao, 2024; Li and Gao, 2024), and digital technologies have become a promising measure to improve energy efficiency and reduce emissions (Zhang, Liu and Fu, 2024).

Therefore, this study is relevant for entrepreneurs, policymakers, researchers and society as a whole, as it contributes to developing effective strategies to support green entrepreneurship and the transition to a more sustainable economy in the context of digitalisation.

Research Methods

The authors proposed a comprehensive approach, which includes researching consumer needs, searching for technological solutions through patent research, evaluating engineering solutions considering technical, operational and market parameters, cost estimation and selection of an engineering innovation following Khaminich *et al.* (2020).

Synthesis, Analysis and Literature Review:

The method of synthesis and analysis was used for the identification of the most effective digital platforms for transferring innovations to green businesses following Barton *et al.* (2007). This method involves combining various pieces of information to form a cohesive understanding and breaking down complex information into smaller components for detailed examination. By synthesizing and analyzing data from the analyzed literature, the study identified the key platforms that facilitate the transfer of innovative technologies and practices to green businesses, highlighting their roles and effectiveness in promoting sustainable development. The following keywords were used to compile a list of reviewed literature on the subject matter under study: “Green entrepreneurship strategies”, “Sustainable energy technologies and digital economy”, “Integration of renewable energy with digital transformation”, “Green economy and innovation in digital platforms”, “Circular economy and digitalization in the energy sector”. The following search and combined queries were also used: “Sustainable business models in green technology and digital economy”, ‘Impact of digitalization on green energy solutions’, ‘Green entrepreneurship and IoT/blockchain in the energy sector’. Appropriate filters were applied, in particular: subject matter (environmental technologies, digitalization of the economy, innovations in the energy sector); chronology (publications mainly for 2018-2024 to obtain the most relevant research); type of sources (scientific journals, peer-reviewed articles, reports of international organizations (OECD, IRENA, EU); databases (Google Scholar, Scopus, Web of Science, SSRN were used). The literature review included sources that present new approaches or analysis of current cases, reports based on verified empirical data, publications with a clear methodology and evidence base, articles analyzing successful cases of integration of environmental and digital solutions, and sources that highlight the relationship between innovation, globalization, and the green economy. The final sample included sources that provide a holistic understanding of the topic and highlight the latest developments in green entrepreneurship and the digital economy.

Monographic Analysis:

The use of the monographic method helped to highlight the trends in global investment in energy efficiency over 8 years (2015-2022), and gross value added in the environmental goods sector in the EU over 20 years (2001-2021). The monographic method is one of the qualitative methods that involves an in-depth study of a single object or phenomenon, using detailed analysis to identify its characteristics and relationships (Lisboa, 2015). It is particularly effective as a study of a unique phenomenon - the development of green business - allowing for a comprehensive description and analysis of current trends.

Content Analysis:

We used the content analysis method to elucidate the challenges inherent to the green economy. This method is based on a quantitative and qualitative analysis of the content of information sources, which allows us to study how green entrepreneurship ideas are reflected in various media, publications, regulations, and business practices. We

examined a range of media materials and statistical data from authoritative sources, including EUROSTAT, UNSD, and GMI (UNSD, 2024).

Generalization:

Practical recommendations for implementing innovative developments, the generalisation method was used, to ensure the development of green business in the context of digital transformation and the study's general conclusion, following Ahtisham *et al.* (2023). This method, due to its versatility, helped to take into account both global trends and local specifics, to systematize innovations into an economic model that meets the challenges of digital transformation and promotes sustainable development.

These methods allowed for a comprehensive study of innovative approaches to green entrepreneurship, identification of effective digitalisation platforms and development of recommendations for their implementation.

Results

Current state of green entrepreneurship and the digital economy

Today, humanity faces three significant challenges: environmental change, severe pollution and the availability of energy resources. The decline in the use of fossil fuels and sudden changes in the environment are forcing us to think about a challenging future. This challenge requires modifications to energy infrastructure and the application of environmentally friendly methods. There is a great need for renewable, biodegradable, and environmentally friendly products and services. The transition from fossil fuels to solar, tidal, and geothermal energy is urgently needed, and not only awareness but also the practical application of these technologies is essential, as highlighted by Sakhrekar and Sayankar (2023). Therefore, in recent years, green entrepreneurship has become one of the most critical factors in achieving competitive advantage and business sustainability.

Today's businesses are becoming increasingly conscious and responsible for contributing to the environment. A green initiative in business is now considered an indicator of social responsibility and a strategic step towards sustainable development. One of the critical aspects of this initiative is efficient energy supply (Ye *et al.*, 2023). It is crucial to compare the correlation between the Human Development Index, one of the indicators of sustainable development of the country's economy, and the Innovation Development Index among the leading countries in 2023 (see Figure 1).

The data show that the HDI is consistent with the GII, i.e., the well-being of humanity and the development of society directly depend on the introduction of innovative technologies. Based on the data from UNDP (2024), we will determine the relationship between HDI and GII on the example of two countries (Table 1).

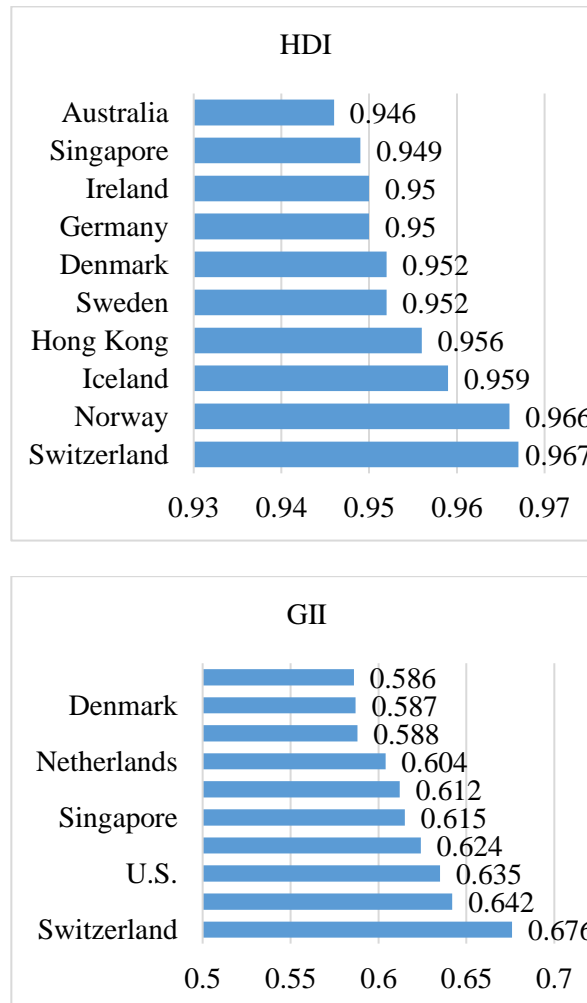


Figure 1: Top 10 countries in the World according to the Human Development Index (HDI) and the Global Innovation Index (GII) 2023 (Conte, 2023; HDI, 2023)

Table 1: Correlation analysis of HDI and GII dependence, (2016-2024)

Parameter	Ukraine		Sweden	
	GII	HDI	GII	HDI
GII	1		1	
HDI	0.9283	1	0.2940	1

The analysis of the data shows that in a country with a high level of economic development, the correlation coefficient is 0.294 (Sweden), and 0.928 in a developing country (Ukraine). Thus, the global human development index and the innovation index were significantly consistent and highly correlated for the countries studied in 2016-2024.

Global investments in energy efficiency

The scientific community believes that in order to ensure sustainable development, it is necessary to divide the development of production processes focused on digitalization and innovation in the economy into stages of standardization, adaptability, and predictability (Sánchez-García *et al.*, 2023). This will ensure a consistent digital transformation that will open up fundamentally new opportunities for creating added value in almost all sectors of the economy (Kraus *et al.*, 2023). Trends in global energy efficiency investments in 2015–2022 are positive (see Table 1).

Table 2: Trends in Global Energy Efficiency Investments, 2015–2022, USD billion

Years	Industry		Buildings		Transport	
	Energy efficiency	Electrification and end-use	Energy efficiency	Electrification and end-use	Energy efficiency	Electrification and end-use
2015	21	18	147	76	96	0
2016	22	18	162	73	112	1
2017	22	18	164	76	95	5
2018	22	19	149	92	94	13
2019	21	18	163	83	105	19
2020	21	17	184	78	55	27
2021	23	19	211	82	95	55
2022	24	20	215	84	128	93
Growth, %	14.3	11.1	46.3	10.5	33.3	*

Source: IEA (2023)

The main driver of this growth has been the active adoption of electric vehicles (EVs) and the development of charging station infrastructure, which is driving the market. Innovations in battery technologies, government incentive programs (e.g., tax breaks), and efforts by automotive companies to increase the range of EV models available to a wide range of consumers also have a significant impact. For example, between 2021 and 2022, the number of available heavy electric vehicle models increased by almost 87%, and the range for passenger cars is projected to expand to 197 models by the end of 2025. This demonstrates the active implementation of electrification at all levels of transportation, which helps reduce dependence on fossil fuels and reduce CO₂ emissions (Pulido-Sánchez *et al.*, 2022). Experts believe these trends will contribute to the development of offshore and onshore projects and the growing popularity of clean fuel alternatives. By 2030, revenues from wind farms are expected to exceed USD 20 billion. The advancement of electrolyzer projects and new policy initiatives will help to make more efficient use of wind energy for clean hydrogen production (GMI, 2024). In 2022, Nova Scotia became the first province in Canada with an industrial wind farm off the coast and plans to add 5 GW of capacity by the end of the decade to support the production of clean hydrogen (GMI, 2024).

Efficient energy supply, including renewable energy sources, significantly reduces greenhouse gas and pollutant emissions. This helps preserve ecosystems and improve the quality of air, water and soil quality. Businesses can reduce their energy costs by

using energy-saving technologies and optimising energy consumption. While the initial investment may be high, the long-term savings in operating costs make it worthwhile. Eurostat data for 2001-2021 show that gross value added in the environmental goods and services sector has increased. This indicates the growing importance of this sector in the economy, as the growing demand for environmentally friendly technologies and services stimulates innovation and investment. The expansion of this sector contributes to the transition to a more sustainable economy by reducing environmental impact and creating new jobs in the field of green technologies (see Figure 2).

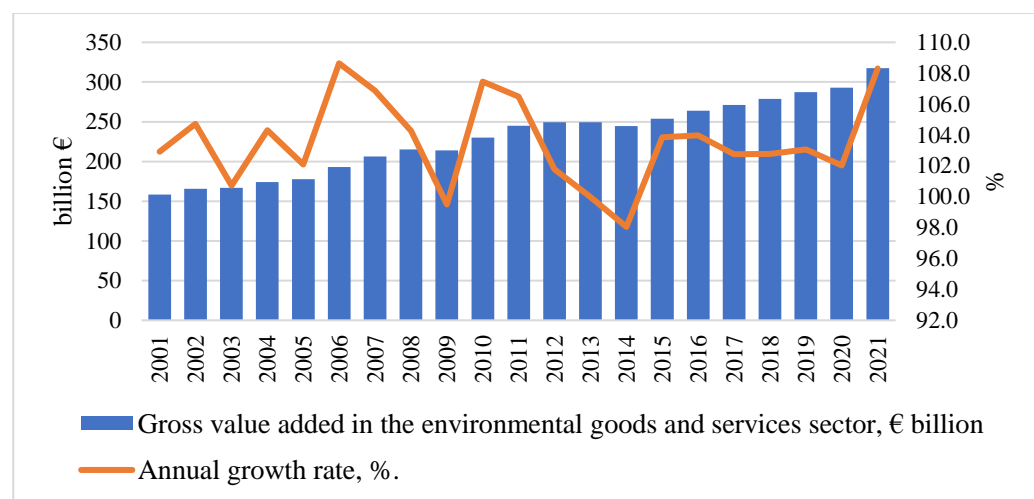


Figure 2: Gross Value Added in the Sector of Environmental Goods and Services (27 EU countries), EUR billion (Eurostat, 2024a)

Data shows that the demand for green lifestyles is growing sharply as people feel the effects of the climate crisis, which calls for the development of green entrepreneurship. Businesses that implement green initiatives can gain a competitive advantage. Consumers and partners increasingly value environmental responsibility, which can increase customer loyalty and attract new partners and investors.

Efficient energy supply is at the heart of a business's green initiative. It not only helps to preserve the environment but also provides economic benefits, increases competitiveness, stimulates innovation, meets regulatory requirements and strengthens the company's social responsibility. Investing in renewable energy sources and energy-saving technologies is essential for sustainable business development and ensuring its long-term success. According to the approximation equation, the share of renewable energy in gross final energy consumption by sector for 2004–2022 has a linear trend with a value of 98.8% ($R^2 = 0.9877$) for 27 EU countries (see Figure 3).

Green business, focused on reducing negative environmental impact and promoting sustainable development, requires transformational changes in business processes. These changes include adapting to environmental standards, using innovative technologies and increasing resource efficiency (Bieliyalov *et al.*, 2023).

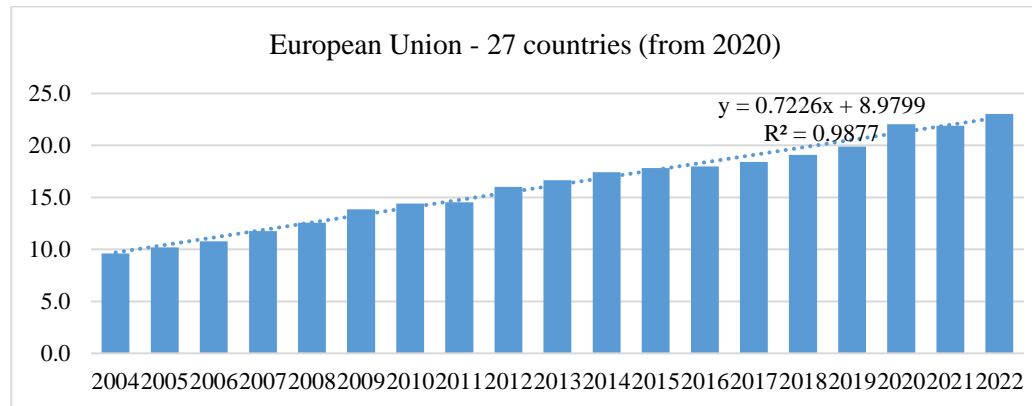


Figure 3: Ratio of Renewable Energy Sources in Gross Final Energy Consumption by Sector (27 EU)] (Eurostat, 2024b)

Green bonds are instruments designed to raise funds for environmentally friendly and sustainable development projects (Sharma and Kautish, 2023). They are issued by governments, financial institutions, or private companies and aim to finance initiatives that positively impact the environment. The general government debt issued as green bonds in 27 EU countries increased more than threefold between 2019 and 2022 (see Figure 4).

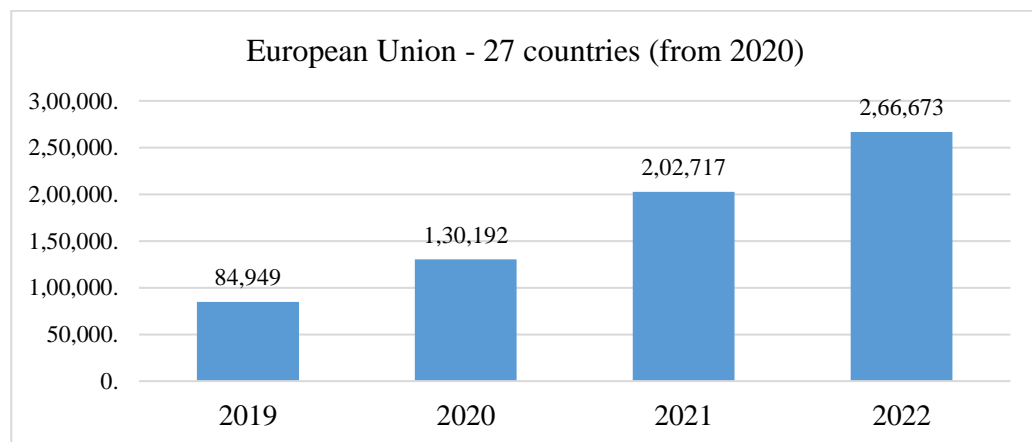


Figure 4: Amount of Public Borrowing through Green Bonds (27-EU), EUR million (Eurostat, 2023)

The growing popularity of green bonds demonstrates the commitment of EU countries to support sustainable development and environmental initiatives. This indicates that governments and the private sector are actively investing in projects that help reduce carbon emissions and protect the environment. Overall, the growth of the green bond market in the EU is a positive indicator of environmental responsibility, economic innovation and political will to support sustainable development.

Digital platforms for green business

Digitalization plays a key role in the development of green business. The integration of energy-saving technologies and the digital economy into green businesses provides economic benefits and contributes to sustainable development and environmental improvement. According to the World Economic Forum's Fostering Effective Energy Transition 2023 report, the global energy transition has stalled after a decade of progress due to the global energy crisis and geopolitical instability (WEF, 2023). The Energy Transition Index, which compares 120 countries on the efficiency of their energy systems and readiness for further change, shows that despite significant achievements in clean and sustainable energy, new challenges are emerging related to energy equity, access to energy at affordable prices, and sustainable economic development. This is due to the fact that many countries have shifted their focus to energy security. It is important to pay attention to the leading digital platforms that facilitate the exchange of knowledge and resources between green businesses and the introduction of energy-saving technologies that support sustainable development and environmental efficiency (see Figure 5).

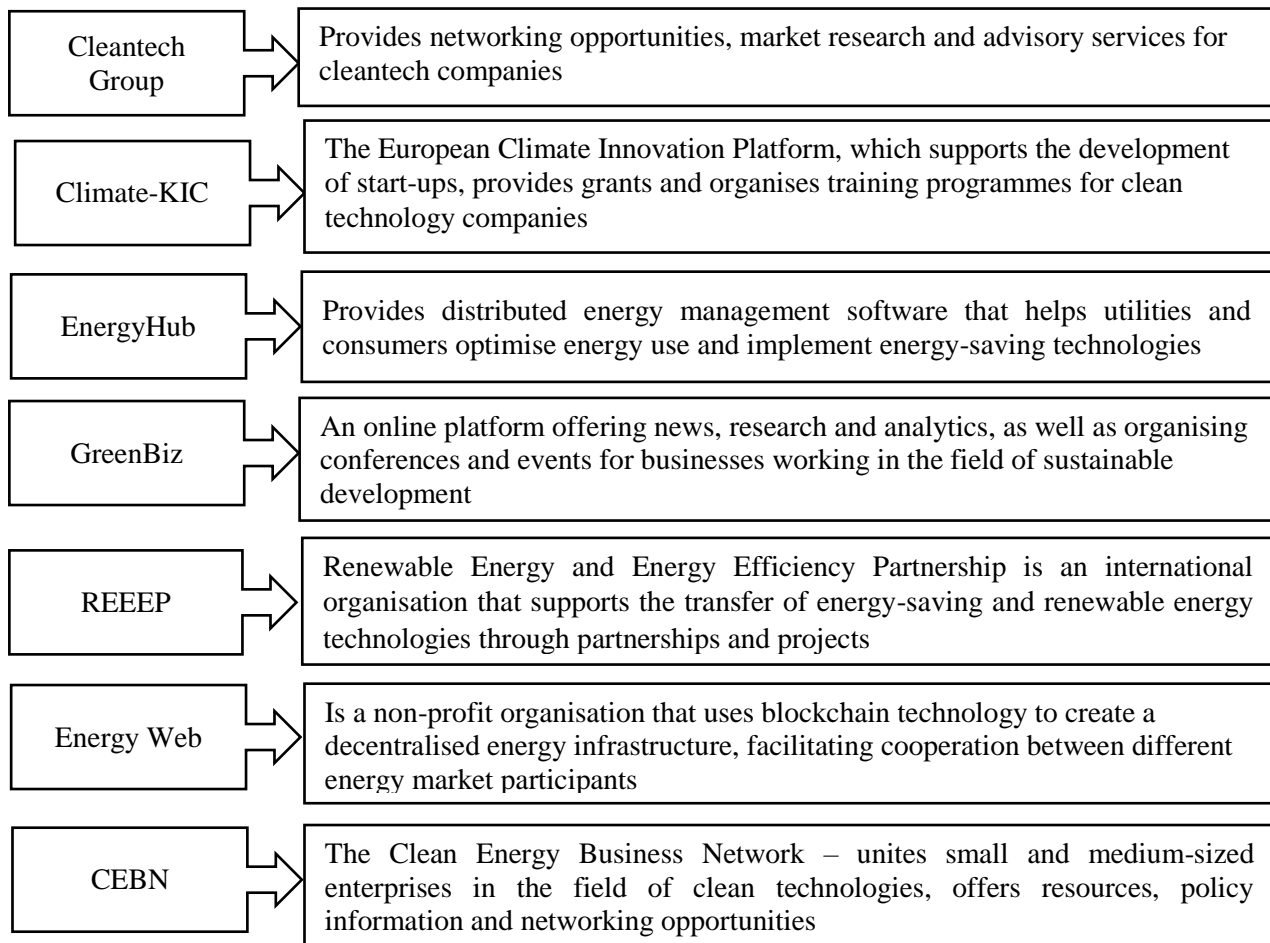


Figure 5: Digital Platforms for Transferring Innovations to Green Business
(Ning, Jiang and Luo, 2023)

These platforms foster business cooperation, support innovation, and help implement energy-saving technologies contributing to a green economy. Integrating digital technologies with energy-saving systems creates smart grids that increase the efficiency and reliability of energy supply, and digital tools provide continuous feedback that allows energy-saving technologies to be quickly adapted to changing conditions.

Discussion

The implementation of green business initiatives faces a number of constraints in regions or industries with fewer resources. The main problems identified in the research include: financial barriers, institutional and regulatory gaps, insufficient infrastructure, and human capital development. The study identified the main gaps and the need for further work. Many studies have focused on developed countries, while in developing countries, the analysis of the impact of green initiatives remains insufficiently studied. That is, there are conflicting views in the literature on the profitability of green entrepreneurship, especially in sectors that traditionally depend on fossil fuels (Söderholm, 2020; Tekala *et al.*, 2024). Although digitalization has significant potential to promote green entrepreneurship, the issue of integrating green technologies with digital solutions requires deeper analysis. In our opinion, further research is needed to overcome these challenges, including: developing affordable financial mechanisms for SMEs; studying the impact of digitalization on stimulating green entrepreneurship in resource-limited settings; and developing training and knowledge dissemination strategies in less developed regions.

Mitigating climate change's effects is a critical issue on the global political agenda. Many governments and local authorities have committed to ambitious targets to transition to a greener and more sustainable economy. Around 200 countries have signed the Paris Agreement, committing to keep the rise in global average temperature to well below 2 degrees Celsius above pre-industrial levels, with many planning to achieve zero greenhouse gas emissions by 2050 (UN, 2015). This requires rapid innovation, investment in new technologies, and implementing policies that change the behaviour of individuals and companies. The COVID-19 pandemic enabled governments to accelerate this process by leveraging economic incentives that can support environmental measures. The war in Ukraine and rising energy prices have highlighted the need to find new, reliable energy sources. Green businesses are anticipated to open up new markets for entrepreneurs and serve as key drivers of global change. Government agencies play a crucial role in stimulating and supporting green entrepreneurship by creating favourable conditions, providing financial assistance, developing infrastructure, and supporting innovation and collaboration (see Table 3).

Governments can bridge the digital and green divide by implementing the following strategies: financial incentives for innovation, investment in the Internet and green energy, creation of innovation clusters, training programs to develop digital and environmental skills, support for start-ups through incubators, public-private partnerships, technology grants, and removal of bureaucratic barriers. Other measures include developing energy autonomy through renewable energy sources, providing access to high-speed Internet, and using big data to identify regions in need of support. Policy should be based on analysing the socioeconomic context of the regions. Priority

should be given to areas that have the potential to quickly integrate innovations, which will provide a multiplier effect for other areas. Such strategies not only reduce regional gaps but also stimulate the development of sustainable and inclusive economic growth.

Table 3: Practical Recommendations on Innovation Transfer to Ensure the Development of Green Business in Digital Transformation

<i>Focus</i>	<i>Practical activities</i>
<i>For entrepreneurs</i>	
Integration of digital technologies	Using IoT to monitor and manage energy and resource consumption and automated systems to optimise production processes and reduce waste
Development and implementation of environmentally friendly products	Implementing eco-design principles to create easily recyclable or reusable products and environmental certificates to confirm that products meet environmental standards.
Digital platforms and marketing	Active use of social media to promote its products and raise consumer awareness of environmental benefits, expanding the range of online sales in digital marketplaces to increase market coverage.
Partnerships and collaborations	Forming diversified networks of green entrepreneurs to share experiences and jointly solve problems and innovation hubs.
Financing and investment	Use crowdfunding platforms, grants and subsidies to attract funding from environmentally conscious investors to implement green technologies.
<i>For government agencies</i>	
Policy measures	Legislative support (tax benefits, subsidies) to stimulate the development of green entrepreneurship and establish and update environmental standards for products and processes in line with modern requirements.
Economic measures	Targeted subsidies and grants will support research, the transfer of innovations in green business, and the introduction of preferential lending programmes for small and medium-sized enterprises engaged in environmentally friendly projects.
Education and outreach	Developing training programmes and courses to improve entrepreneurs' skills in green technologies and digitalisation, conducting information campaigns to raise awareness of the importance of green entrepreneurship among the public and entrepreneurs.
Infrastructure support	The creation of innovation hubs and clusters will facilitate cooperation between entrepreneurs, researchers, and government agencies and the development of renewable energy infrastructure.
Monitoring and evaluation	Establishing a system for monitoring and evaluating the effectiveness of green technologies and support programmes, creating a database, and analysing the development of green businesses to improve policies and programmes to continuously support them.

Source: Based on analyzed literature (GWI, 2023; NYU STERN, 2024; OECD, 2022; SA, 2024; Sharma and Kautish, 2023)

The first main conclusion about the integration of digital technologies into green entrepreneurship is confirmed by researchers from around the world (Fernandes, Pires and Alves, 2022; Mondal, Singh and Gupta, 2023b; Wang *et al.*, 2024; Xu, Zhang and Wang, 2024). Some studies clarify the determinants of corporate green innovations, identify key factors that influence their implementation, and provide important information for making strategic decisions to improve the environmental responsibility of businesses. In addition, the study sheds light on the relationship between green initiatives and digital tools, emphasizing the importance of synergy between these areas for the sustainable development of companies. This contributes not only to improving environmental efficiency but also to creating long-term value for all stakeholders in the process of corporate digital transformation (Li and Shen, 2021; She and Zhang, 2024; Zhu, Huang and Koompai, 2024). In 2024, the “Call for Proposals for Digital and Green Innovation in Africa” was announced among African countries (D4D Hub, 2024).

The second main conclusion is the socio-economic development of society and the greening of production. Shamsuzzoha *et al.* (2023) emphasize the need to build environmental security, and offer a new theoretical justification for the links, taking into account the mediating problems of green innovation strategies, including the lack of government support, lack of resources and skilled labour. It is believed that future research should cover more regions and countries and take into account economic and cultural aspects, especially in newly industrialized countries. For future research on green business development, it is important to extend the analysis to more regions and countries to provide a more complete understanding of global trends. In particular, taking into account economic and cultural aspects can ensure the relevance of findings for newly industrialized countries (NICs), such as India, Brazil, or Indonesia, where green business development faces economic challenges such as the impact of different income levels of on the adoption of green innovations; limited access to investment and credit for small and medium-sized businesses; and uncertainty about the long-term profitability of environmental projects. Cultural aspects include: local habits and traditions that influence the consumption of environmentally friendly products and services; perception of risks and benefits associated with the green economy; and the level of awareness of environmental issues.

Research by scientists from the Baltics emphasizes the ability of green startups to solve environmental problems and influence economies and communities. An important role of green entrepreneurs is to use creative thinking and progressive connections to promote positive change. Further environmental initiatives are needed to have a greater impact on the transition to a sustainable society (Prokopenko *et al.*, 2024). At the same time, human capital is a factor in our global growth, prosperity and progress. The meaning and role of this little word, green, are so significant that our lives and future depend on it (AlQershi *et al.*, 2023). Therefore, practical recommendations for entrepreneurs on implementing innovative approaches in green business development and digitalisation are needed: increasing competitiveness, optimising resources, reducing environmental impact, meeting regulatory requirements, stimulating investment, supporting sustainable development, and ensuring digital transformation. The implementation of SDG 7 creates a framework for the sustainable development of green business, promotes investment and innovation in this area, and integrates environmental principles into economic activity (UNDP, 2015). As a result of the conducted research, it has been established

that: digital tools, such as automation and analytics systems, allow for more precise control and optimisation of energy consumption, which reduces costs and improves efficiency; data analysis tools enable the forecasting of energy needs and the planning of purchases, which helps to lower energy resource costs; the implementation of energy-saving technologies and the use of renewable energy sources reduce greenhouse gas emissions and improve the environmental footprint of enterprises; companies that use energy-efficient and environmentally friendly technologies can obtain green certificates, enhancing their image and competitiveness; integrating modern technologies enhances enterprise innovation and increase their appeal to both investors and consumers. Additionally, green initiatives and energy-efficient technologies strengthen a company's reputation as a responsible and sustainable business; the use of energy-saving technologies supports compliance with national and international environmental initiatives and programmes; digitalisation helps to reduce waste and conserve resources through more accurate control and management. Integrating innovations, energy-saving technologies, and the digital economy creates a synergy that contributes to achieving more significant results. Thus, implementing such measures is an investment in the future of entrepreneurship, ensuring long-term sustainability and the development of the national and global economy.

Conclusion

This study aimed to explore the impact of digital transformation on green business development, identifying critical recommendations for entrepreneurs and policymakers. The findings reveal that integrating IoT, eco-design, and digital marketing significantly enhances sustainability and economic viability. These recommendations provide a roadmap for transitioning to a greener economy while addressing global challenges such as climate change, resource scarcity, and economic inequality. The correlation analysis between the Human Development Index (HDI) and the Global Innovation Index (GII) demonstrates that well-being and societal development are closely linked to the adoption of innovative technologies. The significant correlation found between HDI and GII in countries with varying levels of economic development emphasizes the importance of innovation in achieving sustainable development goals. The expansion of the environmental goods and services sector and the increase in gross value added reflect the growing importance of green technologies and services in the economy. Businesses that implement energy-saving technologies and optimize energy consumption are not only contributing to environmental preservation but also gaining competitive advantages, economic benefits, and increased social responsibility. The growth of the green bond market in the EU signifies strong commitments from both governments and the private sector towards sustainable development. This trend is indicative of a broader movement towards environmental responsibility and economic innovation, supported by political will and financial investments. Digitalization is identified as a key enabler in the development of green businesses, facilitating the integration of energy-saving technologies and enhancing overall efficiency. The role of digital platforms in fostering business cooperation and innovation is crucial for the continued progress towards a green economy. The main recommendations for government agencies include legislative support, subsidies and grants, soft loan programs, training courses, innovation hubs, and monitoring the effectiveness of green technology implementation. For future research directions, it is important to focus on the following issues: comparing the effectiveness

of government policies to stimulate green entrepreneurship in different regions; studying the role of transnational companies in promoting green business through supply chains; analyzing economic incentives for attracting investments in green business in developing countries; studying social innovations and their contribution to the development of environmentally friendly enterprises. These studies will help create a more holistic picture of the development of the green economy and contribute to the formation of universal approaches to integrating environmental initiatives in different economic and cultural contexts.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	Yes
Collected the data	No	No	Yes	No	No
Contributed to data analysis and interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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Educational Approaches to Cultivating Environmental Consciousness among Higher Education Students in Ukraine

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Abstract

In the face of escalating environmental challenges such as climate change, resource depletion, and biodiversity loss, higher education institutions (HEIs) play a critical role in fostering environmental consciousness among future professionals. The research aims to analyze current pedagogical strategies, examine innovative development and digitalization factors, and explore how higher education can promote sustainable environmental consciousness among graduates. A combination of complementary methods, including analysis, synthesis and abstraction were used. The essential structural elements of the system of ecological consciousness, as well as the criteria and indicators of its formation, are also defined. Results revealed that the main prerequisites for low environmental awareness among students of higher education institutions in Ukraine are the insufficient development of civil society institutions, lack of motivation to comply with environmental legislation, and an inadequate level of public awareness of sustainable development and environmental stewardship priorities. Environmental education in higher education is often delivered in a traditionally minimalist format, with a narrow sectorial focus that fails to adequately foster environmental awareness development among future professionals. An innovative vision of the pedagogical strategy for forming environmental awareness of students of higher education institutions through fundamental life values, attitudes towards the intrinsic value of nature, and society's responsibility for their conservation and sustainable development is proposed.

Keywords

Environmental awareness; Environmental communication; Emotional intelligence; Communication ethics; Methods of forming

Introduction

Current trends in the transformation of educational practice lead to growing contradictions between society's need for highly qualified specialists and the diminishing emphasis on fostering the importance of forming an ecological worldview within higher education. As the world faces escalating environmental challenges such as climate change, resource depletion, and biodiversity loss, fostering environmental consciousness has become more pressing. Higher education institutions (HEIs) are critical in shaping future professionals' knowledge, values, and skills. As global trends increasingly integrate social and natural environments, there is an urgent need to cultivate environmental awareness among students within higher education institutions (Acosta Castellanos and Queiruga-Dios, 2022). This awareness should enable future professionals across various fields to harmoniously align their activities with ecological principles, contributing to society's broader goals of sustainable development. In this context, it is particularly important to develop the latest pedagogical strategies, which are the foundation of the formation of environmental consciousness among students of higher education institutions.

There is a need to highlight the conceptual foundations of the formation of environmental awareness among students of higher educational institutions, to highlight the stages and principles, and to select pedagogical tools (Hadjichambis and Paraskeva-Hadjichambi, 2020). In the scientific and pedagogical literature, this issue has been explored only partially and given the rapid progress of innovative pedagogical technologies, it requires updating and alignment with the requirements of a modern information society (Iakuba, 2022). This highlights the need for a more in-depth examination of educational technologies to foster environmental awareness among students in higher education institutions. In Ukraine, the development of environmental consciousness among students is essential for addressing global ecological issues and vital for the country's sustainable development, especially in the context of its recovery from war-related environmental damage (Dillon and Herman, 2023).

The increasing recognition of the need to integrate environmental awareness into the systems of professional competencies for higher education students has sparked a growing interest in the scientific community. Koval and Volokhata (2022), Khryk, Povlin and Mozul (2023), Tkachuk and Kravchenko (2024), Nesterenko (2021), and Tomchuk and Tomchuk (2022) have explored the complex interrelationship between economic development and environmental safety. These scholars argue that environmental degradation exacerbates economic crises while poor economic conditions harm the environment. Scientists are convinced that the destructive state of the environment deepens the economic crisis, while the depressed state of the economy significantly worsens the state of the environment.

Research on sustainable development in Ukraine has highlighted the crucial role of environmental awareness in achieving the country's European integration goals. Studies by Iakuba (2022), and Kalenskyi, Herliand and Nahaiev (2022) underscore environmental consciousness as essential for the success of Ukraine's alignment with European sustainability standards. Hadjichambis and Paraskeva-Hadjichambi (2020) and Uralovich *et al.* (2023) studied the formation of environmental competence of future

specialists in higher education. They emphasise that modern environmental thinking as a system of values, views and orientations to various forms of environmental protection and activities should be nurtured through a value-based education system, which encourages students to engage in various forms of environmental protection activities as a core outcome of environmental awareness. In addition, Dillon and Herman (2023) have focused on the theoretical and methodological foundations of training future specialists in higher education institutions, determining the specifics of the psychological, pedagogical, and didactic conditions for forming a worldview of sustainable interaction between society and the environment. However, despite these valuable contributions, many studies still address the formation of environmental awareness for future professionals in a fragmented manner.

Today, among innovative pedagogical strategies, the potential of immersive learning, based on virtual and mixed reality, demonstrates the highest effectiveness. This method of digitalising targeted higher education can significantly transform the system for developing environmental consciousness, providing an entirely new level of visualisation. Motivated and environmentally conscious graduates of higher education institutions, regardless of their chosen field, have the potential to change the functioning of various industries towards environmental awareness, contributing to Ukraine's steady progress in sustainable development. This issue is seen as a gap within the scope of existing research in this field.

This study aims to identify and evaluate pedagogical strategies for fostering environmental consciousness among students of higher education institutions in Ukraine, considering digitalization and the country's needs in post-war recovery. To achieve this aim, the following objectives were addressed:

- To conduct a comprehensive analysis of current pedagogical strategies for developing students' environmental consciousness in the context of higher education.
- To examine factors related to innovative development and digitalization in higher education, as well as potential challenges and risks.
- To analyze how higher education can be directed toward the formation of sustainable environmental consciousness among graduates, regardless of their field of study.

Research Methodology

This study employed a combination of theoretical and analytical methods to investigate pedagogical approaches to cultivating environmental consciousness among higher education students. The methodology was designed to ensure a systematic and objective analysis of educational practices, integrating multiple scientific techniques to address the research objectives effectively.

Research Design: The study adopted a qualitative research design, focusing on the analysis of existing educational strategies, frameworks, and theoretical concepts. A critical review of literature, publications in academic journals, and analytical reports was conducted to identify key trends, challenges, and innovative practices in fostering environmental awareness.

Publications indexed in leading academic databases such as Scopus and Web of Science were used. The search employed keywords such as "Environmental awareness," "Environmental communication," "Emotional intelligence," "Communication ethics," and "Methods of forming." The inclusion and exclusion criteria for publications were based on spatial-temporal indicators and the level of information reliability. Preference was given to publications from the period 2019–2024. Among the methods used to assess the risk of bias in the included studies were brainstorming and cause-and-effect analysis. The geographical scope was limited to the European region.

The analysis enabled the clarification of definitions and conceptual categories. This process helped distinguish essential elements from non-essential ones and allowed the classification of priority innovative solutions in educational approaches to developing environmental awareness among students in higher education institutions in Ukraine.

Unlike the analysis, synthesis combined separate components and properties identified through analysis into a unified whole. This process involved meaningful integration, moving from identical and essential aspects to differentiation and diversity, uniting both general and specific elements into a single concept of developing environmental awareness among students in higher education institutions in Ukraine. Through the method of generalization, proposals were formulated to address existing needs in the studied area, the main research findings were theoretically substantiated, conclusions were drawn, and questions requiring further study were identified.

Analytical Methods: The analysis method was used to deconstruct the education system into its core components, allowing for an in-depth exploration of its structure and identifying the essential elements that contribute to environmental awareness. Synthesis was then applied to integrate these components, constructing a comprehensive framework that combines general principles with specific educational strategies. This dual approach facilitated the development of a unified concept for cultivating environmental consciousness among students. The abstraction method was used to derive theoretical generalizations, define key concepts, and draw conclusions about the priority vectors of innovative development of environmental competence in higher education in the digital national post-war space.

Criteria for Data Inclusion: To ensure the reliability and relevance of the data, specific inclusion and exclusion criteria were established 1) Spatial-temporal relevance - Only studies published within a defined timeframe and geographically pertinent to the research context were included; 2) Reliability - Priority was given to peer-reviewed journal articles, authoritative reports, and other credible sources.

Results and Discussion

Modern approaches to the formation of an ecological worldview

Prerequisites and Challenges:

The main prerequisites for low environmental awareness among students of higher education institutions in Ukraine are the insufficient development of civil society institutions in this context, the lack of motivation to comply with environmental

legislation and inadequate public awareness of sustainable development and environmental stewardship priorities. Solving current global environmental problems requires, among other things, raising the level of environmental values among the younger generation. Existing environmental legislation in Ukraine does not meet the personal needs of young people, and environmental knowledge remains primitive. Environmental education in higher education is often delivered in a traditionally minimalist format, and narrow sectoral specificity cannot ensure the formation of environmental awareness at the appropriate level among future professionals. A new educational paradigm is needed and should synergize the processes of mastering modern students' professional, social and environmental competence. The positive progress in the relationship between the economy and the environment is primarily determined by the educational environment for the development of professional competence, which should form a sustainable environmental awareness in students based on the moral and ethical norms of human interaction with nature in the format of eco-partnership. Such an approach will allow the student to develop the ability to counteract the environmental crisis and empower them to become proactive environmental stewards. The ecological worldview has been described as a product of environmental education, which is an inevitable transformation of consciousness in the context of worldview problems in terms of formulating, understanding and finding ways to mitigate global environmental problems (Mialkovska *et al.*, 2024; Martyniuk *et al.*, 2023). The foundation of the ecological worldview is ecological knowledge, which is a systematic body of scientific understanding regarding the interaction between society and nature and rational environmental management.

Indicators and Methods of Effective Environmental Education:

The ecological outlook of students of higher education institutions serves as a general indicator of the effectiveness of environmental education and training. It reflects an individual's integrated environmental values, internal motivations, beliefs, and nature-oriented reactions. The latter should be based on an understanding of the value of the natural environment and manifested in practice in the context of a conscious ability to use environmental knowledge and skills to solve and prevent environmental problems (Koval and Volokhata, 2022; Tomchuk and Tomchuk, 2022). The structure of environmental awareness includes cognitive, emotional and behavioural elements. It is worth noting that the definition of environmental awareness has the essence of a state, not a process, and consists of a system of individual knowledge, perceptions, judgements and emotions that determine the level of readiness of an individual to act or not to act to influence the state of the environment.

The definition of environmental awareness has acquired the status of an interdisciplinary category with a high level of generality. The process of forming students' environmental awareness involves the development of scientific, theoretical, normative, evaluative and practical concepts (Nesterenko, 2021). In general, the awareness of higher education students of the functionality of their co-creation in the context of solving environmental problems is positioned to be effective if several pedagogical prerequisites are met, including:

- 1) the content of the process of forming students' environmental awareness, which is based on the interdisciplinary integration of scientific knowledge, is implemented in practice at the level of scientific material, academic disciplines and pedagogical practice;
- 2) mastery of the system of basic environmental knowledge by higher education students in assimilation with moral and ethical norms that determine the potential boundaries of interaction between society and nature;
- 3) formation of students' value-evaluation positioning of the environmental knowledge system;
- 4) the process of understanding environmental issues should bring students to a worldview level of perception;
- 5) the formation of students' environmental awareness should be carried out in the context of the principles of ecocentric consciousness, which is the interaction between society's perception of nature and society's nature.

Among the innovative educational methods of today are learning through argumentation, research-intensive learning methods, immersive projects, cross-learning, and practical learning. Specifically, the methodology of learning through argumentation helps in mastering the skills of discussing a wide range of topics with the practical application of theoretical subject skills. This improves the learners' critical thinking, teaches them the methodology of argument differentiation and persuasive communication, and enhances language and grammatical skills. A vital component of the argumentation process is the ability to listen, which also contributes to the development of universal valuable skills for personal and professional growth. Additionally, active discussion of current issues significantly increases motivation to learn (Hadjichambis and Paraskeva-Hadjichambi, 2020). The research-intensive learning method involves acquiring knowledge, skills, and competencies through developing targeted scientific projects or implementing research. In doing so, valuable data analysis, presentation, critical thinking, communication, and teamwork skills are gained (Bovill, 2020). The method of cross-learning in modern educational programmes is a comprehensive pedagogical approach that combines elements of formal and informal education. This method helps develop the ability to engage in constructive discussion, encourages learners to form open questions, and develops an individual language-communicative model of argumentation (Kukulska-Hulme *et al.*, 2024). The practical learning method is considered potentially effective. It promotes maximum interaction between learners and the surrounding environment and actively motivates them to apply the knowledge, skills, and competencies acquired during learning in real-life situations (Oliveira and De Souza, 2022).

Integrating various interactive technologies and digital methods can significantly improve learning outcomes. Innovative digital educational platforms, online resources, and mobile applications are seen as promising. Immersive technologies should be involved in creating a learning environment that is as close as possible to real-world conditions. These are identified as a way to integrate virtual content into the physical environment, creating conditions for effective interaction.

Theoretical and methodological foundations for the formation of environmental consciousness in students of higher educational institutions

The formation of environmental awareness in students of higher education institutions involves the acquisition of environmental knowledge, mastering the skills of environmentally responsible behaviours, and developing environmental culture through the implementation of active learning methods (Koval and Volokhata, 2022; Tomchuk and Tomchuk, 2022). The formation of students' environmental outlook should contribute to acquiring motivations and guidelines for interaction with the natural environment, increasing environmental literacy, progressive development of environmental thinking and active environmental protection, and forming sustainable environmental beliefs and worldviews.

It is essential to form environmental awareness among the younger generation during a full-scale war. Ukrainians understand the importance of environmental issues during the war: none of the proposed environmental problems received less than 26% support in a sociological survey (Figure 1). Integrating environmental competence becomes a critical priority for optimizing educational strategies in this context.

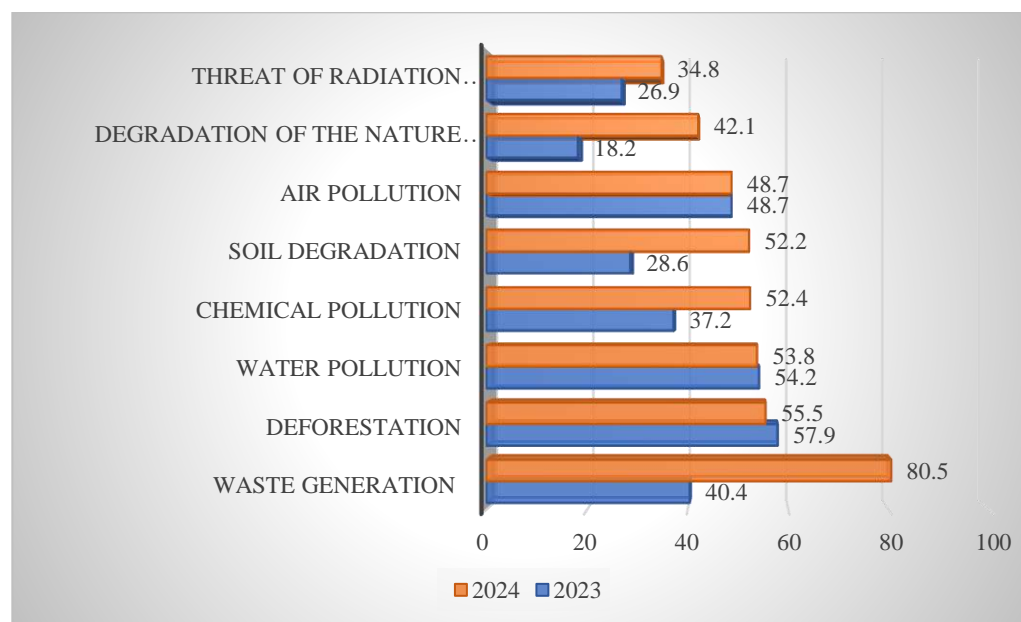


Figure 1: Key Environmental Issues in Ukrainian Public Perception, %
Source: DiXi Group (2024)

It should be noted that the formation of students' environmental outlook in the context of developing a modern integrated learning environment of higher education has specific features. In particular, this process is characterized by the preventive nature of knowledge, which involves forecasting and modelling environmental impacts to prevent destructive effects. In the mind of a future specialist, there should be a constant assessment of potential environmental consequences (Kalenskyi, Herliand and Nahaiev, 2022; Yakuba, 2022). In addition, the modern requirements of integrated education provide for the multifunctionality of a modern specialist, who is not only a narrow specialist in a particular field

but a competent personality with a systematic vision of environmental problems and the variability of their avoidance in his or her practical activities, able to make competent decisions to prevent environmental damage (Dillon and Herman, 2023). To successfully form an ecological outlook, the higher education system today should focus on solving the main tasks: forming a system of relevant ecological ideas, forming a subjective attitude to the natural environment, forming a system of skills and abilities to interact with the environment in the context of targeted technologies and strategies. In general, forming an ecological outlook involves a specific component: ecological self-awareness, ecological worldview, the ideal relationship between humans and nature, and strategic ways to approach it (Koval and Volokhata, 2022).

Active, intensive, and problem-based approaches are traditionally used in teaching methods to increase the environmental awareness of higher education students. At the same time, providing psychological and pedagogical conditions is of particular importance in that the student can take an active personal position and maximize his or her potential as a subject of learning activities. Such pedagogical conditions include:

- 1) integration of environmental context into the content of professional disciplines to form a system of environmental views, knowledge, beliefs, orientation and prejudices;
- 2) systematic motivation of higher education students to master fundamental environmental values for further practical application of environmental knowledge and skills in their future professional activities;
- 3) stimulating active extracurricular, environmentally oriented educational work to gain positive interaction and experience with the environment (Dillon and Herman, 2023; Hadjichambis and Paraskeva-Hadjichambi, 2020).

Stages of implementation of pedagogical conditions for the formation of students' environmental awareness

The outlined pedagogical conditions are components of a single general educational structure that forms students' environmental outlook in higher education institutions. They are implemented in a particular stage: theoretical (orientation), practical (mastering), and independent work (transformation).

The first stage is theoretical (orientation) pedagogical activity, which aims to create conditions for the effective formation of students' environmental outlook and positive orientation towards environmentally oriented professional activities in the future (Khryk, Povlin and Mozul, 2023; Tkachuk and Kravchenko, 2024). In particular, students can be asked to create a chip to position the connection between ecology and the profession and choose the correct terminology. The role of the teacher is, in this case, to assess the level of sufficiency of the use of appropriate methods: creativity, critical thinking, analysis, cognition, identification, and modelling, as well as the student's ability to choose the best options for behaviour, to isolate the essential from the global, to determine the strategy and tactics of behavioural response (Iakuba, 2022; Kalenskyi, Herliand and Nahaiev, 2022). At this stage, it is advisable to actively use a rating system to assess higher education students' knowledge level, which motivates and encourages them to do further research.

The second stage is a *practical (mastering)* phase, emphasizing the application of higher education students' environmental ideals, positions, and values. During this stage, students test the acquired knowledge, skills and abilities in a simulated professional environment. To this end, the innovative pedagogical strategy involves using such methods as a dialogue between students and teachers, problem-solving, microteaching, business and simulation games, and other active teaching and learning methods. These methods engage students in hands-on experiences, fostering a deeper understanding of environmental concepts in real-world contexts. It is worth noting that the formation of students' environmental outlook in the second stage is based on the synergy of environmental theoretical knowledge and practical experience. Creating a microclimate of creativity is particularly influential among the pedagogical technologies of the innovation strategy. For this purpose, the formats of a seminar or training as a group discussion and comprehension of the material in an environmentally oriented context are optimally suited (Hadjichambis and Paraskeva-Hadjichambi, 2020; Uralovich *et al.*, 2023).

Finally, the third stage of the pedagogical strategy for forming environmental awareness of students of higher educational institutions is *independent work (transformation)*. In this concept, it is appropriate to perform a problem task, which is carried out in a specific algorithmic sequence: first, students independently summarize theoretical and scientific materials and research results during seminars and practical classes; identify the vector, content and volume of the workload; introduce a unique course that synergizes environmental determinants and professional context; and then, independent work (transformation), which aims to develop an individual's self-development of an environmental outlook (Khryk, Povlin and Mozul, 2023; Tkachuk and Kravchenko, 2024). It is worth noting that to influence the formation of environmental awareness actively, an innovative pedagogical strategy involves the implementation of learning activities that allow students not only to receive ready-made information but also to stimulate them to expand and deepen their knowledge, to search for original solutions creatively, and to think critically and prognostically. Students mastering professional disciplines should further develop their acquired knowledge and skills.

Scientific novelty and recommendations for optimisation

Given the limitations of traditional pedagogical tools, it is appropriate to integrate elements of innovative solutions regarding teaching methodology, particularly in the context of interactivity, immersive technologies, and personalisation of learning. Based on current innovative pedagogical approaches highlighted in several publications (Bizami, Tasir and Kew, 2023; Bovill, 2020; Iakuba, 2022; Pihkala, 2020), the following practical solutions have been developed to enhance the effectiveness of environmental education in higher education:

- 1) Audiovisual method: with its help, students' perception of the semantic value of ecologically oriented educational material, which is implemented with the help of visual non-verbal clarity, in particular, filmstrips, motion pictures, videos, podcasts and other content, is ensured;
- 2) The case method: by using real-world cases, this method provides the accumulation and organisation of educational and practical experience by allowing the integration of elements of environmental education into the professional training of any profession;

- 3) Socio-cultural methodology: the emphasis in educational programs shifts to the content-communicative essence, often on an intuitive level, which is implemented in the direction of forming students' skills of critical ecological thinking and the way of action depending on the situation, deep integration of ecological consciousness into everyday activities;
- 4) Project methodology that forms practical skills in ecologically oriented professional activity;
- 5) Thematic studies, the pedagogical essence of which consists in the formation of a discussion to discuss real situations in an artificially created environment;
- 6) Problem-research method that motivates students to cognitive activity, self-education, and creative thinking, forming students' interest in the process and result of education;
- 7) Immersive technologies: integration of elements of virtual and mixed reality for visualisation of educational material;
- 8) Reproductive methods that ensure a more accurate and faster flow of the cognitive component of the educational process and easier identification of typical errors, which is considered particularly effective in the case of informative and complex content of the educational process;
- 9) Practice-oriented training, which promotes the maximum interaction of students with the environment and actively stimulates them to apply theoretical skills in real situations;
- 10) Embodied learning gives the educational process a playful character, motivating students' interest and increasing the effectiveness of learning. It also creates a comfortable atmosphere in the educational environment.

Analysis and discussion in the thematic scientific field

Despite numerous interdisciplinary studies, the understanding of the formation of an individual's ecological worldview — its definition, essence, components, and methods of development—remains fragmented. In particular, philosophical studies (Ardoin, Bowers and Gaillard, 2020; González-Salamanca, Agudelo and Salinas, 2020) regard the issue of the ecological worldview of the individual synergizes with environmental education in the format of the worldview basis of sustainable development of society. On the conviction of Ardoin, Bowers and Gaillard (2020), environmental education fosters connections between effective research and field practices, creating synergistic spaces where stakeholders collaborate to address dynamic environmental challenges over time. At the same time, González-Salamanca, Agudelo and Salinas (2020) study the principles of integrating environmental skills into the curriculum, find possible ways of teaching and evaluating them, and explore how this process can be personalized with the help of information and communication technologies.

Kukulska-Hulme *et al.* (2024) highlight the reorientation of the traditional anthropocentric worldview to an ecocentric worldview as one of the main conditions for the effectiveness of ecological education of youths. According to scientists, it is primarily about forming an ecologically oriented worldview as a central, motivational and meaningful component of environmental consciousness and individual behaviour.

The report gives context to the pedagogy of effective climate change and integrating environmental topics into educational programs. For example, outdoor activities and sustainable development projects that foster environmental responsibility and awareness have proven effective. At the same time, a method of creating student advocacy and expanding the boundaries of its powers is proposed, which encourages students to deal with local environmental problems, propose solutions and advocate for changes in local environmental policy. Reflective practices, such as journals and multimedia projects, allow educators to cultivate environmentally conscious professionals ready to tackle climate change and other environmental issues, promoting responsibility and sustainability for future actions.

In several studies, such as Alam (2022) and Pocol *et al.* (2022), the problem of the ecological consciousness of the individual is considered in the context of the relationship with the social promotion of ecological thinking. A systematic review by Alam (2022) provides a better understanding of how the concepts and mechanisms of transformative learning theory are implemented in sustainable development research. At the same time, Pocol *et al.* (2022) argue that the co-creation of knowledge strengthens the link between university and business, where modern universities seek to adapt their curricula to the demands of the labour market. Environmental consciousness should include emotional, cognitive, and behavioural elements and be formed from personal perceptions, knowledge, emotions, and judgments about a person's willingness to influence the environment. The research question is also thoroughly developed in the field of environmental psychology in a foreign scientific field, particularly within the ecology of creativity vector (Glavič, 2020), which focuses on the interaction of psychological and situational factors in the development of individual abilities. The subject of ecological-psychological-pedagogical research by several authors (Bizami, Tasir and Kew, 2023; Bovill, 2020; Pihkala, 2020) highlighted ecological consciousness or the worldview component of consciousness. In addition, modern scientists are investigating the methods of forming ecological knowledge and practical skills of ethical interaction of the individual with the environment, particularly during specially organized ecologically oriented activities.

The vector of the development of the environmental competence of the individual was studied by the authors (Maurer and Bogner, 2020; Oliveira and De Souza, 2022), who positioned it in the context of awareness of the integrity of the natural environment, its aesthetic and socio-economic significance. In particular, Oliveira and De Souza (2022) presented the development and experimental approbation of a method of digital transformation in education, aimed at achieving the goals of Education 4.0, to increase students' understanding of climate change through the development of projects to mitigate environmental problems caused by anthropogenic activities. Some researchers (Zidny, Sjöström and Eilks, 2020) position the process of forming future specialists' ecological consciousness as mastering the system of ecological values in a practice-oriented educational environment. The system's main component is values and beliefs regarding society's responsibility for preserving natural potential.

Conclusion

The study found that the concept of forming environmental awareness among students of higher education institutions is rapidly developing from innovation to the practical range of tools used. Its implementation in the paradigm of educational policy is positioned as a promising necessity and a factor in intensifying the quality of education in the higher education environment. The environmental awareness of future specialists in various vectors of activity should provide for a harmonious combination of human activity goals with environmental trends complementary to the general principles of sustainable development of society.

The structure of the environmental awareness system includes emotional, cognitive, and behavioural elements. Environmental awareness is measurable at different levels and is formed from personal perceptions, knowledge, emotions, and judgements about a person's readiness to influence the environment. Ecological self-awareness, ecological worldview, and an understanding of strategic ways of approaching the ideal of the relationship between nature and society form an innovative pedagogical strategy for shaping the ecological consciousness of higher education students through active, intensive and problem-based learning approaches. In addition, the formation of students' ecological outlook in higher education institutions is implemented in a particular stage, which includes theoretical (orientation), practical (mastering) and independent work (transformation). To actively influence the formation of environmental awareness, an innovative pedagogical strategy should include the implementation of learning activities that allow students not only to receive ready-made information but also stimulate them to expand and deepen their own, to search for original solutions creatively, and to think critically and prognostically. Students mastering professional disciplines should further develop their acquired knowledge and skills.

Among the optimal practical pedagogical tools and approaches for the formation of environmental competence of students in an innovative format, it is worth offering the audiovisual method, case method, socio-cultural method, project methodology, case studies, problem-research method, immersive technologies, reproductive methods, practice-oriented learning, embodied learning. The prospect of further development of scientific research is to study the potential of innovative pedagogical technologies and digitalization of the educational process to form the environmental awareness of students of higher education institutions.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>	<i>Author 6</i>
Conceived and designed the research or analysis	Yes	No	Yes	No	Yes	No
Collected the data	No	No	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	Yes	No	No	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	Yes	Yes	No	No
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes	Yes
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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

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Development of Renewable Energy Sources: Impact on Sustainability and the Environment

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Abstract

The increasing global demand for energy represents one of the critical challenges faced by humanity today. Energy production is essential for social development and fulfilling human needs. However, energy production and consumption often result in significant environmental degradation and adverse effects on human health. Most energy companies use coal, oil and natural gas, which causes significant emissions of harmful substances into the atmosphere, pollution of water sources and other negative consequences. This article aims to explore the potential and environmental impacts of renewable energy sources. We conducted an in-depth study of thematic research and scientific literature on the development of renewable energy over the past five years. This research focused on issues of global renewable energy and ecology. The study found that energy production, while essential for social development, often leads to significant environmental degradation and adverse health effects. Traditional energy sources like coal, oil, and natural gas contribute to harmful emissions and water pollution. Technological advancements have facilitated more environmentally sustainable energy sources, such as wind, solar, hydroelectric power, and biofuels. The article concentrates on exploring the potential of renewable energy in the context of its impact on the environment. The findings highlight the importance of phased adoption strategies for renewable projects, tailored to financial capabilities, as demonstrated in Ukraine. This approach contrasts with large-scale investments and offers a model for countries with similar GDP values. Further research is recommended to compare the environmental effects of different renewable energy sources and develop financial support schemes for minor projects. Strengthening the link between financial incentives and investments in renewable energy is crucial for creating optimal conditions for sustainable development.

Keywords

Alternative energy; Sustainable development; Energy legislation; Energy relations; Environmental management

Introduction

Under Russian aggression and the constant increase in energy prices, the developing energy-intensive national economy suffers significant losses, leading to decreased production and inhibition of socio-economic development. Therefore, there is a problem of reorienting needs and proposals related to developing the country's energy sector. Despite the significant contribution of scientists to the development of theoretical and practical aspects of introducing renewable energy sources in Ukraine, several problems remain unresolved, particularly regarding the advantages and prospects of using alternative energy sources in Ukraine.

Renewable energy is energy obtained from natural sources replenished faster than consumed. Such sources are sunlight and wind; they are inexhaustible. Renewable energy sources are all around us. Meanwhile, fossil fuels — coal, oil, and gas — are non-renewable resources that took hundreds of millions of years to form. When fossil fuels are burned to produce energy, they release harmful greenhouse gases such as carbon dioxide contributing significantly to environmental degradation and climate change (Kostakis, 2024). According to the Climate Protection Strategy for 2050 developed by the European Commission, greenhouse gas emissions in EU countries can be reduced to zero within the next 30 years. This goal is planned to be achieved by abandoning fossil energy resources, which emit significant amounts of carbon dioxide during combustion (Marsh, 2023). Given the stable international support for transformational processes in Ukraine, it seems expedient to utilize the maximum potential of transitioning businesses to renewable energy sources to reduce emissions and enhance resilience to climate change during the post-war recovery period. Subsidized financing prospects within the framework of the Eurointegration development strategy open up significant practical opportunities in terms of utilizing renewable energy sources in business (Radmehr *et al.*, 2022).

Analyzing the experience of European countries and the policies of the European Union as a whole, it can be concluded that there is an effectively coordinated approach aimed at developing "green" energy. Significant attention is paid to minimizing air emissions by abandoning traditional energy sources, improving energy efficiency, conserving natural resources, and increasing the share of alternative energy sources in the energy production structure (Twidell, 2021). For instance, as early as 2007, the Polish Government adopted two laws on the production of bio-components and liquid fuels, along with mechanisms for monitoring and controlling the quality of such products. The rapid development of wind energy technologies in Romania was facilitated by an official financial incentive system for "green energy" producers, which aimed to stimulate investment growth in Romania's energy sector. Sweden initiated ambitious goals for its green certificate system (Li *et al.*, 2022).

Contemporary studies highlight aspects of the concept of sustainable development using innovative renewable energy technologies (Ang *et al.*, 2022; Berezovetska *et al.*, 2024; Breyer *et al.*, 2022; Deshmukh *et al.*, 2023; Maradin, 2021; Petruk, Kotsiubynska and Matsiuk, 2014). They analyze the functionality of alternative energy sources in modern business environments, examine the foundations of forming business models in the alternative energy market, and explore sustainable solutions for green financing and investment in renewable energy projects. At the same time, some researchers have

generalized the issues of the convergence of sustainable entrepreneurship, innovation, and business models during the period of global socio-economic transformation towards sustainable development, minimizing destructive environmental impacts, and preventing climate change (Gurieiev *et al.*, 2020). However, issues related to the functional characteristics of fully or partially replacing traditional energy sources with renewable ones, the analytics of relevant tools, and the potential to improve the structural-functional process model through innovative approaches to motivation and stimulation largely remain beyond the focus of contemporary academic research or have been insufficiently studied. Additionally, there are several policy gaps and barriers to developing renewable energy in Ukraine, such as regulatory frameworks, infrastructure issues, and cooperation between the public and private sectors, which underscore the need for an expanded study of this research topic.

It is necessary to develop new, alternative sources of energy, such as solar, water, wind and biogas, to compensate for the shortcomings of the existing energy system, reduce carbon dioxide emissions, improve the ecological situation and solve the problem of environmental degradation. Among the potential benefits of renewable energy are job creation, the reduction of energy poverty, and the promotion of rural development. This issue gains particular importance in the context of the energy crisis. Innovative technologies in renewable energy (e.g., advanced battery storage systems) can address problems related to stability and disruptions in electricity supply (Dmytriiev *et al.*, 2022).

In light of the above knowledge, the article tries to clarify the present challenges toward the transition toward renewable energy, namely the ways of achieving sustainable economic growth as an equitable development of green infrastructures, as well as high initial costs. Therefore, it is also unclear what kind of institutional support and financial stimuli are needed in the long term so that the results can be achieved in terms of sustainable development. However, while the transition to renewable energy is critical for environmental protection, the economy also requires a stable energy supply, which alternative energy sources cannot consistently guarantee. Therefore, the issue of reducing energy dependence through the formation of an adequate energy-saving program and the development of alternative energy in Ukraine should be classified as a strategically important issue that requires an urgent solution.

Methodology

We reviewed emergent literature and statistical data to critically investigate modern trends in assimilating alternative energy technologies with national energy systems. To ensure the standards of transparency, the following steps were undertaken:

Data Source Identification: The data was collected from sources such as official government databases (State Agency on Energy Efficiency and Energy Saving of Ukraine, 2018), scientific journals, and other official publications. Sources were chosen according to their themes of renewable energy sources with additional consideration of the source publication date as a criterion for its practical relevance.

Data Selection Criteria: The selection was based on the following criteria. We searched for the latest literature from 2014 to the present. The search queries included the

following keywords: Alternative energy; Sustainable development; Energy legislation; Energy relations; and Environmental management. Accordingly, our study focused on literature primarily dedicated to European countries and Ukraine, with diverse sources of renewable energy considered, including solar, wind, bioenergy, and others. Specific focus was made on data that characterise the effect of renewable energy sources on the environment. Data were obtained by querying databases and using Pubmed for a systematic review of the literature. Consistent type of search and method of selection procedures were used, such as keywords, themes and date of publication. Data collection was continued for two months to get more relevant information.

Data Quality and Reliability Checks: To increase the reliability of data collected, whereby independence may lead to some inconsistency, efforts were made to cross-check from some other sources so that inconsistencies may be checked. Due to the social and environmental consequences of renewable energy consumption, special focus was placed on ethical factors where potential effects on flora and fauna, and people were evaluated.

Results & Discussion

Current trends in the development of alternative energy in Ukraine

In recent years, Ukraine has observed increasing trends in using renewable (alternative) energy sources (State Agency on Energy Efficiency and Energy Saving of Ukraine, 2018). This corresponds to global trends, especially in the countries of the European Union. This shift can be attributed to global factors, such as the consequences of the development of the world economy (technical progress, which leads to the search for alternative sources of energy, the need for diversification of energy sources and optimization of the fuel-energy balance, as well as with the aggravation of environmental problems). Additionally, local and temporary reasons such as the rise in energy prices and periodic interruptions in the supply of energy due to irregular transit conditions, have further pushed the demand for alternative energy sources. The use of alternative energy sources is also aimed at increasing energy and environmental security, which is an integral component of sustainable development that directly contributes to improving the quality of life of the population. In 2017, the Government of Ukraine adopted a new Energy Strategy of Ukraine until 2035, titled "safety, energy efficiency, competitiveness". This document outlines the strategic guidelines for the development of the fuel and energy complex of Ukraine up to the period 2035 (Government of Ukraine, 2017). In particular, special attention is paid to developing renewable energy sources. The part of energy obtained from alternative sources is about 3% today. According to the Ukrainian energy strategy, by 2035, the part of alternative energy in the country's total energy balance will increase to 20%. The primary and most effective directions of renewable energy in Ukraine are wind energy, solar energy, bioenergy, hydropower, and geothermal energy (Table 1).

According to the new Energy Strategy of Ukraine, until 2035, electricity production from renewable energy sources will increase yearly. The transition to more ecologically clean sources of energy, which include the sun, wind, water and biogas, will help reduce the rate of climate change. After all, the main advantage of using

renewable energy sources is environmental friendliness and the complete absence of harmful emissions into the atmosphere (Dobryanska, Lagodiienko and Torishnya, 2020; Government of Ukraine, 2014).

Table 1: Indicators of the development of the use of renewable energy sources according to the energy strategy of Ukraine (all units in million tons)

<i>Energy source</i>	<i>Year</i>		
	<i>2010</i>	<i>2020</i>	<i>2035</i>
Bioenergetics	2.7	6.3	9.2
Solar energy	0.032	0.284	1.1
Small hydropower	0.52	0.85	1.13
Geothermal energy	0.08	0.19	0.7
Wind energy	0.21	0.53	0.7
In total	3.542	8.154	12.83

Specialists of the Institute of Renewable Energy of the National Academy of Sciences of Ukraine forecast the introduction of renewable energy sources (RES) in Ukraine with a perspective until 2050 (Kudria, 2018). Table 2 shows the data obtained according to the primary development scenario regarding the installed capacity and volumes of gross electricity production from renewable sources. The electricity consumption forecast for the specified period is also given.

Table 2: Forecast of the Institute of Renewable Energy of the National Academy of Sciences of Ukraine regarding the implementation of RES in Ukraine until 2050

<i>Types of RES</i>	<i>2020</i>		<i>2030</i>		<i>2040</i>		<i>2050</i>	
	<i>GW</i>	<i>billions kWh</i>	<i>GW</i>	<i>billions kWh</i>	<i>GW</i>	<i>billions kWh</i>	<i>GW</i>	<i>billions kWh</i>
Small Hydroelectric Power Plants	0.15	0.34	0.25	0.56	0.33	0.9	0.34	0.95
Wind Power Plants	1.5	4.2	10.0	30.0	18.0	54.9	23.0	73.0
Photoelectric Plants	2.0	2.4	4.5	5.5	8.0	10.0	14.0	20.0
Geothermal Energy	0.02	0.12	0.5	3.0	1.0	6.0	1.2	7.2
Biomass	1.0	4.2	1.6	7.0	2.4	10.6	2.7	12.5
In total	4.6	11.3	16.9	46.1	29.7	82.4	41.2	113.7
Part of RES, %		6.2		23.6		36.8		44.9
Large hydroelectric power plants	5.8	10	6	12	6	12	6	12
Part of RES with hydroelectric power plants, %		11.7		29.8		42.1		49.7

Source: Institute of Renewable Energy of the National Academy of Sciences of Ukraine (2024)

Ukraine has significant renewable energy potential that can be used to improve the trade balance, create jobs and stimulate economic activity at a time when the country must overcome significant economic challenges (Bondarenko *et al.*, 2019; Lebedeva, Dobrianska and Gromova, 2018; Savchenko, Yurkevych and Liubuska, 2023a). Renewable energy development will also be an essential contribution to post-war

reconstruction. Such an energy supply will also better ensure energy security (Sirotyuk, 2015).

Reasons for low environmental awareness and existing restrictions on the development of renewable energy sources

One of the major challenges facing the energy industry today is the problem of sustainable energy supply since generating electricity by stations based on renewable energy sources is variable. To maintain a stable and sustainable energy supply, it is necessary to address several problems related to the integrated use of renewable energy sources, the creation of innovative dispatching models (smart and virtual networks), the reliability of energy production forecasting, and the accumulation of electric and thermal energy. The use of alternative energy sources has economic and environmental benefits. Ecological aspects of the use of renewable sources are highlighted in the works of (Donovan, 2015; Kasich and Litvynenko, 2017; Melnykova and Degtyar, 2019).

Critical analysis suggests that renewable energy sources can replace traditional fossil fuels, reduce dependence on imported fuel, create additional opportunities for specific branches of industry and agriculture, and reduce emissions of greenhouse gases and other harmful substances (Donovan, 2015). However, certain limitations complicate the development of the field of alternative energy. The most significant among them are high initial investments in infrastructure and technologies and insufficient opportunity to assess the positive consequences of using alternative energy sources in monetary terms (Prokip, Dudiuk and Kolisnyk, 2015).

Besides the positive, alternative energy sources have negative environmental consequences. The main environmental drawbacks associated with renewable energy sources are linked to issues such as land use, noise, landscape change, and the use of new materials, some of which can have adverse environmental impacts — such as the extraction of silicon for solar panels. The nature of the interaction of these installations with the environment is fundamentally different from the harmful effects traditionally associated with fossil fuels (Marsh, 2023). Therefore, an analysis of possible consequences should be carried out during the development and design stages. This will make it possible to avoid the mistakes made with traditional power plants where technological systems were developed first, and environmental concerns were addressed only during operation. When evaluating the environmental advantages and disadvantages of renewable energy sources, it is necessary to consider the capacity of their installations, which depends on the degree of impact on the environment. Low-power installations are practically safe from an environmental point of view; the positive effect of their operation is much higher than possible environmental damage.

Wind power as a promising alternative energy source

The operation of wind energy is determined by the following most critical environmental factors, such as blocking land territories and noise effects, which increase with increasing power and number of wind turbines; high metal capacity of wind turbines, related to the requirements of the previous cycle of metal extraction and processing; vibration effect on biota; leading to the death of many birds under the blades of vibration

motors (Twidell, 2021). Wind power plants create high-frequency noise, so they need large plots of land for their placement, and they also disturb nearby settlements. Additionally, the generators of large wind turbines rotate at a speed of about 30 revolutions per second, close to the synchronisation frequency of television signals. Therefore, giant wind turbines can interfere with the reception of transmissions at a distance of up to 1.6 kilometres (Dam, Işık and Ongan, 2023). Wind turbines can change the microclimate in their location, reducing air humidity and increasing temperature. Furthermore, wind turbines can impact groundwater and water flows, negatively impacting local ecosystems.

The maximum power that can be obtained from 1 km² of area varies widely depending on the area of use, the type of station and the technological features of the design (the average value is ~ 10 MW/km²). The noise effect near the wind turbines can reach 50 dB to 80 dB, while the threshold endurance of the human ear, based on pain sensations, is 180 dB (Sadorsky, 2021). A separate environmental problem arises from the noise effect of installations of significant power (over 250 kW) when the airflow velocities at the ends of the blades of large-diameter windmills are supersonic (Butt, Khan and Xia, 2024). At the same time, an infrasound effect appears, negatively affecting humans and other biological subjects. An important role is played by the metal consumption indicator per unit of capacity, it determines the volumes of the raw material preparation cycle for production. Depending on the power level, this indicator for wind turbines varies approximately in the range of 50 kg/kW and 70 kg/kW, and a significant number of high-strength materials is required. At present, there is a tendency to replace elements of metal structures (primary blades of windmills) with fibreglass ones (Yousaf *et al.*, 2024). An ecological analysis of the consequences of chemical production related to creating those structural materials is necessary. The impacts of wind energy on the environment are summarized in table 3.

Table 3: Impact of wind energy

<i>Type of influence</i>	<i>Positive influence</i>	<i>Negative influence</i>
Renewable energy source	+	-
No greenhouse gas emissions	+	-
Minimal use of natural resources	+	-
The possibility of placement in remote locations	+	-
Sound pollution	-	+
Impact on the landscape	-	+
Injury to birds	-	+

Source: Sadorsky (2021)

Solar power plants and small hydropower

The use of solar energy requires large areas of land for the construction of solar power plants, and the photocells used for the manufacture of solar batteries contain poisonous substances, such as lead, cadmium, gallium, and arsenic (Dmytriiev *et al.*, 2022). Low-temperature solar heat and water supply systems are currently the most common in industrialized and developing countries. From an ecological viewpoint (Shevtsov, 2019; Vozniuk, 2015), the operation of low-temperature systems is characterized by

environmental impacts from the extraction and processing of raw materials. However, they also reduce negative environmental effects by lowering emissions from traditional boiler houses and decreasing thermal pollution. Medium- and high-temperature solar installations are still in the intensive development stage. Several stations have been created worldwide using distributed parabolic concentrate systems (with a total capacity of 400 MW). The experience of their operation has shown that the main environmental factor for solar power plants (SPPs), according to the thermodynamic cycle of energy conversion, is the blocking of significant land areas by the equipment. Thus, the average potential of this cycle is estimated at 30...40 MW per 1 km².

The disadvantage of small hydropower is the flooding of territories and the drying up of small rivers, and if the dam is planned in the wrong place, it can disrupt ecosystem change and lead to biodiversity loss, particularly affecting fish species (Melnykova and Degtyar, 2019). In particular, today, the Terebly River has been almost destroyed due to the construction of the Terebly-Rytska HPP and reservoir. Beyond the hydroelectric dam, the river does not exist for more than 5 km. Due to constant changes in water levels (turning on turbines in the direction of the Terebly River), having such an area and being a continuation of a natural water body, the reservoir is one of the least productive fish habitats in Transcarpathia. Attempts at one time to carry out mass stocking and acclimatisation of individual species turned out to be fruitless. According to ecologists, to avoid a natural disaster in Transcarpathia, small hydropower plants should operate exclusively in the mode of natural flow. All this indicates that when deciding to construct hydroelectric power stations on mountain rivers, it is necessary to take a very responsible position. It is easier to destroy the natural balance, and restoring it is very difficult takes a long time, and may not be possible (Sotnyk *et al.*, 2023). Reducing the negative impacts of using mini-hydroelectric power plants with improved hydro turbines operating at low pressures has less environmental impact. Such installations have a minimal impact on the environment, as they do not require the construction of dams, reservoirs, and coastal structures. The effects of hydropower on the environment are summarised in table 4.

Table 4: The impact of hydropower on the environment

<i>Problem</i>	<i>Negative influence</i>
Loss of natural ecosystems	Big
Flooding of large areas	Potentially large
Impact on local fauna and flora	Considerable
Destruction of river ecosystems	Considerable
Obstruction of fish migration	Considerable
Influence on the regimes of rivers and water resources	Considerable
Impact on the population	Potentially large

Energy from waste and biomass: benefits and risks

Biomass processing, based on gasification, pyrolysis and production of liquid fuel, has gained significant development (Potemkina and Kosinskyi, 2020). As a result of the fermentation process during biomass processing into ethanol, by-products are formed, particularly washing water and distillation residues. The latter is a severe source of environmental pollution. Their mass is several times (up to 10) more significant than the mass of the produced product, i.e. ethyl alcohol.

Technologies that make it possible to obtain mineral substances to clean these wastes, used in the chemical industry and mineral fertilizers, are of interest. Various areas of organic waste utilization are characterized, first of all, by a sharp ecological orientation. To a large extent, it is focused on waste processing (Sotnyk *et al.*, 2023). The elimination of the latter and the associated improvement of the ecological and sanitary-epidemiological conditions of the populated environment play an even more significant role than the energy effect based on using this type of raw resource. This is especially important for regions with humid, warm climates and large cities. It is here that the technology of waste elimination plays an extraordinary role, which makes it possible to use their energy potential at the same time. Scientists have also established that it is inefficient to make biodiesel from rapeseed oil because it takes approximately 1,500 litres of oil to fuel one car for a year, which is the size of a football field with a rapeseed yield of up to 3,000 kg/ha (Sotnyk *et al.*, 2023).

In addition, growing plants for biomass can lead to deforestation, loss of biodiversity and other environmental problems. Some plants require large amounts of water and fertilizers, which can lead to water pollution and a decrease in soil quality. Carbon dioxide and other harmful emissions are released during biomass processing into energy. Although these emissions may be lower than using traditional fuels, they still have some impact on the environment. The effects of the use of bioenergy are summarized in table 5.

Table 5: Impact of bioenergy

<i>Type of influence</i>	<i>Positive influence</i>	<i>Negative influence</i>
Sustainable source of energy	+	-
Reduction of harmful emissions	+	-
Increasing energy independence	+	-
Use of waste	+	-
Impact on land and forest resources	-	+
Impact on biodiversity	-	+
Use of water resources	-	+

Geothermal energy and its environmental impact

The ecological impact of geothermal power plants and geothermal technological installations on the environment is reduced to the action of mineralized geothermal waters and steam, to the lowering of the earth's surface (sometimes significant in size) located above the geothermal layer that is being developed and to the increased (compared to TPPs of the same capacity) thermal effect of GeoTPS on the environment (Savchenko *et al.*, 2023b). Thus, geothermal energy development is associated with significant adverse environmental consequences. The first is the excessively high cost of the equipment that collects and converts geothermal heat, that is, the high cost of obtaining energy. The second is a significant negative impact on the environment – degradation of forests and ecosystems around deposits, significant subsidence of the land after extraction of water and steam from the depths, the release of gases together with steam, severe pollution of soil, air and water in the places of extraction of hydrothermal vents, and this requires quite severe control. In addition, hydrothermal deposits are often located in hard-to-reach places (Gurieiev *et al.*, 2020). Geothermal water has increased corrosive properties, and therefore, the gas-water mixture intended to produce electricity

must be separated in advance on centrifugal separators into dry steam and water. The remaining hot water and condensed steam must also be either pumped back into the ground or used as a means of heating. However, the problem of mineralization of geothermal waters remains: the large amount of salt in them pollutes reservoirs and pipes. Nitrides, chlorides, sulfides of some metals, and dangerous chemical elements (boron, arsenic) are in the composition of waters brought to the surface; hydrogen sulfide (harmless – in small quantities, toxic – with increasing concentration). In the absence of reverse injection into the formation, there is a danger of soil salinity in the area of use and a drop in formation pressure (Atstaja *et al.*, 2022). The change in pressure in the reservoir during the long-term operation of the wells affects the groundwater level in the area. It can negatively affect the operation of artesian wells and water supply.

Decarbonisation of energy processes

Wide deployment of renewables is crucial to decrease electricity production's emission intensity and energy efficiency. As electricity production is seen as potentially emission-free thanks to renewables being the primary source, electrification of many processes has started to take off (e.g., electric vehicles and heat pumps, or various industrial processes originally dependent on energy from fossil fuels), supported by increasing energy efficiency. Therefore, it is expected that electricity will cover an increasing part of the energy needs of our society in a decarbonized economy.

The use of renewable energy sources is relevant today for Ukraine because traditional energy reserves (oil, gas, coal) are non-renewable; that is, sooner or later, they will be exhausted. In addition, the advantages of renewable energy sources are their environmental friendliness (they reduce greenhouse gas emissions and do not disturb the climate balance), their regenerative nature (they are inexhaustible), and it is also a modern new trend that is popular in all developed countries of the world. Ukraine has significant potential for using alternative energy sources, particularly solar and wind energy because its geographical position and climate favour it. However, it is also necessary to consider the adverse effects of renewable energy sources.

Concepts of the issue in the scientific research of individual researchers

Li *et al.* (2022) and Twidell (2021) demonstrate the dependence of financial development indicators of socio-economic systems on the level of integration of renewable energy. The findings demonstrate that the goals of sustainable energy development are achievable through managerial incentives and compelling tax motivation. Such strategic measures contribute to increased demand for renewable energy sources and enhanced investment potential in the energy sector. Empirical studies also convincingly show that intensive financial development is driven by rising demand for environmentally friendly energy sources. The effect of renewable energy on sustainability demonstrates mixed outcomes. For example, Dam, Işık and Ongan (2023) argued that renewable energy alongside institutional quality can stabilize the environment. In contrast, Sethi, Behera and Sethi (2023) find that the growth in the economy and utilization of energy have maximum limits, but achieving optimum utilization of resources along with the conservation of the environment is much tougher and not as cost-efficient as now to build green infrastructure. According to Dam *et al.*,

the results are consistent with their views, that better-developed institutions can significantly facilitate the progress of renewable energy technologies and their permanency. For instance, Noor *et al.* (2024) confirm that compared to the other world regions, South Asia's difficulties in its transition to the exploitation of renewable energy sources are somewhat different because of economic disparities and reliance on the least renewable power supply. This regional disadvantage is quite opposite to the studies conducted on developed countries like the G7 member countries where Radmehr *et al.* (2022) prove the effectiveness of renewable energy initiating globalization along with human capital investment. These challenges enrich the idea that for less economically developed regions, financially and politically oriented specific interventions are to be needed. The current study's findings also show that financial incentives are, however, effective, they should be supported by financial incentives that must accord to the region's economic and environmental circumstances.

Dam, Işık and Ongan (2023) examine the effects of renewable energy and institutional quality on environmental stability and propose a new perspective on the inverted load capacity factor: An insight into energy and sustainable development. Noor *et al.*, (2024) focus on the South Asian region and the impact of renewable and non-renewable energy on sustainable development. Behera *et al.* (2024) show the connection between energy consumption and economic growth in India and illustrate how the more extensive utilization of both kinds of energy can help the economy.

Sustainability according to Sethi *et al.* (2023) adopted economic growth and energy consumption and emphasised that a balanced resource approach is critical for sustaining the environment. Kirikkaleli and Adebayo (2022) are concerned with Brazil to assess the impact of a green financial system and innovation in enhancing the quality of the environment, and the capability of institutional and financial measures in reducing environmental impacts. Specifically, in Dhillon and Kaur (2023), there is a focus on the relation between sustainable development, energy usage, and economic growth considering such aspects of data analysis as both the aggregate and disaggregate levels.

Idroes *et al.* (2024) discuss how Indonesian renewable and non-renewable energy influenced CO₂ emissions and ecological footprint, thus rejecting a simplistic approach to decrease dangerous emissions. Static and dynamic CO₂ emission indicators: Voumik *et al.* (2023) analyse generation from different sources of electricity in G7 countries. Raihan and Tuspekova (2022) establish the correlation between economic growth, the use of renewable energy, and urbanization with emissions in Turkey, which presents many problems related to economic development and its impact on the environment.

Recently, Radmehr *et al.* (2022) discussed the further use of renewable energy and the level of the ecological footprint in G7 economies, which is facilitated by globalization and human capital. Kostakis (2024) examines the relationship between renewable energy, financial openness and environmental pollution in ASEAN countries by arguing that financial support of environmental programs is useful. Financial development and renewable energy have been analyzed by Yousaf *et al.* (2024) for Asian countries on environmental quality to conclude that financial incentives for environmental security indeed work. Lüdeke-Freund (2020) discuss the effect of different energy sources on

natural gas rents with a specific focus on imported energy and its effect on the natural resources available, which favours de dependency on imported energy.

The necessity of renewable energy development in Ukraine offers the same problems, and potentiality and requires institutional backing and genuine financial reward contour. Consistent with prior studies, this paper's observations corroborate that general agreement emphasises policy structures that reduce high initial investment threats. However, different from some other papers that argue for direct large-scale green investments (e.g., Butt, Khan and Xia, 2024), our analysis highlights a gradual shift in policy supported by small-scale RE projects as a feasible approach. This approach reduces the cost implication drastically and allows incremental implementation as influenced by changes in technologies.

Our study aligns with the previous findings, that renewable energy has environmental benefits, it is also evident that implementation significantly differs by region and economics. There exists a major research gap regarding country-specific renewable energy strategies and small-scale renewable energy projects because large projects raise the problem of development fix and increase the initial risks associated with renewable energy projects.

Conclusion

Renewable energy sources have emerged as strategic interventions toward the achievement of sustainable development, emanating from the reduction of the reliance on fossil fuels, and controlling the negative impacts. Thus, it is possible to conclude that the subject of this research exhibits the need for the proper integration of IT development ideas with the relevant institutional support for environmental responsibility. Therefore, the study establishes that the adoption of renewable energy improves the quality of the environment while supporting political consensus is paramount to enhance the changes. The findings of the study reveal the concept of a phased adoption strategy of undertaking renewable projects that correspond to the financial capabilities of Ukraine. This approach contrasts with large-scale investment projects which some researchers have suggested, oriented to lesser economic load during the first transition steps. Although few studies are carried out at the regional level and actual statistical data on the environmental effects of discrete renewable energy sources in Ukraine are rather scarce, we conclude that the fluent status of the economic situation creates problems for the steady investment in green technologies. The practical importance of this work is in illustrating the potential of a step-by-step strategy for the development of renewable energy sources that may be utilized in other countries with comparable Gross Domestic Product (GDP) value. Therefore, the outcome of the study is useful in forming strategies for energy security and environmental management at the national level. Further research is required in comparative analysis of the effects of different kinds of renewable energy sources on the environment, and the elaboration of financial support schemes for minor renewable energy projects. Furthermore, it is suggested that the existing link between the offered and paid financial incentives and investment in renewable energy sources strengthens the creation of the best conditions for sustainable development.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Artificial Intelligence in Waste Management in the Context of Implementing Circular Economy

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Abstract

The depth of the ecological crisis raises the issue of implementing innovative solutions and technologies in waste management that align with the principles of the circular economy. This research explores the advantages of using artificial intelligence (AI) in waste management systems in Ukraine. The study employs methods of systems analysis, formalization, abstract and logical analysis, in addition to the linear trend method. A comparative analysis of waste management in Ukraine and EU countries was conducted. It was found that the waste generation level in Ukraine is 11.1 tons per person per year, compared to 4.8 tons in the EU. Only 8.24% of waste in Ukraine is sent for recycling, while this figure reaches 49.6% in the EU. The analysis revealed that insufficient infrastructure, poor-quality legislation, and the destruction caused by the war significantly affect waste management practices in Ukraine. An exhaustive review of current startups and technological solutions in waste management utilizing AI was conducted. The findings show that the implementation of AI in waste management can increase recycling rates by 20-30% and reduce operational costs by 10-15%. It is projected that by 2033, the global AI market for waste management will reach USD 18.2 billion, demonstrating an annual growth rate of 27.5%. The study concludes that applying AI in waste management in Ukraine could significantly reduce waste incineration and increase recycling rates to 70% by 2030, aligning with the goals of the National Waste Management Strategy.

Keywords

Digital technologies; Innovative tools; Sustainable development; Landfills; Startups

Introduction

The primary challenge in rebuilding the agricultural sector in post-war territories will be restoring natural areas affected by ecocide and ensuring their sustainable recovery. This problem also closely affects the issue of waste recycling based on the circular economy model, as the scale, extent, and depth of the environmental disaster require the use of innovative technologies, such as agro drones and robotics to prevent the risks of harm to people, etc. Saving the planet requires new approaches and technologies. One innovative solution is the use of artificial intelligence in waste management.

The artificial intelligence is the ability of computer systems to learn on their own and make decisions based on the data collected. Implementing artificial intelligence enables the development of effective waste management algorithms that reduce the negative impact on the environment (ITU, 2024). AI can be utilized at various stages of waste management, beginning with collection and sorting. By analyzing vast datasets, AI can efficiently classify waste by type and determine the optimal recycling methods. This process helps minimize landfill waste and promotes the reuse of materials (The AI Limited, 2024).

Waste management is an important tool to curb climate change, as it reduces greenhouse gas emissions from landfills. Automation and the circular economy are revolutionizing the future of waste management. Integrating artificial intelligence in waste management is gaining popularity due to its speed and efficiency. Thanks to the development of monitoring systems, an increasing amount of waste data is becoming available for analysis. In addition, businesses are increasingly turning waste into energy and other useful products or raw materials, which promotes circularity and sustainability. Sydney-based Arc Ento Tech is a firm that turns plastic into industrial fuel while using organic waste to make fertilizer and fish feed (The Australian, n.d.). Many authors and researchers have studied the circular economy, especially given its importance in sustainability and environmental initiatives. This field encompasses various aspects including legislative initiatives and regulatory changes that facilitate the shift to a circular economy; business models; new technologies and approaches that help close material use cycles; and practical examples of successful implementation of circular practices across different industries.

The main difficulties faced by companies and government agencies in Ukraine in the transition to circular business models are explored in the works of Derij, Butenko and Zosimenko (2021). The main problems of Ukraine's transition to a circular economy include an insufficient legal framework, a lack of clear policy, low awareness levels, and incomplete infrastructure for waste collection and recycling. Based on this, the authors theoretically substantiate the implementation of Ukraine's environmental policy in the context of sustainable economic development.

For the successful implementation of the circular economy in Ukraine, it is necessary to focus on the development and implementation of an appropriate regulatory framework, raising awareness among entrepreneurs and consumers, as well as creating effective systems for waste management. Savchuk (2023) recommends a more active involvement of businesses in the transition to a circular economy by promoting innovations in

recycling and waste reduction, along with developing state strategies to support sustainable development. The significance of tailoring circular business models to the Ukrainian context is highlighted in the works of Gorbali and Plish (2021). The authors emphasize the need for support from the state and society to achieve sustainable development through regulatory initiatives and financial incentives. Strategies for the reuse of agri-food waste are considered by Facchini *et al.* (2023). The study explored methods to decrease agri-food losses through sustainable practices that not only minimize waste but also generate economic and environmental advantages. They stress the importance of integrating innovative technologies and effective resource management to achieve sustainable development in the agri-food sector. The importance of strategic configuration of digital innovation for the successful renewal of companies' business models is discussed by Cheng *et al.* (2022). The authors explore how companies are using the attributes of digital innovation to transform their business models. They propose a configurational approach that allows firms to adapt digital innovations to the specific requirements of their business models, taking into account various factors such as technological capabilities, market conditions, and organizational resources.

Panetto *et al.* (2020) propose implementing digital technologies in agricultural supply chains to increase their efficiency and sustainability. They emphasize the importance of using AI to streamline processes, reduce waste, and improve resource management. The authors also look at the challenges posed by this transformation and offer practical recommendations to overcome them. Ayed *et al.* (2022) point to the effectiveness of integrated technologies. The integration of different technologies for the transformation of agri-food waste provides higher efficiency compared to the use of separate technologies. Integrating these methods can reduce costs, improve product quality, and reduce negative environmental impacts. The use of artificial intelligence in waste management is gaining increased attention from many researchers due to its potential to solve critical agro-industrial challenges. According to Cheng and Wang (2022), and Ancín, Pindado and Sánchez (2022), these technologies are transforming business practices, impacting workflows, and creating new ways to interact with customers, suppliers, and other stakeholders. Kassim *et al.* (2022) think that artificial intelligence can contribute to the implementation of efficient recycling and disposal systems. By examining data on various material properties, artificial intelligence can devise optimal recycling technologies that lower energy costs and maximize resource recovery. This position is supported by Ayed *et al.* (2022). According to the authors, artificial intelligence contributes to the acquisition of new knowledge and informed decision-making based on the processing of large amounts of data.

The integration of artificial intelligence into the agro-industrial complex will be a source of hope in the face of growing concerns about global sustainability. Recanati *et al.* (2022) believe that innovative collaboration has the potential to address some of the most pressing challenges of our time, such as sustainable waste management. This collaboration also supports the implementation of circular economy principles, especially in developing countries. Agro-industrial waste is a significant and often underestimated resource for ensuring sustainable food supply chain. Facchini *et al.* (2023) in their research, emphasize that the use of artificial intelligence in the field of waste management in the future will help reduce the negative impact on the environment, which is becoming critical against the backdrop of the global climate crisis.

The study of these aspects enables participation in the ongoing discussion about the need to use artificial intelligence in the waste management system. However, the practical value of using this tool at the level of Ukraine has not yet been sufficiently studied. The primary objective of this review is to substantiate the benefits of integrating AI into Ukraine's waste management system. To achieve this, the study focuses on:

1. Analyzing the current state of waste management in Ukraine and its disparities with EU practices.
2. Conducting a systematic review of startups and technological solutions leveraging AI in waste management.

By addressing these aspects, this review aims to contribute to the ongoing discourse on sustainable waste management and provide actionable insights for policymakers and stakeholders in Ukraine.

Materials and Methods

To achieve the research goal and address the objectives set, a systematic literature review was conducted, focusing on the analysis of modern startups and technological solutions in the field of waste management, including artificial intelligence.

Inclusion & Exclusion Criteria: During the study, inclusion and exclusion criteria for startups and technologies were established. The inclusion criteria comprised technological innovation (integration of artificial intelligence in waste management, such as automated sorting, big data analytics, and IoT platforms), contribution to sustainable development (reducing waste volumes, increasing recycling rates, and minimizing environmental impact), and economic efficiency (reducing costs associated with waste disposal or recycling). The exclusion criteria included solutions that do not adhere to the principles of the circular economy, projects in the early stages of development without tangible results or prototypes, and solutions that fail to address the problem of reducing environmental impact.

Data Sampling: The geographical scope of the study is global and includes an analysis of innovations that demonstrate successful implementation experiences in EU countries and the USA, which can be adapted to the Ukrainian context. The study covers the period from 2017 to 2024, selected based on several significant events. In particular, in 2017, Ukraine adopted the National Waste Management Strategy until 2030, marking the beginning of active modernization in this field. In 2022, due to the consequences of the war, the need for innovative solutions to managing construction waste significantly increased, which led to the active use of artificial intelligence. The data sources include the State Statistics Service of Ukraine¹, Eurostat (2024a, 2024b), scientific publications, and analytical materials. Through systematic analysis, the problem was identified, and the research objective was established. This approach enabled a comprehensive study of waste management in Ukraine, taking into account the interconnections between all relevant factors. Additionally, abstract and logical analysis was applied to substantiate conclusions and develop recommendations. This method focused on exploring how

¹ Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: <http://www.ukrstat.gov.ua/> [Accessed on 13 June 2024].

artificial intelligence could improve waste management. A comparison of waste management practices in Ukraine with those in EU countries was conducted to identify differences and potential improvements.

Statistical Analysis: To compare waste management practices in Ukraine with those in EU countries, a statistical analysis of data was conducted using SPSS software, based on data from the State Statistics Service of Ukraine. SPSS was employed to process data on waste volumes, aiming to identify relationships between waste volumes, the number of landfills, and the quantity of recycled waste. A SWOT analysis was conducted to evaluate the strengths, weaknesses, opportunities, and threats associated with the application of artificial intelligence in waste management in Ukraine. Special attention was given to studies related to legislative initiatives and regulatory changes, business models in waste management, new technologies, and approaches to waste recycling. This approach provides a comprehensive examination of the topic, considering both theoretical aspects and practical experience in implementing innovative technologies in the field of waste management.

Results and Discussion

Global Waste Generation Problem

By 2025, global waste production is projected to increase annually, reaching approximately 2.3 billion tons. While developed nations contribute 34% of the world's waste, they represent only about 16% of the global population. Around 15-20% of all waste is recyclable. Inadequate waste management not only poses serious health risks and damages the environment but also exacerbates climate change issues (Verkhovna Rada of Ukraine, 2019). In Ukraine, the level of waste generation was 11.1 tons per person per year, and in the EU countries, this figure averages 4.8 tons (Eurostat, 2024b). Low levels of waste recycling and recovery have led to an annual accumulation of waste volumes in Ukraine. In Ukraine, from 2023, it is impossible to obtain reliable information on the indicators of reuse, recycling and disposal due to the lack of reliable statistical data. As of 2022, the volume of household waste in the country reached 7 million tons. Of this amount of waste, 9.9% was recovered, 1.66% was incinerated, 8.24% was sent for recycling and sorting (49.6% in the EU countries), and the rest of the waste was taken to landfills. The low level of recycling indicates a gap in waste treatment methods between Ukraine and the EU countries (UNEP, 2022).

National Waste Management Strategy

The primary aim of the circular economy is to minimize waste while ensuring economic growth. In 2017, Ukraine adopted the National Waste Management Strategy until 2030, as part of the Association Agreement with the European Union. The implementation of this strategy is planned in three phases: the first phase from 2017 to 2018, the second from 2019 to 2023, and the third from 2024 to 2030. The strategy's objectives align with several EU directives and include specific requirements for product production standards, waste recycling, packaging design, and more. For instance, by 2030, Ukraine aims to recycle 70% of all market-entering packaging, 55% of plastic, and 85% of paper and cardboard. Additionally, by 2030, the plan includes establishing 800 new facilities

for processing secondary raw materials, utilizing and composting biowaste. The disposal volume of household waste should be reduced from 95% to 30%, and the total volume of waste in landfills from 50% to 35%. Moreover, it is intended to create a network of 50 regional landfills that comply with the EU directive.

As of 2022, there were more than 6 thousand landfills and polygons in Ukraine, the area of which was about 9 thousand hectares. Of these, more than a thousand landfills are either overflowing or do not meet safety standards. In addition, more than 300 landfills need to be created in the country. (Zelenkov, 2022).

Current Challenges in the Management of Waste

Ukraine faces a specific problem of waste management, which arises as a result of the predominance of technologies in the national economy that consume significant amounts of resources. At the same time, there has been no adequate response to these challenges for a long time. Large volumes of resource use and specialization in energy-efficient, multi-waste technologies, along with outdated technological infrastructure, lead to significant generation and accumulation of waste. This situation leads to an aggravation of the economic crisis and deepening of socio-economic problems, which requires reforms and development, taking into consideration domestic and world experience in resource and waste management. The issue of waste is emerging as one of the most urgent environmental challenges, particularly from a resource perspective.

The difference between the Ukrainian situation and the situation in other developed countries is that Ukraine has significant volumes of waste generation, insufficient infrastructure and a lack of financial instruments for the implementation of international waste management practices. Meanwhile, the availability of such infrastructure is a prerequisite for all developed economies. The vast accumulation of waste in Ukraine's economy and the insufficient effectiveness of measures for its control, utilization, and disposal deepen the ecological crisis and hinder the country's development. To understand the true scope of the issue, it is crucial to assess the extent of land used for landfills, which remains the primary method of waste storage in the country. Table 1 illustrates the total area occupied by landfills in the region, highlighting key challenges related to territorial load, as well as the environmental, economic, and social consequences of this issue.

As shown in table 1, the areas used for landfills are substantial, creating numerous challenges for long-term territorial planning. This underscores the need to implement recommendations such as separate waste collection and the expansion of recycling initiatives. In Ukraine, there are 5.7 thousand landfills occupying approximately 8 thousand hectares. Among these: 162 landfills are overloaded, 693 fail to meet environmental and safety standards, and 2,197 landfills require reclamation. Additionally, illegal landfills (estimated between 33,000 and 35,000) remain an increasingly serious issue, although their exact size and impact are difficult to assess. This situation significantly complicates land management in Ukraine and necessitates the adoption of effective strategies such as separate waste collection, recycling, and landfill reclamation. A significant portion of Ukraine's land is allocated to landfills, which has several critical consequences.

Table 1: Total area of landfills in Ukraine as of 2022²

Administrative-Territorial divisions	Total area of landfills, ha		
	Just	Congested	That do not meet safety standards
Vinnytska	781.6	0	0
Volynska	96.8	77.9	22.7
Dnepropetrovska	875.66	3	172.98
Donetska	85.129	0	3
Zhytomyrska	758.93	91.5	63.38
Zakarpatska	153.32	28.96	38.565
Zaporizhia	5.7	0	0
Ivano-Frankivska	74.9	7.9	8.14
Kyivska	270.377	42.3	204.377
Kirovohradska	518.08	18.69	40.4
Luganska	0	0	0
Lvivska	136,47	11.32	6.5
Mykolaivska	524,4	19.8	225.3
Odeska	1046.32	5.9	39
Poltavska	439.95	21.3	123.96
Rivnenska	429.13	12.2	0
Sumska	146.99	9.76	17.96
Ternopil'ska	113.5	12.8	3,5
Kharkiv'ska	82.06	37.51	44.55
Khmelnitska	136.13	45.54	0
Cherkasy	202.68	3	32.25
Chernivtsi Oblast	254.2	4.3	0
Chernihiv'ska	797.3	37.2	41.1
C. Kyiv	91.8	0	0
Total in Ukraine:	8021.426	490.88	1087.662

Environmental Impacts

The expansion of landfill areas leads to soil and groundwater contamination, reducing environmental quality. This poses significant health risks, particularly in areas adjacent to landfills. Furthermore, the increasing number of illegal landfills exacerbates the problem of uncontrolled environmental degradation. The lack of proper monitoring and management of these sites results in the release of harmful substances into the soil, water, and air, creating long-term environmental and social risks. The absence of accurate accounting and effective strategies for their elimination also complicates the planning of environmentally safe waste management systems.

² Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: <http://www.ukrstat.gov.ua/> [Retrieved on 13 June 2024].

Economic Impacts

The use of large land areas for landfills limits opportunities for alternative land use, such as agriculture, construction, or industry. This reduces the economic potential of regions and requires significant financial resources for waste management and land reclamation.

Social Impacts

The proximity of landfills to residential areas negatively affects the quality of life for communities. Concerns about health risks among residents decrease the attractiveness of regions for investment and create discomfort in living conditions. In addition to specific waste stored in landfills, Russia's armed aggression has introduced additional challenges related to the generation of large volumes of construction debris. The destruction of over 100,000 structures has resulted in more than 450,000 tons of construction waste, which is internationally characterized as "ecocide." As of April 2024, the total mass of such waste amounted to 223,237.3 tons, emphasizing the scale of environmental and management challenges. Table 2 illustrates the volume of construction waste generated as a result of the destruction, providing critical context for analyzing the management of these wastes.

Table 2: Amount of demolition waste in Ukraine as of April 2024³

<i>Administrative-Territorial divisions</i>	<i>Amount of waste from destruction</i>	
	<i>Tons</i>	<i>m3</i>
Vynyasa	-	-
Volynska	-	-
Dnepropetrovska	587.9	16.75
Donetska	4429.7	56456.9
Zhytomyrska	8.0	668.16
Zakarpatska	-	-
Zaporizhia	53.43	19.5
Ivano-Frankivska	1.6	400
Kyivska	189229.4	133487.0
Kirovohradska	14.6	-
Luganska	-	-
Lvivska	2015.8	-
Mykolaivska	6010.3	-
Odeska	1902.2	2.0
Poltavska	-	-
Rivnenska	82.03	-
Sumska	726.0	-
Ternopil'ska	10.2	445.8
Kharkiv'ska	1123.5	3277.8

³ Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: <http://www.ukrstat.gov.ua/> [Retrieved on 13 June 2024].

<i>Administrative-Territorial divisions</i>	<i>Amount of waste from destruction</i>	
	<i>Tons</i>	<i>m³</i>
Khmelnyska	1362.1	541.5
Cherkasy	2612.9	117.6
Chernihivska	6700.0	2600.0
Kherson	-	-
C. Kyiv	1078.1	-
Total in Ukraine:	223237.3	235780.9

The volume of demolition waste as of April 2024 highlights the extensive challenges associated with managing construction debris caused by armed aggression. The significant volume of this waste emphasizes the critical need for effective recycling and disposal strategies. The total amount of waste (223,237.3 tons) underscores the enormous quantity of materials requiring proper management. This creates both technical and administrative challenges. Without appropriate disposal measures, this waste can cause significant contamination of soil, water resources, and air. Considering the international classification of such large-scale waste generation as "ecocide," its management is critically important for Ukraine's environmental safety. The large volume of waste in affected regions complicates infrastructure recovery, deteriorates living conditions, and poses health risks due to exposure to toxic materials. Managing construction waste demands substantial financial resources, including costs for transportation, sorting, recycling, and disposal, placing a significant burden on local budgets. These challenges highlight the importance of implementing a systematic approach to waste management. Waste generation occurs across various sectors of the national economy, requiring the adoption of a unified strategy. In EU countries, following European standards, five key principles of an effective waste management system have been implemented: collection, sorting, recycling, incineration, and disposal (Figure 1). Studying this experience could provide a foundation for developing a similar model in Ukraine, addressing its current challenges.

In 2022, according to the State Statistics Service of Ukraine, the lack of effective waste management tools, particularly in sorting and separate storage, led to the accumulation of 7 million tons of household waste. The mixing of food waste with packaging and other household materials complicates sorting and processing, significantly hindering recycling efficiency. While the agricultural, forestry, and fisheries sectors demonstrated relatively high waste utilization rates of 76%, other industries, such as the processing sector, contributed substantially to the country's waste problem, producing 23.3 million tons. Furthermore, with 2.8% of landfills over capacity and 12% failing to meet environmental standards, Ukraine faces critical challenges in managing its waste sustainably.⁴

Environmental and Legal Impact

These challenges are compounded by broader systemic issues that threaten environmental security on a global scale. It is important to recognize that environmental

⁴ Ukrainian State Statistics Service (2023). *Statistical Yearbook of Ukraine 2023*. Available at: <http://www.ukrstat.gov.ua/> [Retrieved on 13 June 2024].

crimes, crimes against humanity, and war crimes disrupt global environmental security, and endanger the right of future generations to a safe environment. The ongoing Russian invasion impacts not only Ukraine but the global community as well, disregarding established legal standards for environmental protection. International cooperation in the field of combating offences that harm the environment provides for various forms of interaction between states and international organizations to prevent irreparable damage to the environment and humanity as a whole. The handling of such large volumes requires significant financial, human and technological resources.

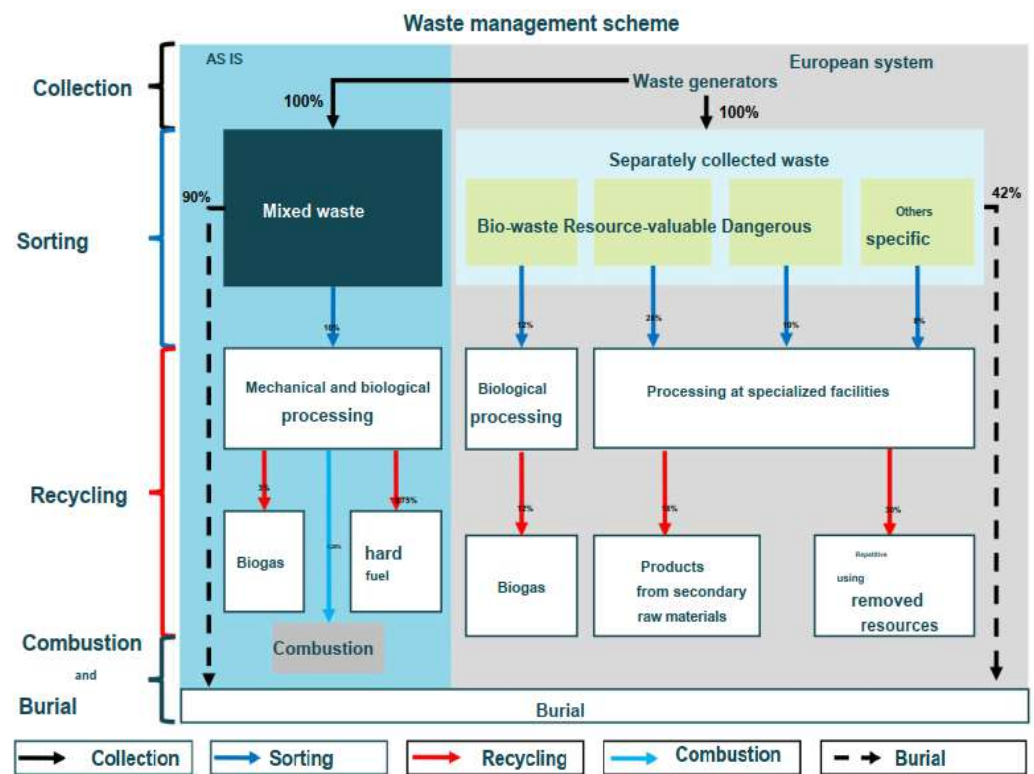


Figure 1: European Waste Management Model (Eurostat. (2024a))

Legal Framework and International Standards

One of the main obstacles to waste management is the absence of a comprehensive legislative framework, including specific recycling standards. As Ukraine advances in its European integration efforts, examining the legal basis for ecocide accountability within EU countries is essential, reinforcing the global movement to criminalize ecocide. Currently, international law provides limited environmental protection, directly and indirectly, during times of armed conflict. Such protection is found in significant humanitarian agreements, like the UN Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD Convention) and the Additional Protocol to the Geneva Conventions of August 12, 1949, for protecting war victims (Ministry of Infrastructure of Ukraine, 2023).

National and EU Regulatory Integration. Ukraine is committed to harmonizing its national laws with EU environmental principles under the Association Agreement with the EU (Table 3).

Table 3: The current state of Ukraine's regulatory framework compared to the EU and other international obligations (EU4Environment, 2023)

<i>National Regulatory and Legal Acts</i>	<i>EU Directives</i>	<i>National Strategies</i>
Law on Waste Management (from 2023)	Directive 2008/98/EC on waste and repealing certain Directives	National economic strategy for the period until 2030
Law of Ukraine on Public Procurement	Directive 94/62/EC on packaging and packaging waste	State strategy of regional development for 2021-2027 (updated)
Draft Law of Ukraine on Packaging and packaging waste	Directive 1999/31/EC on the landfill of waste	Strategy for the development of industrial parks for 2023-2030 (2023).
Draft Law of Ukraine on Waste Mining Activity	Directive 2006/21/EC on the management of waste from extractive industries and amending Directive 2004/35/EC	Strategy for the economic security of Ukraine for the period until 2025
	Directive 2012/19/EU on waste electrical and electronic equipment (WEEE)	The main principles (strategy) of the state environmental policy of Ukraine for the period until 2030 and the National Action Plan until 2025
	Regulation EU 2023/1542 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC	National waste management strategy in Ukraine until 2030
		National waste management plan until 2030
		Strategy for environmental security and adaptation to climate change for the period up to 2030

Lack of coordination between authorities in the field of circular economy and inconsistency of terminology in regulations may lead to the introduction of ineffective measures. The vast majority of EU directives, which were noted in the National Waste Management Strategy of Ukraine until 2030, have not yet been integrated into national legislation. Draft legislative acts envisaged by the National Waste Management Plan of Ukraine until 2030 have not yet been adopted and have not entered into force effect. The uncertainty of the deadlines complicates the monitoring and implementation of commitments, which undermines the trust of partners and can lead to the loss of opportunities for Ukraine and slow down its integration into the European space. The necessary tools are currently being developed to support the transformation of the recycling market, but cross-sectoral coordination between authorities and the definition of the range of issues for recovery, that meet the purpose of the circular economy remains an important issue (Figure 2).

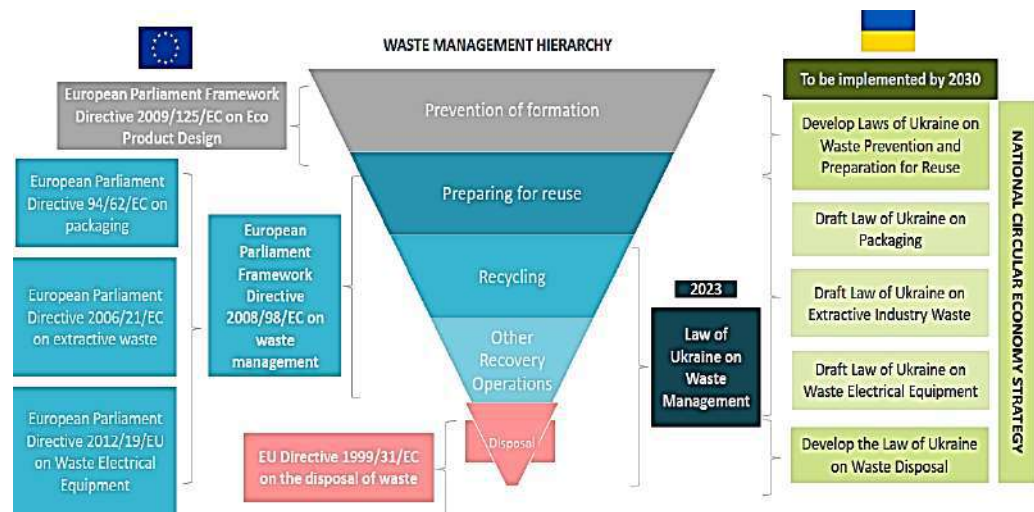


Figure 2: Waste Management Hierarchy: Comparing the EU and Ukraine in Perspective of a Circular Economy Strategy (EU4Environment, 2024)

Figure 2 compares the waste management hierarchy between the EU and Ukraine, highlighting gaps and opportunities within the circular economy framework. Ukraine’s progress in adopting EU-aligned strategies remains inconsistent, with significant room for improvement in meeting environmental sustainability goals.

Circular Economy and AI integration

The implementation of waste directives in Ukraine could lead to an annual GDP increase of 3%. By 2035, introducing a closed-loop processing cycle is projected to contribute approximately 3% of Ukraine's annual GDP growth, or \$8.8 billion. In Ukraine, the implementation of the Circular Economy Strategy opens up new markets, which has a direct and indirect impact on macroeconomic indicators.

Phase 1 (2023-2025): Adoption of laws to regulate market interactions.

Phase 2 (2026–2030): Partial implementation in residential and agro-industrial sectors.

Phase 3 (2031 and beyond): Transition to a circular economy, with gradual waste reduction aligned with European standards.

The multiplier effect in related industries is significant due to resource optimization, waste reduction and innovation.²² To achieve these goals, Ukraine should adopt the experience of the best international practices for circular production. UNIDO's (2024) Report Circular Economy for Industrial Development in Ukraine: Status Study selected four best practices for each of the priority manufacturing sectors (Table 4).

Ukraine faces several challenges in implementing its circular economy strategy, particularly in waste management: flaws in legal regulations, manufacturers' lack of commitment to environmental principles, and inadequate recycling infrastructure e.g., insufficient sorting stations, recycling facilities, and collection systems complicate waste handling. Additionally, public awareness of the circular economy's benefits remains low.

Artificial intelligence is a powerful tool for advancing circular economy strategies, increasingly serving as an innovative asset in waste management. Leveraging its ability to analyze and process extensive datasets, AI is revolutionizing waste management strategies, promoting more efficient and sustainable practices. In their research, Ayed and Hanana underscore the efficacy of AI in waste management, illustrating how data processing empowers machines to make well-informed decisions (Ayed *et al.*, 2022). By applying advanced algorithms and machine learning, waste management companies can gain insights into waste characteristics and composition, aiding informed decisions in recycling and waste reduction. AI can support various waste management stages, from collection to sorting. By analyzing large datasets, it classifies waste by type, identifies optimal recycling methods, and reduces landfill volume.

Table 4: List of best practices and their alignment with the circular strategies of the CE Framework

<i>Best Practices</i>	<i>Connection with the strategic Circular Group Economy</i>	<i>Linking to the Circular Strategy</i>
EDP Company, from exhaust gases Steel Brewery production up to Electricity (Spain)	Turning waste into fuel Waste-to-energy production Interaction with industry companies to create Shared Value and Synergy Definition	Obtaining energy from waste or producing fuel and energy resources from waste. Collaborating with companies in the industry to participate in business projects or scientific research that support the development of a circular economy, such as industrial symbiosis.
SIGUREC, Initiative "Smart machines for Waste Recycling" (Romania)	Reuse, repurpose and recycle waste within the same industry	Repurposing waste products and materials for reuse within the same industry sector. Processing waste into materials and products of lesser value is still utilized within the same industry. Establishing collection

<i>Best Practices</i>	<i>Connection with the strategic Circular Group Economy</i>	<i>Linking to the Circular Strategy</i>
		programs to prepare products and components for reuse or recycling specifically within the same sector.
ZIKOM Company, IT Recovery-equipment (Poland)	Delivery of goods to customers with the help of business models, that provide maximum Value	Sale of reusable spare parts. Sale of replacement parts. Reuse, repurpose, and recycle the waste within the same industry.
The initiative "Vive Textile Recycling» (VTR) (Польша)	Reuse, repurpose, and recycle the waste within the same industry.	Repurposing waste products and materials for reuse within the same industry sector. Reprocessing waste into lower-cost materials and products that can be utilized in the same industry. Implementing collection programs to ensure that products and components are adequately prepared for reuse or recycling within the same sector.

AI also contributes to efficient recycling systems by analyzing material characteristics, developing energy-saving recycling methods, and maximizing resources' renewable potential. Artificial intelligence enables waste management organizations to significantly enhance recycling rates. Algorithms can swiftly identify reusable materials. This not only reduces the volume of waste directed to landfills but also aids in the conservation of valuable resources. Artificial intelligence can also optimize recycling processes. By analyzing data on the types and volumes of waste, algorithms can recommend the most effective treatment methods. For example, they can apply whether incineration, anaerobic digestion, or composting are the best options for a particular type of waste, which reduces negative environmental impacts and improves resource recovery. Joshi (2022) observes that numerous waste collection systems are antiquated, with inefficient route planning leading to congestion and increased fuel consumption. AI enables the development of optimized routes for garbage trucks and helps identify when bins need emptying. This dynamic, adaptable waste management system benefits businesses, organizations, and the public. Israeli startup Algoretail (2024) machine learning to streamline procurement in retail, covering the entire journey from supplier to warehouse and store shelves. Their Algoretail IO tool forecasts sales based on data, helping to prevent losses from perishable goods, such as bread, milk, and butter, nearing expiration. The Algoretail IO tool has been widely used in fruit and vegetable distribution. Fruits and vegetables have a limited shelf life due to their rapid spoilage, and therefore delays in delivery, manual ordering and the lack of accurate data on the stocks of these products in each retail outlet only added to the problems and errors. Specific parameters of fruits and vegetables are taken into account in the automated order module, which was implemented by Algoretail (2024). This allows you to automatically create orders based on projected sales volumes. Due to this, the level

of stocks in each object of the retail chain corresponds to daily consumption. These technologies offer a range of benefits, including increased efficiency, improved product quality and safety, reduced waste, and environmental sustainability. French startup Trizzy (2024). Has launched an AI-powered assistant for waste management, designed to assist businesses and community groups. Accessible via websites, social media, and mobile apps, this assistant can identify various waste types, answer users' questions on disposal methods, and provide details on waste collection times, composting schedules, and nearby recycling centres. Additionally, Trizzy's platform features a marketplace for reusable goods, fostering a circular economy approach. With the help of the Trizzy virtual assistant, Tetra Pak, an international company specializing in food processing and packaging, together with Orlait, which sells the dairy brand J'aime le Lait d'Ici, equipped milk bottles with QR codes. Consumers can use QR code scanning to get any information about the composition, processing, and certification of packaging. This initiative is part of the transparency process and is in line with the environmental commitments of international companies (Maddyness, 2022). The American startup has introduced Zabble Zero, a cloud-based enterprise mobile platform designed to achieve zero waste. This innovative solution automates the collection and analysis of waste data for waste management professionals and integrates seamlessly with back-office systems. By leveraging machine learning algorithms, the platform offers real-time insights and recommendations, expediting decision-making processes for managers. Named after the Zabbalins, Egypt's "garbage people," Zabble's software is already being utilized in several municipalities across California. Utilizing this platform allows companies to markedly decrease the amount of waste directed to landfills and reduce their carbon footprint.

The effectiveness of the use of artificial intelligence in the processing of agricultural products has been repeatedly pointed out in the works of. Lezoche *et al.* (2020). This automates the processes of sorting, classifying, and packaging agricultural products. It can be used to predict yields and identify food safety risks. By leveraging the latest AI-based technologies, it enhances productivity and efficiency in the food supply chain, while simultaneously advancing agriculture and preserving biodiversity. In Ukraine, artificial intelligence is being utilized in waste management at the foundational level, including the use of intelligent containers and automated sorting systems (current implementation stage). In EU countries, these technologies are already integrated and used at a more advanced level, with a high level of automation and precision. In EU countries, AI systems for waste management are part of broader urban ecosystems, where all elements interact with each other. In Ukraine, such integrated solutions are not yet widely available. Common. In EU countries, new innovative solutions are constantly being developed and implemented, such as robotic sorting systems and AI-based forecasting. In Ukraine, such technologies are just beginning to appear, which creates the potential for rapid development in this area table 5.

The application of artificial intelligence (AI) in waste management has demonstrated notable success in various cities globally. In Singapore, an AI-powered waste sorting system utilizing advanced sensors and machine learning algorithms has reduced landfill usage by 30% and increased recycling rates by 20% (V8 Environmental, n.d.). In Barcelona, 'smart bins' equipped with AI technology have optimized waste collection routes, cutting emissions from garbage trucks by 40% (Blue Sky Creations, n.d.). In San Francisco, an AI system employing image recognition technology for sorting recyclables has lowered landfill waste by 35% and boosted revenue from recyclables by 20% (CBS

News, n.d.). Overall, the integration of AI in waste management facilitates a reduction in operational costs by 10-15%, an increase in revenue from recyclables by 20-30%, and a decrease in waste disposal expenses by 30-40% (Fast Company, 2023). Environmentally, this results in a reduction of greenhouse gas emissions from garbage trucks by 30-50%, an increase in recycling rates by 20-40%, and a reduction in soil and water pollution by 15-25% (Fast Company, 2023). Although Ukraine currently lacks specific examples of AI implementation in waste management, the country is moving towards modernizing its systems, as demonstrated by the adoption of the National Waste Management Strategy for 2030. The introduction of AI technology could significantly accelerate waste processing in Ukraine, where only 8.24% of waste is currently recycled, compared to 49.6% in the EU. This will help achieve strategic goals, including increasing recycling to 70% by 2030 (DLF Attorneys-at-law, n.d.).

Table 5: Application of Artificial Intelligence in Waste Management in Ukraine and Developed Countries (Bigbelly Worldwide, 2024; Dnepr Express, 2019)

<i>In Ukraine</i>	<i>In the EU and the USA</i>
<p><i>Smart Waste Containers:</i> Projects with smart containers are already being implemented in Ukraine, which use sensors to monitor the occupancy of containers. For example, startups such as Ecois. It is developing systems that notify when waste needs to be removed, optimizing garbage truck routes.</p>	<p><i>Advanced Smart Containers:</i> Many cities in the U.S. and Europe use smart bins with more advanced features, such as recognizing waste types and automatically sorting them. Companies like Bigbelly integrate such containers with real-time monitoring systems.</p>
<p><i>Machine learning-based sorting systems:</i> Some sorting stations in Ukraine use artificial intelligence for automated recognition and sorting of waste. This allows you to improve recycling efficiency and reduce human error.</p>	<p><i>Robotic sorting systems:</i> In Sweden and the Netherlands, robots based on artificial intelligence are actively used to sort waste in factories. Such systems can recognize and sort materials with great accuracy and speed.</p>
<p><i>Data Analysis Platforms:</i> Use of platforms to process a large array of information by an order of magnitude to optimize recycling and recycling processes. Such platforms help to predict waste volumes and develop strategies to reduce it.</p>	<p><i>Analytical and predictive models:</i> Japan and Germany have adopted AI-driven forecasting models to enhance urban waste management. These systems allow for accurate predictions of future waste volumes, efficient resource allocation, and a reduction in environmental impact.</p>
<p><i>IoT-based waste management platform</i> Under the "Smart City" initiative in Dnipro, the city is exploring the implementation of a unified IoT-enabled platform for managing urban waste. This platform would integrate data from multiple sources — such as smart bins, waste collection trucks, and sorting facilities — to develop an optimized waste management ecosystem.</p>	<p><i>Internet of Things (IoT) and Integration with Urban Systems:</i> In Singapore, the integration of IoT and artificial intelligence makes it possible to organize systematic waste management systems, where smart containers, garbage trucks, and sorting stations operate in a single ecosystem, streamlining the entire process.</p>

Ukraine still has to go through the implementation and adaptation of these technologies, but there are already positive examples and significant potential for further development, which requires large investments. In the EU and the US, the circular economy and artificial intelligence technologies are being actively integrated into national and regional policies. For example, the EU is implementing the Circular Economy Action Plan (Environment, 2023), which includes stringent requirements for waste recycling and incentives for innovative technologies such as artificial intelligence in this area. Ukraine is just taking the first steps towards integrating the principles of the circular economy and artificial intelligence technologies into waste management. Implementation of the National Waste Management Plan until 2030 is an important step, but this document is still in the process of adaptation. The legal framework is evolving but often does not comply with international best practices. Legislative initiatives are aimed at the integration of European standards, but their effectiveness is reduced due to insufficient implementation and the lack of clear control mechanisms. In the U.S. and EU countries, there is substantial support from both the public and private sectors. Investments in technologies that promote the circular economy and the use of artificial intelligence are considered strategic and are significantly larger in scale compared to Ukraine. For instance, the EU Green Deal allocates substantial resources for the development of these technologies. In contrast, public investment in the circular economy and the adoption of artificial intelligence in Ukraine is limited, with much of the funding derived from international grants and aid programs. This constraint hampers the speed and scale of implementing innovative solutions.

As waste management processes become more efficient and precise, investments in AI-powered solutions are increasing. Projections indicate substantial growth potential for this sector by 2030. By 2033, the global AI market in waste management is expected to reach approximately \$18.2 billion, up from \$1.6 billion in 2023, reflecting a compound annual growth rate (CAGR) of 27.5% between 2024 and 2033 (Market.us, 2024). Ukraine is actively participating in this trend. The Ministry is collaborating with international entities, particularly the European Union's LIFE program, which allocates funds for innovative projects, including those focused on waste management and AI integration/ Investment strategies will predominantly target enhancing funding for automated waste sorting systems that employ machine learning and computer vision technologies to improve accuracy and decrease recycling costs; implementing intelligent route optimization systems for waste collection vehicles to reduce fuel consumption and CO₂ emissions; investing in analytical platforms for predicting waste generation and planning infrastructure based on big data analytics (Big Data); and engaging the private sector in the development and deployment of innovative AI-driven waste management solutions.

Innovations in Waste Management Technologies and Prospects

Investing in AI-driven waste management systems is expected to decrease waste incineration and boost recycling, reuse, and recovery due to several factors. According to Market.us (2024), AI enables enhanced waste efficiency by streamlining waste collection, sorting, and recycling processes. This is achieved through accurate waste volume forecasts, identifying efficient disposal methods, and uncovering new recycling opportunities. Moreover, AI technology automates waste sorting, as noted by Blue Sky Creations (n.d.), allowing for a higher recovery rate of reusable materials. This

innovation aligns with the findings by ALGORETAIL (2024), which emphasizes AI's role in optimizing recycling techniques and increasing revenue from recycled materials.

AI contributes significantly to environmental protection. For instance, Blue Sky Creations (n.d.) reports a 40% reduction in emissions from garbage trucks due to AI-optimized waste collection routes in Barcelona. Additionally, the integration of AI in waste management improves sustainability by decreasing soil and water pollution (Market.us, 2024). While Ukraine faces challenges in adopting AI in waste management, the adoption of the National Waste Management Strategy for 2030 demonstrates the country's commitment to modernizing its waste management systems. Currently, only 8.24% of waste is recycled in Ukraine compared to 49.6% in the EU (DLF Attorneys-at-law, n.d.) AI-driven technologies could significantly increase recycling rates, as similar technologies in other countries have shown (CBS News, n.d.). Despite these opportunities, Ukraine must overcome several barriers, including insufficient legislation, limited infrastructure, and financial constraints (Market.us, 2024). Moreover, public awareness and skilled labour shortages are critical issues. Addressing these challenges through investments in education, infrastructure, and international cooperation can help Ukraine achieve its strategic goals of sustainable waste management and environmental security.

Conclusions

The research suggests that Ukraine is in the initial stages of adopting circular economy principles and integrating artificial intelligence (AI) in waste management. There is a significant disparity between EU countries in terms of waste recycling and utilization: only 8.24% of waste is recycled in Ukraine, versus 49.6% in the EU. Underdeveloped infrastructure, overcrowded landfills, and non-compliance with environmental standards necessitate immediate attention. Systemic issues in policies and regulations have been identified: there is a lack of coordination between state bodies, inconsistency in terminology, and a low level of integration with European directives. Four leading international practices in circular manufacturing have been examined, the implementation of which would improve Ukraine's economic and environmental situation.

Regarding the use of AI, Ukraine is still in its early stages, whereas EU countries have made considerable advancements in this field. The adoption of AI could potentially increase waste recycling rates by 20-30% and reduce operational costs by 10-15%. To fully realize the potential of AI and circular economy principles, it is crucial to develop a legislative framework to support innovative technologies, invest in the modernization of waste collection and recycling infrastructure, raise public awareness, and involve the private sector in adopting circular economy practices. AI pilot projects should be initiated in various regions of Ukraine, and opportunities for integrating AI with other digital technologies should be explored. The implementation of these measures will not only enhance environmental sustainability but also foster economic development by creating new markets and jobs in the green economy sector. The adoption of circular economy principles and the application of AI in waste management are crucial for Ukraine's sustainable development and its integration into the European framework.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5	Author 6
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes	Yes
Collected the data	No	No	Yes	No	No	No
Contributed to data analysis & interpretation	Yes	No	Yes	Yes	Yes	Yes
Wrote the article/paper	No	No	Yes	Yes	No	No
Critical revision of the article/paper	Yes	Yes	No	No	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Advancing Waste Reduction and Resource Conservation through Circular Economy Practices: A Rational Review

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Abstract

The modern world is undergoing profound changes due to globalisation, digital transformation and the depletion of natural resources; it requires radical modernisation of the economy and repeatedly involves introducing new organisational and economic models that combine economic development, environmental safety and the rational use of natural resources. To address these challenges, it is crucial to shift towards a sustainable lifestyle that balances short-term economic interests with long-term environmental impacts. As the foundation of the new industrial revolution, the circular economy offers a pathway to creating more competitive and sustainable economies where waste becomes a resource and economic development does not contradict environmental protection, but its implementation requires a comprehensive approach. This study aims to demonstrate the necessity of transitioning from a linear to a circular production model to minimize waste and conserve natural resources through the integrated application of cyclicity principles. This approach enables enterprises to achieve profitability while alleviating the strain on natural resources. Using a systematic approach and various scientific methods such as analysis, synthesis, deduction, generalisation, and abstraction, this review investigates modern environmental challenges and identifies one of our most significant environmental problems: waste minimisation and conservation of natural resources. The paper evaluates the potential and limitations of implementing the circular economy in contemporary economic contexts to enhance efficiency and safety. The critical indicators of the circular economy were analysed, allowing a general idea of the progress in this area in recent years, based on the example of the European Union. The study concludes that a successful transition to a circular economy requires a comprehensive approach that creates new business opportunities and promotes interaction between enterprises, society and the state, ensuring the exchange of experience and knowledge.

Keywords

Innovations; Sustainable development; Natural resources; Circular economy; Waste minimisation

Introduction

The crisis of natural resource depletion is one of humanity's most critical challenges in the 21st century. Economic development has triggered several acute problems, including global warming, resource scarcity and deepening social stratification. Irrational use of natural resources leads to environmental degradation and climate change, threatening the stability of our planet. The rate at which humanity depletes its resources will soon cross a critical threshold potentially leading to irreversible environmental disasters. The depletion of natural resources and environmental disasters prove that traditional production, consumption and waste disposal models have exhausted their viability and need to be radically reassessed.

The transition to a circular economy reduces dependence on finite natural resources, stimulates innovation, and creates a more resilient economy capable of withstanding global challenges. This innovative approach radically changes the outdated economic model by moving from a linear production-consumption-disposal system to a circular one, where resources circulate in a closed loop. The efficient use of resources in a circular economy contributes to environmental protection. It impels economic development and job creation, as companies can reduce their raw material and energy costs, increase competitiveness and create new business models (Korhonen *et al.*, 2018)

The European Union, as an example of successful implementation of the circular economy, invests heavily in its development, allocating hundreds of millions of euros annually (Ellen MacArthur Foundation, n.d.). This not only helps preserve natural resources but also creates the potential for economic prosperity without worsening the environmental situation (Atstaja *et al.*, 2022). Due to significant EU investments, the circular economy is becoming increasingly attractive to businesses, boosting the development of innovative solutions and employment growth while reducing the environmental burden.

Globally, other regions are also making strides in implementing circular economy principles. For instance, Japan has introduced comprehensive recycling and resource management policies, while China has incorporated circular strategies into its national development plans, focusing on industrial symbiosis and resource efficiency. However, despite progress in various regions, the shift to a circular economy remains a long and challenging process. The objectives of this research are to examine the current state of circular economy practices globally, identify key barriers to its implementation, and propose strategies to enhance waste reduction and resource conservation.

Literature Review

Scientific research aimed at developing sustainable management models that will preserve natural resources for future generations proves that this issue is crucial for the future of humanity. Research by Vergara and Jammi (2022) shows that soil, air and water pollution, clogging of storm drains and waste incineration, and the release of toxic substances into the air and water are severe environmental problems that result from improper waste management, threatening human health and the environment and leading to the degradation of natural ecosystems. In addition, it leads to socio-economic

problems, as noted by Fanning *et al.* (2021), namely significant inequalities in the distribution of wealth and resources within and between countries; many people are unable to meet their basic physiological needs; the rich consume significantly more resources than the poor, and thus contribute to environmental overconsumption. The study's findings by Winkler *et al.* (2021) highlight the need for urgent action to preserve the earth and its resources. They also point to the need to revise current land management strategies and develop new approaches that take into account more accurate estimates of land use change.

The analysis of the adverse effects of human impact on the environment has led the scientific community to conclude that traditional approaches to economic development need to be rethought, as Harpprecht *et al.* (2021) noted. This has spurred an active search for innovative solutions and contributed to the rapid development of new economic models to preserve the environment. The term "circular economy" first appeared in the 1990's work of British ecologists Pearce and Turner (1990). In the study "The Economics of Natural Resources and the Environment", the authors draw particular attention to the fact that the linear model of the economy, which involves the extraction of resources, production and disposal of waste, has led to the depletion of natural resources and the deterioration of ecosystems (Murray *et al.*, 2015). They propose an alternative approach – a circular economy, where materials are constantly circulating, and waste is minimised or wholly recycled, allowing for a more sustainable economy that does not harm the environment. Publications on the circular economy in the global scientific literature have a long history, associated with a long period of research and development of this economic model in the world's leading countries (Arsawan *et al.*, 2024; Atstaja *et al.*, 2022; Koval *et al.*, 2023). The active interest in this regard is that many countries have embarked on its implementation several decades ago, which stimulated relevant research. After analysing the theoretical foundations underlying sustainable development and the circular economy, Strapchuk (2020) concluded that the circular economy is a critical element of sustainable business 2.0 and a powerful incentive to rethink traditional approaches to business. According to Kirchherr *et al.* (2017), the circular economy is a business model based on the reuse of resources that combines economic efficiency, environmental sustainability and social justice. Geissdoerfer *et al.* (2017) describe the circular economy as a constantly renewed system that minimises resource consumption through reuse. We share the point of view of Haas *et al.* (2015), who define the circular economy as a strategy to minimise resource use and waste generation by creating closed loops.

Research shows that the "circular economy" concept is critical to launching recovery and regeneration processes in industry. Murray *et al.* (2015) emphasise that the circular economy involves careful planning and organisation of all stages of production and consumption to minimise waste and maximise resource efficiency. This concept is based on four main components: social and environmental responsibility, circular economy principles (R-principles), rational use of resources and promotion of recycling. However, in 2018, the World Economic Forum presented an updated model of the circular economy, which includes ten fundamental principles that contribute to more sustainable development: refuse to rethink, minimise, recycle, repair, restore, adapt to new use, recycle, and renew energy, compost (Schwab, 2018; Tymoshenko *et al.*, 2023).

Developed European countries are actively working to implement the principles of the circular economy, understanding their potential for sustainable development, being a leader in producing and exporting high-tech goods, consistently implementing policies to stimulate innovation and moving to a circular economy model. Studying the trends in the development of the circular economy noted that even with common European principles of the circular economy, their specific implementation in each EU country has its nuances due to national characteristics of the economy, culture and legislation Horbal *et al.* (2021). The European single market and the development of digital technologies create a favourable environment for implementing the circular economy, which will increase the competitiveness of the European industry and stimulate innovation (Roleders, 2023). Although the number of publications on the circular economy is considerable, the depth of understanding of the transition to this model requires further research, especially in the context of the current challenges of digitalisation, geopolitical changes and the increased level of militarization in the world.

The study aims to justify the need to move from a linear production model to a circular one to minimise waste and preserve natural resources by analysing the potential of the circular economy as an effective tool for solving global problems, which will allow businesses to make a profit while reducing the burden on natural resources. The study's main objective is to identify the key factors influencing the level of circular economy development in the EU countries and its advantages and disadvantages to justify a comprehensive model of interaction between governments, businesses, and the public for its successful implementation.

Methodology

This study uses a systematic review methodology to examine the impact of the circular economy on waste minimization and resource conservation. A systematic review was chosen because it allows for a structured synthesis of existing research, providing a comprehensive understanding of the topic.

A thorough literature search was conducted across multiple academic databases, including Scopus, Web of Science, and Google Scholar. Search terms included “circular economy”, “waste reduction”, and “resource conservation”. Peer-reviewed journal articles, reports, and conference proceedings published between 2015 and 2023 were included to ensure a current analysis. Articles were selected based on relevance, availability in English, and focus on empirical or theoretical aspects of the circular economy. Papers without a robust methodological foundation or those that focused exclusively on related issues, such as renewable energy, without addressing the principles of the circular economy were excluded.

The data obtained was systematically evaluated using thematic analysis to identify recurring patterns, strengths, weaknesses, and critical gaps in existing research. Systems analysis was applied to understand the relationship between waste accumulation, environmental pollution, and the implementation of circular economy strategies.

Results

Driving forces for developing a circular economy

One of today's most significant environmental challenges is minimising waste and preserving natural resources. Continuous population growth, urbanisation, industrial development and consumer lifestyles are driving factors behind this issue. Intensive human economic activity, enhanced by scientific and technological progress, leads to the degradation of natural ecosystems and the disruption of global ecological balance (Fanning *et al.*, 2021). Limited recycling services, improper landfill disposal, and harmful incineration practices stem from low environmental awareness.

Although some pollutants have declined significantly in their nature and source point, problems with harmful particles, nitrogen oxides, and sulphur dioxide exist, especially in cities with high transport and industrial activity (Harpprecht *et al.*, 2021). Pollution of surface and groundwater with nitrogen, phosphorus and other substances from agriculture and industry remains a significant concern. Climate change is exacerbating existing environmental problems by causing more frequent extreme weather events, sea level rise and biodiversity loss, and rapid industrialisation in developing countries is leading to increased emissions of greenhouse gases and other pollutants (Persson *et al.*, 2022). Despite recent downward trends in the European Union, the increased consumption and production of disposable goods continue to elevate greenhouse gas and air pollutant emissions, as well as pressure on natural resources (see Figure 1). Still, the consumption of raw materials remains almost unchanged.

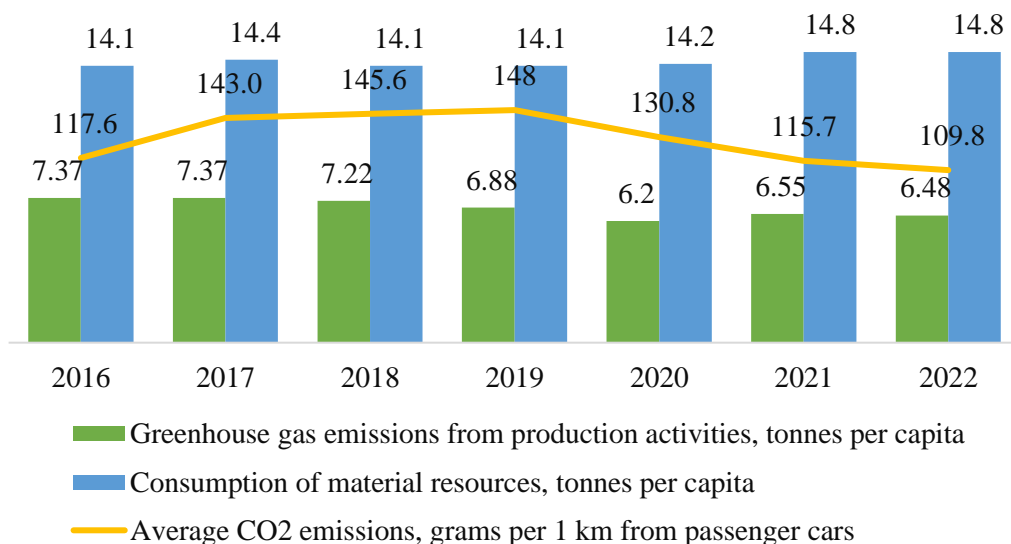


Figure 1: Consumption of material resources, greenhouse gas and air pollutant emissions in the EU countries in 2016–2022 (Source: Eurostat, n.d.)

The circular economy is a new paradigm that involves moving away from the traditional linear model of the economy and towards a model in which resources are used as efficiently as possible throughout the entire product life cycle. In a circular economy, products and materials are continuously circulated to retain their value for extended

periods. This approach optimises the use of natural resources and promotes their renewal, which helps to save resources and reduce damage to the ecosystem (Artyushok *et al.*, 2023; Horbal *et al.*, 2021). Through the circular economy, society can achieve a harmonious combination of economic growth and environmental sustainability, abandoning the traditional linear “take-make-use-discard” model used in the past.

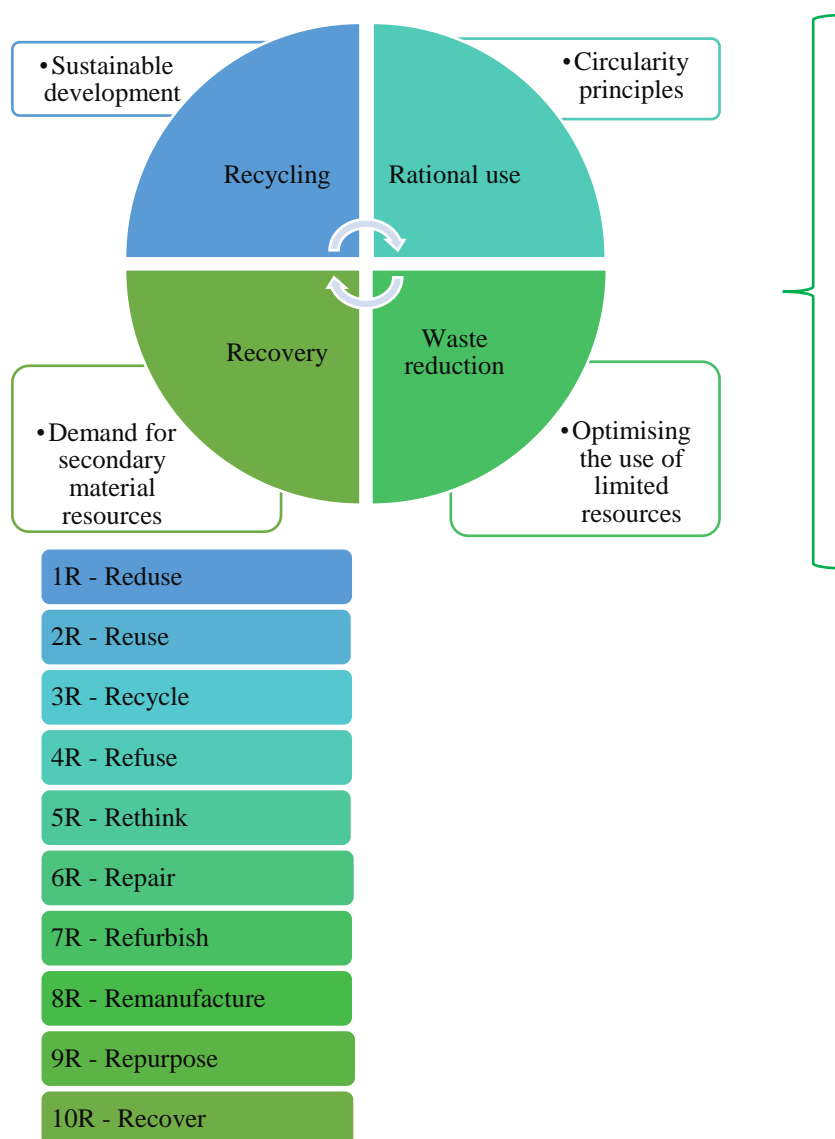


Figure 2: A comprehensive model for implementing the circular economy
 (Source: Cobirzan *et al.*, 2023)

The concept of circular economy merges the best ideas from diverse fields, including ecological economics and sustainable development theory (Boulding, 1966). The main objective of the circular economy is to reduce the ecological footprint through the rational use of resources. As a closed-loop structure, the circular economy redefines traditional economic models by converting waste into valuable resources. The circular

economy is a desirable goal, but achieving it in full may be extended. It should be rephrased even partially implementing its principles can bring significant results (Korhonen *et al.*, 2018a; Korhonen *et al.*, 2018b; Reike *et al.*, 2018). We believe that any economic system can progress towards circularity by gradually introducing its principles. Instead of the linear extraction-production-consumption-disposal scheme, the circular economy creates a closed loop where resources are constantly circulated, reducing waste to an absolute minimum through rational use (Figure 2).

The European Union has set a global example of successful adaptation to the circular model, actively developing the theoretical foundations and practical tools for its implementation. Various financial instruments have been introduced, such as grants, loans, capital investment guarantees, and programmes to support businesses implementing circular solutions, funded by various agencies such as the EU Regional Development Fund (ERDF), the Cohesion Fund by various agencies, and the Horizon Europe Programme. These instruments aim to foster the emergence and development of new ideas, technologies and business approaches and help companies overcome financial barriers to circularity (CGR, 2023; Kirchherr *et al.*, 2018). Through a comprehensive approach that combines policy, investment and cooperation, the EU has achieved significant results in reducing waste, increasing recycling and energy efficiency and stimulating innovation in these areas (Figures 3 and 4). Optimisation of production processes with new technologies could reduce industrial raw material consumption by 17-24% by 2030 (BMZ, 2023), potentially saving businesses €630 billion annually (Venturini, 2021).

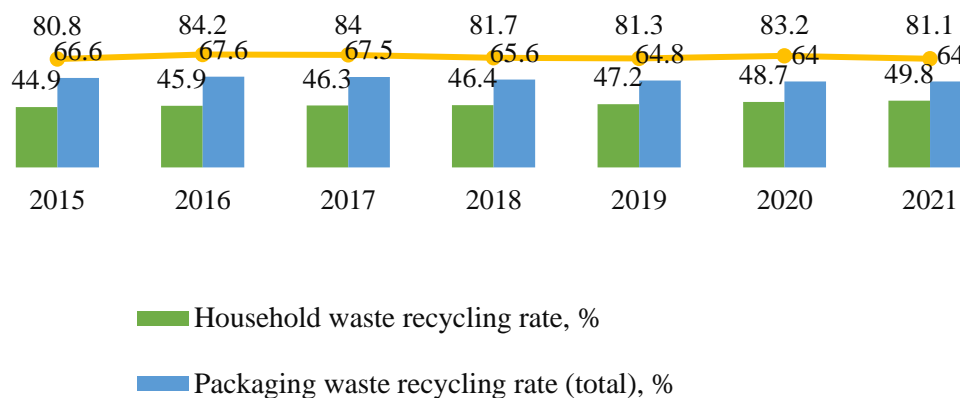


Figure 3: Dynamics of waste management and innovation indicators in the EU circular economy in 2015–2021 (Source: Eurostat, n.d.)

The circular economy establishes closed loops for products, materials, and energy, enabling economic development without depleting resources. The 10R model highlights the gradual shift towards a zero-waste economy, beginning with basic strategies such as waste reduction and gradually introducing more sophisticated approaches such as reuse and recycling (Venturini, 2021). Recycling is based on the principle of “best to worst”: first, high-value products are created, and then, if this is not possible, waste is used to generate energy (Murray *et al.*, 2015; Salvador *et al.*, 2020).

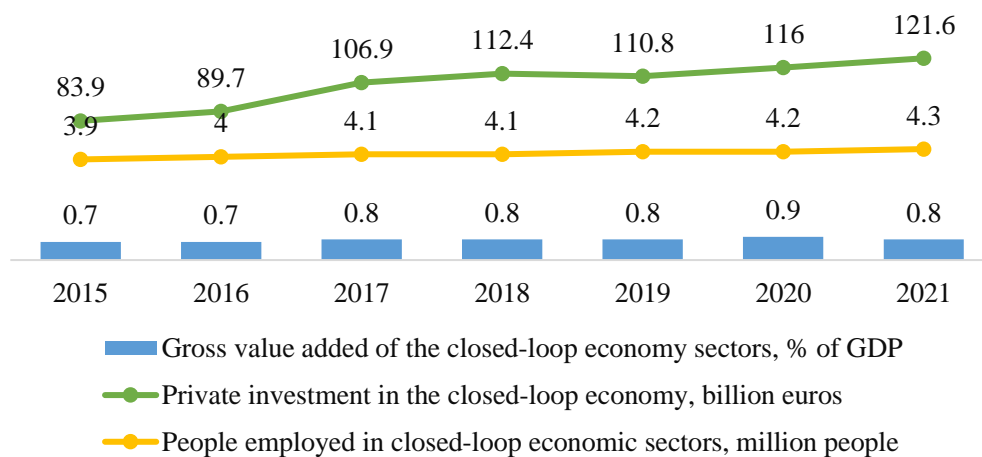


Figure 4: Dynamics of competitiveness and innovation indicators in the circular economy of the European Union countries in 2015–2021 (Source: Eurostat, n.d.)

The uniqueness of the circular economy lies in internal mechanisms that can independently stimulate its development and remove obstacles that arise along the way. Each element facilitating the transition to a circular economy influences overcoming barriers and the successful implementation of strategies (Ritzén and Sandström, 2017; Schögl *et al.*, 2020). For example, product design determines these strategies' cost-effectiveness, scalability and quality. By transitioning from product sales to creating value, companies are adopting models centred on providing services and supporting the product lifecycle, thereby increasing revenue and strengthening customer relationships. Like any other system, the circular economy has its advantages and disadvantages, as shown in table 1, so it is essential to understand them to make informed decisions about its implementation.

Table 1: Advantages and disadvantages of the circular economy

<i>Benefits of a circular economy</i>	<i>Disadvantages of a circular economy</i>
<ul style="list-style-type: none"> –Conservation of natural resources. The circular economy helps conserve natural resources and reduce environmental pressure by reusing materials and minimising waste. –Reducing greenhouse gas emissions. Recycling and reusing materials requires less energy than producing new products from virgin raw materials, which leads to lower greenhouse gas emissions. –Creation of new jobs. The transition to a circular economy stimulates the development of new technologies and business models, which creates new 	<ul style="list-style-type: none"> –High initial investment. Transitioning to a circular economy requires significant investment in new technologies, infrastructure and staff retraining. –Difficulty of implementation. Implementing a circular economy requires a change in thinking and action at all levels, from producers to consumers, which can be complex and time-consuming. –Inadequate infrastructure development. Many regions lack the necessary infrastructure for waste collection, sorting and recycling.

<i>Benefits of a circular economy</i>	<i>Disadvantages of a circular economy</i>
<p>jobs in sectors such as recycling, repair, and product development.</p> <p>–Increased competitiveness. Companies that implement circular economy principles can reduce their raw material costs, increase production efficiency and create new products that meet the needs of modern consumers.</p> <p>–Strengthening the economy. A circular economy can contribute to more sustainable economic growth by reducing dependence on commodity price fluctuations and ensuring more stable supply chains.</p>	<p>–Lack of standards and regulations. A lack of standards and regulations can make it challenging to implement a circular economy.</p> <p>–Difficulty in assessing effectiveness. Evaluating the effectiveness of circular projects can be difficult due to the lack of standard methodologies and indicators.</p>

Source: Cherevko (2022)

The circular economy is a promising model for addressing many global issues, but its successful implementation necessitates collaboration among governments, businesses, and the public (Figure 5), alongside significant investments in research, development and infrastructure (Bocken and Ritala, 2021). In addition, it is giving rise to new business models such as sharing, renting, repairing and recycling, which creates new business opportunities and fosters cooperation between different companies, academic institutions and NGOs, allowing for the exchange of knowledge and experience, where each party has its roles and responsibilities. The complete transformation of the economy to a circular model is indeed an ambitious goal that requires a comprehensive and coordinated approach from all stakeholders, but further efforts and cooperation of all stakeholders are needed to achieve a sustainable effect in the following areas (Ometto *et al.*, 2024; Sillanpää and Ncibi, 2019; Tan *et al.*, 2022):

- jointly defining goals and priorities to develop joint strategies and action plans that take into account the interests of all parties and contribute to the achievement of long-term sustainable development goals;
- developing an effective waste management system to create infrastructure for waste collection, sorting and recycling; developing incentives for separate waste collection;
- supporting innovation by creating a favourable environment for the development of innovative technologies and business models related to the circular economy;
- educational and training activities as part of information campaigns to raise public awareness of the principles of the circular economy, as well as the inclusion of sustainable development topics in the educational programmes of higher education institutions;
- creating spatial platforms for dialogue, such as forums, conferences and other events to share experiences and best practices;
- creating circular economy clusters within associations of enterprises, research institutions, universities and local governments to develop and implement joint projects;

- developing standards and certification to unify standards for products and services that meet the principles of the circular economy;
- creating markets for secondary resources and conditions for their efficient functioning, which will stimulate recycling and reuse of used products;
- Providing financial and advisory support to businesses transitioning to circular business models.

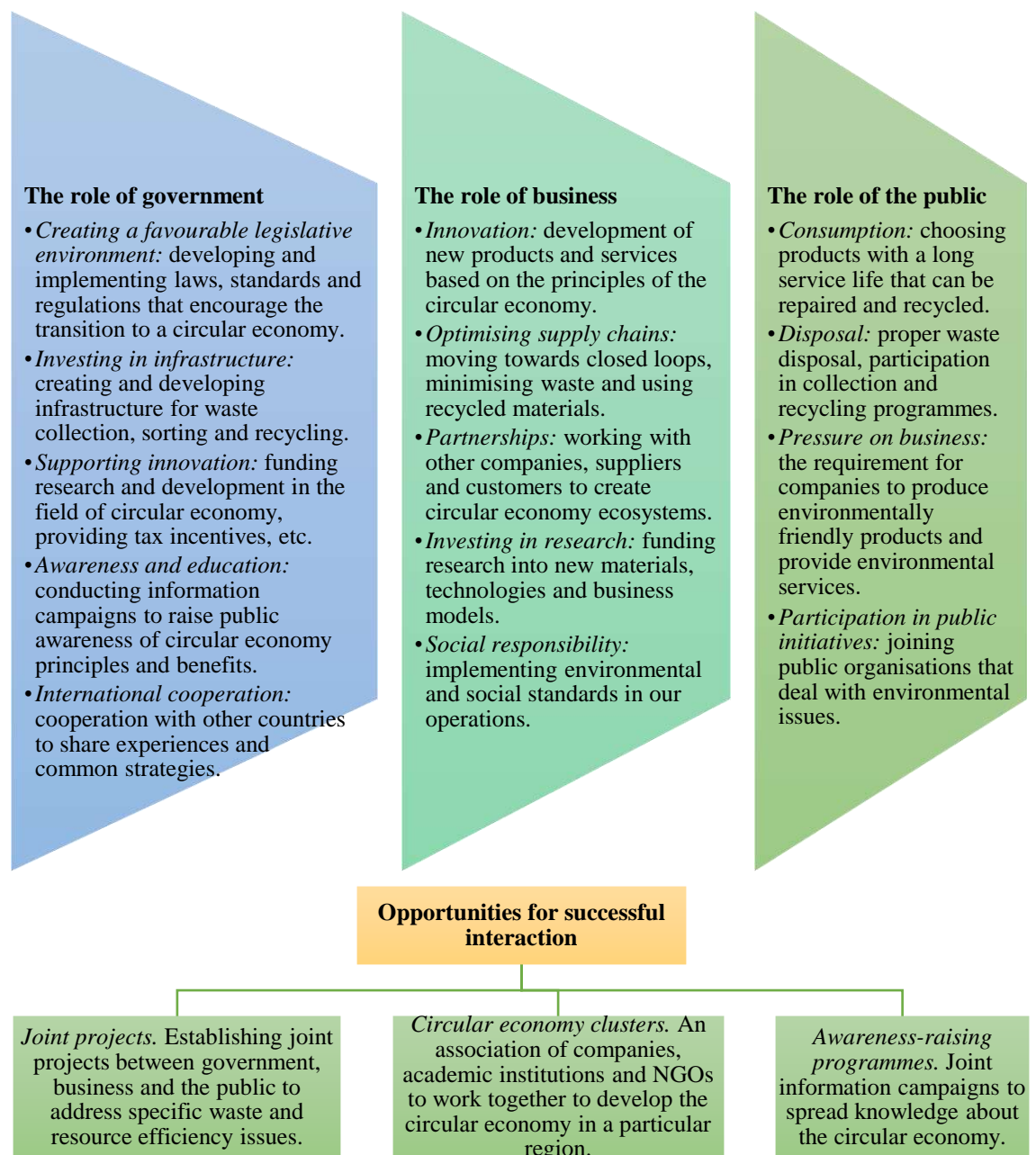


Figure 5: Interaction between governments, businesses and the public for the successful implementation of the circular economy

The circular economy has a multilayered structure, founded on essential components and complemented by active elements that drive its development. In addition, an integral part of this structure is the social component, which ensures a fair distribution of resources and opportunities. Due to these components, the circular economy will become more accessible and attractive to various economic sectors, accelerating its spread (Jonker *et al.*, 2022). The proposed components can serve as a basis for developing national programmes and individual strategies of individual companies, allowing for the coherence of actions at different levels. The model based on these components can be scaled up and applied to developing national strategies for the transition to a circular economy and creating corporate sustainability plans.

Discussion

This study highlights the critical role of the circular economy in mitigating environmental challenges arising from rapid technospheric development and anthropogenic pressure. The findings indicate that adopting circular economy principles — such as waste reduction, resource conservation, and improved recycling practices — can significantly enhance environmental sustainability. Key insights reveal that integrating circular systems into industries and communities fosters ecosystem resilience and reduces biodiversity loss, aligning with broader climate goals. However, the methodological limitations of this study should be acknowledged. The analysis predominantly relies on secondary data sources, which may introduce biases due to variability in data collection methodologies. Additionally, the scope of the study is constrained to general global trends, which might not fully capture regional variations in the adoption and impact of circular economy practices. Future research should focus on longitudinal studies and incorporate more localized data to provide deeper insights into specific geographical contexts.

The rapid pace of technospheric development, driven by anthropogenic activities, continues to threaten the natural mechanisms of biosphere self-healing. This disruption is evidenced by climate change, biodiversity loss, and ecosystem degradation. Society's lack of environmental awareness, reflected in inadequate waste sorting and recycling practices, further exacerbates these challenges (Persson *et al.*, 2022). To address these issues effectively, transitioning from a linear sustainable development model to a circular economy is imperative.

The European Union countries are among the leaders in implementing circular economy principles today, making significant efforts to improve the environment and transition to a more sustainable economy. This approach has become a strategic goal for the EU, integrating the economic, social, and environmental aspects of sustainable development (Roleders, 2023). The fruitful work has resulted in the adoption of several directives and regulations that stimulate the transition to a circular economy, including the Waste Directive, the Packaging and Repeating Waste Directive, the Ecodesign Regulation, the Extended Producer Responsibility (EPR) Principle, the EU Plastic Strategy (Bocken and Ritala, 2021). Significant funds are being allocated for research, development, and investment in projects related to the circular economy and active cooperation with member states, businesses, academia, and the public. Producer responsibility has been expanded, waste sorting and recycling has been encouraged, eco-friendly product design

requirements have been set to facilitate their repair, reuse and recycling, energy-efficient solutions in construction, industry, and households have been promoted, a second-generation biofuel market has been created, and the bioeconomy is actively developing (Salvador *et al.*, 2020).

Although the circular economy is not aimed at maximising GDP as much as sustainable development, it can still significantly accelerate economic growth through several positive effects, such as reduced dependence on scarce resources and increased productivity. Its potential lies in reducing the risks associated with resource scarcity and environmental pollution. However, it is often underestimated, and most analyses do not consider how the circular economy can significantly reduce environmental restoration costs. Fluctuations in the prices of non-renewable resources result from the interaction of factors such as the development of extraction technologies, the depletion of easily accessible deposits, optimal extraction volumes and growing resource scarcity.

Externalities are one of the main barriers to an effective transition to a circular economy, but introducing appropriate policies, such as tax incentives and regulatory measures, can significantly reduce their impact (Bocken and Ritala, 2021). For example, an increase in taxes on the extraction of primary raw materials combined with a reduction in corporate taxes can encourage companies to use resources more efficiently without negative consequences for the state budget in the short term and even contribute to economic growth in the long term. Ignoring the environmental impact of economic activity leads to the depletion of natural resources and environmental pollution. Adopting a circular economy can mitigate this negative impact while maintaining economic growth.

The transition to a circular economy has become a global trend, with many countries actively implementing various initiatives to achieve this goal. The EU has devised an ambitious action plan to position Europe as a global leader in the circular economy. This plan encompasses a broad range of measures, including setting targets for waste reduction, promoting innovation and investment in the circular economy, and harmonising legislation. Many EU countries have introduced bans on using certain types of single-use plastics, such as plastic bags, disposable cutlery, and tableware, which helps reduce plastic pollution and encourages more eco-friendly alternatives.

Many US states are developing programmes and laws to advance the circular economy. For instance, certain states are implementing deposit return systems for bottles and cans, to promote recycling. A law passed in 2021 provides for significant investments in infrastructure, including recycling and waste disposal programmes, aimed at creating new jobs and stimulating the growth of the circular economy in the US. China is heavily investing in developing a circular economy, particularly in the waste recycling and green product manufacturing sectors, and is developing national standards for the circular economy while supporting innovative projects in this field. Japan has a long history of implementing resource conservation and waste recycling measures and continues to advance these initiatives, mainly through adopting new technologies and promoting circular economy development across various sectors.

Canada is actively developing a national circular economy strategy, including measures to reduce waste, promote innovation, and raise public awareness. Australia has

developed a national waste management plan, significantly reducing the waste sent to landfills. Despite different approaches, a joint global trend towards the development of the circular economy is evident: governments are investing in research and developing new technologies for waste recycling, producing environmentally friendly products, and creating more efficient resource management systems. They also work with businesses to develop and implement new business models based on circular economy principles. They are running public awareness campaigns to emphasize the importance of the circular economy and promote changes in consumer behaviour.

Conclusion

The transition from a linear to a circular economy represents a transformative approach to addressing pressing environmental challenges, including waste reduction, resource conservation, and ecosystem preservation. This study demonstrates that adopting circular economy principles not only fosters economic sustainability but also promotes environmental resilience by minimizing resource depletion and pollution. The analysis highlights the potential of circular systems to redefine traditional production and consumption models, shifting towards closed-loop processes where resources are reused and recycled effectively. European Union policies and initiatives exemplify the successful integration of these principles, showcasing the importance of a comprehensive approach involving financial incentives, innovative technologies, and collaborative frameworks.

Key recommendations for advancing the circular economy include:

1. Collaboration among governments, businesses, and communities to establish cohesive strategies that align with sustainable development goals.
2. Developing infrastructure for waste collection, sorting, and recycling, alongside incentives for responsible waste disposal.
3. Encouraging the development of technologies and business models that align with circular economy objectives.
4. Raising awareness and integrating sustainability topics into educational curricula to foster a culture of environmental responsibility.
5. Establishing forums, conferences, and circular economy clusters to facilitate experience sharing and joint project development.
6. Creating conditions that stimulate the recycling and reuse of materials through regulatory and financial support.

Although the transition to a fully circular economy remains an ambitious goal, gradual implementation of its principles can lead to significant environmental and economic benefits. The success of this transformation depends on the cooperation and commitment of all stakeholders, alongside sustained investment in research, infrastructure, and public engagement.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	No	No	No
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	No	Yes	Yes	No	Yes
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The Role of the Circular Economy in Advancing Environmentally Sustainable Industrial Production

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Abstract

In the last decade, the circular economy has transformed into a new paradigm that attempts to tackle global environmental and resource challenges. Starting in the late 20th century, this concept began as a reaction to the growing realization of the limits of linear economic systems, focused on the extraction and abandonment of resources rather than sustainability. Technological progress, policy reforms, and heightened environmental consciousness have led over the years, to the adoption of circular principles in industrial processes. Initial efforts were oriented towards waste management and recycling, these being developed to comprehensive approaches that encompass such initiatives as product design, resource regeneration and systemic innovation. The study examines the factors that enhance the application of circular economy in environmentally sustainable industrial production and resource efficiency and environmental damage. Applying circular approaches in the Netherlands leads to a 30% decrease in the demanded primary resources and a 25% decrease in industrial waste. On the same note, the circular economy models have been used in China to reduce CO₂ emissions in heavy industries by 20%. Currently, Japan has managed to recycle 80% of its plastic waste and Germany has applied regenerative technologies into construction to reduce the usage of natural resources by 35%. Nevertheless, the following challenges are evident: high implementation costs, weak legislation and regulatory frameworks, and insufficient waste disposal facilities. The findings of this research will enable partnership support in overcoming these challenges in the promotion of a circular economy as a viable model for industrial transformation.

Keywords

Circular economy; Environmentally sustainable development; Industrial production; Environmental sustainability; Renewable resources

Introduction

The transformative model of environmentally sound industrial development is the circular economy, optimal use of resources and minimization of waste. While such economic systems differ from traditional linear economic systems possessing an emphasis on resource extraction and disposal, circular models rather support resource regeneration and reuse, as highlighted by Ghisellini, Cialani and Ulgiati (2016). This approach especially becomes important given the growing issues of environmental degradation and resource scarcity worldwide and in Ukraine, where industrial sectors are undergoing growing pressure to adopt sustainability. Though recognized, the use of circular principles in Ukraine is nascent, lacking essential implementation, and regulatory support.

However, previous research points to the enabling nature of cutting-edge technologies, like automation and artificial intelligence, for improving resource efficiency (Kirchherr, Reike and Hekkert, 2017; Falkman, 2024). Processes such as product lifecycle management, waste recycling and material sorting are improved using these technologies, reducing dependency on primary resources (Geissdoerfer et al, 2017; Stahel, 2016). But both these advancements have been applied in less than adequate ways in Ukraine, because of a lack of investment in research and development, and a lack of appropriate infrastructure plus fragmented policy frameworks. Although facilities in Ukraine have advanced in waste management and recycling, in energy-intensive industries—steel and construction in particular — Ukraine has not yet integrated fully into the circular economy process.

Studies have shown that the circular economy plays a global role in delivering environmental and economic benefits. Particularly, European Union programs have targeted circular activities and have been successful in lowering primary resource consumption and CO₂ emissions in the main industries (European Commission, 2019; World Economic Forum, 2023). As in the Netherlands and Sweden, also countries have managed to develop models of a circular economy linking advanced technologies and organizational innovations (Circle Economy, 2023). On the other hand, Ukraine's industrial production remains linear, preventing the country from growing in a sustainable, planetary-oriented fashion.

In addition, recent studies argue that circular models have the inherent potential to stimulate social and economic benefits, including job creation and improved productiveness (European Investment Bank, 2023). This is, however, lacking research to explore the local economic benefits of circular practices in Ukraine, including whether such models can be scaled for different sectors of the industry. The gap emphasized the need to explore how circular strategies can be integrated into Ukraine's specific economics, environment and regulatory situation.

The definition of circular economy (CE) is the new development model to increase resource availability and mitigate risks for the environment. The linear process of making a product, using it and in the end throwing it away has caused much devastation to the environment. At present, over 90% of the raw materials mined annually are distributed as waste materials that cannot find their way back into the production loop

hence worsening the negative impacts on the natural environment and fast depletion of resources. The construction industry in particular and automobiles in general are some of the biggest consumers of raw materials and are also the biggest polluters of the environment due to their command of an uninformed production line model. This Perspective shows that the world must transition to the use of circular economy models in which recycling, reuse, and component longevity replace linear business models that rely on virgin resources and produce significant amounts of waste.

Interestingly, there is no lack of work to demonstrate how circular activities can be sustainable. One such example of a circular economy in the Netherlands is helping save 30 per cent of primary resource use and 25 per cent of industrial waste (World Economic Forum, 2023). Similar circular economy models for China have enabled a 20% cut of CO₂ emissions in heavy industries (Yang *et al.*, 2023). Within this context, PCM and waste recycling are not only effective but also require replacements for the conventional linear economy (Geissdoerfer *et al.*, 2017; Kirchherr, Reike and Hekkert, 2017). The circular economy serves as a means by which we studied how its potential to improve the efficiency of resource utilization in industrial production could help make that sort of industrial production less vulnerable to environmental degradation.

This study aims to fill these gaps by assessing whether the circular economy models can increase resource efficiency in Ukraine's industrial production without degrading the environment. This research introduces insights from global successful practices together with local challenges to offer actionable recommendations for scaling up the sustainable industrial transformation in Ukraine. Such findings are especially well-timed for the country at a time when it must navigate the intersection of economic recovery and ecological sustainability.

Methodology

Considering that the previous research had used only quantitative methods to evaluate the impact of circular economy models on industrial production, this research employed the mixed method to assess the impact of the circular economy models on industrial production. Data for the analysis were collected from peer-reviewed articles, annual reports, and indexing databases like Scopus, Web of Science and PubMed using publications from 2015 to 2023. The sources used in this study were based on the European Investment Bank Reports (EIB), Global Competitiveness Index and Circular Economy Report, which are all cited appropriately throughout this study.

Quantitative Analysis

Using multiple regression techniques, the quantitative data analysis quantified the relationship between circular economy practices and key performance indicators including resource efficiency and waste minimization. Precise measurements of the effect of these practices on different industrial sectors were possible, by the use of SPSS software. Variables, such as sector-specific values of waste generation, resource

utilization and production outputs were accounted for in regression models and used as a means of obtaining insights into circular economy models efficiency.

Qualitative Analysis

To perform qualitative analysis, content analysis was used based on coding frequencies to identify themes and patterns in descriptive data spanning leading enterprises. The approach explored commonalities in implementation challenges, innovation contribution and stakeholder views on the practice of circular economy. The coding process was performed to ensure validity and reliability with intercoder reliability checks above 0.8 (a Cohen's Kappa score meaning high agreement between coders). As a result of this comprehensive analysis, a nuanced understanding of how circular economy principles are used in different industrial environments was achieved.

Validation Techniques

The triangulation method was used to ensure the robustness of the finding. The credibility of the conclusions was cross-verified with data from multiple sources such as industrial case studies, statistical reports and who could know better than industrialists themselves. This was the case for the acquisition of qualitative data as well, which underwent iterative analysis cycles to ensure that all insights drawn were both consistent and comprehensive.

This study integrates these methodologies to deliver a comprehensive assessment of circular economy practices, as well as their applicability to promoting sustainable industrial production.

Principles of the Circular Economy and Impacts on Industrial Production

A fundamental understanding of the circular economy (CE) principles is needed for enabling environmentally sustainable industrial development. In contrast to the linear economic model based on resource extraction, product production, consumption and disposal, a CE is a closed-loop system where resources are reused and recycled to achieve zero waste and the least environmental footprint (Kirchherr, Reike and Hekkert, 2017). These ecological and economic challenges are driven by a shift that seeks to address the depletion of raw materials and the increase in industrial waste (Ghisellini, Cialani and Ulgiati, 2016). The relevancy for Ukraine is of course particular given its dependent industries with the highest resource-intensive ones including steel and even more, growing problems of waste management (Kotyrla *et al.*, 2023). In addition, the move toward CE models would enable Ukraine to follow the European Union legislation on reduction of waste and resource efficiency is bound to increase its industrial competitiveness and environmental sustainability (European Commission, 2019).

1. Closed material cycles. This principle means that all the materials and resources utilised in production should be taken back to the production line as far as possible to reduce the use of new materials. This implies that many products are developed to promote easy disassembly, recycling, and reuse when they are finished with them (Kirchherr, Reike and Hekkert, 2017). For instance, in the electronics manufacturing

area, there are currently measures known as modular, where individual parts may be changed or altered but not the whole product. Closed loops help managers and other stakeholders minimise production costs since the process will likely involve using materials that have been used before. In cases where the materials are new, they are not necessarily expensive or complicated to come by. Besides, it mitigates preservable negative environmental impacts, pollution, and wastage (Geissdoerfer *et al.*, 2017).

2. Focus on regeneration and recycling. The principle of this pillar suggests the highest level of material recovery and recycling after their first usage (Ghisellini, Cialani and Ulgiati, 2016). For instance, concrete structures must be recycled in the construction industry to develop materials and waste raw materials to make products. Environmental dispersion cost in product manufacturing is also controlled through recycling and resource recovery to avoid extra disposal costs. It also increases the potential for further advancements in developing new technologies and employment in recycling sectors (European Commission, 2019).

3. Extend the life cycle of products. This principle is about improving our ability to use products for more than one life by focusing on design, which enables repair, upgrade or modernisation of products to give them a longer life instead of having to dispose of them (Stahel, 2016). For instance, instead of discarding automobiles to be replaced by new ones, it is possible to design autos that can be altered or fixed as conveniently as possible. Economies of scale are another benefit of lengthening the product life cycle because it reduces demand for new products with their respective resources, thus slightly decreasing production costs and environmental effects. Industrial enterprises can also develop some service extensions for the repairing or refurbishing service of the product (Kotyrló *et al.*, 2023).

4. The system of renting or sharing products. This principle reverses an item of property with a rental model or use by several people (Kirchherr, Reike and Hekkert, 2017). For instance, some organisations enter into leases of computers, television sets, or any other home-use appliances, and the customer can return the machines to the company after the lease period to be reused or disposed of. The lease model, therefore, preserves the ownership right of companies on products to enhance better control of their life cycle and reuse of resources. It also opens up possibilities for new environmentally sustainable business strategies involving non-one-time selling (World Economic Forum, 2023).

The impact of the circular economy on environmentally sustainable industrial development is shown in figure 1.

The principles of the circular economy significantly positively impact the industry's environmentally sustainable development through more efficient resource use, reduced environmental impact, and stimulation of innovation. These principles open new opportunities to increase enterprises' competitiveness, promote socio-economic development, and improve environmental conditions.

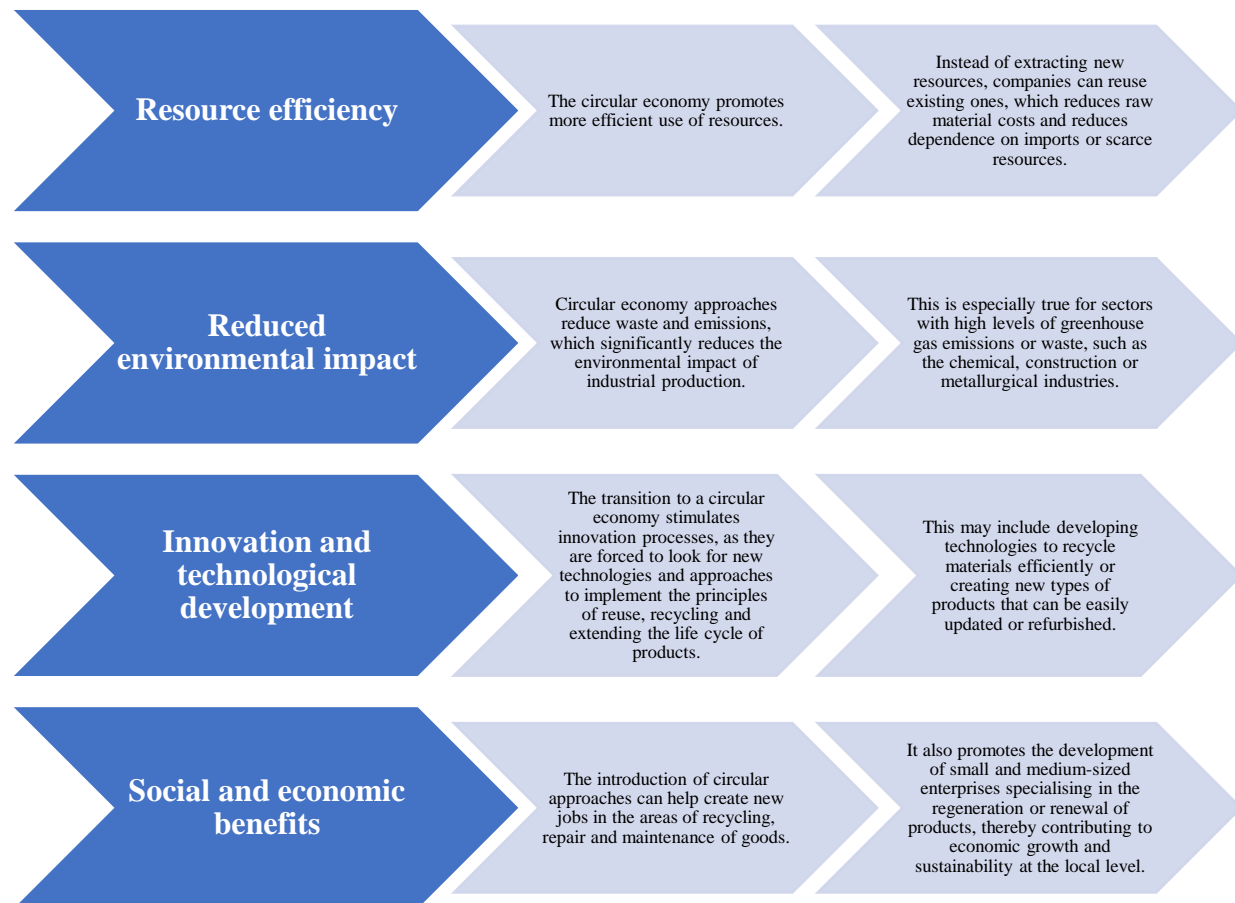


Figure 1: Impact of the circular economy on environmentally sustainable industrial development [Sources: Ghisellini, Cialani and Ulgiati (2016); Kirchherr, Reike and Hekkert (2017); Stahel (2016); European Commission (2019)]

Best Practices of Circular Economy in Global Manufacturing Sectors

Table 1 below provides examples of successful practices of implementing a circular economy in different manufacturing sectors worldwide. This table demonstrates how different countries have successfully applied circular economy principles in manufacturing sectors to increase resource efficiency, reduce waste, and reduce negative environmental impact.

The development of the circular economy in the context of environmentally sustainable industrial production offers excellent prospects but is accompanied by several challenges. Let's examine the dynamics of the circular economy.

Table 1: Examples of successful practices of circular economy implementation in manufacturing sectors of different countries

<i>Country</i>	<i>Manufacturing sector</i>	<i>Practical implementation of the circular economy</i>	<i>Results and Impact</i>
Netherlands	Electronics manufacturing	Philips Circular Lighting: The company has switched to a rental model for lighting systems, allowing customers to use lighting fixtures without buying them.	Extending product life cycles involves reducing electronics waste, increasing resource efficiency, and reducing the production of new lighting products.
Finland	Pulp and paper sector	UPM Biofore: Processing of forestry waste to produce biofuels and biomaterials. Utilisation of wood by-products for energy generation.	Reducing CO ₂ emissions: Optimising the use of forestry waste, reducing dependence on fossil fuels, and reducing energy costs.
Sweden	Furniture production	IKEA: The company has created a take-back programme for old furniture, which can be recycled or reused. Customers can return used furniture in exchange for discounts.	Reducing waste: Raising consumer awareness of furniture reuse, reducing the production of new furniture, and minimising waste.
Germany	Automotive industry	BMW: To produce electric vehicles, recycled and secondary raw materials are used. Modular design is implemented to extend the life cycle of components.	Reducing the use of new materials: Optimising production, improving energy efficiency, reducing negative environmental impact.
Japan	Electronics and household appliances	Panasonic Eco Technology Centre (PETEC): This recycling centre for old household appliances, where refrigerators, televisions, and other appliances are recycled to reuse materials.	Maximising recycling: High metal and plastic recycling level, waste reduction, and resource savings.
France	Fashion and textiles	Patagonia: Worn Wear programme encourages consumers to repair and reuse clothing. The	Raising environmental awareness: Reducing textile waste, encouraging the reuse

<i>Country</i>	<i>Manufacturing sector</i>	<i>Practical implementation of the circular economy</i>	<i>Results and Impact</i>
		company accepts used items for repair or resale.	of goods, and reducing the production of new garments.
Italy	Construction	Italcementi: Using industrial waste such as slag and ash to produce environmentally friendly cement.	Reducing the consumption of natural resources: Optimising waste management, reducing CO ₂ emissions, and reducing the use of energy-intensive resources.

Source: European Commission (2019), Ghisellini, Cialani and Ulgiati (2016), Kirchherr, Reike and Hekkert (2017), Stahel (2016)

The level of circularity. According to the Circularity Gap Report (2023), only 7.2% of the global economy operates within a circular model, reflecting a decline from 9.1% in 2018 (Circle Economy, 2023). This means over 90% of the materials extracted annually are wasted or unused for reuse. However, implementing circular solutions can reduce the use of materials by one-third, which is a significant step towards achieving climate goals (World Economic Forum, 2023).

Reducing CO₂ emissions. Using circular approaches in production can reduce CO₂ emissions by 45% by 2030 and achieve carbon neutrality by 2050. This is especially true for construction, steel and aluminium production industries, where material recycling significantly impacts environmental performance (Yang *et al.*, 2023).

Investments. The European Investment Bank has allocated more than €3.4 billion for circular economy-related projects in 2018-2022. The primary investment areas are the industrial, bioeconomic, waste and water management sectors (European Investment Bank, 2023).

Jobs. According to the International Labour Organization, the transition to a circular economy could create 7 to 8 million new jobs worldwide by 2030. These new jobs will come from increased product recycling, repair, and reuse (European Investment Bank, 2023).

Table 2 summarises the development of the circular economy and shows its leading indicators based on the latest research and data.

Countries leading the way in implementing the circular economy are demonstrating active policy and innovation initiatives to improve resource efficiency and reduce waste and emissions. For instance, instead of an abstract goal, the Netherlands has adopted a National Strategy for the Circular Economy (Circular Economy, 2050), which sets the ultimate goal of moving to a 100% circular economy by 2050. The medium-term goal is to reach 50% circularity by 2030. The strategy includes specific legislative initiatives,

such as the Waste Management Law (2017), which regulates the reduction of the use of primary resources (Circle Economy, 2023). *China* introduced the circular economy concept in 2006, including it in the 11th Five-Year Plan for Social and Economic Development. A further impetus came from China's Circular Economy Promotion Law (2008), which actively encouraged investment in renewable resources and innovative practices, especially in industrial sectors (Circle Economy, 2023). Japan has been using the Basic Recycling Law since 2000. The law is entirely aimed at recycling plastic waste in the country. Japan has also adopted the Plastic Waste Circular Economy Strategy of 2019, whose primary goal is to minimise the effects of waste in the country (Circle Economy, 2023). The UK has a National Circular Economy Strategy that was adopted until 2025. It encompasses distinct concepts on recycling such resources, and an excellent record of this would be noted in the Circular Economy – Future Possibilities Index (2024). Sweden and Germany have laws for the circular economy. For instance, Germany has adopted the Resource Management Act (2012), in which circular economy principles are given special consideration, especially in construction and manufacturing, by Construcía (2023).

Table 2: Key indicators of circular economy development in the world by years

<i>Year</i>	<i>Country</i>	<i>Main indicators</i>	<i>The main goal of developing a circular economy</i>	<i>Development and implementation concept (developed or approved by countries)</i>
2025	European Union	Reduced use of primary resources by 20%, recycled 60% of household waste	Improving resource efficiency and reducing environmental impact	According to the EU Circular Strategy 2020, developed by the European Commission and approved by the EU countries
2030	Netherlands	Achieve 50% circular economy	Become a 100% circular economy by 2050	According to Circular Economy 2050, developed and approved by the Dutch government
2028	China	Reduced industrial emissions by 25%, recycled 70% of industrial waste	Improving resource efficiency in the industry	The Circular Economy Law of 2008, approved by the Chinese government
2030	Japan	Recycling 80% of plastic waste	Reduce plastic waste generation by 50% by 2050	According to the Plastic Waste Circulation Strategy 2019 developed by the Japanese government
2025	United Kingdom	Recycling 65% of industrial waste	Creating a circular industrial system	According to the National, Circular Economy Strategy developed and approved by the UK government.
2030	Germany	Reduced consumption of natural resources by 30%	Optimising the use of resources in the construction industry	The Resource Management Act 2012, approved by the German government

Source: World Economic Forum (2023), Yang *et al.* (2023), European Investment Bank (2023)

Impact of Circular Models on Enhancing the Efficacy of Resource Utilization in Industrial Production

Countries can prove their leadership through established national approaches, innovative technologies, and investments in circular technologies for environmentally sustainable economic development. Analysing the impact of circular economy models on resource efficiency in industrial production: Table 3 evaluates the effects of circular Economy models on the resource efficiency of production systems. This table shows how circular economy models improve resource efficiency in industrial production through cost differentiation, product life extension, waste minimisation, and renewable energy sources.

Table 3: Impact of circular models on improving the efficiency of resource use in industrial production

<i>Circular model</i>	<i>Model description</i>	<i>Impact on resource efficiency</i>	<i>Examples of applications in industrial production</i>
Recycling and regeneration of materials	This model uses recycled materials to produce new products instead of extracting new resources.	Reduced consumption of primary resources: Recycling allows us to use existing materials, reducing the need to extract new ones, which saves resources and reduces the environmental burden. Increased energy efficiency: Recycling materials (especially metals and plastics) often requires less energy than producing new ones from raw materials.	Metallurgical industry: The use of recycled metals to make new products. Plastics industry: Recycling plastic to make new products.
Designing for an extended life cycle	This model involves designing products to be easily repaired, upgraded or updated.	Reduced costs for new resources: Minimising the rate at which consumers replace products means fewer materials are needed in their construction. Reduced waste: Products that can be repaired or upgraded do not become waste as quickly as such products.	Electronics: Modular design that allows for easy replacement or upgrade of components. Automotive: Technologies enabling cars to be refurbished rather than completely replaced.

<i>Circular model</i>	<i>Model description</i>	<i>Impact on resource efficiency</i>	<i>Examples of applications in industrial production</i>
Shared use or lease model	This model involves renting or sharing products instead of traditional ownership.	Optimising the use of resources: By sharing, one product is used by more consumers instead of many similar products produced from the standard shared material. Reducing the need to produce new goods: Renting and sharing reduces the general production volume of units within a given period.	Rental of equipment and tools: People can hire equipment for various construction projects. Car sharing: Car sharing is an alternative to personal transport.
Cascading use of resources	This model involves the multi-stage use of resources in various production processes before they become waste.	Maximising the efficiency of material use: The same resources can be used at different stages of production for different purposes, extending their proper life cycle. Reducing waste: Materials are used until their value is thoroughly exhausted.	Woodworking industry: The remaining wood is employed to make furniture, and the waste is utilised to produce biomass or energy. Food industry: By-products (e.g., husks or skins) are used in secondary processes such as feed production.
Transition to renewable resources	Use of energy from renewable sources instead of fossil fuels in production processes.	Reducing the carbon footprint: Accessing renewable energy sources has been shown to reduce greenhouse gas emissions for environmentally sustainable development. Reduced energy costs: Finally, many forms of renewable energy, such as the sun or wind, can become cheaper than conventional energy over time.	Electronics production: Using solar energy to power production lines. Automotive industry: Transition to using biofuels or electricity in production processes.

<i>Circular model</i>	<i>Model description</i>	<i>Impact on resource efficiency</i>	<i>Examples of applications in industrial production</i>
Innovative technologies for automated processing	Implementation of automated systems for waste collection and recycling.	Increased accuracy and processing speed: Automation expedites the sorting and processing of the material, making it cheaper to process. Optimising the use of resources: Technologies help reduce resource losses during processing.	Waste processing plants: Automated waste sorting and recycling lines. Textile industry: Technologies for automatically sorting fabrics for reuse or recycling.

Source: Geissdoerfer *et al.* (2017), Ghisellini, Cialani and Ulgiati (2016), Kirchherr, Reike and Hekkert (2017), Stahel (2016)

Innovation as a Key Driver in Implementing the Circular Economy in Industrial Sectors

In industrial sectors, the role of innovation is key for advancing the circular economy as emerging technologies, innovative processes, and new business models enable the practical implementation of the main principles of the circular economy, including closed material cycles, resource recovery as well as the extension of product life cycles (Ghisellini, Cialani and Ulgiati, 2016; Kirchherr, Reike and Hekkert, 2017). These innovations find solutions to these critical industry issues by moving from a linear to a circular economy mindset, increasing resource efficiency by reducing waste and minimizing environmental pollution (Circle Economy, 2023; Stahel, 2016). Below are some key areas that are key to bringing innovation into play when implementing circular economy strategies.

1. Innovative materials and recycling technologies. The reverse nature of the circular economy is one of the most essential criteria for reusing and recycling materials. New products, designed with the circular model, are less environmentally degradable and more accessible to recycle than the previous materials. For instance, biopolymers derived from renewable sources are experiencing steady advances in replacing conventional plastic products and controlling waste (Ghisellini, Cialani and Ulgiati, 2016). Fourthly, the exploitation of advanced recycling processes, including chemical recycling, makes polymers depolymerised to their molecular structures and then recycled to produce materials. All these innovations are ways of achieving closed material loops, using and minimising the requirement of new materials, and at the same time, they also contribute to mitigating environmental pollution (Kirchherr, Reike and Hekkert, 2017).

2. Digital technologies and automation. Technological elements like IoT, AI, and big data are critical for enhancing resource utilisation efficiency (Circle Economy, 2023). For instance, companies can monitor production lines through sensors and the IoT, help

managers detect issues, improve efficiency, and reduce losses (Stahel, 2016). AI is also applied to digest the most effective ways of sorting and recycling waste to increase efficiency in using the available resources in the market. Technological advancement gives firms better control over resource utilisation because they can lessen leakages (TOMRA, 2023).

According to this, Artificial Intelligence (AI) and the Internet of Things (IoT) are pivotal technologies for supporting recycling in the framework of the circular economy. These speed up sorting, monitoring, and processing leading to lower material waste and higher recycling yields (Circle Economy, 2023; Falkman, 2024). For example, TOMRA, the global leader in sensor-based solutions, uses AI-powered optical sensors to sort recyclable materials with very high precision. It enables its technology to differentiate between plastics, metals and glass and direct every material reliably to the right recycling channel, preventing contamination and optimising the quality of recycled materials for manufacturing use (TOMRA, 2023). In addition, IBM's AI and IoT-enabled platform 'IBM Plastic Bank' addresses the problem of plastic waste from the coast to the ocean. Combining block technology, IoT sensors and machine learning algorithms, this idea seeks to encourage local communities to collect plastic waste, and yet send it to IoT-managed recycling centres, for some coins. AI helps to monitor exactly where all the plastic and its chain of supply is, so we know when, if any leakage happens, where that's going to take place (IBM, 2023). Veolia Environnement also embeds IoT sensors in waste management systems to measure the fill-up of waste containers and recyclable bins. By tripling this data with AI algorithms, we optimize collection routes to minimize fuel consumption and emissions. Besides, IoT sensors' data collected by Veolia help forecast sustainable waste recycling and management strategies (Veolia, 2023).

3. Innovative business models. We need the adoption of innovative management approaches to transition to a circular economy. Another well-known example of this is the Product as a Service (PaaS), where companies supply access to a product's utility instead of selling the product itself. Moreover, it extends the product lifespan by providing manufacturer's upgrades and maintenance (Kirchherr, Reike and Hekkert, 2017), minimizing resource use (Among the model). Businesses in the electronics and machinery sectors are beginning to explore PaaS approaches in Ukraine in fields such as industrial equipment and home appliances, providing clients with the option to rent or hire rather than buy. The sharing economy is another emerging model in Ukraine that is represented by platforms aimed at the sharing of tools, vehicles and even office space. Circular economy principles (Kotyrló *et al.*, 2023) are demonstrated by these initiatives in their reduced demand for new goods and encouragement of resource-efficient practices.

4. Innovations in product design. Designing long-lived products is key to the circular economy as it means that components can be taken apart, upgraded or repaired rather than wasted. These architectural innovations reduce waste and maximize resource use (Ghisellini, Cialani and Ulgiati, 2016). However, such modular designs have previously been adopted by several tech start-ups in Ukraine to replace electronic device components without getting rid of the whole product. Also, manufacturers of furniture have started incorporating designs that encourage easy repair and reuse of materials from European reference practices (Stahel, 2016). Such strategies lead to reducing waste,

reducing production costs, and increasing usability of products from cradle to grave and therefore are particularly appropriate for resource-intensive industries of Ukraine.

5. *Development of closed supply chains.* Advances in supply chain technologies discussed earlier enable the creation of Closed-Loop Supply Chains that provide for product utilisation and then return products to the supply cycle for recycling. These chains decrease the demand for new material, minimising waste. Only innovative product traceability technologies can generate such supply chains since it would be challenging to identify their origin, constituents, and recyclability. Finalising the supply chains means reducing resource consumption and recycling initiatives in industries. They also discovered that innovation is vital for transitioning towards a circular economy within the industrial sector, which uses resources better, improves environmental performance, and generates new economic development prospects (Ghisellini, Cialani and Ulgiati, 2016; Kirchherr, Reike & Hekkert, 2017). Technological progress in materials science, information technology, management, product design, and logistics support the development of a green and less costly manufacturing system.

Under the circular economy concept, there is a great potential for industrial development in Ukraine, which may greatly decrease resource wastage and environmental damage. For instance, implementing circular strategies within sectors like cement, aluminium and plastics could prevent up to 45 per cent of greenhouse gas emissions in 2050, the equivalent of removing all the pollution from all the cars in the world today (European Investment Bank, 2023). Such strategies are especially relevant in Ukraine, where its cement and steel industries are the largest emitters and resource exploiters in the region (Kotyrló *et al.*, 2023).

In addition, if artificial intelligence advancements continue to advance recycling efficiency and predict repair and refurbishment needs to extend product lives and minimize waste (Falkman, 2024). These inventions will bring big changes to Ukraine's already inefficient and low recycling rates of waste management systems. The localization of production is another promising approach that can improve local economic independence and expand supply chains, essential for Ukraine's recovery and long-term sustainable development amid existing circumstances (World Economic Forum, 2023).

Adopting these strategies would enable Ukraine to join the global trends for industrial competitiveness and reduce its environmental footprint.

However, there are some barriers to applying a circular economy business style. One of the main ones is the regulatory constraints on material recycling and reuse since legislation defines materials as 'waste' (World Economic Forum, 2023). Furthermore, it identified that the initial cost of setting up recycling infrastructure and transitioning to low-waste models of producing and consuming goods are relatively substantial and that shifting business models such as product-as-a-service are expensive to realise (Falkman, 2024). Lastly, cultural factors and consumers' mistrust due to the low quality of remanufactured products continue to be significant challenges for the growth of the circular goods market (International Society for Industrial Ecology, 2023).

The outcome of this work shows that the definition of circular models in industrial production can enhance resource utilisation and minimise environmental harm. According to the present research outcomes, it is possible to note their similarity with other authors, such as Ghisellini, Cialani and Ulgiati (2016) and Kirchherr, Reike and Hekkert (2017), who investigated the significance of circular business models in decreasing waste and reuse of material. However, unlike these authors, the circular economy in industrial processes needs more digitalisation innovation, including artificial intelligence and the Internet of Things, which can enhance waste processing and monitoring (Stahel, 2016; World Economic Forum, 2023).

Geissdoerfer *et al.* (2017) also classify the barriers; the major challenge in implementing circular models is the high initial investment necessary for developing new infrastructures for processing and implementing new business models. These findings for our research show that financial aspects are among the most significant concerns if businesses adopt a circular economy. However, long-term benefits like money saved for future use and less money spent on raw materials will cover the costs, which research done by the European Investment Bank (2023) has shown. Citizens may have some truth with this commendation even though the circular economy is highly accepted in academia, with few critics like Falkman (2024) questioning its efficiency, particularly in energy-intensive industries, including steel and aluminium. The analysis of the mentioned industries lets us state that circular strategies such as recycling and reuse can decrease CO₂ emissions. However, lifting new technologies and governmental support for innovations are necessary to achieve maximum effect (Kotyrló *et al.*, 2023).

Investments in the circular economy are stymied by obstacles in waste management and regulation and a shortage of local expertise for performing thorough economic analysis. Even today, in Ukraine, and many regions around the world, some materials deemed hazardous waste can still be recycled (classified as such under contemporary regulations). One example is the many industrial by-products listed in the hazardous waste category by the European Union Waste Framework Directive (Directive 2008/98/EC) which, through strait laced handling and disposal requirements, reduce recycling rates to extremes (European Commission, 2019). Likewise, the Resource Conservation and Recovery Act in the USA categorizes some secondary materials flowing in from industrial processes as hazardous and barriers for companies aiming to utilize these materials in circular production (Kotyrló *et al.*, 2023).

Waste classification and management practices present similar problems in Ukraine. A lack of a clear distinction between recyclable and non-recyclable waste does not allow the country to optimise its material recovery. Poor waste infrastructure, as well as weak enforcement of environmental regulations, also prevent progress to a circular economy. Japan already has a Basic Act on Establishing a Sound Material Cycle Society, which allows the recycling of “Specially Controlled Waste” under certain conditions (Stahel, 2016).

There are also regulatory barriers, both in the sense that recycled materials are not universally accepted within an industry and in the fact there are no standards for recycled material at all. For instance, the German Circular Economy Act defines the quality and safety of recycled products for manufacturers and consumers (Ghisellini, Cialani and

Ulgiati, 2016). Perhaps such standards should also be adopted by Ukraine, particularly in the construction and metallurgy sectors, as these industries are essential for recycled materials use to reduce raw material consumption and environmental impact (Kirchherr, Reike and Hekkert, 2017).

Another important area for regulatory improvement is to incentivize circular practices. Tax exemptions and subsidies for businesses that participate in circular economy activities could favour the transition from a linear to a circular model. For example, the European Investment Bank provides a Circular Economy Incentive Program wherein companies can compensate for the costs of a circular venture with government support (European Investment Bank, 2023). However, introducing similar incentives in Ukraine has the potential to overcome the financial and logistical barriers and make local industries more accessible to circular models.

In prior literature, cultural and regulatory factors that can impede the circular economy implementation have not been consistently emphasised. For instance, some authors (Kirchherr, Reike and Hekkert, 2017) identify legislation constraints that do not always encourage the reuse of products since certain types of waste are labelled “hazardous”. The solution to this problem is reforms in the legal framework and increased cooperation between industrial corporations and the authorities. The results thus confirm the hypothesis that the circular economy advances environmentally sustainable industrial development by improving resource productivity and mitigating environmental impacts on industrial sectors. However, new investigations and concrete applications of such techniques, such as automation of processing and utilisation of renewable energy sources, are still required to realise the full benefits of circular models (Stahel, 2016).

The drawbacks of our work include the incomprehensive character of available data on the actual economic effects of applying a circular economy at various stages of production processes. Subsequent research should be dedicated to a deeper study of how the CE influences the long-term economic implications and industry differentiation.

Recommendations

Put in place Tax Incentives for Circular Practices. The government must adopt tax relief schemes for organizations operating a circular economy process like recycling, reusing and designing durable products. Subsidies given to businesses in order to use eco materials or run closed-loop practices are examples of such incentives that help overcome the financial hurdle barrier and push for cause from linear to circular ways.

Endorse Government Funded Programs for Recycling Infrastructure. To fill the gap created by the lack of recycling facilities, authorities should give grants or subsidized loans to establish new recycling centres or improve old ones. Material recovery rates will be maximized with this enhanced infrastructure and will support circular economy initiatives.

Quality Standards for Recycled Materials Develop and Enforce. Recycled materials need some clear benchmarks regarding their quality and safety that’s where policymakers and industrial leaders need to collaborate. Introducing recycled products will gain confidence

not only from the manufacturers but also from the consumers, which will increase the adoption of recycled products with internationally recognized standards.

Contribute to the promotion of Research and Innovation in Circular Technologies. Recycling processes, resource recovery and product durability will be improved by encouraging research and development in advanced technologies, like artificial intelligence and IoT. Public and private sector partnerships should foster the support of innovations in waste classification, automation and sustainable product design.

Education and Awareness Programs must be encouraged. Students, professionals as well as the public in general should be targeted by educational initiatives and awareness campaigns, in order to raise awareness of circular economy principles. Lesson learned: Workshops, training sessions and programmes on community engagement can promote the economic and environmental advantages of adopting circular practices, reaching way beyond only a smaller section of the business, the final buyer, or producer.

Actionable steps toward fostering sustainable, long-term adoption of circular economy models, and long-term economic resilience are outlined in these recommendations.

Conclusion

The potential contribution of the circular economy to improved resource productivity, diminished environmental impact and sustainable industrial development is very high. Achieving the full benefits of a circular economy will depend on the coordination efforts between policymakers and industry leaders, points out this study. However, regulatory, financial, and cultural barriers inhibit the great potential for a successful implementation of circular practices. To address these challenges, we need to develop a targeted strategy, for example, incentives, the development of infrastructure and educational initiatives that will establish a framework for a robust transition to a circular economic system, from a linear one. Industries can then focus on innovation, standardization, and awareness, assuring sustainable growth, without a large impact on their ecological footprint. Key recommendations concluded in the study include:

- **Tax Incentives for Circular Practices:** Provide tax reliefs for organizations engaging in recycling, reuse, and eco-friendly designs. Financial incentives will encourage the adoption of circular approaches.
- **Government-Funded Recycling Programs:** Establish programs with grants or subsidized credit to build recycling facilities, improving the return and reprocessing of materials.
- **Quality Standards for Recycled Materials:** Collaborate to ensure high-quality recycled materials meet safety and performance standards, boosting consumer and manufacturer confidence.
- **Promote Research and Innovation:** Fund research in recycling technology, resource retrieval, and product durability. Encourage AI and IoT advancements in waste management.
- **Education and Awareness Programs:** Increase understanding of circular economy principles through educational programs, workshops, and campaigns.

These strategies provide a roadmap for policymakers and stakeholders to foster sustainable development and reduce climate impact.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5
Conceived and designed the research or analysis	Yes	No	Yes	Yes	Yes
Collected the data	Yes	No	Yes	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes
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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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Using Innovation and Energy Efficiency Technologies to Drive Business Competitiveness

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Abstract

This study evaluates the impact of innovations and energy-saving technologies on improving business competitiveness within a dynamic market landscape. We collected relevant data on energy consumption (from 2000 to 2021) and the proportion of renewable energy sources (from 2002 to 2023), alongside investments in innovative technologies from the IEA reports, the World Bank, IRENA, and governmental databases. The practical significance of using innovations and energy-efficient technologies to enhance business competitiveness is seen in the prospect of reducing the use of non-renewable resources for sustainable societal development, consistent decarbonisation, and the preservation of ecosystems' natural potential. Additionally, scientific literature on the adoption of energy-efficient technologies across various economic sectors was reviewed. The study also explored successful companies that have embraced innovations, based on an analysis of public reports. A benchmarking analysis was performed to assess the effectiveness of new technology implementations across different industries. This was followed by forecasting the percentage of renewable energy sources in the global energy mix by 2030. The findings revealed that innovations and energy-efficient technologies significantly enhance the competitiveness of companies. They streamline costs, improve production efficiency, and bolster corporate reputations among environmentally conscious consumers. The transfer of innovations accelerates the adoption of new technologies, which aids in making informed environmental decisions. Government support for innovation and energy efficiency is also vital for the swift integration of these technologies. Ultimately, innovations and energy-efficient technologies foster sustainable business growth and positively impact the environment. The results pinpoint key areas where government support can stimulate innovation and enhance energy efficiency in the business sector.

Keywords

Innovations; Digital marketing; Energy-saving technologies; Innovative entrepreneurship; Innovation parks; Competitiveness

Introduction

In today's rapidly evolving economic landscape, businesses encounter a myriad of challenges that necessitate continuous improvement and adaptation. Innovations and energy-efficient technologies have emerged as critical factors that impact business competitiveness amidst globalization and rising consumer expectations. With finite resources and intensifying competition, companies are compelled to optimize costs and enhance production efficiency. Energy-saving technologies not only lower energy expenses but also boost overall productivity. The increasing focus on environmental concerns and climate change drives businesses to adopt sustainable practices. Implementing innovative energy-efficient technologies is vital for minimizing corporate carbon footprints, which is crucial for attracting both investors and consumers. Companies that embrace cutting-edge technologies and innovations can respond swiftly to fluctuating market conditions and evolving consumer preferences, enabling them to secure leading positions in the market and improve their competitiveness.

Many governments offer financial assistance and other forms of support to businesses that adopt innovative and energy-saving solutions. This creates additional opportunities for businesses and promotes their development and modernisation. Modern consumers increasingly value socially responsible companies. Investing in energy-saving technologies can enhance a company's image and contribute to building long-term relationships with consumers.

The eco-transformation of businesses through energy-saving practices is crucial for the low-carbon transition. Consumers influence eco-friendly production, which requires a systematic approach to business. ESCOs play a unique role in guaranteeing project efficiency. Changes in business models and resource integration will expand service-oriented businesses, promoting cooperation between manufacturers, suppliers, and consumers. Co-creation of value is key to energy services, and developing models for managing investments will foster growth. There are no alternatives to the eco-transformation of businesses due to global efforts to transition to a low-carbon economy (Kovalko, Eutukhova and Novoseltsev, 2022). To implement the strategies, it is proposed to publish data on innovation activity, develop projects in collaboration with clusters, and register them with the Ministry of Science and Higher Education of Poland (Mironova *et al.*, 2022). It is important to choose effective channels to attract clients and increase loyalty. Models for optimising investments in digital marketing based on portfolio investment theory have been developed previously (Niziaieva *et al.*, 2022).

The issue of fossil resources remains particularly problematic. Researchers (Maradin, Malnar and Kaštelan, 2022) argue that burning fossil fuels for energy production releases harmful greenhouse gases, such as carbon dioxide, which significantly contribute to environmental degradation and climate change (Quiroz, 2020). In Europe, considerable attention is devoted to minimising air emissions by increasing the share of alternative sources in energy production, improving energy efficiency, and ensuring the careful use of natural resources (Kuzmynchuk *et al.*, 2024).

The prospects for targeted financing and integrating economic tools within the framework of the European integration development strategy reveal significant practical

opportunities for the use of renewable energy sources in business (Hu and Zeng, 2024). Despite the relevance of the issue, there are still several research gaps concerning these aspects. Among such gaps are the role of environmental taxes in promoting the transition to renewable energy sources, the potential for increasing environmental taxation, and its impact on sustainable development.

Thus, the study of the role of innovations and energy-saving technologies is extremely relevant to modern business challenges. Understanding their impacts on competitiveness allows companies to adapt to new conditions and achieve sustainable development.

Literature Review

Studies on technical, economic, and social aspects, but the share of economic and social studies remains low. Collaboration between countries, particularly the USA, the UK, China, and Germany, promotes research development. These studies highlight the need for further research on the economic and social consequences of implementing energy-efficient and renewable energy technologies. Mechanisms need to be developed for the implementation of innovative technologies and “zero” energy consumption standards in new and renovated buildings (Sotnyk *et al.*, 2023).

Business innovations can both support and disrupt the market. Companies can improve their positions through innovative products and organisational changes or create competition for larger enterprises by developing new market segments. Actively seeking and implementing new ideas is critical to gaining advantages from innovations. In addition to attracting new clients, companies can receive tax breaks and grants for complex technological projects (Palmer, 2024).

Analysing the interaction of energy market participants based on oligopoly models allowed for developing recommendations to ensure strategic security and energy independence. For effective energy demand management, the implementation of budgetary regulation is recommended (Kuzmynchuk *et al.*, 2024).

After preliminary research into innovative solid-state electric devices with compact architecture, Italian researchers examined their impact on the annual energy balance and visual comfort of integrating glass into facades with various glazing technologies (Cannavale *et al.*, 2018). The research findings of another Italian scholar suggest that strategic analysis of the competitive structure and knowledge of the regulatory framework positively impact efficiency, improving service capabilities. Considering the expected increase in demand for new energy-efficient products, industrial processes require solutions with a smaller energy footprint and energy management services to facilitate the decarbonisation of the economy (Di Foggia, 2021). Comprehensive results from Portuguese scientists, obtained from a conceptual model, analyse the competitiveness of tourism and innovation factors. The study identifies and verifies the links between innovations (factors and barriers) for enhancing the competitiveness of destinations and their companies (Teixeira, Ferreira and Almeida, 2024).

Studies show that top management support and international pressure for energy conservation are key factors for successful energy management implementation. Less important factors include risk management, awareness of energy-efficient technologies, strategic planning, research, competitive advantage, green manufacturing, and supplier management. These findings will help managers take the necessary steps to effectively implement energy-efficient technologies (Iqbal *et al.*, 2021).

Government incentives are vital in fostering energy efficiency in smart buildings, particularly in rapidly developing areas like Saudi Arabia and the UAE. These incentives promote the adoption of advanced technologies by providing financial support, tax benefits, and a supportive regulatory framework, facilitating modernization. For entrepreneurs, grasping these incentives is essential, as they can help lower environmental impact, cut costs, and achieve competitive advantages (SQC, 2024).

Chen *et al.* (2023) utilize SCM, PSM-DID, SDM-DID, and mediation models to investigate how energy-saving urban construction policies influence the efficiency of green innovation in cities, using the NEDC policy as a case study. The findings reveal that the results from the SCM approach indicate that the adoption of the NEDC policy considerably enhances green innovation efficiency in pilot cities. Furthermore, this positive impact tends to grow over time and exhibits regional variations.

The study assesses the significance of innovations and energy-saving technologies in boosting business competitiveness within a fast-evolving market landscape.

Methodology

Data collection and analysis

Data for the study was obtained from national and international statistical data on energy consumption for 2000-2021, as well as the share of renewable energy sources (2002-2023) and investments in innovative technologies and their impact on business efficiency, were collected and analysed. Forecasting was used to predict the share of renewables in the global electricity sector by 2030, following Hu and Zeng (2024), Iqbal *et al.* (2021), and Mateos and Delgad (2024). The information was based on reports from the International Energy Agency (IEA), the World Bank, the International Renewable Energy Agency (IRENA), and government databases. Scientific publications on implementing energy-saving and innovative solutions in various economic sectors were analysed. Reviews and meta-analyses were conducted using Google Scholar, Clarivate, and Elsevier databases. An empirical analysis of case studies of companies that successfully integrated innovative and energy-efficient solutions was conducted based on publicly available business reports and industry studies. The case study method examined successful companies that achieved significant results through innovation. Benchmarking analysis was applied to compare the effectiveness of implementing innovative and energy-saving technologies in various sectors and countries. Benchmarking is an analysis of the world's best practices in a particular industry, an analysis of competitors, and a search for the best market offers that a company can implement in its processes. In simple terms, benchmarking is a comparative analysis when a business needs to change its direction in the process of

identifying new needs of users of its products. The main task of benchmarking is to bring the company to a new level and make it more competitive. The research findings and the identification of critical areas of government support needed to stimulate innovation and improve business energy efficiency were summarised using the synthesis method. Through synthesis, individual components and properties identified through analysis were combined into a unified whole. In this process, meaningful integration occurred, moving from identical and essential elements to differentiation and diversity, integrating both general and specific aspects into a single concept.

Results and Discussion

Innovations and Energy Efficiency

Large corporations spend millions on energy and significant amounts on logistics and outsourcing. However, many companies view energy only as a cost, which is a strategic mistake, as it neglects opportunities for value creation and reducing risks. Innovations in energy technologies and global carbon emissions regulations create new challenges and opportunities for improving energy efficiency. Sub-metering systems help companies monitor energy consumption in real-time, allowing for cost reduction and better energy-saving goals. Nevertheless, many organizations remain unaware of the advantages offered by these technologies. Meeting government requirements can be leveraged for competitive advantage if approached with awareness and innovation. The energy sector is transforming into a unified service sector, requiring companies to view energy suppliers as partners. Corporate responsibility initiatives increasingly influence organizational reputations, making it essential to have an energy efficiency strategy. An accurate understanding of energy consumption is essential for achieving corporate objectives. Changing the corporate approach to energy efficiency is critical for survival in today's economic climate (Quiroz, 2020).

Energy efficiency is becoming increasingly popular because reducing energy consumption benefits the planet and businesses. It helps decrease the carbon footprint and increase profits. Companies can benefit from energy efficiency in offices, stores, and other facilities. It allows for reduced energy costs, which is important for profitability, and lowers financial risks associated with rising energy prices.

Customers value a business's environmental efforts and are willing to pay more for “green” initiatives. Energy efficiency can help attract top talent, as 67% of employees consider a company's sustainability necessary (Budderfly, 2023). Reducing the carbon footprint demonstrates real action, increasing the chances of attracting talented employees. Energy efficiency is becoming crucial for businesses, and its implementation can become a competitive advantage.

According to the International Renewable Energy Agency (IRENA, 2024), global renewable energy capacity reached 3865 gigawatts (GW) in 2023 (Datawrapper, 2024). This is 473 GW more than in 2022, marking the most significant annual increase since records began (QERY, 2024). The share of renewable energy in the global energy balance increased significantly from 2000 to 2023 (Figure 1).

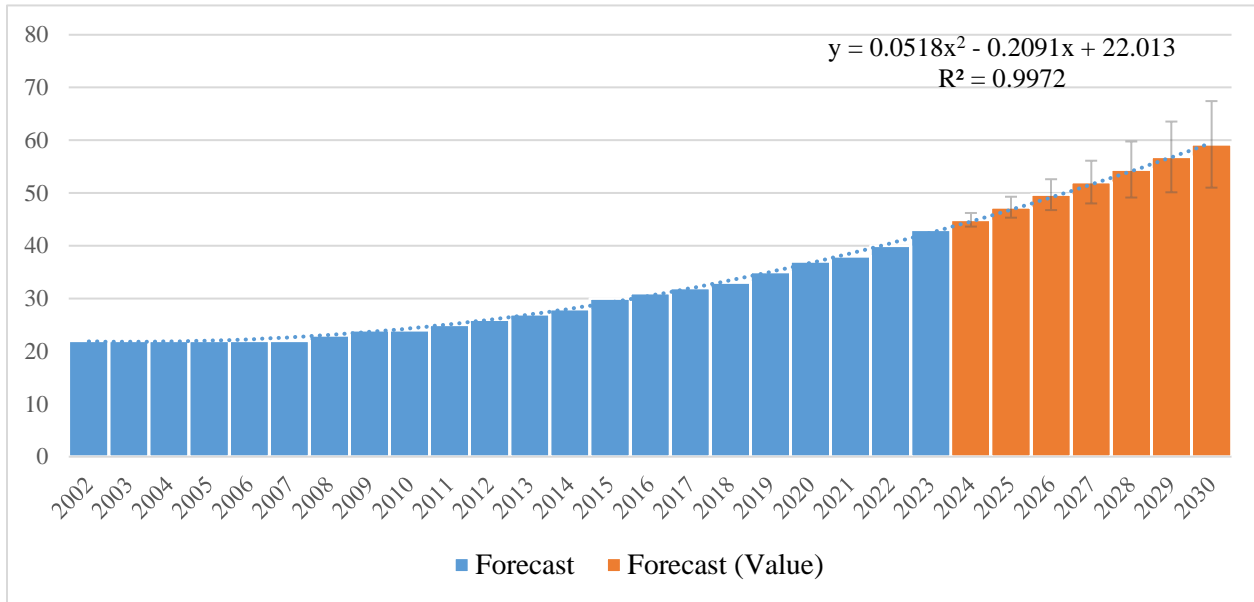


Figure 1: Percentage Contribution of Renewable Sources to the Total Capacity of the Global Electricity Industry (QERY, 2024; IRENASTAT, 2024)

Since the early 2000s, the share of renewable energy in the global energy balance has steadily increased. This growth has been driven by adopting solar, wind, and hydropower technologies. During the 2010s, investments in renewable energy sources significantly increased due to government support programmes, tax incentives, and the decreasing cost of technologies. The most rapid growth occurred in the solar and wind energy sectors. According to the International Renewable Energy Agency (IRENA, 2024), the share of renewables in global electricity generation reached around 43% in 2023, a record figure (IRENASTAT, 2024). Global renewable energy capacity reached 3865 GW, far exceeding the 2000 level. In addition to developed countries, significant growth in renewables was observed in developing countries, especially China and India, which have actively implemented solar and wind installations. This growth reflects the global trend toward transitioning to clean energy sources to reduce CO₂ emissions and combat climate change.

In competitive markets, innovation is crucial for the survival and growth of companies. Those that do not adopt innovations risk losing market share. However, competition can negatively impact innovation. Companies that focus on short-term profits may not invest enough in research and development. Intense competition may lead to incremental improvements rather than bold, breakthrough ideas. Thus, the impact of competition on innovation depends on market dynamics, competition intensity, and corporate strategies. A balanced competitive environment and policies that encourage innovation can promote innovation growth and overall economic expansion (Ferrante, 2023).

A business innovation culture is critical for medium-sized companies as it allows them to stay ahead of competitors. Creating an environment encouraging creativity, experimentation, and risk-taking helps these companies adapt to changing market conditions and quickly implement new solutions (Forbes, 2022). Businesses can

generate competitive advantages by being open to new ideas and willing to invest in research and development. An innovation culture also helps attract talented professionals who seek to work in dynamic and progressive environments. This enables companies to retain existing customers and attract new ones, ensuring sustainable growth and development. Implementing innovative processes, such as agile methodologies or design thinking, can improve efficiency and respond quickly to customer needs. Therefore, a business innovation culture is not just an advantage but a necessity for medium-sized companies striving to compete successfully in today's market. Energy consumption intensity per capita reflects a country's level of development, energy policies, capacity for innovation, and efficient resource use. Analytics for the period from 2000 to 2021 demonstrate trends toward adopting more energy-efficient technologies, the impact of global decarbonisation initiatives, and the spread of renewable energy sources (Figure 2).

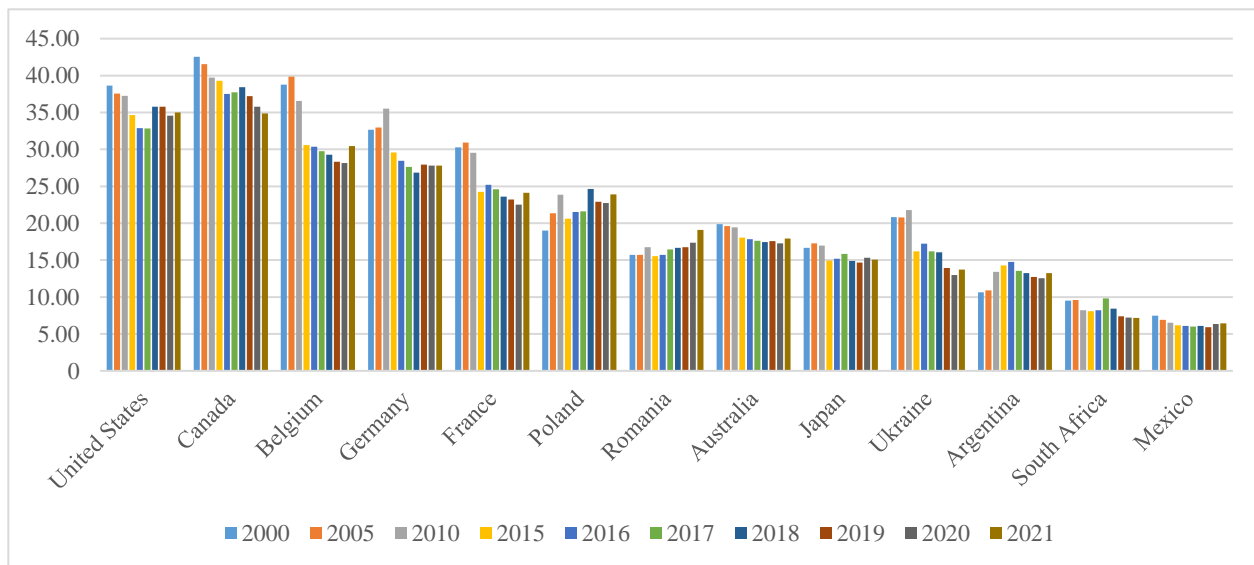


Figure 2: Energy Consumption Per Capita in Selected Countries of the World, (2000-2021), GJ/person) (IEA, 2022)

Energy consumption intensity per capita from 2000 to 2021 reveals that this metric is generally higher in developed countries due to the high industrialisation, infrastructure, and consumption of energy-intensive goods and services. Economically developed countries like the United States, Germany, and Japan demonstrate higher energy consumption rates. At the same time, implementing energy-saving technologies and policies indicates a reduction in per capita energy consumption growth. This is due to improvements in energy efficiency, the transition to renewable energy sources, and reduced dependence on fossil fuels. Energy efficiency indicators depend on climatic and social factors: countries with colder climates (Canada, Norway) have higher consumption levels due to heating, while warmer countries (Mexico, Argentina) have lower levels, although air conditioning in hot regions increases consumption. Rapid population growth and urbanisation affect energy consumption in developing countries (China, India). Many governments have implemented decarbonisation policies, which contribute to reducing consumption intensity.

Several world-renowned companies run successful businesses by efficiently using innovations and energy-saving technologies (Table 1).

Table 1: Benchmarking Analysis of Best Business Practices in Using Innovations and Sustainable Technologies

<i>Company</i>	<i>Field of activity</i>	<i>Practical activities</i>
Tesla, Inc	Automotive	Pioneer in electric vehicles and renewable energy. Their cars are equipped with autonomous driving, and the company also produces solar panels and batteries for energy storage.
Siemens AG	Electronics and automation	Develops energy efficiency solutions for industry and construction, including smart buildings that optimise energy consumption through automation and monitoring. It also introduces digital twin technologies to reduce energy costs.
Unilever	Consumer goods	Implements sustainable development strategies, including reducing its operations' carbon footprint, actively using energy-saving technologies and renewable energy sources, and developing environmentally friendly products.
IKEA	Furniture retail	Uses renewable energy to power facilities, incorporates energy-saving technologies into products, and promotes recyclable furniture design.
Patagonia	Clothing	Focuses on environmental responsibility by using recycled materials in its products. The company supports environmental protection initiatives and encourages customers to repair and recycle clothing.
Apple Inc.	Technology	Reduces the carbon footprint of its products by using renewable energy sources in factories and offices and developing energy-efficient components.
Schneider Electric	Energy management	Develops energy efficiency solutions, including energy management software, and is actively innovating in automation and smart grids.

Source: APPLE (2024), Hu and Zeng (2024), Maradin, Malnar and Kaštelan (2022), Patagonia (2024), PxWEB.IRENA (2020), SIEMENS (2024), Unilever (2021), WEF (2023)

The companies examined illustrate how innovations and energy-saving technologies can be integrated into business models to achieve sustainable development, reduce costs, and enhance competitiveness. These examples serve as benchmarks for organizations aiming to adopt similar practices.

Mechanisms for Supporting Innovations

Mechanisms for supporting innovation in different countries largely depend on the specifics of the economy, level of development, and national priorities. However, several key approaches can be identified to support innovations and contribute to business competitiveness in the face of global challenges and climate change (Table 2).

Table 2: Fundamental Mechanisms for Promoting Innovation to Increase Business Competitiveness in the Era of Global Challenges and Climate Change

<i>Direction</i>	<i>Country</i>	<i>Support mechanisms</i>
Financial support and investments	European Union	It actively invests in Horizon Europe and Green Deal programmes, which aim to promote sustainable economic growth, decarbonisation, and environmental technologies through innovation transfer.
	United States	The Green New Deal and Energy Star programmes provide massive investments in renewable energy and innovative technologies to combat climate change.
	China	Through the Made in China 2025 initiative, the government is investing heavily in the development of green energy and the research and development of innovative technologies.
Tax incentives and benefits	Germany	A system of tax incentives has been introduced for companies investing in renewable energy or energy-efficient technologies. The Energieeinsparverordnung (EnEV) programme supports reducing energy consumption in production.
	France	In addition to subsidies, tax credits are available for companies engaged in research and innovation in energy savings and CO ₂ emissions reduction.
	Canada	The Scientific Research and Experimental Development (SR&ED) programme offers tax credits for companies that invest in research and innovation, including green technologies.
Support for research and development (R&D)	South Korea	Investment in research and development of energy-saving technologies is one of the priorities of the government strategy. South Korea also stimulates the development of new technologies through public-private partnerships.
	Japan	The Japanese government actively funds research into new energy solutions, such as hydrogen energy, and programmes to introduce innovations in industry (the Top Runner programme).
Creation of innovation clusters and infrastructure	Finland	Creating research and innovation parks, such as the Espoo Innovation Garden, promotes the development of startups and innovative companies in technology and energy saving.
	Singapore	The Singapore government creates clusters for the development of green startups and supports research in energy and future technologies.

Source: FG (2014), Galvin and Healy (2020), Mateos and Delgad (2024), Nair (2022), OECD (2023), Scandicorp (2024), Schwanen (2017), Vattenfall (2024), WBG (2023), WIPO (2024)

Mechanisms for supporting innovation globally often emphasize financial support, tax incentives, the development of research and technology, and public-private partnerships. These measures help businesses implement innovative solutions and energy-saving technologies, strengthening their competitiveness in the global market.

Trends and Forecasts in Energy Intensity Reduction

Energy intensity, or the amount of energy used to produce a unit of GDP (TPES/GDP), decreased by 36% globally from 1990 to 2021, although these figures vary significantly between regions (Figure 3).

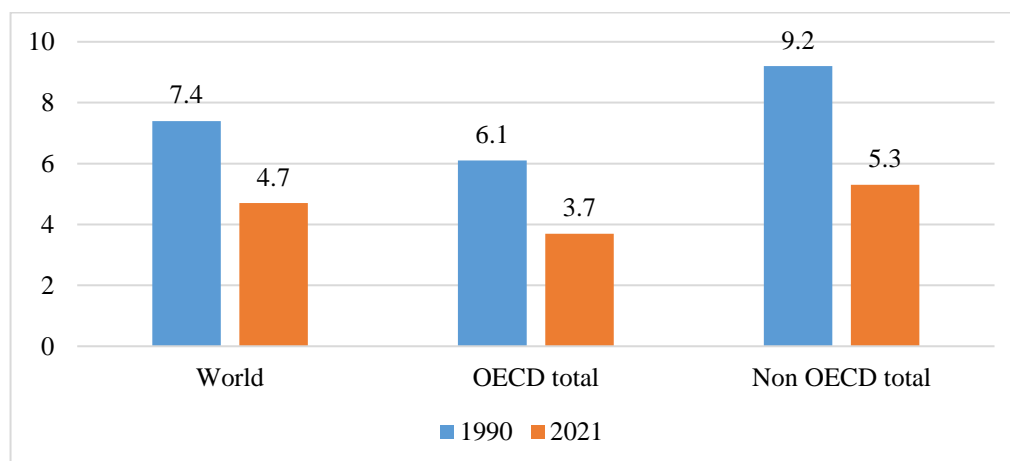


Figure 3. Energy Intensity of the Economy in 2021 vs. 1990 (GJ per thousand USD) (IEA, 2022)

The largest reduction was observed in non-OECD countries. For example, during this period, energy intensity decreased by more than half, by 72%, in China, indicating a significant improvement in energy resource efficiency in its economy. Such regional differences reflect the varying pace of economic reforms and the level of implementation of energy-saving technologies.

Estimated energy savings in 2023-2024 at the global level are expected due to several important factors, including stricter energy efficiency policies and increased use of renewable energy sources. According to data from the International Energy Agency (IEA, 2024), developing and developed countries are actively implementing measures to improve energy efficiency. Global energy intensity continues to decline, thanks partly to the electrification of industry and transport, building upgrades, and the adoption of more energy-efficient technologies. In some countries, such as China, a significant reduction in energy intensity of more than 4% per year has been observed in recent years.

Forecasts for 2024 predict that the main energy savings will be achieved through more efficient use of materials and energy in industry, the transition to the electrification of transport, and the growing demand for energy-efficient technologies in construction. Global energy consumption could decrease by up to 10% by 2030 while maintaining economic growth, provided countries adhere to ambitious measures to improve energy efficiency. At the same time, political instability and wars, particularly in Ukraine, may

continue to impact energy markets, but the current trend toward reducing dependence on fossil fuels will contribute to overall energy savings in 2023-2024.

Role of Government Policy

Government policy is key in promoting innovation and energy-saving technologies in business (Figure 4).

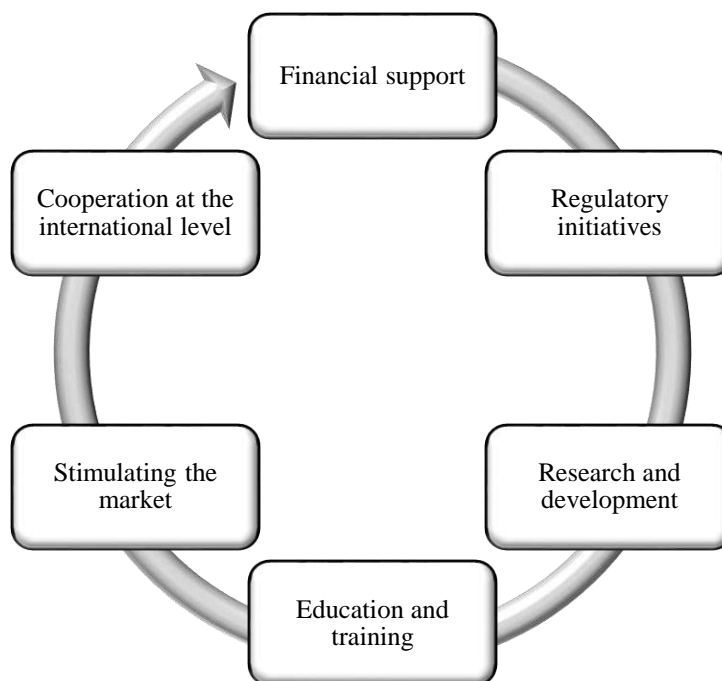


Figure 4: Government Support as a Key Factor for Innovation and Energy Efficiency in Business

Government programs can offer businesses subsidies, grants, and tax incentives for adopting innovative and energy-efficient technologies, thus minimizing financial risks and promoting investment in new solutions. The establishment of standards for energy efficiency and environmental safety encourages companies to implement new technologies, including mandates to reduce emissions, utilize renewable energy sources, and enhance production efficiency. Additionally, the government can invest in research and development, backing innovative projects for industrial application. Partnerships among universities, research institutions, and businesses stimulate innovation. Moreover, government initiatives can increase awareness of energy-efficient technologies and provide the necessary training for personnel through programs, seminars, and exhibitions. Creating favourable conditions for developing the energy-efficient products and services market, including supporting startups and small businesses, can accelerate the adoption of new technologies. Engagement in international agreements and programs allows countries to exchange experiences, technologies, and resources for the implementation of innovative and energy-saving solutions. In general, effective government policies can foster a supportive environment

for innovation development and enhanced energy efficiency, resulting in cost reductions, improved business competitiveness, and better environmental conditions. However, the shift towards innovative technologies and energy conservation comes with various economic and social risks (Figure 5).

Economic risks	Social risks
<ul style="list-style-type: none"> • Implementation costs (initial investment, contingency costs) • Market risks (uncertainty of demand, competition) • Dependence on external factors (raw material prices, economic instability) 	<ul style="list-style-type: none"> • Unemployment (job losses, retraining) • Social inequality (access to technology, education gap) • Changes in lifestyles (social change, resistance to change)

Figure 5: Socio-Economic Risks of Implementing Innovative Technologies and Energy-Saving [Source: Cannavale *et al.*(2018)]

Adopting new technologies and upgrading equipment can impose a substantial financial burden on businesses. Additional costs may arise from staff training and technical support for these innovations. Transitioning to new technologies may not always align with consumer needs, potentially leading to a drop in sales. Market changes can heighten competition, risking market share for companies unable to adapt. Rising raw material prices essential for new technologies can also negatively impact expenses, while global economic crises may limit funding for innovative initiatives. Automation and new technologies could lead to job reductions, especially in traditional sectors. Employees may need to learn new skills, creating social tension. Unequal access to innovations might worsen social inequality, particularly in resource-limited regions. Educational programs may struggle to keep up with rapid changes, leading to disparities in access to knowledge and technology. Additionally, the transition to new technologies may alter consumer lifestyles and habits, requiring time for adaptation. Society might resist innovations due to fear of the unknown.

While ongoing technological development may mitigate some risks, it also introduces new challenges. Changes in government policies can affect business models and innovation strategies. The increasing emphasis on sustainable development and climate change may create new economic opportunities but also heighten social risks. Thus, an effective transition to innovative technologies and energy conservation necessitates a comprehensive approach that includes strategic planning, education, and support to minimize risks and ensure sustainable development.

Conclusion

The study aimed to assess the impact of innovations and energy-saving technologies on improving business competitiveness in a dynamic market environment. The study also planned to investigate successful companies that have implemented innovations based on the analysis of public reports. The study found that innovations and energy-saving technologies are crucial for enhancing companies' competitiveness. They enable cost

optimization, increased production efficiency, and improved brand image among environmentally conscious consumers. Reducing energy consumption and transitioning to renewable energy sources not only lower energy costs but also enhance businesses' environmental sustainability, which is increasingly vital amid climate change concerns. We found that innovative technologies allow companies to quickly adapt to new requirements, including environmental standards and regulations, helping them stay competitive. Effectively using energy-saving technologies boosts productivity and reduces operational costs, making companies more resilient to market fluctuations, economic downturns, and rising resource prices. The transfer of innovations is key to accelerating the integration of new technologies and adopting more sustainable solutions globally. Additionally, strong government support for innovation and energy conservation is essential for easing technology implementation and promoting its wider adoption. Therefore, innovations and energy-saving technologies are fundamental to sustainable business development, offering both economic advantages and positive environmental outcomes. The results of the study will facilitate the prompt identification of fluctuations in resource security zones in the dynamics, timely identification of existing risks, threats and imbalances, and their ranking by the strength of influence, which will allow making optimised management decisions. A promising area for further research is a detailed study of the potential of economic incentives and the motivation of businesses for sustainable development.

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Contribution	Author 1	Author 2	Author 3	Author 4	Author 5
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

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The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

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Political and Legal Framework for the Formation of Effective Strategies for Managing Sustainable Development in a Geographical Context

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Abstract

The ecological condition of the planet, issues of the rational use of resources, responsible and rational behaviour, and equal access to civilizational opportunities determine the relevance of the actual state of ensuring sustainable development and the level of implementation of green initiatives not only at the planning stage but also during implementation. The negative impacts on the environment pose an urgent need for policy solutions to stimulate and support the development of green technologies, essential for promoting sustainable lifestyles. We explored sustainable development in-depth, analysing its economic, social, environmental, and political challenges. The basis for conducting this study are climate change, air and water pollution, loss of biodiversity, and active and disproportionate use of natural resources. Additionally, disparities in access to education, healthcare services, resource utilization, economic crises, and global conflicts play a role. We utilised analytical research methods (analysis and synthesis, induction and deduction), summarised information, and examined previous publications in this field (reviewing literature from recent years). The results revealed the importance of ensuring fair access to resources and opportunities for everyone and developing effective management and regulatory strategies to ensure sustainable development in all areas of life. The study suggests that the involvement of the public in discussions on sustainable development is essential in addressing challenges and achieving sustainable development goals successfully. Forming forums, networks, and communities where the public can exchange experiences, ideas, and best practices regarding sustainable development to promote the development of shared responsibility and cooperation is also encouraged.

Keywords

Sustainable development; Geographical factors; Political will; Legal challenges

Introduction

Studying the legal and political challenges of sustainable development is vital for political and governmental leadership, research, and scientific endeavours, as well as advocating for changes in policies and programmes aimed at sustainable development. Norway is one of the leaders in implementing policies that support sustainable development, particularly in energy and environmental protection. In 2016, Norway introduced the ambitious "Norwegian Strategy for Sustainable Development." The Norwegian government supports projects for developing renewable energy sources, such as hydropower plants and wind farms. It is actively working to reduce carbon emissions by promoting eco-friendly transport solutions. Since 2020, Norway has had the world's highest per capita sales of electric vehicles (Horbach, Ruban and Humeniuk, 2024). Sweden has incorporated the "Sustainable Development Goals" (SDGs) into its national strategy. It became the first country to introduce carbon taxes and support green investments in scientific research and technologies for environmental conservation (Vasylytsiv, Sarahman and Mahas, 2024). This topic is pertinent for guaranteeing legality and stability. Identifying legal norms and political decisions that define societal and economic rules is crucial. Legal aspects of sustainable development help establish frameworks for ecological stability, considering different social groups' interests and representing each benefit. Political influence on decision-making plays a significant role, and without comprehensive legal regulation, it is usually decisive (Stoliarchuk, Ilnytskyi and Rudkovskyy, 2023). Political processes determine which interest groups gain advantages in decision-making and resource allocation. For example, political instability or corruption can result in natural resources being used inefficiently or distributed unfairly, ultimately harming both the economy and the environment. In Nigeria, for instance, despite significant oil resources, a large portion of the country's revenue ends up in the hands of a small elite (Kasyan, 2024). In contrast, local communities near oil fields often face environmental pollution and related social and economic challenges. Political decisions also influence land resource allocation. In India, political processes sometimes favour large agribusinesses over small-scale farmers, contributing to social inequality and environmental issues like declining soil fertility and water scarcity (Kasyan, 2024). In many countries, political processes influence water resource distribution among agriculture, industry, and domestic use, leading to inefficient or inequitable usage.

Studying political challenges helps understand group interactions, identify conflict points, and seek compromise solutions within resource limits (Trushkina, 2023). Effective resource management requires legislative frameworks and political will. Understanding natural resource management's legal and political aspects and reducing environmental impact are crucial for global cooperation, as many issues transcend national borders. For example, rivers such as the Nile, Indus, Mekong, and others flow through multiple countries, and the nations within their basins often have differing interests regarding using these resources. One of the most significant disputes arises between Egypt and Ethiopia over the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Nile River (Horbulin and Mosov, 2023). Ethiopia sees the dam as vital for energy development, while Egypt fears it will reduce water flow, impacting agriculture and water access. Studying political challenges helps understand international cooperation and develop conflict resolution mechanisms. Legal and policy

aspects of sustainable development are crucial for a stable, equitable socio-economic system. Observations in this field highlight policy issues, including the short-term priorities of governments and politicians, which often conflict with the long-term goals of sustainable development requiring significant investments and time (Kudinov, 2023). For instance, in 2020, a temporary ban on the export of roundwood was introduced in Ukraine, aimed at stopping illegal logging and preserving forest resources. According to the State Ecological Inspectorate of Ukraine, the moratorium has reduced illegal deforestation and improved conditions for reforestation. However, the ban was not adhered to due to political pressure and economic interests, and illegal logging continued. This undermines efforts to protect the environment and manage forest resources sustainably (Budiachenko, 2020).

Another problem is the lack of a unified political direction for the country's development. The absence of a unified political direction for a country's development, particularly in sustainable development, stems from various factors, including political fragmentation, competing priorities among different political forces, and more. In Ukraine, as in many other countries with unstable political situations, various political parties and groups have programmes, interests, and goals that often do not align. Governments change, and with them, priorities and policies shift, making it challenging to establish and maintain a unified, stable development plan, especially in complex and long-term matters such as sustainable development (Shkvarylyuk, 2024). Political forces often have differing priorities. Conservative parties typically support economic growth through traditional industries like oil, gas, and mining, with less emphasis on environmental standards and sustainable development. In contrast, Green parties in Europe, such as Die Grünen in Germany, promote renewable energy, CO₂ reduction, and biodiversity. However, their initiatives often face resistance from businesses reliant on traditional energy sources and high-carbon industries (Tkachuk, 2024).

Changes in political course, government shifts, and party agendas create instability in sustainable development policies. Constantly changing political contexts make planning research and recommendations difficult for scientists. Polarized views among government structures and politicians, particularly on environmental issues, add to this instability. For instance, the 2014 Revolution of Dignity in Ukraine shifted political priorities, delaying environmental reforms and affecting international agreements and EU cooperation (Korniievskyi, 2023). Additionally, business lobbies significantly influence policy implementation. Powerful corporate interests, especially in industries dependent on traditional resources (e.g., mining, fossil fuels), often significantly influence politicians and can hinder the implementation of environmental initiatives. A major conflict between economic interests and environmental policy is the use of fossil fuels. During Donald Trump's presidency, the U.S. supported policies reducing environmental regulations for oil and gas companies, under pressure from these industries. This included rolling back measures regulating methane emissions and permitting extraction on federal lands. In Nigeria, oil extraction, though economically vital, causes significant environmental problems like water, soil, and air pollution. Companies are often accused of unauthorized oil spills, causing extensive damage. Despite this, the Nigerian government continues to support the oil industry, leading to conflicts with international environmental organizations and local communities (Savytska, 2021). This can create a conflict between economic interests and scientific

recommendations. For example, coal mines receive state funding despite being economically unviable, due to lobbying (Sheka, 2024). This political protection hinders green energy development. Additionally, sustainable development research is often underfunded, especially in resource-limited countries, hindering large-scale research and innovation. For example, in Ukraine, the issue of waste management is acute due to a lack of funding to create modern infrastructure for recycling and waste disposal. Many projects in this area remain unrealised due to limited state funding, and investments from the private sector allow for implementing only small-scale initiatives from a sustainable development perspective (Sahaidak-Nikitiuk, Nikitiuk, and Zhurenko, 2024).

During economic instability or crises, governments often cut funding for environmental programmes to support more urgent economic needs. This can slow down progress in achieving sustainable development goals. After the annexation of Crimea and the conflict in eastern Ukraine, along with the full-scale war waged by Russia on Ukrainian territory, the economic crisis forced the government to focus on economic and security issues. During this period, many environmental projects were postponed or reduced due to a lack of funds and the need to allocate resources to more urgent needs, such as defence and social support for the population (Martyniuk, 2024).

Geography is crucial in shaping management strategies due to factors like natural resources, climate, ecology, infrastructure, transportation, and socio-cultural features. Each component's detailed examination is vital. Geographic location and territorial characteristics determine resource use, such as water, soil, and minerals, guiding their rational use and conservation. Climate conditions influence opportunities in agriculture, tourism, and renewable energy, aiding in climate adaptation and risk minimisation. Ecological characteristics, like biodiversity and ecosystems, must be considered in resource management to preserve the environment. Geographic features impact infrastructure and transportation development, requiring practical planning. Additionally, geographic factors affect demographic and socio-cultural aspects, informing strategies for social stability and local interaction. Therefore, geography plays a crucial role in shaping effective management strategies by helping comprehending the region's natural, ecological, infrastructural, demographic, and socio-cultural conditions while incorporating them into decision-making processes (Makarenko *et al.*, 2024).

This study examines sustainable development's critical legal and political aspects, particularly the role of national and international legislative initiatives, political structures, and strategies in ensuring resource sustainability and ecological balance. Additionally, it will analyse how geographical factors—such as the distribution of natural resources, climatic conditions, and urbanisation — affect effective policies to achieve sustainable development across different regions. The research will focus on the interaction between legal, political, and geographical aspects in the context of ensuring economic and environmental stability. This article seeks to identify the main challenges legal and political systems face in ensuring sustainable development. It discusses how geography can help to address these challenges by analyzing the impact of geographical factors on governance decisions and strategies.

Methodology

In this study, the key question is the identification of legal and political challenges to sustainable development and the impact of geographical factors on the formulation and implementation of sustainable development strategies. The research question at the core of this review is to determine how legal, political, and geographical aspects influence the achievement of sustainable development and what main problems arise in this context.

The first stage of the research involved determining the inclusion and exclusion criteria for studies. This included selecting works published in peer-reviewed journals from 2000 to 2024, focusing on legal, political, and geographical aspects of sustainable development. Articles that focused solely on economic or purely scientific issues without detailed analysis of legal and political aspects were excluded. Several databases, such as Scopus, Web of Science, Google Scholar, JSTOR, and SSRN, were used to search for relevant articles. The search queries covered topics related to legal challenges of sustainable development, political barriers, global cooperation on climate change, and other key aspects important for understanding the challenges of sustainable development.

The next step was the selection process for studies that met the established criteria. Initially, selection was carried out based on titles and abstracts to assess the relevance of the articles to the research question. Subsequently, the full text of each article was reviewed for final inclusion in the review. Following the selection of relevant articles, a data extraction method was developed, which involved collecting key information from each article. For each study, data such as the type of research (empirical, review, or theoretical), geographical focus, main legal and political challenges, policy recommendations, and research methods were collected. This enabled the creation of a unified database for further analysis.

To assess the quality of the included studies, various tools were used to evaluate the methodological rigour of the articles. For empirical studies, the CASP checklist (Critical Appraisal Skills Programme) was used, while for review and theoretical articles, the AMSTAR tool (A Measurement Tool to Assess Systematic Reviews) was applied. Additionally, to ensure transparency and systematic approaches, the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) were employed for overall quality assessment of the studies.

Furthermore, after data collection, synthesis was carried out. In this study, a qualitative approach was used for synthesising results, allowing thematic analysis to highlight key themes, patterns, and gaps identified in studies on legal, political, and geographical challenges to sustainable development. Overall, this methodological approach enables a comprehensive assessment of legal and political challenges to sustainable development, revealing not only theoretical aspects but also practical issues faced by countries and international organisations in the process of formulating and implementing sustainable development policies. The techniques employed in this study can be applied in future systematic reviews, enabling the replication of this process and achieving high accuracy and reliability of results.

Results and Discussion

Modern approaches to the study of legal and political challenges to sustainable development

Many scholars have researched sustainable development over time. Key figures in this field include Gro Harlem Brundtland, Robert W. Sachs, Angela Merkel, and Nicholas Stern (Malenko, Voroshylova and Pozdnii, 2024; Ziuba, 2024). Literature reviews on sustainable development's legal and political challenges typically cover works from various disciplines, such as law, political science, economics, sociology, and geography. In 1987, the Brundtland Commission Report, also known as "*Our Common Future*", defined the concept of sustainable development and emphasized its significance for the future of humanity (Dryzek, 1997; Kazarian, 2024). John S. Dryzek's "*The Politics of the Earth: Environmental Discourses*" analyses the political aspects of environmental discourses and explores their influence on forming sustainable development policy. Additionally, "*Global Environmental Governance: Options and Opportunities*" by John J. Kirton and Michael J. Trebilcock is another crucial work in this field (Kirton *et al.*, 1998). It investigates the possibilities of global environmental governance and the role of international institutions in advancing sustainable development. "*The Geography of Thought: How Asians and Westerners Think Differently...and Why*" by Richard Nisbett is a book that presents research on cultural and geographical differences in thinking and their impact on decision-making regarding sustainable development (Nisbett, 2003). The book "*Environmental Policy: New Directions for the Twenty-First Century*" by Norman J. Vig, Michael E. Kraft and Barry G. Rabe proposes novel political mechanisms to address environmental issues and promote sustainable development (Vig, Kraft, and Rabe, 2015). The sources offer varied perspectives and research on the legal and political aspects of sustainable development, as well as the influence of geography on management strategies. The global debate on climate change is a significant issue (Timmons and Parks, 2007).

Theoretical and methodological foundations to formulate effective strategies for managing sustainable development based on a geographical approach

Sustainable development is a critical concept in the modern world. It involves achieving economic efficiency, financial stability, economic growth, and the development of social and environmental subsystems while considering the needs of the present generation and the opportunities of future generations. It requires balancing the interests of individuals, society, and the state while accounting for limitations related to national security and external environmental factors (Fedorov, 2024). However, achieving sustainable development faces numerous challenges, with legal and political aspects playing a significant role. In this context, geography is a critical factor in shaping effective management strategies for sustainable development, as geographical conditions—such as climate, geological structure, water resources, and natural disasters—significantly influence the development of regions and countries. Understanding these factors allows for better forecasting of problems and the development of management strategies that consider geographical characteristics (Lelechenko, 2017).

One of the most significant legal challenges to sustainable development is the lack of clear international legislation that regulates sustainable development principles on a global scale. Many countries' environmental protection and sustainable development laws are fragmented or outdated, making it challenging to coordinate international efforts and effectively achieve common sustainable development goals (Sumets *et al.*, 2022). Furthermore, a lack of political will often acts as a barrier to adopting and implementing adequate laws, which can result in inadequate legal support for national and international initiatives in this area. These issues require resolution, as they have a significant impact on achieving sustainable development and ensuring its effective implementation at all levels — from national to international (Dobrovolsky *et al.*, 2021). Existing agreements and treaties often lack explicit norms and mechanisms for enforcement, which can complicate their implementation and effectiveness. Therefore, there is an urgent need to create international legal instruments that promote sustainable development.

Additionally, political challenges arise due to insufficient political will and consensus among countries to take necessary actions. Addressing complex environmental, economic, and social problems often encounters opposition from certain political groups or countries pursuing their short-term interests. Political will and stakeholder cooperation are necessary for significant progress in sustainable development. Furthermore, existing political systems and structures may not always align with the requirements of sustainable development. Political processes are frequently lacking in transparency, and mechanisms of power and influence are not aimed at achieving sustainable development goals. Reforming political systems to be more democratic, open, and accountable can aid in resolving sustainable development issues effectively.

Historical aspect of forming the political and legal basis for sustainable development strategies

The movement towards sustainable development as a global issue began in the early 1990s. Globalization has positively influenced sustainability, but it also has negative aspects. These negative aspects are particularly noticeable in developing countries and pose significant obstacles to achieving global sustainable development. According to Brzezinski (2004) and Young (2001), monopolistic globalization results in a new system of exploitation. The benefits and opportunities of globalization are concentrated in the hands of a small group of countries. However, globalization poses significant challenges, threats, and uncertainty for many, particularly in the economic and social spheres. Globalization can lead to economic constraints, social isolation, and detachment from complex social and environmental issues. It is essential to ensure that people in developing countries feel the positive impact of globalization. For globalization to truly become a global process, it must benefit all people and contribute to the welfare of humanity (Bilorus, 2005). In summary, it is critical to note that legal and political challenges pose severe obstacles to sustainable development. Overcoming these challenges requires joint efforts from the international community, including developing clear international legal standards and creating a conducive political environment for implementing sustainable development strategies. According to some authors, it is necessary to reduce anthropogenic influences on climate change (Rockström *et al.*, 2009; Patel, 2020).

Concepts of the research issues in the context of individual regions and countries

The problem of sustainable development is not new, but it remains unresolved. Many conflicts in this field are caused not only by political aspects and personal interests of individual politicians but also by contradictions with large corporations (Horbata, 2024). In their pursuit of profits, the latter seek increased revenues and higher stock values, and under the guise of development and production expansion, overlook the global impact on the planet, adherence to sustainable development strategy, responsible resource use, and adequate waste disposal. Certain legal "loopholes" also aid these corporations, notably, the imperfections in the legal framework. This can be an objective factor (an outdated and inadequate legislative framework, poorly thought-out mechanisms for implementing government recommendations) or a subjective one (planned sabotage of specific bills by interested parties). Environmental protection and sustainable development legislation is fragmented or outdated in many countries, including Ukraine. For instance, the legislative framework in Ukraine regarding waste management or the use of natural resources is often insufficiently detailed or outdated, making it challenging to implement effective environmental practices. This issue particularly applies to the law on environmental protection, which requires updating and adaptation to modern conditions and requirements (Stoliarchuk, Ilnytskyi and Rudkovskyy, 2023).

Moreover, Ukraine is not the only country in such a situation. Let's take a closer look at India. India's legislative framework on environmental protection and sustainable development is outdated and ineffective in addressing modern environmental challenges. For instance, the 1986 Environmental Protection Act was created as a general law to regulate environmental issues, but it contains many gaps and shortcomings. For example, it does not provide adequate regulation of waste management issues, which have significantly increased since the law was passed. India also faces problems with implementing its laws at the local level, leading to a low level of enforcement (Kornilovych, Spasonova and Veselska, 2021). For example, the 2016 Solid Waste Management Bill aimed to modernise waste management approaches, but its implementation faced numerous difficulties due to bureaucratic obstacles and a lack of infrastructure. As a result, the issue of waste disposal remains acute (Maksymchuk, 2022). Brazil is also in a similar situation. In Brazil, legislation in the field of environmental protection often conflicts with economic interests, leading to conflicts and imperfect regulation. The 1965 Brazilian Forest Code was significantly updated in 2012 to regulate land use in the Amazon. However, despite this update, new amendments caused a severe controversy, allowing for expanding land use previously protected for agricultural activities. This has led to a significant increase in deforestation, which negatively impacts global climate change. Nevertheless, the 2012 Amnesty Bill on land use granted amnesty to farmers who had previously illegally cut down forests. Environmental organizations sharply criticized this bill for encouraging further illegal logging (Gazarian, 2024). Kenya faces the problem of insufficiently detailed legislation on water resources and waste management. For example, the 2002 Water Resources Management Act was one of the first steps towards regulating water use in the country. However, it did not provide adequate control over the use of water resources, leading to the degradation of rivers and lakes. The lack of proper enforcement mechanisms has also caused severe water shortage problems in many regions. In 2016, the Kenyan government passed a new Water Resources Management Act, but effective enforcement

remains a significant challenge even after its adoption. The lack of proper funding and infrastructure to implement this law continues to hinder achieving sustainable development goals in water resources (Tomozov, 2024). Despite progressive legislation, the United States also faces significant discrepancies between federal and local laws, which can complicate the implementation of sustainable development policies. For example, the 1972 Clean Water Act is the primary federal law regulating water quality in the United States. However, its implementation faces challenges due to discrepancies between federal standards and local regulations and lobbying by large industrial groups, which influences the decision-making process. In the progressive year 2020, the US administration changed the rules regarding water resource protection, narrowing the scope of the Clean Water Act. Environmentalists criticized this decision as it weakened the protection of wetlands and small waterways, which could negatively impact ecosystems and water quality (Yemeljanov and Pedko, 2024). These examples demonstrate that problems with the imperfection of the legislative framework in sustainable development are widespread in various countries worldwide and can have serious environmental consequences. Addressing these issues requires legislative reform, improved enforcement, and closer cooperation between government, scientists, and the public (Serdiuk, 2023).

The role of geography in sustainable development

Geography plays a crucial role in shaping management strategies aimed at achieving sustainable development. A region's natural resources, climatic conditions, topography, and geological structure significantly impact its economic, environmental, and socio-cultural development. Understanding these geographical peculiarities enables the development of more effective strategies that consider each region's potential and limitations.

Geographical conditions play a crucial role in determining the availability and utilization of resources. Different regions have varying potentials for developing renewable energy sources, agriculture, tourism, and other sectors based on their natural conditions (Bayev *et al.*, 2022; Niziaieva *et al.*, 2022). For example, regions with abundant sunshine are favourable for solar energy production, while regions with limited water resources require efficient management of water reserves. Secondly, the vulnerability of regions to natural disasters and climate change is influenced by geographical conditions (Goldberg, Gustafson and Wang, 2020). Risk management associated with these factors requires a strong understanding of geographical peculiarities and using scientific data to develop risk mitigation plans. Furthermore, the geographical location of regions defines their role in global economic and environmental processes (Chen *et al.*, 2020; Rosenzweig and Hillel, 2015). Regions located on international borders or with a high concentration of economic resources can play a significant role in international communities and organizations. Therefore, understanding geographical factors is essential for developing and implementing management strategies to achieve sustainable development. Geography offers valuable context and information for making informed decisions and developing effective strategies that promote sustainable development at different levels, from local to global (see Figure 1).

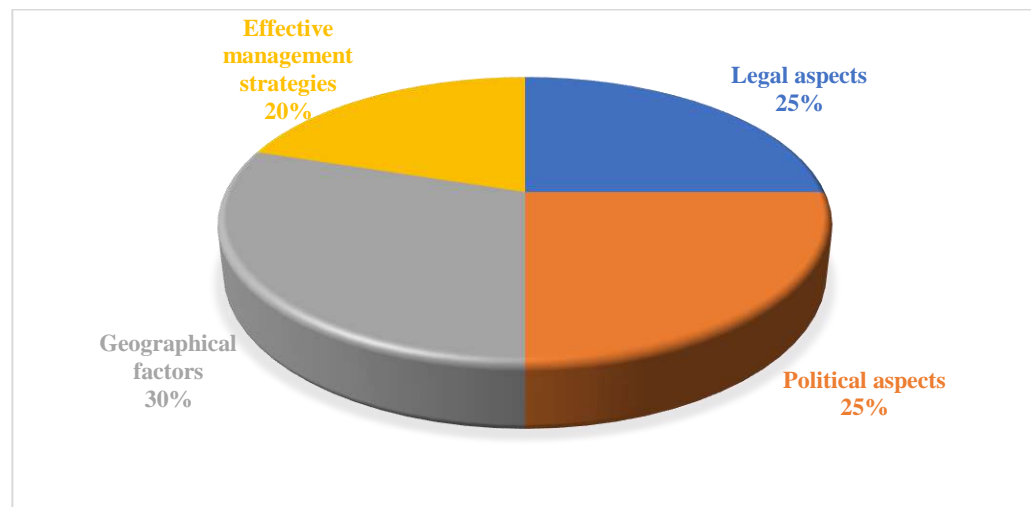


Figure 1: Aspects of sustainable development strategy implementation

Sustainable development can only be achieved by developing and implementing effective management strategies that consider the geographic peculiarities and meet the needs of specific regions or countries. Firstly, geographic conditions such as climate, geological structure, topography, and natural resources significantly influence economic, social, and environmental development. Therefore, management strategies should consider these characteristics and leverage them as advantages. For instance, renewable energy sources can be particularly effective and increasingly significant in many regions worldwide, mainly where conducive conditions exist (Kalair *et al.*, 2020). Specifically, Europe is at the forefront of green energy development, with significant investments in wind, solar, and hydro energy (Merzliak, 2002). Germany, Denmark, and Sweden have made significant strides in transitioning to renewable energy sources. In the USA and Canada, wind and solar energy are gaining popularity, especially in states and provinces with great potential for these energy sources, such as California and Alberta. Countries in Southeast and South Asia, such as India and China, are actively developing wind and solar energy to meet rapidly growing electricity demand and reduce greenhouse gas emissions. Brazil relies primarily on hydroelectric power for electricity and wind and solar energy development. Similarly, Chile and Mexico are making significant strides in renewable energy. In Africa, countries such as South Africa and Morocco are investing in wind and solar energy due to their abundant solar radiation and wind resources. These regions are crucial in the global transition to green energy, contributing to carbon reduction and sustainable development.

Secondly, management strategies should be integrated and cross-sectoral, ensuring interaction between different sectors and levels of governance. It is essential to consider the interconnections between economic, social, and environmental development and to develop strategies that balance these aspects. For instance, green technology programmes can contribute to economic growth, improve quality of life, and reduce negative environmental impact. In addition to climate change, there is a growing trend towards sustainable natural resource management and developing the market for environmental goods and services. Furthermore, there is an increase in the production of equipment and eco-technologies to support the green economy. In developed countries,

the increasing level of prosperity leads to a greater focus on quality of life. This results in an increased demand for environmental goods and services and the expansion of companies' activities in green technology. Identifying the aim to liberalize trade in environmental goods and services within the Doha Round of trade negotiations as a critical aspect in the OECD's Interim Report on the 'green' growth strategy is necessary (OECD, 2010).

In addition, management strategies must be adaptable to changes in the geopolitical, economic, and environmental landscape. The fast pace of technological change and growing instability in global politics necessitates constant updating and adjustment of management strategies to address new challenges and opportunities. In conclusion, developing effective management strategies for sustainable development requires a comprehensive approach that considers geographical peculiarities and ensures integration and adaptability. This is the only way to ensure long-term stability and success in development.

Development stability is an increasingly pressing necessity in the modern world, where economic, environmental, and social challenges are becoming ever more complex. Legal, political, and geographical aspects are crucial in shaping effective management strategies for sustainable development. To address legal challenges, it is necessary to establish a clear international legal standard that regulates and defines the principles of sustainable development on a global scale (Ribun *et al.*, 2024). Additionally, mechanisms for monitoring compliance with agreements and treaties related to sustainable development should be established to ensure their effectiveness. Political challenges in achieving sustainable development goals include a lack of political will and consensus among countries regarding necessary measures. Disputes and differences in political interests often complicate the implementation of sustainable development strategies, hindering the achievement of common goals. The role of geography is to consider the geographical characteristics of regions when developing management strategies. Natural conditions, such as climate, topography and water resources, determine the opportunities and constraints for economic development in the regions (Hessen, Kryvoruchko and Sidorenko, 2016). The topic of sustainable development is relevant and prominent, but it is complex and requires an understanding of several critical issues to consider practical solutions and improve the environment.

These questions represent the essence and meaning of sustainable development, highlighting its importance for modern society and future generations. Addressing such vital issues makes it possible to forecast the ecological crisis as such, along with the likelihood of its occurrence, progression, and the consequences it may bring. The impact of human activity on the environment and its effect on our quality of life, as well as strategies for conserving natural resources, environmental innovations, and the global dimension, are all essential to consider when addressing this issue. What international communities and organizations are working towards achieving sustainable development, and what role do we each play in this process? Answers to these and other questions can be easily found in the age of free access to the World Wide Web. Notably, publications such as Nature provide valuable research on various aspects of nature, including sustainable development and natural resource conservation. Science is a scientific journal that covers contemporary research in biology, ecology, and other scientific fields

related to ecology. The Guardian Environment Section is a section of The Guardian's online publication dedicated to news and analysis on environmental protection and sustainable development. Environmental Research Letters is a scientific journal specializing in publishing ecology and environmental research, including works on sustainable development (Radchenko, 2024). World Resources Institute (WRI) Insights is an online platform that provides analytical materials, research, and articles on ecology, climate change, and sustainable development (Leiserowitz *et al.*, 2019). It is a valuable source for obtaining updated and authoritative information on sustainable development and ecology.

However, there are still questions related to the legal and political challenges of sustainable development and the role of geography in forming effective management strategies, which require further research and description. The geopolitical aspects of sustainable development pertain to the influence of geopolitical relations and international conflicts on implementing sustainable development strategies. Geopolitical factors, such as conflicts between countries or groups, the geostrategic location of resources, and geopolitical interests, can affect efforts to create a more sustainable and environmentally secure society (Bondarenko *et al.*, 2022; Sych, 2012). Conflicts and instability in the region can create obstacles to implementing sustainable development programmes. This is due to the destruction of infrastructure, diversion of resources, and damage to natural environments. Furthermore, conflicts can cause environmental disasters, such as pollution or depletion of natural resources, which worsen environmental problems and complicate the resolution of sustainable development issues. Secondly, the geostrategic significance of certain regions can result in competition between countries for control over resources, such as energy and water. This can cause tension and conflicts, as well as complicate cooperation in the field of sustainable development.

Legal framework for sustainable development

The legal frameworks for sustainable development refer to the need to define legal mechanisms and international agreements that ensure the implementation and adherence to the principles of sustainable development. These frameworks encompass various legislation and international agreements regulating resource use, environmental protection, social justice, and economic development. Legal frameworks may include constitutional provisions, environmental protection laws, international conventions, treaties, regulatory standards, and norms. The principles of sustainable development are an essential component of the global legal framework. They encompass ecological integrity, social justice, economic efficiency, public participation, and comprehensive decision-making. However, effective control mechanisms must be thoughtfully formulated. Such verification mechanisms are necessary to properly implement and adhere to legal frameworks that support compliance with the sustainable development plan. This requires the development of appropriate institutional structures, access to justice to safeguard individuals' and communities' rights, and monitoring and evaluation of decisions' impact on sustainable development.

Managing and regulating ecological crises involves developing effective mechanisms and strategies to handle situations where severe threats to the environment and society

arise. Ecological crises, such as natural disasters, environmental pollution, or ecological accidents, can severely affect ecosystems, human health, and the economy. Swift and effective action is necessary to minimize damage and restore stability. The issue of political strategies for sustainable development involves identifying practical approaches and governance strategies that contribute to achieving sustainable development goals. These strategies encompass a wide range of actions and measures to balance economic, social, and environmental growth, conserve natural resources, and improve the quality of life. Critical aspects of political strategies for sustainable development include creating legal and regulatory mechanisms, stimulating innovation and creativity, ensuring public participation, providing financial support and investment, promoting international cooperation, and employing diplomacy (Kuybida *et al.*, 2023). The management of territorial resources is a global issue that requires analysis of various aspects affecting the process and identifying potential ways to achieve sustainability in all spheres of life. Economic aspects are fundamental, as achieving sustainable development requires balanced economic growth that meets the needs of the present without compromising future generations. This involves creating innovative economic models that promote poverty eradication and the equitable distribution of resources (Borowski, 2021). Social factors are crucial for sustainable development to enhance the quality of life for all individuals, including access to education, healthcare, housing, and other social services. Achieving this requires implementing social programmes and policies that reduce inequalities and ensure the inclusion of all groups (Bilinchuk, 2024). Environmental aspects are a crucial element of sustainable development, encompassing the conservation of natural resources and the protection of the environment. This requires enforcing strategies and technologies to reduce emissions, promote renewable energy sources, and preserve biodiversity (Maksymova, Ishchuk and Slobodian, 2024). Successful sustainable development requires the active involvement of government and international organizations in addressing environmental, economic, and social challenges. This involves creating political programmes and mechanisms to support sustainable development policies and promote cooperation between countries (Sai *et al.*, 2024). Sustainable development necessitates collective efforts and cooperation from all countries and public organizations at the international level. This requires developing international agreements, exchanging knowledge and technology, and financial support for developing countries. These aspects are interconnected and crucial for achieving sustainable development globally.

Scientific Novelty and Recommendations for Optimization

The analysis of scientific literature on the legal and political challenges of sustainable development has raised more questions than answers. This indicates that the issue requires further research and analysis of its details. Although these details may seem insignificant individually, they collectively impact the sustainable development strategy and its outcomes (Bogolyubov *et al.*, 2012; Heiets *et al.*, 2020). Therefore, it is crucial to understand geopolitical realities and consider their impact on implementing sustainable development strategies. This awareness is necessary to formulate effective political and managerial decisions to ensure stability, peace, and sustainable development at regional and global levels. Legal frameworks are crucial in promoting sustainable development, and it is the responsibility of national and international governments, civil society organizations, and the private sector to ensure compliance

and improvement. Managing environmental crises is a complex task that requires coordination, cooperation, scientific data and expert knowledge to ensure society's safety and sustainable development. Political strategies for sustainable development are imperative for achieving global sustainable development goals and ensuring a viable future for everyone (Broun, 2008). A comprehensive approach and joint efforts of all stakeholders are necessary to ensure a resilient, fair, and environmentally safe future.

Irreversible and progressive climate changes, increased anthropogenic pressure on the environment, and the depletion and limitation of natural resources necessitate prioritizing an ecological approach to new scientific and technical solutions. A particularly relevant issue today is the conflict between spatial planning and sustainable urban development, alongside the unavoidable reality of the threat of ecological disaster (Serhiienko, 2023). It is essential to rethink the approach to legislative and regulatory frameworks in the sector, which should spark interest in modern, innovative urban planning opportunities to achieve an effective symbiosis of energy efficiency and environmental sustainability.

Analysis and discussion in the thematic research field

Despite the numerous scientific studies in an interdisciplinary context, the understanding of the problem of forming geopolitical sustainable development strategies, in terms of defining its essence and components, as well as the political and legislative paths to their formation and development, has been researched only fragmentarily. In particular, the studies by Biermann *et al.* (2022) highlight the issue of forming an ecological worldview as the foundation for the sustainable development of society, which requires the creation of a synergistic space for the interaction of legislative, political, and societal initiatives, where stakeholders collaborate to address prolonged environmental problems.

Ruggerio (2021) and De Sadeleer (2020) see the reorientation of politicians' and managers' traditional anthropocentric worldviews towards an ecocentric one as one of the main conditions for the effectiveness of sustainable development strategies. According to these scholars, it is primarily about forming an ecologically oriented worldview as the central, motivational, and meaningful component of society's ecological consciousness. Scholars, such as Sikora (2021), have studied the problem of geopolitical differentiation of sustainable progress strategies in the context of their connection with the societal advancement of ecological thinking. A systematic review provides a better understanding of how the concepts and mechanisms of legislative transformation theory are implemented in the study of sustainable development. At the same time, researchers argue that the link between government, society, and business is strengthened through the co-creation of knowledge. The issue under study has been thoroughly developed in the field of jurisprudence in the foreign academic field, particularly within the framework of ecological law (Ahmed *et al.*, 2022), which focuses on the interaction of strategic and situational development factors. The subject of research by Ahmed *et al.* (2022) is the ecological worldview component of legislators' consciousness. Furthermore, contemporary scholars explore methods of forming ecological knowledge and practical skills of ethical interaction between society and the environment, particularly in specially organized ecologically oriented activities.

The vectors for addressing the legal and political challenges of sustainable development in a geopolitical context have been studied by authors (Qin *et al.*, 2023; Nguyen *et al.*, 2023), who position it in the context of understanding the integrity of the natural environment, its aesthetic and socio-economic significance. In particular, the researchers have developed and experimentally tested legislative initiatives for transforming ecological responsibility to achieve sustainable development goals and to increase public understanding of climate change through developing projects to mitigate environmental problems caused by human activities. Some researchers' position forming the political and legal basis for ecological sustainability as mastering a system of ecological values in a practice-oriented legal environment. In this case, the system's main component is the values and beliefs regarding society's responsibility to preserve the natural potential and promote a sustainable way of life.

Conclusion

This study has identified the global challenges that legal and political systems face to ensure sustainable development. By analysing critical literature and events worldwide, we found that sustainable development requires coordinating national and international efforts, involving all stakeholders, and effectively utilising available resources. One of the key factors determining success in this area is the political aspect. Political decisions can drive innovation by fostering the development of new technologies that reduce emissions, minimise environmental pollution, and improve resource efficiency.

In particular, government funding in support programmes, subsidies, and incentives can aid in developing and implementing green technologies, making them more accessible to businesses and consumers. Furthermore, appropriate legislation and regulation can create a stable and transparent environment for developing such technologies, reduce risks for investors, and encourage innovation (Sytnyk, Zubchuk and Orel, 2022). Promoting market competition is also crucial, as green technologies can only remain competitive in an open and competitive market, which is also influenced by political decisions. International cooperation plays a crucial role in achieving these objectives, as political decisions at the international level can facilitate the exchange of technological knowledge and resources between countries, accelerating and enhancing the global adoption of green technologies. In addition, an important aspect is the analysis of specific positive initiatives and their presentation to society. In fact, our further research is planned to focus on analysing the successes and failures of specific strategies. The importance of presenting positive experiences will help to promote the importance of adhering to sustainable development strategies globally. In our view, public support for a particular strategy is only possible through the popularisation of its results. If it is possible to gain the approval of a large portion of the planet's population, the obstacles to its implementation will disappear on their own.

Therefore, political decisions are necessary for stimulating and supporting the development of green technologies, which are essential in reducing negative environmental impact and promoting sustainable lifestyles. The decision-making process in politics is complex and involves various actors. These include political parties and their leaders, government structures (such as parliaments, government agencies, and committees), corporations, industrial associations, non-governmental organisations, and

international institutions such as the United Nations, the World Trade Organization, and the International Monetary Fund. Only by consolidating all of these social institutions and coordinating their interests can we create a stable and prosperous future for everyone and preserve our planet for future generations.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5
Conceived and designed the research or analysis	Yes	No	Yes	Yes	Yes
Collected the data	Yes	Yes	Yes	No	No
Contributed to data analysis and interpretation	Yes	Yes	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	Yes	Yes	Yes
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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Leveraging Media and Public Relations Strategies to Advance Sustainable Development: Approaches, Frameworks, and Tactics in Modern Conditions

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Abstract

The use of media and PR materials in the modern context of gamification and interactive communication actively engages audiences in complex sustainable development issues. The research aims to analyze the strategies, models, and methods of media and PR technologies for promoting the principles of sustainable development in society. A combined approach was used, incorporating thematic case studies and secondary data analysis, to examine the impact of media and PR technologies on sustainable development. The study focused on recent media and PR technologies and data from twenty-four countries on public trust in media and its dynamics in Ukraine from 2020 to 2024. The article highlights the potential of PR and media campaigns to influence individual and corporate actions, offering strategies to optimize their impact in promoting sustainable development. We discussed the strategies and formats for successfully applying media and public relations technologies to advance the principles of sustainable development. The study examines practical examples of implementing media and public relations projects that utilize innovative communication tools for achieving the Sustainable Development Goals. It analyses the level of trust in media resources worldwide and the dynamics of trust in media in Ukrainian society. The research emphasizes the importance of media in raising environmental awareness, promoting sustainable business practices, and supporting the United Nations' Sustainable Development Goals (SDGs).

Keywords

Media; Sustainable development; PR technologies; Environmental awareness

Introduction

The principles of sustainable development, recognized by the United Nations, aim to address urgent issues that require significant changes in societal processes on a global scale (Lu *et al.*, 2021; Ye *et al.*, 2020). The current stage of global societal development is characterized by the substantial influence of media and Public Relations (PR) on stakeholders at various levels, which is intensified by the rapid development of social networks. Depending on their direction and goals, media and PR resources can be positive and negative factors in developing societal trends (Petropavlovska *et al.*, 2018).

Today, there are several ways to effectively use media and PR technologies to promote global principles of sustainable development. The subject of this study is positioned as relevant in the context of both developed countries with successful advancements in the concept of sustainability and developing countries (Jie and Jiahui, 2023). Strategies in these cases will differ, based on the achieved level of sustainable progress and national priorities: in highly developed countries, society itself actively seeks opportunities to engage in activities aimed at preserving environmental sustainability. In contrast, in less developed countries, society requires active educational outreach efforts (Troise and Camilleri, 2021). In both cases, media and public relations play an important, albeit somewhat different, functional role. In particular, they can raise audience awareness of priority environmental issues, promote sustainable business practices, encourage responsible consumption, and educate about sustainable development (Pimonenko *et al.*, 2020). Examples include gamified campaigns and challenges (e.g., "The Recycle Rally", "The Clean Seas Challenge"), interactive exhibitions and installations (e.g., "The Ocean Clean Up"), interactive websites (e.g., "The Sustainable Development Goals Hub"), as well as virtual conferences and events (e.g., "The Virtual Island Summit") (Smith, 2020; Gregory, 2020). The role of media and PR in achieving the Sustainable Development Goals has not yet been fully assessed, as in addition to highlighting global issues, these resources have the potential to directly impact sustainable development through the active integration of communication tools, media projects, and targeted media campaigns with significant social influence (Hrebeniuk and Okseniuk, 2024).

Given that the engagement of communication mechanisms, such as PR and media, holds the potential for practical impact on social development, the need arises to study the specifics of modern media campaigns and media projects that steer social progress towards sustainability. The integration of these tools into sustainable development campaigns is hindered by issues of financial support and stakeholder investment (Ozcan *et al.*, 2021). The role of media in sustainable development remains undervalued, as investors in developing countries often expect quick returns and are unwilling to allocate significant resources to the "common" cause (Smith, 2020; Lim, 2022). Attracting social media traffic and drawing public attention to a sustainable development brand through media and PR platforms involves a set of measures aimed at engaging social media as channels for promoting the company and optimizing business objectives (Savtyska, 2017). As a result of the informatisation of society, consumers are influenced by information about companies and their products from a wide range of sources. Advertising, personal selling, sales promotion, and public relations are classic marketing tools that influence end consumers and collectively create an overall impression of the company (Čábelková *et al.*, 2022). All of this can be actively integrated into strategies

for implementing the principles of sustainable development in various aspects of societal progress.

The study aims to analyze media and PR technologies' strategies, models, and methods for promoting the principles of sustainable development in society. The research focuses on the strategies and formats for the successful application of media and PR, identifying related challenges and highlighting the most effective tools. The results may have a potentially positive impact on the formation of regional, local, or national programmes for the implementation of sustainable development principles in public life.

Methodology

The role of media and PR in achieving sustainable development goals, raising environmental awareness and promoting responsible consumption was determined using several general scientific research methods.

Sampling Method. The study employed a combined approach to examine the impact of media and PR on sustainable growth, taking into account various socio-economic conditions. This research falls into the descriptive category and incorporates thematic case studies and secondary data analysis. The research procedure consisted of two main stages: data collection and analysis. In the first stage, primary data sources were utilized, obtained through an analysis of industry-specific statistical information and publications. Publications indexed in leading academic databases such as Scopus and Web of Science were used. Keywords such as "Media," "Sustainable Development," "PR Technologies," "Marketing," and "Environmental Awareness" were applied in the search process. The inclusion and exclusion criteria for publications were based on spatial-temporal indicators and the level of information reliability. Among the methods used to assess the risk of bias in the included studies were brainstorming and cause-and-effect analysis. Initially, over fifty industry-specific publications were collected, and according to the specified criteria, thirty of them were selected for the study. This sample size was deemed appropriate in light of practical realities while ensuring adequate statistical power. The study focused on media and PR technologies from recent years, as well as indicators from twenty-four countries regarding public trust in media resources and the dynamics of this indicator in Ukraine for the period 2020-2024.

Study Design. The research employed a variety of general scientific methods, including analysis and synthesis (to explore contemporary theoretical concepts and scientific developments on the impact of media and PR technologies, refine terminology, and assess their impact on socio-economic development); comparison (to systematize conceptual approaches to defining basic concepts and criteria for selecting practical directions of media influence under conditions of instability, as well as identifying associated risks and obstacles); and structural-logical methods (to develop proposals for improving the organizational mechanism). These methods were adapted to the research focus in the educational field, and the unique characteristics of educational technologies in the context of globalization and digitalization. Media and PR technologies were analysed in the context of their potential to increase awareness, promote sustainable business practices, and achieve the UN SDGs. The study's main conclusions were formed through deduction. Abstraction was used in this, highlighting the potential

feasibility as a process of mental detachment from the standard properties of managerial technologies, concepts, and tools while simultaneously emphasising the essential properties being sought. The comparison revealed the qualitative and quantitative characteristics of the studied managerial practices, their similarities and differences. It also compared the specifics and essence of innovative managerial technologies in education, which meet the requirements of globalization.

Data Analysis. Data analysis was conducted using mixed methods, incorporating both quantitative and qualitative statistical analysis techniques. Quantitative research focuses on numerical data that can be assessed using statistical tools. Microsoft Excel was utilized for conducting the analysis. Qualitative research emphasizes rich, detailed data that can provide insights into the experiences and perspectives of contemporary researchers regarding strategies and methods for using media and PR technologies to promote the global principles of sustainable development.

Literature Review

The issue of leveraging media and PR technologies as tools for promoting specific socially significant strategies, including the principles of sustainable development, has been addressed in several contemporary scientific works. For instance, several studies have explored the potential of these technologies in the context of achieving global goals through the convergence of value orientations towards sustainable development (Hrebenuk and Okseniuk, 2024; Lelechenko, 2020; Mialkovska *et al.*, 2023a; Mialkovska *et al.*, 2023b; Mialkovska *et al.*, 2024; Sadchenko, 2023). Some studies also highlight the specific aspects of this issue (Voronkova, Nikitenko and Vasylichuk, 2022; Zelenenko, 2024). At the same time, Tomakh (2023) and Firich (2024) emphasize the necessity of monitoring and controlling the dynamics of public trust in media resources, highlighting the specific aspects of this issue. Moreover, Gregory (2020), Smith (2020), and Lim (2022) analyze the potential of PR technologies as modern models of practical influence in shaping societal trends within the context of sustainable development. However, many scholarly contributions highlight the research gaps in this context which leaves room for further in-depth scientific exploration in developing modern communication tools in media and PR aimed at achieving Sustainable Development Goals in the light of the current dynamics of societal processes.

Troise and Camilleri (2021) analyze the potential of social networks to promote ideas and aspirations through media and PR content. The authors explore the relevance of the process to marketing strategies and emphasize the necessity of carefully coordinating various digital tools to ensure effective audience engagement. Meanwhile, Wielki (2020) developed the concept of influencer marketing, which, when combined with PR technologies, is capable of effectively promoting the ideas of sustainable development. The study underscores the potential of digital influencers as sources of social ideas that are readily accepted and practically implemented across various social strata. Borah *et al* (2022) examine the relationship between the use of social media and innovative opportunities for enhancing the stable integration of sustainable development principles into public life. The scholars argue that, in addition to showing the impact of social media on the stable effectiveness of sustainable development, the results demonstrate the mediating role of innovative opportunities provided by media and PR in shaping digital

leadership. Balogun *et al.* (2020) argue that digitalization influences the socio-economic dynamics of communities, using innovative high-tech tools to transform traditional approaches to work, including media and PR. The authors anticipate that digitalization will further affect urban areas in the future, transforming workplaces and lifestyles, with far-reaching consequences on the resilience of cities and their ability to adapt. The researchers reveal the potential of digital PR and media technologies to support more effective systems of early warning and emergency response, improve food and water security, enhance energy infrastructure efficiency, engage citizens, and implement adaptation measures to minimize climate hazard impacts.

Ulucak, Danish and Khan (2020), while analyzing the connections between the development of information and communication technologies and carbon emissions through globalization channels, specifically focus on media resources that serve as a means of targeted influence on the public. The authors emphasize the need to maximize the potential of media technologies in the digital space to promote sustainability, particularly in engaging the younger, digital-native generation. Kulkov *et al.* (2024) further develop this issue in the context of sustainability driven by artificial intelligence. The authors explore the contribution of artificial intelligence to sustainability, focusing on three key areas: organizational, technical, and technological aspects. The researchers recommend incorporating artificial intelligence into media and PR efforts related to sustainable development in terms of strategic alignment, infrastructural development, change management, and continuous improvement. By addressing these key areas, organizations can harness the potential of artificial intelligence to achieve positive social, environmental, and economic outcomes, thereby contributing to Sustainable Development Goals. Theoretical and methodological principles for using media and PR technologies are presented in works such as Bilovodska (2021), who studied the formation and implementation of a media company's marketing strategy in the digital environment by stages and evaluation indicators; Oklander, Oklander and Yashkina (2017), who identified the stages of development, features, and characteristics of digital marketing; Petropavlovska, Lysak and Malakhovska (2018), who researched social media as a tool for managing consumer loyalty; Savytska (2017), who outlined the stages of planning a brand's social media presence strategy; and Semenenko (2021), who revealed the specifics of using online promotion tools.

Results and Discussion

The effect of media and PR technologies in promoting the principles of sustainable development

Social processes of societal progress fuel the active development of media and PR resources, which are currently positioned as socially essential formations. The study of these resources is generally relevant from the perspective of social influence, as it allows us to understand how media and PR technologies' methods and strategies impact the consumer, where pragmatics are implemented through virtually all available linguistic means and all possible public relations. The realities of irreversible and progressive climate change, increasing anthropogenic pressure on the environment, and the depletion of natural resources require prioritizing an environmental approach in innovative solutions.

These technologies' effectiveness in promoting sustainable development principles is achieved through the appropriate and practical synergy of several patterns and phenomena (Vasylchuk, 2022; Zelenenko, 2024). Within the framework of current societal development concepts, media and PR resources are powerful tools for influencing various social groups. However, relying solely on strategic efforts focused on these resources does not guarantee success in promoting the Sustainable Development Goals (Sadchenko, 2023). Without a close connection with other elements of the management paradigm, media and PR initiatives risk ineffectiveness and could potentially lead to adverse outcomes. Modern PR can become a hub of scientific and technical information on environmentally friendly and sustainable technologies, incorporating elements of industrial greening, industrial design, climate change mitigation, and resource efficiency practices.

As an integrated communication environment, the global network provides a unique array of ways to promote sustainable development to the target audience through media and public relations. Public relations result from a reputation for understanding, engaging, supporting, and influencing societal behavioural responses and cognitive development trends (Bielousov *et al.*, 2023; Firich, 2024; Tomakh, 2023). These definitions reframe PR as a management art, involving systematic activities in disseminating information spread by stakeholders in a positive context. The primary goal is to generate interest in modern innovative opportunities that prevent ecological destruction, aimed at a harmonious synergy of energy efficiency, environmental friendliness, natural resource management, and climate culminating in the integration of sustainable development principles into the built environment.

Overall, the Internet is characterized by a mechanism similar to the actions of a crowd. Therefore, correctly directed and rapidly disseminated information can be effectively implemented in media and PR campaigns, leveraging psycho-technologies to create favourable conditions for the independent distribution of well-crafted messages. In this case, communication effectiveness is seen in finding a way to engage the most suitable target audience (Gregory, 2020; Lim, 2022; Smith, 2020). Sustainable development strategies, such as circular metabolism, climate and natural disaster resilience, clean air, clean water, clean transport, clean energy, and preservation of the cultural and natural environment.

Today, social networks engage over one-third of the world's population (Vasylchuk, 2022; Zelenenko, 2024). At the current level of societal development, the network allows for focusing influence on a particular target audience, identifying subgroups within it to create more personalised media and PR messages, and recording and noting the individual specifics of each recipient. In this context, identifying the target audience is particularly significant, as it allows for building communication in the necessary format and achieving the set goal as efficiently and quickly as possible, promoting the idea that carbon-neutral buildings, energy and transport can make modern human environment energy efficient and significantly reduce environmental impact; energy, for instance, can be extracted from liquid and solid waste; and the urban space of the future preserves and regenerates natural resources - soil cover, species diversity, tree plantations - that provide thermal comfort, reduce pollution and actively absorb carbon.

Public relations and media technologies are directly connected to public management. Professionals in this field work with the mass media, coordinate official events, and manage charitable initiatives. Internet technologies now allow information to be disseminated instantly, requiring prompt and complete control. Considering the increasing readiness of public opinion for change and the global community's openness to financially supporting environmental projects, there is a strong belief in the feasibility of transforming towards a sustainable environment. Particularly interesting directions are seen in the optimization of urban planning, the implementation of sustainable landscape principles, strict control over the quality of building materials and construction waste, and the introduction of dynamic analytical monitoring systems in the field of urban beautification.

In today's era, media and PR technologies pervade daily life: messages reach audiences through television, the Internet, social networks, and visual advertising. Emerging media and PR technologies are developing, quickly gaining popularity and becoming new PR platforms. These directions include blogs, podcasting, discussion forums, RSS feeds, search engine optimization (SEO), and endless mass media for distributing quotes, articles, and interviews (Firich, 2024; Kovtunyk *et al.*, 2023; Radchenko *et al.*, 2023; Tomakh, 2023). Media and PR professionals manage a broad spectrum of modern media mix elements, including digital and traditional technologies, targeted resources, online meetings, broadcasts, and viral videos. Constant monitoring ensures public perception remains tolerant and engaged, fostering the promotion of sustainable development. At the same time, the advantages of PR technologies as a constant communication-psychological feedback loop within the management paradigm with society allow for the creation, regulation, and maintenance of a favourable environment for promoting the Sustainable Development Goals (Hrebenuk and Okseniuk, 2024; Lelechenko, 2020).

In practice, the effectiveness of media and PR activities in promoting sustainable development principles largely depends on media intermediaries (specifically journalists who decide what to present and in what form) and on the position of media owners. These people most significantly influence the nature of the communication process. One of the key advantages of using modern media and PR technologies is that they can reach a broad audience, as most of them are highly popular among various demographic groups and potentially engage people in ways that traditional media cannot.

Trust in media resources in the global community

Today, the global community has a relatively low trust in media resources. The general statistics as of 2023 are shown in figure 1. According to the Edelman Trust Barometer (2023), a low (destructive) level of trust is classified as 1–49%, a medium level as 50–59%, and a high level as 60% and above. This situation reflects a general decline in trust towards media outlets due to their increasing tendency to use PR and media resources primarily for advertising or, worse, manipulative purposes (Dynamics of trust in social institutions in 2021–2023, 2023). Notably, this trend is primarily characteristic of developed democratic countries. Meanwhile, traditionally, high levels of trust in media are maintained in countries with authoritarian policies and a traditional emphasis on the pro-government position.

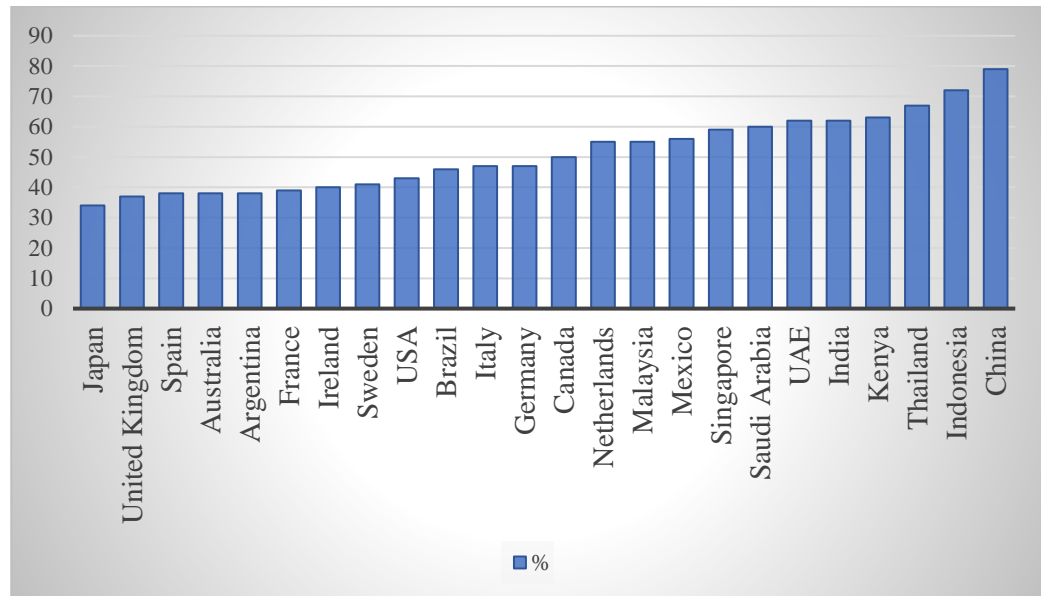


Figure 1: Level of Public Trust in Media Resources, in % for 2023 (Edelman Trust Barometer, 2023)

The trend depicted in figure 1 is mirrored in the dynamics of Ukrainian citizens' trust in media resources. Figure 2 highlights the necessity of reforming approaches to using media and PR technologies. In the context of Ukrainian realities, the situation is complicated by public outcry due to wartime tensions. The media industry's lack of credibility is just one element of a larger narrative of deep polarization. However, during the post-war recovery period, media and PR technologies should emerge as powerful tools for influencing societal consciousness in prioritising sustainable development principles (Gregory, 2020; Lim, 2022; Smith, 2020).

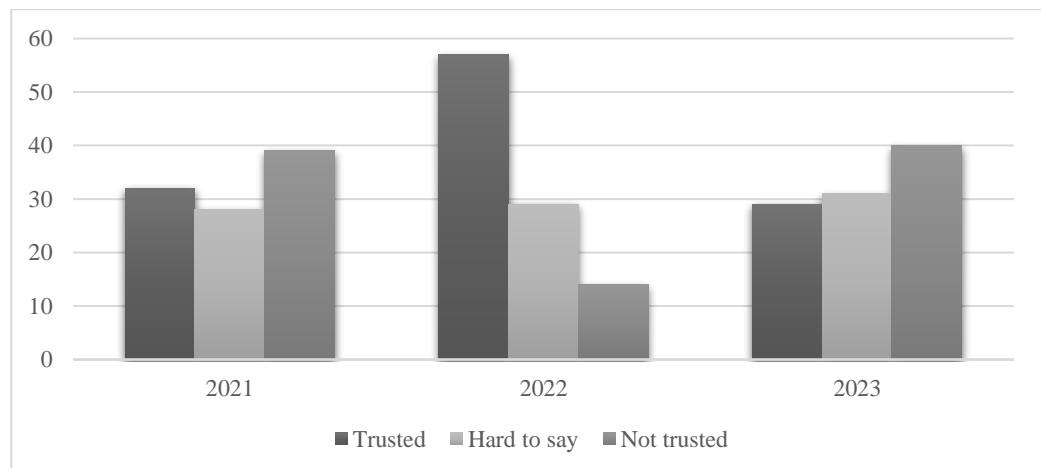


Figure 2. Dynamics of the Level of Trust of Ukrainian Society in Media Resources, % for 2020–2023 (Edelman Trust Barometer, 2023)

By leveraging the potential of media and PR strategies, media organisations can drive sustainable development and foster social change. They strategies serve as effective tools

for altering society's attitudes toward specific concepts and shaping corresponding behavioural responses. PR and media amplify the relevance and demand for sustainable development issues, transforming societal perceptions of sustainability and motivating practical actions (Hrebenuk and Okseniuk, 2024; Lelechenko, 2020).

Strategies and methods of using media and PR technologies to promote global principles of sustainable development

Today, several strategies and methods are gaining traction for using media and PR technologies to popularise global principles of sustainable development. Among them, the following are noteworthy:

- 1) Gamified simulations explicitly designed to equip users with knowledge and skills on a particular issue (for example, the simulation case game “Climate Interactive”, which allows users to study the impact of various actions and political decisions on climate dynamics; and the severe simulation game “World Without Oil”, which encourages the development and implementation of sustainable solutions in the energy sector);
- 2) Campaigns and challenges focused on popularising sustainable behavioural decisions within society (for example, the “The Recycle Rally” campaign focused on waste recycling issues, or “The Clean Seas Challenge”, which engages the popular social network Instagram to encourage the reduction of plastic waste pollution);
- 3) Virtual reality (VR) and augmented reality (AR) technology tools (for example, the virtual experience “Project Drawdown VR” on various climate solutions, or “WWF Free Rivers AR” to demonstrate the impact of pollution on river ecosystems using augmented reality technologies);
- 4) Mobile apps for actively promoting the principles of sustainable development (for example, the game “Big Little Farmer”, which teaches the practice of sustainable agriculture, or “Eco” – a gamified app focused on building a sustainable society);
- 5) Interactive installations, exhibitions, and other targeted events that engage the public in the practical implementation of the concept of sustainable development (for example, the interactive exhibition “The Ocean Clean Up”, which vividly demonstrates the consequences of plastic waste pollution) (Lim, 2022; Smith, 2020);
- 6) Interactive educational technologies for integrating the concept of sustainable development into education and self-learning (for example, the UN program “Planet Blue” focused on the regeneration and protection of natural water resources by the principles of sustainable development);
- 7) Targeted online resources containing informative content on the experience of promoting the principles of sustainable development (for example, interactive web resources “The Water Footprint Calculator”, “The Sustainable Development Goals Hub” (ElAlfy, Darwish and Weber, 2020);
- 8) Online events, seminars, and conferences to form the theoretical and practical basis and interactive experience in the context of promoting the implementation of the concept of sustainable development (for example, the meeting of world community leaders within the framework of the annual

conference “The Virtual Island Summit” to discuss issues of sustainable development) (Gregory, 2020; Sheehy and Farneti, 2021).

Achieving the Sustainable Development Goals marks the beginning of a new era of peace and sustainability. It is precisely free, independent, and pluralistic media that allows citizens to take an active part in public life. They can reinforce people's commitment to democratic values and help cultivate a culture of respect for the rule of law, where just laws are upheld by everyone.

The approaches mentioned above utilize interactive tools to engage diverse audiences, motivating them to implement sustainability principles practically. Media and PR allow for the promotion of a wide range of topics related to climate change and greenhouse gas emissions, particularly carbon, as well as air quality monitoring and pollution control, land resources, biodiversity and green spaces, environmental services, and the demand for them. At the same time, it is advisable to consider the relevant topics in a broader context, with a rethinking of the structure and functions of the modern city, as the urban space of the future preserves and regenerates natural resources—soil cover, species diversity, and tree plantations, which provide thermal comfort, reduce pollution, and actively absorb carbon. Simultaneously, the process of reducing greenhouse gas emissions and mitigating the effects of climate change primarily involves minimizing the use of fossil fuels through the use of alternative transport and renewable energy sources, as well as an efficient system for processing problematic waste and using environmentally friendly building materials with low energy consumption. This message must be communicated effectively through the innovative capabilities of PR and media. The media also contribute to the formation of an environment of civic integration. They are both sources of knowledge and platforms for developing competencies. The media strengthen notions of inclusion, accountability, solidarity, and tolerance and counteract extremism, xenophobia, and gender discrimination. They are an important link in the interaction between democratic governance and the development of human capital. Conversely, a lack of information has unfavourable political implications and economic consequences.

Timely, reliable, and high-quality information is critical for better resource allocation and decision-making. Media are also essential for collecting, analysing, and refining indicators of Sustainable Development Goals (SDGs). The quantity, quality, and reliability of the data circulating and available to society depend to a certain extent on the structure and content of the existing media landscape.

Discussion of the issue in academic circles

The research results position media and PR technologies as innovative and promising tools for effectively promoting sustainable development. The findings of modern scholars (Lu *et al.*, 2021; Pimonenko *et al.*, 2020; Ye *et al.*, 2020) confirm that one of the most effective means of optimising the strategy for implementing the concept of sustainable development is the active use of modern interactive technologies such as virtual reality, gamification, PR projects, and social networks. As the research conclusions of Fonseca, Domingues and Dima (2020) convincingly show, in the context of promoting the principles of sustainable development, training, educational

technologies, and coaching that leverage virtual reality technologies gain particular significance, with augmented reality applications prioritised for user experience.

Certain researchers, such as Ruggerio (2021) and Servaes (2022), who study the potential of media resources in integrating sustainable development principles into social life, emphasise the need to anticipate related challenges and risks. The researchers' conclusions focus on the opportunities modern media technologies provide for the concepts of sustainable development through practical activities, broad audience engagement, and the stimulation of genuine interest in positive changes. Tkáčová *et al.* (2021) highlight specific prerequisites for the effective implementation of media and PR technologies based on an integrated approach, emphasising the necessity of having a relevant resource base, society's readiness for change, and a high level of public trust. Additionally, de Luca *et al.* (2022), and Jie and Jiahui (2023) suggest using the potential of VR tools in the form of training technologies within professional education, revealing their functionality for enhancing the practical significance of the principles of sustainable development for any profession. The conclusions of the above studies are consistent with each other in the context of the underestimated potential of PR and media technologies for sustainable growth and influence on the consciousness of society, in particular, young people.

Some modern authors (Čábelková, Smutka and Strielkowski, 2022; Ozcan *et al.*, 2021) position the monitoring of public trust in media and PR resources as an essential indicator of the effectiveness of the applied technologies. Researchers have conducted a series of studies examining the use of mixed reality, social networks, interactive formats, and communication tools to promote the principles of sustainable development. The research findings indicate that the current period of societal development necessitates a rethinking of the functionality of media and PR strategies, which should acquire characteristics of competence, reliability, and non-commercial focus and foster unity in society regarding the principles of sustainable development. In the context of Ukraine, amid active progress towards European integration, particular attention must be given to embedding the principles of sustainable growth strategies into the public consciousness. At the same time, the situation is accompanied by specific challenges that Ukraine faces in integrating innovative media and PR technologies to achieve this goal. Unlike other global contexts where these technologies are successfully implemented, Ukraine is characterised by a relatively low level of environmental awareness. This issue primarily affects the younger generation and the business sector. While the situation with youth can be largely addressed through optimising the educational process, the business sector remains reluctant to invest in this area of research, as it does not fully comprehend the importance of forward-looking investments in sustainable development.

While not diminishing the significant scientific achievements in the studied field, the issue of practically adapting the latest models and tactics of media and PR solutions for promoting the principles of sustainable development to the realities of the Ukrainian social environment remains unresolved. Modelling modern trends in societal development should contribute to forming realistic perceptions, greater involvement and motivation, and deeper cognitive processing of information regarding urgent global issues.

Conclusion

The essence of media and PR resources as a sphere of public communication is best realised within the global network. The Internet is positioned as a relatively new environment for communication and mass information, requiring the development of new media and PR technologies and offering new opportunities for their advancement due to its interactivity, global reach, immediacy, and decentralised nature.

The research substantiated that modern media and PR technologies possess significant potential in implementing global principles of sustainable development. In particular, interactive exhibitions and meetings, globalised online conferences, gamification, and targeted use of rapidly developing social networks are seen as promising.

Given the range of challenges currently facing the global community in implementing the strategy for sustainable development, it becomes evident that media and PR technologies serve as essential tools for addressing these issues. Their ability to stimulate increased interest and practical engagement from society regarding the issues intensifies societal activity and awareness. Moreover, creating interactive experiences can educate and motivate society to integrate sustainable development principles into every day and professional life.

Further research within this area should be focused on the possibilities of virtual and augmented reality, creating engaging, practical applications to support sustainable development principles. Specifically, there is considerable scientific interest in the effectiveness of gamification mechanisms in promoting sustainable views and behavioural patterns, as well as the potential for collaboration between sustainable development organisations and media companies.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>	<i>Author 6</i>	<i>Author 7</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No	Yes	No
Collected the data	Yes	No	Yes	No	No	Yes	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No	No	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	No	Yes	No	No	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

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The Role of Communication in Developing Environmental Awareness and Concern for Environmental Issues

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Abstract

Communication is a very critical field of study in today's society as environmental challenges increase globally, the effect of communication on the development of environmental awareness and increasing public attention to environmental issues in society is becoming central to study especially in light of increasing environmental challenges. This paper examines how various communication tactics can create environmental literacy, raise awareness, promote concern for environmental issues, and encourage participation in sustainable actions to address environmental problems. We analysed the existing communication theories and conducted empirical studies through surveys and experiments. According to the findings, digital platforms, including the internet, social media and others, reach out to the greatest numbers of users (65 per cent more users engaged by 2023 than 2021), while traditional media such as television and print drew in percentages of declining by 52 per cent and 60 per cent, respectively. Together, these results reinforce the importance of using modern approaches to communication to cover diverse audience groups. More and more people were using digital communication, which led to a significant drop in the same in traditional media like television and print. With these findings, relevant data must be duly taken into account to think of digital strategies that involve different audiences and promote sustainable behaviour. Our findings provide insight into the most effective communication approaches for promoting environmental awareness and addressing environmental issues. It has practical significance for developing more effective education strategies and encouraging public participation. This research presents practical recommendations for environmental programs and media campaigns, outlining tailored communication approaches.

Keywords

Agricultural animals; Hunting animals; Breeding; Genetics; Ecology in agriculture

Introduction

Environmental issues are becoming more pressing nowadays, requiring collective efforts and a shift in societal thinking to reduce pollution levels, preserve biodiversity, and combat climate change. Effective communication is crucial in raising environmental awareness and addressing these problems. The process of raising awareness relies on several critical factors, including communication as an educational tool, conscious consumption of information, stimulating discussions and exchanging opinions, engaging target audiences, and enhancing environmental literacy. Information exchange plays a crucial role in shaping opinions and attitudes in today's information society. Raising public awareness as well as engaging the people themselves are all made easier by communication. Modern media (traditional as well as social networks) allows transparent information sharing that leads to sustainable behaviour and better decision-making.

Media and social networks play a significant role in communicating environmental issues. Through social media, for instance, the sharing of knowledge on environmental matters is now more engaging. Various social networks also provide an ongoing flow of ideas and insights sharing and actively engage the public, as individuals are free to directly support various environmental initiatives (Antonopoulos *et al.*, 2019; Bramwell-Lalor *et al.*, 2020; Chung *et al.*, 2020; Christensen and Nilsson, 2018; Harris, 2017, 2018; Lester, 2015; Waititu, 2021; William, 2022). This digital engagement is further differentiated from traditional media, which, if useful in delivering large-scale messages, does not complement the formation of constructive environmental awareness with the latter more participative dimensions deemed essential in the process.

Environmental challenges in today's world are taking up many vessels of environmentalists, demanding not only countrywide effort but also local effort. It is imperative to raise environmental awareness in Ukraine, because of the acute problems in their environmental areas, for example, industrial regions and air pollution; poor waste and natural resources (Shevchenko *et al.*, 2021). For instance, the State Statistical Service of Ukraine reports that the rate of waste recycling is still very low and aggravates an environmental crisis. In this environment, effective communication is a key intervention to increase public perception of environmental challenges and prepare society to act. Growing attention to environmental issues has increased, but most Ukrainians know too little and don't actively participate in resolving them. While most of the research in this field addresses global or specific case studies only and fails to meet local needs and the peculiarities of communication in the Ukrainian context, it does not. Especially, there is little research on how modern digital platforms, including social media, can draw in varying social groups including youth, rural communities and vulnerable people to environmentally responsible behaviour (Vyhovskiy, Vyhovska and Vyhovskiy, 2019; William, 2022). In addition, cultural and socio-economic factors are shown to shape public attitudes about environmental issues largely in Ukraine (Christensen and Nilsson, 2018; Dziubenko and Andreieva, 2022), and therefore communication strategies need to reflect specific audiences.

In light of the above research gaps, the purpose of this research is to examine the influence of communication on the establishment of environmental awareness, as well as direct viewer attention to a range of environmental issues in Ukraine. Gaps in

knowledge about the effectiveness of various communication strategies across different social and economic conditionalities are addressed, particularly. For example, this study looks at which types of messages and what kinds of sources of information result in which demographic groups are more aware of the hazards. The study also tries to provide practical guidelines for the development of targeted educational programs, media campaigns, and other activities in striving for environmental literacy and, thereby, involving citizens' efforts toward solving environmental problems. These recommendations fill gaps in current knowledge and contribute to socio-economically sustainable development in Ukraine.

Literature Review

Shkolnik and Iholkin (2020), and Bukanov (2020) suggest an initial analysis of tools and conditions for enhancing pro-environmental behaviour and point out the relevance of taking into account cultural backgrounds and social policies for promoting pro-environmental behaviour. Specifically, this is important on the ground in Ukraine, whose industrial heritage and socio-economic disparities present unique challenges. According to Batsurovska and Hruban (2023), the socio-economic costs of the degradation of the environment in Ukraine are important and must be overcome by sustainable policy orientations, which help us to solve the various problems with pollution, wasting raw materials and management of wastes. Among the recent studies, education, social aspects and civil society are shown to enhance environmental education. According to Anatska (2018) and Vyhovskyi, Vyhovska and Vyhovskyi (2019), the tailored educational curricula have to be enriched with a certain level of environmental literacy in places like Ukraine starting to develop in this sphere. We show that social factors, like community engagement and peer pressure, are powerful motivation factors for sustainable behaviour (Bida *et al.*, 2021; Dziundziuk and Yefimov, 2020; Patlaichuk, Stupak and Zholobenko, 2021). Identifying successful cases of mobilization of public action to environmental issues in the Ukrainian context, Byrkovych, Palamarchuk and Byrkovych (2022), and Dziubenko and Andreieva (2022) look at cases of grassroots civil society initiatives through youth environmental movements and local community projects.

Along with technological advancements, there exists a very important aspect of environmental education. Anwar *et al.* (2019) and Mliless *et al.* (2024) demonstrate how early childhood education with digital tools can better enrol pupils in sustainability awareness. In Ukraine, where access to modern resources and education is not equal across regions for Ukrainians, innovations in augmented reality and Web 2.0 tools may well bring great benefits (Açikgöl Firat and Köksal, 2019; Ducasse, 2019). Such tools, according to Geng and He (2021), enhance public satisfaction with environmental governance which is a crucial element of trust and the formation of citizen participation in Ukrainian society.

In comparison, participatory learning techniques and interactive technologies are found to have the potential to increase environmental awareness. For instance, Prandi *et al.* (2021) challenge the use of interactive infographics during teacher training, whereas Torabi *et al.* (2022) suggest participatory methods such as the jigsaw technique to promote environmental values. These approaches could make an enormous difference in

the integration of environmental topics in teachers' teaching in Ukraine, where teachers' training programs are often underfunded. Varela-Candamio *et al.* (2018) and Yarovenko and Ploshchenko (2023) strengthen this argument as case evidence of increasing workplace sustainability programs, all the more so that Ukraine is modernizing its industries and becoming aligned with European environmental standards. Raising environmental awareness also poses plenty of opportunities through entertainment media. As per the opinion of Larreina-Morales and Gunella (2023), it is a recipient of environmental education. As is the case in Ukraine, where the involvement of youth is particularly high in digital engagement, and where gamified approaches and social media campaigns have a particularly good potential, digital engagement may be enhanced by the stimulation of environmental responsibility (Christensen and Nilsson, 2018). Specifically, Bhanye and Maisiri (2023) suggest that digital media is crucial for fashioning corruption in the public sphere as a communal responsibility towards the environment, a defining about-face in Ukraine's public mobilization.

Making a localized approach to environmental challenges in Ukraine this review underscores a strong need. While global insights are valuable frameworks, these insights are culturally and socioeconomically unique to Ukraine and thus require local communication strategies. Critical steps toward developing an environmentally conscious Ukraine include developing education programs, implementing digital tools and includes leveraging civil society engagement.

Methodology

This research utilizes both the qualitative and quantitative methods of data collection to analyze the effects of communication on environmental awareness. The subsequent segments highlight the sampling approach, data acquisition techniques, and methods of maintaining dependability and credibility.

Sampling Process

This finds out how these communication sources affect the environmental awareness of people. Over 3 years (from 2021 to 2023), we surveyed 1,143 people. Participants were drawn from five key sectors: Ministries, campuses, companies, government agencies, hospitals and clinics, and the general public. The sample was once fractionated so they would reflect a diversity among demographic divisions. Age groups were 18–25 years, 26–35 years, 36–45 years, 46–55 years, and >55 years, while education was secondary to postgraduate. Education, healthcare, information technology, finance and public service sectors were covered by the occupations. From this comprehensive approach, the findings used several perspectives which reflected diverse points of view, giving the study credibility and generalizability.

Evaluation and Participant Selection

Participants were selected based on clear inclusion criteria: Previous involvement in eco-initiatives and expressed motivation to globally participate in sustainability-focused discussion; residency in Ukraine, both in urban and rural areas. We recruited both online

and through direct outreach with environmental groups and community groups to minimize selection bias.

To ensure that people participated, respondents filled out a background questionnaire, describing the environment they were involved with (Appendix 1). Among the 1,143 participants, 60% reported having regular exposure to environmental campaigns or media, and 40% worked in a general audience whose level of familiarity with environmental things does vary. It included the more informed ones and the less so, with a humble base on which to begin analysis. As a starting point for applying our project in the future, this study acknowledges that certain limitations of online recruitment may mean that those who aren't using the site will have an advantage over those who aren't digitally literate, with access to the internet. These findings need to be integrated with offline methods of data collection such as local community events or printed outreach to improve the representativeness of the findings.

Data Collection

Data collection was done over three years (2021-2023) to capture trends within the identified themes. This paper adopted an online questionnaire, follow-up face-to-face interviews, and video conferencing to allow participants across geographical centres and limitations like COVID-19. The surveys consisted of closed-ended questions as well as Likert-scale items to examine participants' choice of environmental information, how often they consume the information, and the extent to which participants believed communication influenced their environmental consciousness.

Apart from surveys, 10 interviews with purposefully selected professionals in the field of environmental communication, media and education were conducted. These people were chosen in terms of their profession, experience period, and their participation in environmental activities. The interview questions ranged from 10-20 per participant and the whole interview lasted from 45 minutes to one hour. This qualitative component offered critical findings of the approaches adopted by professionals in communication to improve environmental understanding among the public.

This study contains both quantitative data from surveys and qualitative data from expert interviews but adds weight towards qualitative analysis to further understand the context surrounding the findings. Quantitative data can tell us a lot about trends in environmental awareness, but it's not the best approach to delve into the complexity of individual perspectives and the subtle nature of what drives behaviour. The interviews with the experts were therefore carefully analyzed to identify underlying themes and contextual insights about what may not emerge in the survey data alone. Thus, by integrating these qualitative findings, the study attempts to provide a more comprehensive analysis of the complex layered factors which influence environmental awareness. The combination of the two gives a richer discussion and alleviates the chance that a reliance on quantitative data will overtake differing views.

Data Management and Quality Assurance

To establish the quantitative credibility, statistical analysis was run in SPSS (version 26) to look for patterns and correlations between environmental awareness and

communication strategies. Preference for information sources was explored using cohort comparisons over three years (2021–2023). For example, the analysis found that internet-based information consumption increased by 65 per cent compared to traditional media. The depth and reliability of these findings were buttressed by these statistical results. Thematic analysis of data collected from the expert interviews using NVivo 12. The process involved several key steps: Repetitively reading and transcribing the data, (1) familiarization with data, (2) solving codes of data segments that matter to communication strategies and environmental awareness, (3) finding patterns and themes in codes, (4) review and refine the themes, and (5) finalizing defining and labelling the final themes to bring out significant insights. It also brought forth important properties of existing environmental communication strategies, such as the leading role of social media and digital media in environmental awareness, and they served as the basis for the study's recommendations. Through a combination of quantitative and qualitative methods, the study complemented validity with transparency and ensured an understanding of the effect of communication strategies on environmental awareness.

Reliability and Validity

To increase credibility, an isomorphic approach to data collection and analysis was upheld throughout the study. Data was collected through self-completion questionnaires and interviews were conducted by professional Interviewers using structured questionnaires. Validity was maintained by following the triangulation technique that integrated survey results with analyzer interviews to consider the findings. In addition, to reduce selection bias, the survey instrument was pre-tested among a pilot sample just before the actual data collection phase aimed at finding out potential sources of measurement biases in the questions.

This comprehensive sampling method, participant identification, data gathering and data analysis strengthens the methodological framework of our study, which forms the foundation for assessing the efficacy of communication in promoting environmentalism.

Results

Environmental problems are becoming increasingly acute and their resolution is becoming more urgent for humanity. Reducing pollution, preserving biodiversity, and combating climate change requires collective efforts and a change in society's thinking. Effective communication is one of the key factors contributing to the formation of environmental awareness and drawing attention to environmental issues. Drawing attention to environmental problems, as a result of forming environmental consciousness, is based on leading aspects such as communication as a tool of enlightenment, conscious consumption of information, stimulating discussions and exchange of opinions, engaging target audiences, as well as education and increasing ecological literacy (Figure 1).

Communication as a tool for education

The results of the survey are presented in a histogram (Figure 2). Figure 2 presents an overview of people's channels to receive information on environmental issues. Results

revealed that the Internet and television are the primary sources of information, accounting for 86% of the total volume. The dominance of the internet and television may be associated with their accessibility, ease of use, and wide range of information. The growing popularity of online information sources may explain the decrease in the popularity of printed media. The limited availability of educational programs and events may contribute to low participation rates.

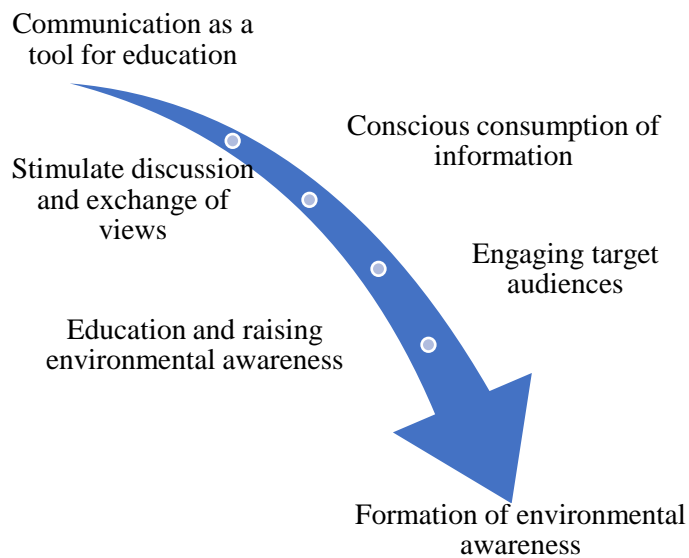
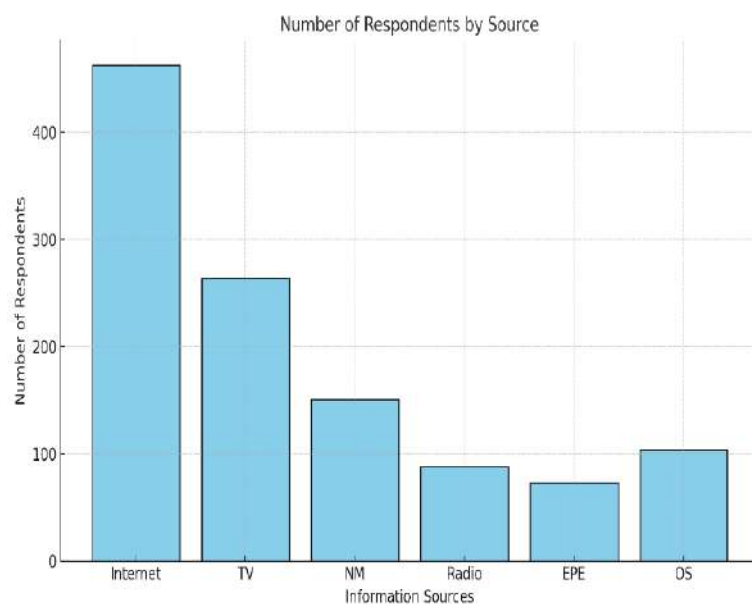
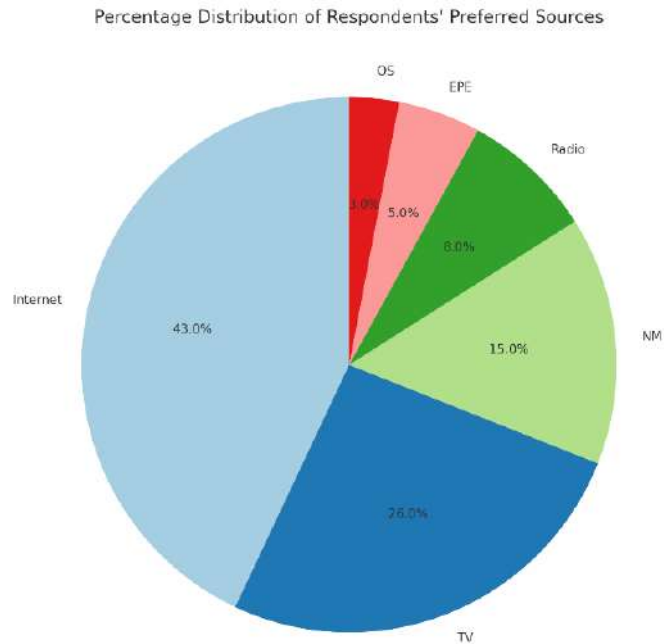


Figure 1: The process of forming environmental awareness



(a)



(b)

Figure 2: Sources through which people receive information on environmental issues in (a) quantitative, and (b) percentage terms. (Internet, TV, NM = Newspapers and Magazines, Radio, EPE = Educational Programmes and Events, OS = Other Sources)

Results of the survey among individuals aged 18-45 describe their preferences for information sources over time (Figure 3).

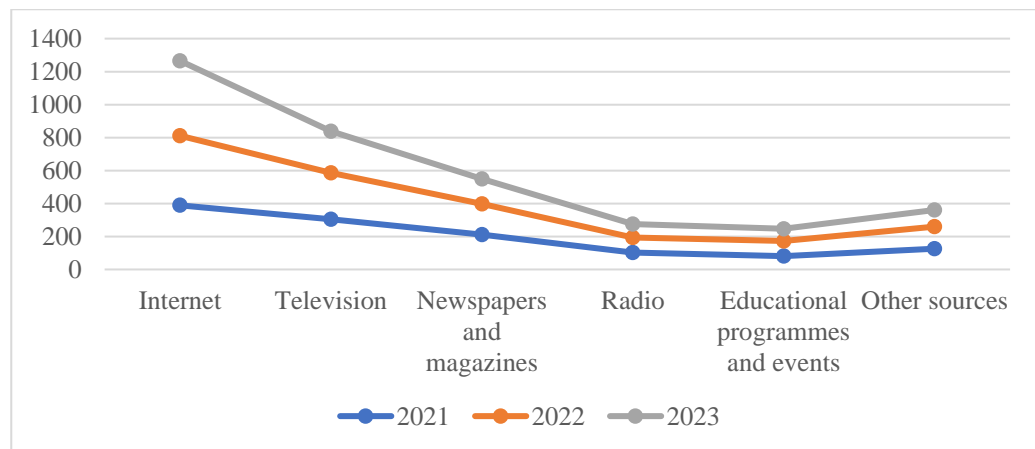


Figure 3: Quantitative dynamics of studying the impact on the formation of environmental awareness and drawing attention to environmental problems for the period from 2021 to 2023

Conscious consumption of information

Below are the statistics on participants' preferences for information sources.

Table 1: Heatmap of Information Source Preferences Based on Respondents' Ratings (2021–2023)

<i>Information Source</i>	<i>5 Points (%)</i>	<i>4 Points (%)</i>	<i>3 Points (%)</i>	<i>2 Points (%)</i>	<i>1 Point (%)</i>
Internet	32	25	20	15	8
Television	18	22	25	20	15
Newspapers and Magazines	12	15	18	25	30
Radio	8	10	15	20	47
Educational Programmes/Events	10	15	20	30	25
Other Sources	15	20	25	25	15

The data analysis reveals that the Internet is the most popular source of information about environmental issues among respondents. 57% of respondents rated the frequency of receiving environmental information online at levels 4 and 5, indicating its significance in dissemination. Notably, only 8% of respondents rated the internet as a level 1 source of information on environmental issues, indicating its widespread use in this field. Television is the second most popular source of information about environmental issues, with the highest significance for respondents at level 3 (25%). However, the percentage of those who rate it at levels 4 and 5 decreases to 40%, indicating less pronounced activity in obtaining environmental information through television compared to the internet. Newspapers and magazines have the most rating discrepancy among respondents as a source of information about environmental issues. While 40% of respondents rated the frequency of receiving information through newspapers and magazines at levels 4 and 5, 55% rated it at levels 1 and 2, indicating its relative unpopularity among some respondents. The radio was rated as the least popular source of information about environmental issues among respondents. A total of 62% of respondents rated the frequency of receiving information through the radio at levels 1 and 2, indicating its relative unpopularity in this field.

Educational programs and events about environmental issues are moderately popular among respondents, with approximately 55% rating them at levels 3, 4, and 5, indicating their significance in disseminating environmental information. Other sources of information about environmental issues are also moderately popular. Around 55% of the respondents rated these sources at levels 3, 4, and 5, indicating their significance in disseminating environmental information.

Therefore, analysing this data enables us to identify the key sources of information about environmental issues among the population and their perception based on the level of activity in obtaining information.

Stimulate discussion and exchange of views

Table 2: Tools to stimulate discussions and exchange of views on the impact of communication on environmental awareness and drawing attention to environmental issues

<i>Tool</i>	<i>Features</i>
Organising group discussions	Regular group discussions can be an effective way to stimulate the exchange of views and ideas. They can include debates on different aspects of environmental issues and discussions on the role of communication in addressing them.
Conducting seminars and workshops	Organising specialised seminars and workshops on communication and the environment, which can include theoretical and practical classes, will help to capture students' attention and interest in the topic.
Using online platforms	Creating online forums or specialised communities on social media dedicated to environmental communication can facilitate an active exchange of opinions and experiences between participants.
Organising debates	Holding debates on various aspects of environmental issues and the role of communication in solving them will help stimulate critical thinking and develop students' argumentation skills.
Using case studies	Analysing specific environmental and communication cases can be valuable for understanding real-world problems and solutions.
Conducting research projects	Offering students the opportunity to research environmental communication issues will help them dive deeper into the topic and develop their skills in analysing and evaluating information independently.

Source: Anatska, 2018; Dziubenko and Andreieva, 2022; Vyhovskyi, Vyhovska and Vyhovskyi, 2019; Açikgöl-Firat and Köksal, 2019

It is crucial to create an appropriate atmosphere for an open exchange of ideas, respect for different points of view and support for constructive dialogue.

Engaging target audiences

Communication plays a crucial role in engaging different target audiences in environmental initiatives. Well-formulated and targeted communication campaigns can attract the general population's attention and specific groups, such as students, business communities or government agencies. Engaging target audiences in learning about the impact of communication on shaping environmental awareness and drawing attention to environmental issues can be achieved in a variety of ways (Table 3):

Table 3: Tools for engaging target audiences in studying the impact of communication on environmental awareness and drawing attention to environmental issues

<i>Tools</i>	<i>Features</i>
Personalised approach:	Understanding the interests, needs, and characteristics of the target audience allows for developing content and communication strategies that will be most attractive and meaningful to this group.
Using various formats:	Various content formats, such as videos, articles, webinars, and games, help engage different audiences and ensure maximum accessibility of information.
Interaction with communities:	Collaboration with environmental organisations, local communities, universities, and other institutions helps reach a broad audience and build a strong network of supporters and activists.
Using social media and online platforms:	An active presence on social media and online platforms helps to reach young people and other target groups and ensures interactive interaction and feedback.
Organising events and campaigns:	Holding events such as festivals, conferences, and greening campaigns contributes to drawing attention to environmental issues and raising environmental awareness.
Educational programmes and training:	Educational programmes and training on environmental issues and communication help broaden the audience's horizons and provide them with the necessary knowledge and skills to actively solve environmental problems.

Source: Vyhovskyi, Vyhovska and Vyhovskyi, 2019; Açıkgül-Firat and Köksal, 2019; (Dziubenko and Andreieva, 2022; Bida *et al.*, 2021)

In the development and implementation of communication strategies, the specifics of the target audience, its age, socio-cultural context, level of education, and other factors must be considered.

Education and raising environmental awareness

Communication is also a tool for education and raising environmental awareness. Through information campaigns and educational programmes, people can learn about sustainable development principles, energy conservation, environmental care and other aspects of environmental responsibility. Over the past five years, there has been a steady increase in the number of educational events held on environmental literacy, reflecting growing public interest and demand for knowledge in this area (Anatska, 2018; Dziubenko and Andreieva, 2022; Yarovenko and Ploshchenko, 2023). It indicates increased public interest and a growing demand for educational programmes. Environmental awareness is a complex and multifactorial concept that depends on various aspects. Some of the critical factors that can influence the formation of environmental awareness are as follows.

Education and knowledge: "Previous research has found that education, and accessibility to information, have a dramatic effect on the ability to understand and recognize environmental issues" (Anatska, 2018; Vyhovskyi, Vyhovska and Vyhovskyi, 2019).

Cultural and social values: Dziubenko and Andreieva (2022) state that 'Cultural norms and societal values are very important for implementing environmental awareness with sustainable behaviours'. Experience and interaction with the environment: "Interaction with nature and environment is directly gained by the individuals, where they had to take experience towards environmental challenge like pollution increases individual awareness and motivation to know more about being environmentally memorable" (Bida *et al.*, 2021).

Communication and information sources: The tools for enhancing public environmental awareness include 'media channels, educational programs, public events' (Açikgöl-Firat and Köksal, 2019; Ducasse, 2020).

Policy and legislation: Measures of political and legislative frameworks are important for stimulating emerging public dialogue and creating the groundwork for environmentally responsible behaviour (Yarovenko and Ploshchenko, 2023; Christensen and Nilsson, 2018).

Discussion

The results from this study show that targeted environmental awareness communication strategies have a large effect on environmental awareness. It was found that the use of digital platforms like social media and internet forums increased engagement by 65 per cent more than traditional media over three years. In addition, debate and community events were found to encourage higher levels of public participation in environmental activities. The results of this study align with past research which stresses the significance of bespoke communication for the engagement of differing demographics (Anatska, 2018; Dziubenko and Andreieva, 2022). However, the study poses certain limitations. Though the data spanned a wide swath of different regions and groups, we did not fully explore the cultural and socio-economic contexts that could involve shaping how people see things. Cultural norms and community-specific values play a large role in determining environmental behaviour (Christensen and Nilsson, 2018). The next steps are to further study these points to make these more generalizable and more inclusive communication strategies. Notably, external validity requires more diverse sampling (e.g., of the population) for example, with a larger sample of poor and/or rural populations. As suggested by Vyhovskyi, Vyhovska and Vyhovskyi (2019), including such populations will help future communication strategies toward addressing the needs and perspectives of all kinds of societal segments. This study focuses on the use of digital media in communicating environmental issues, but it does not go a long way in examining the viability of other novel media technologies such as mobile applications and other AI-driven platforms in increasing the success of communicating environmental problems. Technologies like mobile apps should include updates on events as they occur, such as information based on geographical location and other aspects that make users participate in monitoring the environment and acquiring more knowledge actively. The new social interfaces such as artificially intelligent chatterbots and content recommendation systems could enhance the messaging and targeting of environmental communication strategies by delivering messages that are particularly relevant to a user's profile. The next steps should not only expand the coverage and visibility of a practice, intervention or message but also increase the depth and relevance

of the engagement so that environmental communication becomes more effective and better adapted to the needs of its target audiences.

The results of this study show that the internet and social networks are the most effective means to raise awareness of the environment. This supports the findings of Chung *et al.* (2020), where social media was considered a better medium for promoting environmental education compared to media education. Concerning online media as a significant spread of environmental information, both studies stress increased control of the internet and other forms of new media, particularly among young people. The rise in Internet usage as the primary source of environmental information found in our study supports Waititu (2021), who pointed to the important role of social media as a tool to raise environmental awareness in the community of Kenya.

However, our research indicated a decrease in the viewership of television as well as the use of printed materials, supported by statistics reported by Harris (2017) and Christensen and Nilsson (2018). These authors noted that although television is used in environmental communication, its role has been gradually declining as people access more and newer forms of online media. However, Shkolnik and Iholkin (2020) still concluded that television has remained relevant in expanding the coverage to various populations in a country where internet connection is not readily available proving that the effectiveness of each channel might differ depending on geo-economic conditions.

Furthermore, we concur with Bramwell-Lalor *et al.*, (2020) about the lack of educational programs and events in raising environmental literacy since though the authors presented educative events as effective, they are limited by the ability to reach out to large numbers with considerable efforts. This is contrary to the views of Bida *et al.* (2021) who posited that properly designed educational campaigns in groups of a particular audience could serve to develop awareness of the environmental issues, especially to the students. However, the present work revealed that educational interventions can be less intense and infrequent when compared to simpler online environments. Moreover, the kind of expertise and its relation to the impact on public opinion that is described in the results of the expert interviews support the findings of William (2022). Taken together these studies indicate that only advertising-promoted campaigns are effective for modulating long-term environmental personas, especially among such opinion makers and influencers as policy and educational networks. Still, our study also showed that these campaigns have to be aware of the new environment in which people consume information, a point which was also made by Antonopoulos *et al.* (2019) where they posited that traditional expert communication must be complemented by contemporary methods of digital engagement.

Lastly, the findings of this study extend the call by Vyhovskyi, Vyhovska and Vyhovskyi (2019) and Fedoniuk *et al.* (2022) to communicate and engage target stakeholders in more personalized manners. This approach comes in handy in the establishment of principles so that any communication process conducted is as effective as is needed especially towards the cause of supposed behavioural change.

In conclusion, we reinforced the findings of several significant studies, as well as revealed the dynamic nature of environmental communication during the technological

and media consumption shifts. Future studies must go on searching the relations between traditional and new media, as well as the personal approaches towards improving the public's environmental consciousness and involvement.

These results have important implications for the design of communication strategies and educational programs to promote environmental awareness. More specifically given the results, digital platforms, especially social media, have proven to be very powerful in attracting diverse populations, which underscores the reason for putting more focus on online platforms to achieve the greatest reach and interactivity for future initiatives. Additionally, the diminished impact of traditional mass media such as television indicates the requirement of adjustment tactics associated with the changing media consumption habits of youth. These insights can inform how governments can design campaigns that use cutting-edge communication ways and how educational institutions can introduce environmental topics in the curricula through digital and interactive media. This study reflects critically on these results to provide valuable guidance to practitioners and policymakers on how to better create environmental awareness in more and more digital societies.

Conclusion

The present study underscores the importance of communication in raising the bar on environmentalism and ecological stewardship. When comparing different types of communication, we concluded that digital technologies, especially the internet and social networks, are the most efficient ways to address and involve a broad audience, and audience engagement grew by 65% from 2021 to 2023. However, the use of traditional media, which was also used to some extent in the campaign, was found to have reduced power. This paper thus shows the need to embrace contemporary and specific communications in tackling environmental concerns in society. Also, the study shows the importance of incorporating environmental literacy into curricular systems, conducting informative activities, and addressing demographic and cultural factors. It not only creates awareness but also changes the culture of sustainability and participation. Further studies should examine the possibility of increasing the effectiveness of communication through the use of advanced technologies including artificial intelligence and the use of mobile applications in promoting environmentalism.

Raising awareness of environmental issues through the formation of ecological consciousness involves several key aspects. Firstly, communication is considered a means of education, allowing for the effective dissemination of information about environmental problems and their impact on society. Secondly, conscious consumption of information plays an important role. Realising the importance of environmental issues, people actively seek and absorb information about them. The third aspect of stimulating discussions and exchanging opinions is vital for activating public discourse on environmental issues and finding standard solutions. The fourth aspect involves engaging target audiences, which means targeting communication efforts at specific groups of people to increase their awareness and active participation in problem-solving. Finally, education and increasing ecological literacy are critical elements in forming ecological consciousness. They contribute to the development of sustainable environmental values and an understanding of the importance of ecological balance.

To develop more information on the development of ecological consciousness and on advertising the comprehension of ecological issues among the public, research can examine such dimensions as the efficiency of the instruments of communication, the part of the media technologies, the correlation between ecological consciousness and action, and of ecological consciousness for undertaking environmentally responsible behaviours. Studies conducted in these fields would be beneficial in shedding light on ecological consciousness formation processes and help in the formulation of ways and means to increase public awareness about pressing environmental concerns, to respond to important environmental concerns.

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Appendix-A

Questionnaire

1. Your age:
 - 18-25 years old
 - 26-35 years old
 - 36-45 years old
 - 46-55 years old
 - Over 55 years old

2. Your educational level:
 - Secondary education
 - Higher education (bachelor's degree)
 - Higher education (master's degree and above)
 - Other

3. Your professional field:
 - Education and science
 - Medicine and Healthcare
 - Information technology
 - Finance and business
 - Industry and manufacturing
 - Public service
 - Other

4. Which sources of information about environmental issues do you prefer?
 - Television
 - Internet (websites, social networks)
 - Newspapers and magazines
 - Radio
 - Educational programmes and events
 - Other

To what extent do you consider yourself environmentally literate? (on a scale from 1 to 5, where 1 – not at all literate, 5 – very literate)

Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	Yes	Yes	Yes	Yes
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	No	Yes	No
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes
Supervision	No	Yes	No	No	No
Project Administration	No	No	Yes	No	No
Funding Acquisition	No	No	No	No	No
Overall Contribution Proportion (%)	20	20	20	20	20

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge

The author(s) solemnly declare(s) that this research has not involved Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

Research involving Plants

The author(s) solemnly declare(s) that this research has not involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Thus, during this research the author(s) obeyed the principles of

the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children

The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

Competing Interests/Conflict of Interest

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Developing Strategies for Adapting Business Processes to Climate Change: Minimizing Risks in the Context of Global Climate Challenges

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Abstract

Extreme weather occurrences are on the rise due to the current worldwide trend of climate change. These modifications have the potential to seriously harm infrastructure, making it impossible for it to function. This article aims to create a plan for lowering risks and adjusting corporate procedures to climate change. Analysis, synthesis, induction, deduction, systemic, legal, systemic-analytical, and systemic-structural procedures were among the techniques used in the study. The study focuses on how firms may adapt to climate change, stressing the value of proactive planning and knowledge of particular climate hazards. Through the utilization of a methodical structure, the approach facilitates the incorporation of current data and adjusts to evolving socioeconomic circumstances. The results show that, especially when it comes to the ambiguity around the scope of climate change and its effects, a strategy for adjusting business operations to climate change and reducing related risks aids in determining the necessary adaptation solutions. Crucially, after putting the suggested steps into place, the adaption method developed in this study may be successfully incorporated into enterprise management procedures, providing qualitative benefits in improving the stability of certain business processes. The study emphasizes that one essential feature of corporate organizations is flexibility. Thus, they must align with their entrepreneurial objectives and have the flexibility to quickly adjust to shifting external circumstances to guarantee their efficient operation and growth. When selecting actions to carry out the change strategy for risk reduction and climate change, it is crucial to incorporate an evaluation process of the resources (finances, commodities) that are accessible as well as the resources (investments, innovations) required for the execution of the adaptation plan.

Keywords

Adaptation strategy; Climate neutral economy; Risk reduction; Green bonds; Environmental projects; Social responsibility of business

Introduction

Climate change is a significant global issue that affects the sustainable functioning of natural and economic spaces. It is important to acknowledge that the level of awareness regarding climate change and its specific adaptation challenges is limited among society and stakeholders. This is due to the uncertainty surrounding the level of temperature rise, the regulatory pathways that will be chosen by the governments, and the potential impact on the financial performance of businesses, economic sectors, and markets. As a result, it is difficult to determine how vulnerable corporate processes are to these developments. To successfully adapt their business operations to future developments, members in the economic segment have developed broad suggestions for adaptation within their industries (Ivanyuta *et al.*, 2020). Thus, extreme weather events can have significant consequences, such as the deterioration of financial assets or deteriorating working conditions for employees, which can negatively affect the economic prosperity of the country. These risks can have either direct or indirect impacts, such as directly affecting the activities of a particular enterprise or causing disruptions in markets and logistics.

Businesses are already feeling the financial and physical effects of climate change. Global operations are already being disrupted, revenues are declining, and expenses are rising due to climate change. These are a few major areas of risk (Nusu, 2023): supply chain disruption; increased expenses; reduced sales; disruption of transportation; food shortages; and regulatory risk. In the future, risk management procedures will become much more difficult if these hazards are not addressed. Simultaneously, climate risk adaptation and preparation can spur business innovation and expansion (see Figure 1). However, businesses must first clearly identify their weaknesses and develop a plan to address them. Therefore, it is becoming more and more important to establish methods for lowering risks and adjusting corporate operations to climate change.

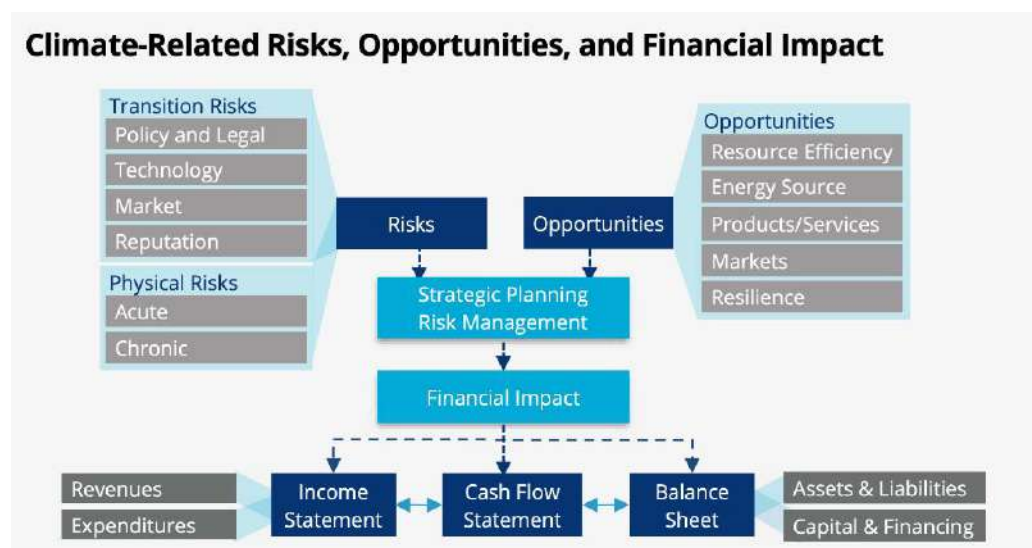


Figure 1: Climate-related risks, opportunities, and financial impact (ASUENE Inc., 2024)

In this context, the article aims to devise tactics for adjusting business processes to changing climate conditions and mitigating associated risks. The research objectives involve defining the essence of the strategy of business process adaptation to climate change and risk reduction. These objectives include the following tasks:

- 1) to characterise the key positions of the strategy of business processes adaptation to climate change and risk reduction;
- 2) to conduct a SWOT analysis of the impact of climate change to develop an adaptation strategy;
- 3) to disclose the stakeholder engagement issues on climate change and risk reduction.

Literature Review

A significant contribution to the study of the development and implementation of enterprise adaptation strategies, particularly in the context of climate change, has been made by many scholars, including Allen and Craig (2016), Alonso-Martinez *et al.* (2021), Altintas (2023), Canevari-Luzardo (2020), Gast *et al.* (2017), Gupta and Dharwal (2022), Karmaoui *et al.* (2023), Kolk (2016), Li *et al.* (2021), Linnenluecke and Griffiths (2013), Pais Seles (2018), Somanathan *et al.* (2021), Vilkaite-Vaitone *et al.* (2019), Yu *et al.* (2022), Zemigala (2021), as well as Ukrainian scientists Arefieva (2022), Basiuk (2021), Bilykh (2022), Chorna (2022), Gonchar (2023), Holych (2021), Ivaniuta, Yakushenko, Kolomiets (2022), Izaguirre, Stenek Losada, & Camus (2021), Kostetska (2020), Kruhlova (2017), Kyrylenko (2020), Nechyporenko (2022), Nikolaienko and Manyk (2022), Prots (2018), Tkachenko (2022), Yakovenko (2020), Zhukova (2021), and others.

There is a rising acknowledgement of climate change's potential and problems for businesses (Atteridge *et al.*, 2016; Goldstein *et al.*, 2019). In response to the Task Force for Climate-Related Financial Disclosures (TCFD), businesses and financial institutions have begun to assess the risks and opportunities posed by climate change in their value chains. Similarly, business models that include climate challenges in corporate governance and risk management have emerged (TCFD, 2018). To support this trend, organizations must create analytical techniques that help them better understand climate risks and actions, as well as their business and customer connections. In particular, Holych (2021) studied the issues of enterprise adaptation as a sustainable process which involves adjustment. She stated that it begins with the establishment and ends with the liquidation of a legal entity, aiming to achieve efficiency and stability in enterprise operations through strategic adaptive actions. Her study is grounded in the idea of adaptation, which enables the identification of critical success determinants, the understanding of the process of interaction between a company and its environment, and the determination of strategic growth directions.

According to Yakovenko (2020), strategy is a set of actions that, by using instruments that have been expressly created, guarantee harmony and balance in the way internal operations are carried out, helping the business to accomplish its goals. In the study, the theory of strategic management defines the key principles of strategy formation, the methods of their implementation, and the effectiveness of their implementation to achieve competitive advantage and sustainable development for the enterprise.

Kostetska (2020) defines strategic planning of company operations as a series of steps required to execute adaptation capacities for new social issues and changes in the external environment, as well as to retain market position in competitive settings. The study based on the theory of strategic planning defines the principles of forming strategic goals, analyzing the competitive environment, and choosing optimal development strategies to achieve the successful competitiveness of an enterprise. In her analysis of comprehensive enterprise strategy, Zhukova (2021) highlights the significance of evaluating several choices about all business activities inside the organization and, in turn, creating strategic sets for every phase of company operation. The theory of integrated strategic management defines methods for integrating strategic goals and analysing alternative ways to achieve success. According to Chorna's (2022) research, business processes are specific to a company. The methodical and sequential division of certain operational activities that yield the intended result reveals these processes. Based on the theory of business process management, the paper identifies methods of organizing and optimizing processes to achieve efficiency and effectiveness. Shkurenko and Chorna (2023) concentrate on the instrument for identifying development possibilities and analysing innovations, such as putting measures in place for adaptability to changes. The writers analyse tactical techniques for adapting to ensure a business's long-term existence, drawing on the idea of strategic management.

Prots (2018) highlights the significance of implementing measures to develop individual adaptation potential for each enterprise in the context of climate security issues. It is important to consider the existing and potential resources required for this purpose. Based on the theory of strategic resource management, the author emphasizes the importance of an individual approach to adaptation strategies for each enterprise. Tkachenko *et al.* (2022) characterize the risks associated with climate change, drawing on the theories of risk management and climate adaptation. They point out that while creating suitable adaptation plans, it is important to take into account the "secondary" hazards that these changes create, such as fires, floods, droughts, and other calamities. Nikolaienko *et al.* (2022) outline how climate hazards affect the transportation industry and stress how important it is to any business. They contend that all businesses and infrastructural facilities are at risk from the transportation industry. The authors examine the effects of climate hazards on the transportation industry and consider possible adaptation measures to guarantee the resilience of businesses using the theories of risk management and strategic management.

Romanko (2019) investigated the eco-legal aspects of state policy regarding climate change, using the theories of environmental and legal regulation and strategic management. The author points out that there aren't many fundamental initiatives to help businesses adjust to the new circumstances since the present legal framework to combat these changes isn't being applied locally. The approved Strategy for Environmental Security and Climate Change Adaptation until 2030 (Decree of the Cabinet of Ministers of Ukraine, 2021) lacks the necessary measures to counteract the researched changes. However, the development of adaptation strategies for business processes to climate change and risk reduction has not received adequate attention.

As Zemigala (2021) rightly claims, global warming, greenhouse gases, and climate change emerged as the three most well-explored topic issues in the business context.

However, strategic management and organizational views on the company, namely in the field of business process adaptation and modelling within the efforts of risk reduction, have not been extensively explored in studies about business strategy and climate adaptation.

Methodology

The research is based on the realism paradigm (realism research philosophy implies the idea of reality's independence of the human mind) (Dean *et al.*, 2006). According to this paradigm, reality is "real" but only imperfectly and probabilistically understandable, necessitating triangulation from several sources to fully comprehend it. Thus, the study employed the literature review method (Harris, 2019). Based on a preliminary selection of sources, based on key phrases "climate change", "climate change impact on business", "business' adaptation to climate change", "climate change risk management in business", "business process adaptation to climate change", "sustainable business", and "corporate social responsibility". The study applied elements of the grounded theory toolkit (Urquhart, 2012), namely coding and categorization. The main categories that were revealed are "adaptation", "tailored strategies", "and potential", "green bond market", "sustainability", and "cooperation with stakeholders".

Collection of sources incorporated literature reviews, case studies, theoretical and conceptual investigations and analyses of existing adaptation strategies to ensure a comprehensive understanding of the subject. The array of included sources encompasses a diverse array of sources, including academic journals, monographs, policy documents, reports, case studies, and statistical data websites. The search was made in Scopus, JSTOR, Google Scholar, and ScienceDirect.

The research materials included regulations on implementing public policy to combat climate change, as well as scholarly articles devoted to studying the development of strategies for business processes adapting to changing climate conditions and reducing risks.

The study employed a range of various methods, in particular, analysis and synthesis to determine the essence and features of the object of study, induction and deduction to conclude the features of adaptation strategy in different industries, systemic approach for a comprehensive study of the impact of climate change on the functioning of enterprises, and legal and systemic-analytical method for analysing regulations on the development of strategies for adaptation to climate change and risk reduction.

SWOT analysis was employed to scrutinize the effects of climate change on businesses and formulate tailored adaptation strategies. To identify important shortcomings, take advantage of opportunities, and address innate strengths and weaknesses, the results are carefully evaluated. The inherent unpredictability of climate change estimates, variations in business adaptability, and resource allocation limits for adaption measure implementation are among the acknowledged difficulties. Furthermore, the efficacy of adaptation strategies may be contingent upon contextual factors and industry-specific nuances.

Results

Businesses face the important task of adjusting their strategic plans to adapt to climate change. The problem is complex and does not have a simple solution. To do so, they must demonstrate flexibility and agility in responding to new challenges and actively mobilize their capabilities and resources to meet consumer needs. This is because, to maintain their development and operation, they need to be in line with their entrepreneurial objectives and be able to quickly adjust to shifting external circumstances (Zghurska *et al.*, 2022).

An adaptation strategy should be understood as a set of long-term and short-term measures aimed at increasing the resilience of a business to the consequences of climate change by adapting business processes, resources and strategic planning to new environmental, economic and social conditions (Basok *et al.*, 2021; Sadler *et al.*, 2022; Zghurska *et al.*, 2022). The formation of an adaptation strategy also involves predicting potential threats, implementing innovative technologies to minimize the impact of adverse factors, integrating environmental responsibility into production and management processes, and should also considering the specifics of the industry, regional capabilities and current legislative requirements related to climate change (Kalogiannidis *et al.*, 2024). Serra *et al.* (2022) assert that incorporating various climate change solutions into regional development not only mitigates the negative effects of climate change but also reveals a wealth of chances for regions to promote social welfare, economic growth, and creativity.

An integral element of such a strategy is stakeholder engagement. This term refers to the process of business engagement with the government, investors, consumers, suppliers, civil society organizations, academic institutions, and local communities (Emeka-Okoli *et al.*, 2024). Adebayo *et al.* (2024) note that such engagement helps align interests, set priorities, and jointly address climate change challenges, providing a more comprehensive approach to adaptation and access to additional resources and knowledge.

As Holych (2021) correctly points out, company models are inherently flexible. Businesses may maintain their competitiveness both internally and internationally by using a crucial strategy of adapting to change. The strategy for adapting business processes to climate change should consist of a register of pre-existing solutions related to emerging risks due to climate change. This register should encompass a wide range of potential threats that could destabilize the operations of a specific enterprise. The sources cited (and Dunska, 2022; Maryuk *et al.*, 2021; Bilykh) provide valuable insights into this topic. Moreover, it is important to consider the potential of the business structure and material resources for implementation.

In this context, the term “risk management” should be considered in terms of its effectiveness in monitoring climate change, assessing its potential impact on business activities, creating response plans and implementing measures to reduce the likelihood or consequences of negative events (Ebirim *et al.*, 2024). Thus, risk management involves a systematic process of identifying, analysing, assessing and reducing the impact of risks arising from climate change.

In 2021, Carbon Brief conducted a global study of per-person emissions of hazardous substances. The issue of accounting for the relative size of the population is approached in two different ways, considering, on the one hand, total and, on the other hand, cumulative emissions (Table 1). These approaches produce markedly different results, emphasizing the complexity of interpreting cumulative per-person emissions.

Table 1: Cumulative emissions per population in 2021, country-based

Rank	Country	Cumulative emissions per-person in 2021, tCO ₂	Rank	Country	Cumulative per capita emissions*, tCO ₂ ** (year 2021)
1	Canada	1.751	1	New Zealand	5.764
2	United States	1.547	2	Canada	4.772
3	Estonia	1.394	3	Australia	4.013
4	Australia	1.388	4	United States	3.820
5	Trinidad and Tobago	1.187	5	Argentina	3.382

* Per capita emissions indicate the emissions of an average individual in a country or area. They are determined by dividing total emissions by population.

** Metric tons of CO₂ emissions [Source: Evans (2021)]

One conspicuous observation arising from the population analysis is the noticeable omission of several major emitters among the top 5, notably China, India, Brazil, and Indonesia, from the presented data table. Despite their significant contributions to the global cumulative emissions, these nations have substantial populations, consequently mitigating their per capita emissions impact. Remarkably, these four nations collectively represent 42% of the global populace, yet their combined contribution to cumulative emissions amounts to a mere 23% (Evans, 2021).

Digitalization is crucial for accelerating the climate movement. The process of digital transformation involves the transition to digital technologies across all areas of activity and plays a key role in the implementation of strategic measures to combat climate change (Hrustek, 2020). Digitalization has a great potential to achieve climate neutrality aimed at mitigating the effects of climate change through the neutralization of carbon emissions. It is impossible to avoid CO₂ emissions, especially given the size and environmental intensity of industrial complexes. According to Maris and Flouros (2021), carbon emissions in each country depend on the main sectors of the national economy and their specializations. In China, for example, up to 70% of greenhouse gas emissions are caused by the widespread use of solid fuels and energy sources in the manufacturing sector. Similar trends are observed in Ukraine, where this figure is 52%. In addition, in Uzbekistan, Armenia, and Switzerland, up to 33% of CO₂ emissions come from households, both private and commercial, as well as public services. The current circumstances make it possible to achieve climate neutrality by reducing the volume of

environmentally harmful production in the country as well as its gradual transformation (Maksymova and Kurylyak, 2022).

In today's business paradigm, given the drive for sustainable development and the need to adapt to the negative impacts of climate change, the strategy of dual digital and green transition is becoming a priority for businesses. This concept is based on the integration of digital technologies with green initiatives to achieve competitiveness and reduce negative environmental impacts. As an example, the utilization of digital technologies, including a mini-CHP plant equipped with a gas turbine and a heat recovery boiler, as well as the automated control of heating and air conditioning systems, has significantly reduced expenses and enhanced the efficiency of the "Land Rover" SUV production facility (TIC Ukraine, 2022). This approach allows businesses not only to adapt to climate change but also to ensure sustainable and cost-effective development in line with modern environmental requirements and challenges. The dual digital-green transition encompasses several strategies and methods aimed at optimizing and efficiently using resources. The collection, analysis and utilization of substantial quantities of data about climate change and environmental indicators are enabled by digital technologies. This transition presents an opportunity to accurately monitor the environment, anticipate changes, and devise efficient measures to mitigate the adverse effects of climate change on business. This will help reduce CO₂ emissions and conserve energy resources (Dziamulych and Reikin, 2024).

The development of environmentally sustainable initiatives can be ensured through the issuance of green bonds and support for the relevant projects financed by them. The establishment and implementation of a green bond market facilitates the adoption of environmentally friendly technologies and practices, thereby aiding in the adaptation to climate change and the digital-green transition. For example, in Ukraine, the legal framework for the introduction and development of the green bond market was created in 2022 (Verkhovna Rada of Ukraine, 2022) and provides for financing the implementation of environmental projects. Instead, the Paris Agreement, in particular Article 2.1(c), emphasizes the redirection of financial flows to support low-emission and climate-resilient development; and Article 9 calls for the mobilization of financial resources to assist in climate adaptation and mitigation in developing countries. In addition, the development of environmentally sustainable initiatives within the United Nations Sustainable Development Goals (SDGs) including Goal 7 (Affordable and Clean Energy) by promoting renewable energy projects, Goal 9 (Industry, Innovation, and Infrastructure) by promoting sustainable industrialization, and Goal 13 (Climate Action) by financing climate adaptation and mitigation measures.

The goal of the adaptation strategy is formulated based on the desired outcomes of the changes. Specific priorities for implementing concrete measures regarding business processes should be identified, and corresponding parameters (temporal and quantitative) should be established to be implemented in conditions of the most probable risks. The strategic objectives include improving the organizational policy to adapt to climate change at all stages of activity, strengthening institutional capacity through expertise, monitoring, and training to support adaptation activities, and creating conditions for resilience to climate change by strengthening management mechanisms and protecting infrastructure objects as much as possible (Nechiporenko, 2020). It is

important to note that these objectives are aimed at achieving a balanced approach without bias towards any particular perspective. To reduce risks and adapt to climate conditions, it is important to assess available resources such as finances and goods, as well as investments and innovations necessary for implementing the adaptation strategy.

The strategy's key pillars include the following:

1) *Risk management.* Climate change poses a huge list of risks to business structures, ranging from material to logistical obstacles. This requires each company to assess the risks it may face in the context of global natural changes to help develop adaptation plans that take into account possible threats (Sumets *et al.*, 2022). To reduce risks and adapt to climate conditions, it is important to assess the available resources, such as finance and goods, as well as the investments and innovations needed to implement adaptation strategies. In addition, financial flows can be attracted by using international government flows when implementing climate change initiatives. In this context, the largest absolute and relative year-on-year increase since the Paris Agreement was in public adaptation finance flows to developing countries. This reflects progress toward the Glasgow Climate Pact, which called for affluent countries to at least double climate adaptation funding to developing countries from USD 19 billion from 2019 to 2025. Even attaining the Glasgow Climate Pact objective would only lower the adaptation financing gap by roughly 5%, which is projected to be between USD 187 and 359 billion per year.

2) *Sustainability of business structures.* Searching for new, even environmentally friendly, models for business activities, abandoning the traditional approach in favour of a “circular” approach will allow to retain resources for the longest time. An example of implementing adaptation strategies is Google, which is implementing innovative climate projects using artificial intelligence. Such projects include optimizing routes in Google Maps to reduce fuel consumption; developing the Flood Hub platform, which provides real-time information about floods and helps prevent their consequences; and creating aircraft inversion trail prediction maps, which help reduce the impact of aviation on the climate. Google also has an ambitious goal of achieving net-zero emissions across its entire value chain by 2030 and moving to a closed-loop economy, using secondary resources as much as possible (Harvard Business School Online, 2024).

3) *Adaptation of business organisation.* Looking ahead, it is advisable to take measures for future adaptation now, to consider opportunities to change the location of the enterprise, placement and implementation of certain business processes, working methods, and development of new goods or services (Hrinchenko *et al.*, 2023). One such example is New Belgium Brewing Company, a craft beer producer that in 2020 made its Fat Tire Ale the first certified carbon-neutral beer in the United States. The company has implemented several measures to achieve carbon neutrality, including using biogas generated from waste at its water treatment plant to generate electricity; installing solar panels in its production facilities; switching from glass bottles to aluminium cans, which have a lower carbon footprint; and actively participating in projects aimed at restoring ecosystems and supporting renewable energy sources (Harvard Business School Online, 2024).

4) *Cooperation with other business structures and stakeholders.* It is important to emphasise that no company can cope with climate change alone, and therefore, to successfully overcome these problems, it is necessary to cooperate with these entities (Sytnyk *et al.*, 2022). Focusing on the experience of Kenya, as explored by Gannon *et al.* (2021), where 89% of Kenya is classified as arid or semi-arid, i.e. characterized by climatic variability. In these conditions, projects such as PREPARED and CA4FS, implemented with the support of international initiatives, have demonstrated significant results in the practical application of partnership methods. Within the framework of PREPARED, the focus was on the modernization of weather stations and increasing the capacity of the Kenya Meteorological Department, thereby generating high-quality climate data that were used by insurance companies to develop reliable crop insurance indices. In turn, by involving the private sector through grant mechanisms and cost-sharing systems, the CA4FS project brought together producers, suppliers of resource-saving technologies and buyers of agricultural products. One of the achievements of the project was the creation of conditions for the introduction of climate-smart agricultural technologies. For example, demonstration plots were used to test innovative technologies that were adapted to local conditions, and businesses producing adaptive goods and services received support to enter new markets.

Business adaptation to climate change and business respect for human rights, including environmental rights, are becoming an integral part of modern corporate responsibility. The present strategy for the sustainable development of Ukraine is based on a method of thinking that emphasizes the importance of safeguarding the environment and generating revenue, while simultaneously ensuring that all individuals are provided with the necessities of the present and the future. In general, the concept of sustainable development is based on the principles of responsibility for the future, equality of opportunities, balance between the economy and the environment, and harmonization of population growth with natural resources (UNDP Ukraine, 2017). Economic growth mustn't disrupt the ecosystem, as environmental sustainability holds the key to positive growth. This entails raising awareness of the impact of business on environmental sustainability and the living conditions of society. It is important to consider the human right to life and a healthy environment when developing a socially and environmentally responsible business. Therefore, businesses are actively implementing environmentally sustainable technologies and using renewable energy sources to reduce emissions of harmful substances. At the same time, businesses must adhere to social responsibility and avoid using low-paid labour and harmful materials (Klarin, 2018). This approach ensures not only the success of the company but also the well-being of society as a whole.

The key positions identified should form the basis for developers of adaptation strategies. These strategies will be successful if they are prepared in advance (Figure 2). It is important to note that stakeholders (Wang *et al.*, 2020) must fully understand climate risks specific to their territories and infrastructure, and therefore, know how to reduce the level of impact and uncertainty. Adaptation measures should include the development of a strategy and implementation plan. These should consider temporal and substantive changes in natural phenomena and analyse possible consequences for socio-economic, climate, and technological spheres (Gonchar and Dzhulii, 2023).

It is important to note that the development of adaptation strategies is typically based on cost and outcome analysis in the context of slow climate changes. This is particularly relevant for complex technical systems such as structures and equipment, as well as information systems with short lifecycles. The strategy's components involve a gradual approach, dividing relevant business processes into mini-cycles (Snizhko *et al.*, 2021), which are applied under specific climate risks. However, decision-making may be untimely due to forecast uncertainty regarding the manifestation of specific types of risks (Grosul *et al.*, 2017). By assessing the vulnerability of the enterprise to meteorological phenomena such as floods, hurricane winds, snowstorms, and high environmental temperatures (Arefieva *et al.*, 2022), potential risks for relevant business processes can be identified. This forms the basis for strategy development. The next step involves analysing existing adaptation options and formulating a program to implement necessary measures.

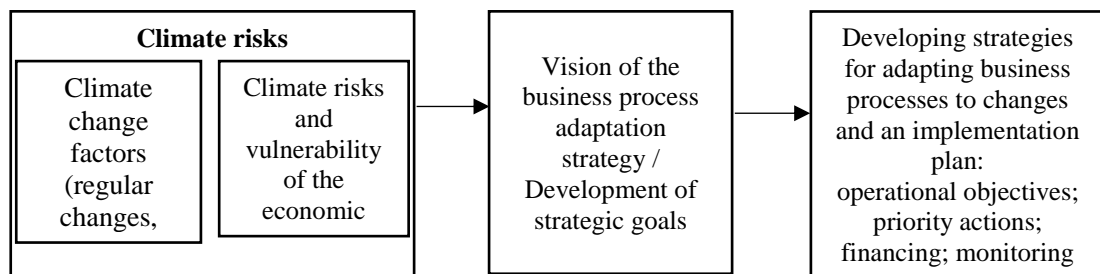


Figure 2: Key elements for developing a climate change adaptation strategy

A basic SWOT analysis template for the impact of climate change on adaptation strategy development (Table 2) is provided. When conducting this analysis, a specific business structure should be developed considering each type of climate impact. The criteria for this analysis include temperature increase, wind speed, and increase or decrease in precipitation. Therefore, it is important to highlight the benefits of climate change impact as a means of gaining a competitive advantage, such as creating new products (Basok *et al.*, 2021). Weaknesses can be addressed by investing in energy-efficient sources or developing more efficient products or services to mitigate the negative effects of climate change. The results of implementing the adaptation strategy for each enterprise are unique and depend on the plan's content. The plan may involve either radical innovative changes in business processes or slow and stable measures (Mironova *et al.*, 2022).

Research on the SWOT analysis of the impact of climate change on the development of an adaptation strategy has shown that in the short term, the changes will be minimal but are expected to increase in the long term (Tymoshenko *et al.*, 2022). Therefore, their impact on business processes may gradually escalate and adapt (Izaguirre *et al.*, 2021). Identified weaknesses indicate a complete reliance on centralized water and electricity systems. This issue could potentially be resolved by implementing autonomous renewable energy power stations and water resource storage systems (Dvigun *et al.*, 2022a). Furthermore, as the earth's temperature increases, the climate becomes drier, which affects the quality of cultivated raw materials, increases pest infestations, and causes various plant diseases to occur more frequently. However, it is important to note that all business process chains are directly dependent on transportation logistics (Chobitok and Shelest, 2021). Therefore, any disruption to transportation logistics could lead to a complete halt in business operations. Implementing measures to protect

transportation infrastructure requires significant investment in the short term (Mahpour, 2021; Trypolska, 2021). However, this investment will help prevent substantial expenses in the future for re-equipping. Simultaneously, it is advisable to evaluate the cost-effectiveness of the implemented adaptation measures about the projected benefits (Masyk *et al.*, 2023).

Table 2: Global E-commerce Growth Forecast

<i>Strengths</i>	<i>Weaknesses</i>
1) concentration on the core business, which is the most profitable for the business structure 2) expanding the scope of training 3) the ability to be flexible and respond quickly to market changes and internal factors 4) maximum proximity to the consumer	1) dependence on a centralised power supply 2) use of water as a cooling element 3) quality of raw materials; presence of pests and diseases 4) dependence on water resources 5) dependence on transport logistics
<i>Opportunities</i>	<i>Threats</i>
1) uniting enterprises in the same industry to overcome problems 2) state support for business structures through the creation of legal frameworks and financial support	1) risks of changes in electricity supply 2) risks of flooding, flooding of crop fields 3) the risk of reduced water resources; etc.

Source: Attar *et al.* (2022), Santos *et al.* (2023), Shunmathy (2024)

Studies have shown that climate change significantly increases the probability of hazardous natural phenomena, which can cause severe emergencies that endanger human life and health, disrupt transportation logistics, cause material losses, and even environmental damage (Dvigun *et al.*, 2022b). The strategy’s adaptation measures should be reviewed and updated, considering forecasts of hazards, vulnerabilities of specific objects, and socio-economic consequences (Figure 3).

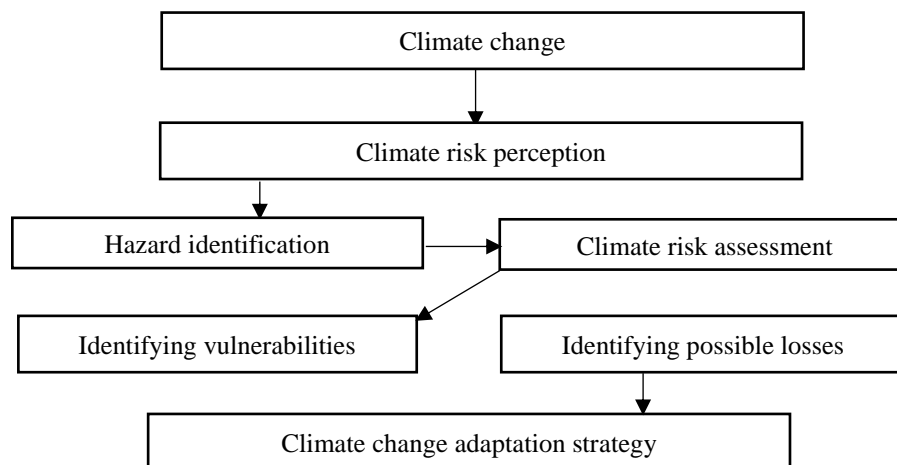


Figure 3: Scheme of forming a strategy for adaptation to climate change

In this context, developing strategies for adapting business processes to climate change and risk reduction requires fostering interaction among stakeholders. These stakeholders include business owners, public authorities, local government bodies, civil society organizations, and other external entities. It is important to ensure that all stakeholders are involved in the process.

Discussion

As the research shows, thus, it can be concluded that climate change acts as a catalyst for developing strategies to adapt business processes and define goals for risk mitigation. The adaptation strategy should include an implementation plan that outlines actions for each type of risk associated with climate change. It is important to note that financial support is a constraining factor in implementing such strategies, which businesses allocate towards addressing threats.

This research outlines a plan of action to protect infrastructure assets during extreme weather conditions. For instance, hurricane winds may cause damage to power lines, leading to power outages. Similarly, transportation routes may be disrupted due to tree collapses and snowstorms (Kyrylenko *et al.*, 2020). Therefore, businesses armed with information about their vulnerabilities can comprehensively assess and identify the most significant threats and circumstances that need to be minimized in the short term for further adaptation activities. Collaborative efforts among business structures and other stakeholders will contribute to mitigating negative impacts and forming the basis for developing proactive strategies to overcome potential threats.

The limitation of our research is the lack of taking into account political factors and SDG agenda at global and national levels, and appropriate further extension of research is needed, with consideration of a broader array of factors, which would make the results more precise. However, our findings still can serve as a benchmark in adapting business processes to climate change.

To prevent maladaptation, it is crucial to conduct an objective assessment of options in both the short and long term. The implementation plan for adapting business processes should be carried out sequentially, reducing the overall risk level to an acceptable level due to climate change with each step. However, the adaptation strategy differs from the traditional approach to executing action plans. It is triggered for implementation over time only when the climate risk reaches a certain threshold (defined for the organization as a red line), which is determined through predictive assessments and meteorological condition monitoring processes (Kryvokhyzha *et al.*, 2023). Once the appropriate measures for adapting to climate change and reducing risks have been selected, they can be implemented according to the execution plan. The evaluation of the effectiveness of these measures influences each subsequent stage, enhancing the quality of the results (Maksymova, 2023; Maksymova *et al.*, 2023).

In summary, the assessment of potential outcomes from implementing the strategy for adapting business processes to climate change and risk reduction involves the following: the strategy is a useful tool for raising awareness among business structures about threats from climate change and the need for management processes of appropriate adaptation

measures. Currently, organizations do not prioritize addressing issues related to meteorological phenomena, as they are focused on achieving entrepreneurial goals. There is no software available that could forecast strategic measures and calculate the costs of adapting businesses to climate change.

With the effects now visible, it is not surprising that some firms have begun to make efforts to adapt to climate change. Many of these activities are reactionary, meaning that businesses are responding to existing climate change consequences or known climate trends. Most clearly, several firms have begun to relocate their headquarters or activities away from potential threats. Other firms are starting to implement or evaluate process modifications in response to the shifting climate. In reaction to growing weather extremes, some farmers have shown an interest in obtaining drought and flood-resistant seeds. Insurance firms are beginning to take initiatives to decrease losses, both by encouraging consumers to mitigate their losses and by modifying underwriting methods (Rivera, 2022).

Successful long-term adaptation, on the other hand, necessitates recognizing and acting on dangers early on, frequently before they materialize, as well as determining acceptable proportional responses. Furthermore, effectively addressing climate change may need a shift in thinking away from dependence on previous patterns and actions and toward an assessment of future climatic changes and their likelihood. As a result, proactive adaptation choices that intentionally anticipate future climate change and incorporate them into decision-making will become less clear and more difficult to detect and assess. Screening to detect the possible dangers of near-term and long-term climate change is the first stage in evaluating if a risk assessment is required to suggest additional activities.

The goal of the screening is to establish whether the business is at risk, what parts are in danger, and from whom, and whether a more comprehensive risk assessment is required to determine what if any, measures are required. The screening's purpose is to assign risks to one of three categories: assess immediately, wait and research, or take no action. Screening (as shown in Figure 4) to determine if climate change is a potentially major element in present decision-making consists of multiple steps: detecting sensitivities, identifying the sorts of decisions that are vulnerable to climate change, and assessing the size of the risk.

Moreover, identifying and responding to the effects of climate change can result in significant competitive advantages. Businesses that proactively adjust to changing conditions may assure operational continuity and build a positive reputation with customers and partners. Furthermore, there is a growing tendency in regulatory compliance in which governments establish severe criteria for sustainable activities and carbon reductions. Companies that follow these policies avoid penalties and are typically given incentives.

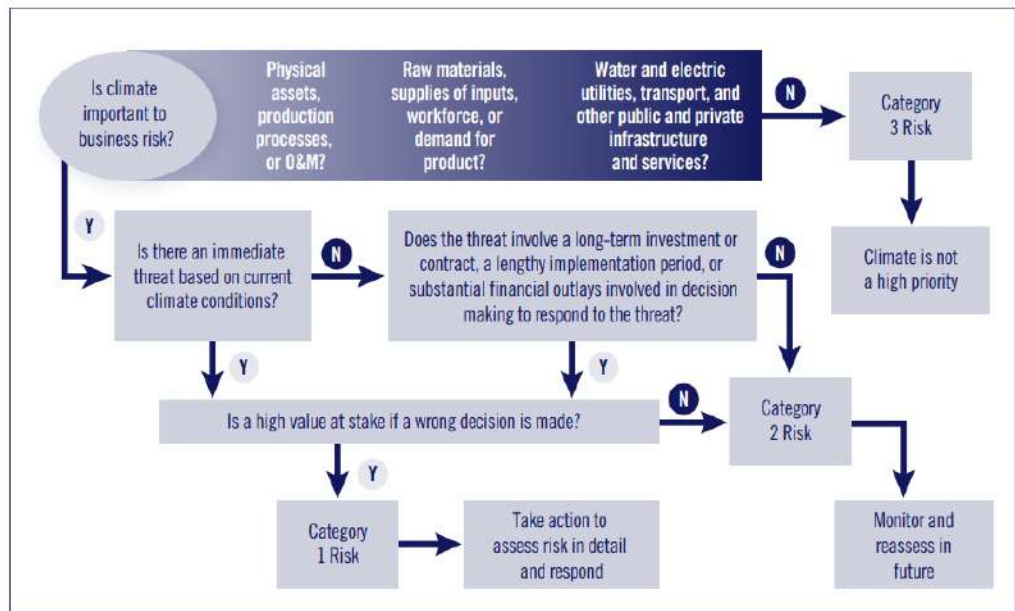


Figure 4: Screening for climate risks (Rivera, 2022)

Conclusion

Some businesses have begun to assess and potentially respond to the physical effects of climate change, but many still believe that these effects - of temperature rise, hydrology changes, storms, and sea level rise - are either irrelevant to business decisions or too uncertain. Meanwhile, the key to successful adaptation is recognizing the extent of the risk and establishing what steps can and should be taken to address it. It is prudent to consider climate change if it has a major impact on a company's operations, value chain, or overall business environment. As a result, determining whether adaptation is necessary - and what adaptation might accomplish - requires taking a deeper look at the dimensions of potential implications on business.

Therefore, a strategy for adapting business processes to climate change and mitigating risks is developed based on a SWOT analysis. This analysis helps to identify the necessary adaptation solutions, given the uncertainty of the scale of climate change and its consequences. The use of a consistent framework enables the incorporation of updated information and consideration of new socio-economic conditions. The adaptation strategy developed in the study can be integrated into the enterprise management process. This will provide qualitative advantages in the stability of specific business processes after the implementation of proposed measures.

Effective climate adaptation necessitates thorough planning and assessment. To properly adapt to the changing climate, firms must focus on these three key areas:

- Extending risk management frameworks to include climate-related concerns is crucial for business continuity.
- Infrastructure resilience (strengthening of physical assets to withstand increasingly frequent and severe climate catastrophes).

- Understanding technological innovation is crucial for successful climate adaptation
- Regulatory compliance and reporting.
- Community and Ecosystem Resilience (businesses should think about the larger ecological and community implications of their adaptation plans).
- Practicing private sector collaboration and policy engagement as crucial tools for shaping effective climate adaptation strategies with governments and international organizations

Thus, our study introduces a novel approach to developing adaptation strategies for businesses facing climate change challenges. It outlines four key pillars: risk management, sustainability, organizational adaptation, and stakeholder cooperation. Practically, it provides actionable insights for businesses to enhance resilience and mitigate environmental impact. Socially, it emphasizes businesses' responsibility in promoting sustainability and respecting human rights. Overall, the study demonstrates the importance of aligning business operations with sustainable development goals and engaging stakeholders to address climate-related risks.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	Yes	No	Yes	No
Collected the data	Yes	No	Yes	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Regulatory and Institutional Frameworks for Ensuring Financial Security in Ukraine's Energy Sector: Challenges and Future Outlook

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Abstract

The study aims to analyze the existing regulatory and institutional foundations for establishing financial security in Ukraine's energy sector in the context of prospects for improvement and addressing related challenges. The article examines the basic conceptual principles of achieving energy security, including integration into a unified European energy space, ensuring stable energy independence, enhancing energy efficiency, and maximizing the potential of renewable energy sources. The proposed model of forming financial security in the energy sector and strategies for diversification and collaboration between Ukraine and the developed international community are critically evaluated. The study identifies ways to optimize the institutional and regulatory framework for financial security in the energy sector, including modernizing energy infrastructure, harmonizing legislation with European standards, and diversifying supply. The findings conclude that Ukraine's integration into the European unified energy space and robust investment support from the international community are considered prerequisites for the intensive development of Ukraine's energy sector.

Keywords

Strategic approach; Institutional and regulatory framework; Energy efficiency; Management mechanisms; Energy security

Introduction

Global challenges concerning energy security underscore the need to optimize the institutional and regulatory framework to strengthen financial security in the energy sector. In this context, attention should be given to energy supply diversification, advancing energy independence, and intensifying renewable energy development (Thaler and Hofmann, 2022). It is essential to position energy security as a critically important area of managerial activity and to stimulate the formation of effective strategic decisions. Ukraine is actively developing digital technologies in the energy sector, which significantly increases financial security (Pecheniuk *et al.*, 2022). In particular, the national programme 'Digital Ukraine' is actively being implemented, which introduces modern monitoring systems and digital management of energy networks.

Ensuring the financial stability of the energy sector plays a vital role in maintaining stable socio-economic development and national security. The vulnerability of energy systems poses significant financial and economic consequences, which have been complicated and intensified during wartime in aspects such as price policy instability, adverse external market conditions against the backdrop of geopolitical risks, and the destructive impact of the industry on the environment and climate policy (Rogovyi *et al.*, 2021). These challenges necessitate transforming approaches to ensuring energy security in Ukraine, emphasizing integration into the international market environment (Stepanenko *et al.*, 2023). This concept will enable the identification of the most effective tools for the sustainable development of the energy sector and bring the institutional and regulatory framework for financial security in the energy sector into alignment with European legislative practices (Sutrisno *et al.*, 2022). Ukraine's path to diversifying its energy supply to guarantee energy security requires finding opportunities to minimise dependence on monopolistic suppliers. This strategy promotes the development of renewable energy while also advancing the country's oil and gas fields. However, several challenges exist in the European context and at the national level: geopolitical instability, infrastructural issues, a weak investment climate, and an imperfect regulatory framework (de Rosa *et al.*, 2022). Energy systems' vulnerability has serious consequences, including geopolitical risks and price instability in the energy sector. Understanding the specifics of strategies and approaches to implementing financial security in the energy sector will allow the identification of the most effective methods to ensure sustainable development.

The relevance of this study is driven by the need to develop financial and legal tools for the sustainable management of natural resources and reduce the economy's dependence on traditional energy sources (Taghizadeh-Hesary and Yoshino, 2020). Gaps in the regulatory and institutional frameworks for achieving financial security in Ukraine's energy sector must be identified. Financial and legal tools require particular attention. The research findings will have potential practical significance regarding integration into regional or national energy security and energy efficiency programmes.

Literature Review

The issue of ensuring financial security in the energy sector has been actively researched by scientists in recent years. Stepanenko, Ovsuchenko and Tokhtamysh (2023) state that

energy security is a prerequisite for sustainable national development. In the works of Medvid (2009) and Vashchenko (2022), the security concept combines the energy sector diversification and the transition towards renewability. The publications of Tkachov (2023) and Furman (2024), Rogovyi *et al.* (2020), and Rogovyi *et al.* (2021) examine the functionality of financial security in guaranteeing resilience in the energy supply sector under conditions of instability and crisis phenomena.

Several studies, such as Galkin *et al.* (2019), Batygin, Golovashchenko, and Gnatov (2013), Shabala and Matiichuk (2023), and Khotian and Rozen (2022), explore the functionality of management bodies and international cooperation in ensuring energy security. Meanwhile, Iatsenko and Mohylna (2023) and de Rosa *et al.* (2022) analyze the interdependence between energy resource availability, financial and economic security, and the level of geopolitical conflict. The issue of assessing the level of financial security in the energy sector amid active European integration processes is studied in the works of Sutrisno, Nomaler and Alkemade (2022), Iakovenko (2023), and Thaler and Hofmann (2022).

Contemporary publications examine the role of alternative energy sources in the modern business environment (Kothari, Ranjan and Singal, 2021), highlighting aspects of sustainable development using innovative renewable energy technologies (Papadis and Tsatsaronis, 2020). They also explore sustainable solutions for green financing and investments in renewable energy projects (Ozili and Iorember, 2024). They also analyze the foundations for forming business models in the alternative electricity market (Lu *et al.*, 2020). Recent developments position the studied phenomenon as a priority for sustainable economic development, converging societal, managerial, and business efforts to achieve high decarbonization goals soon (Qadir *et al.*, 2021). Individual researchers generalize the convergence issues between sustainable entrepreneurship, innovation, and business models during the global transformation of socio-economic processes toward minimizing environmental impacts and preventing climate change (Polzin and Sanders, 2020).

The conceptual horizons of the studied issues are further expanded in the work of Wang, Sun and Iqbal (2022), who propose a model for encouraging renewable energy use in businesses through managerial motivation and raising the level of environmental awareness. Most cited researchers interpret the transition to renewable energy sources as a foundation for reducing emissions, increasing resilience to climate change, ensuring sustainable development within circular economic processes, and prospective strategic greening of the energy sector.

Despite these significant achievements, the financial security of the energy sector requires further exploration in the context of improving Ukraine's regulatory and institutional foundations. The study's relevance is due to the need to develop financial and legal instruments for the sustainable management of natural resources and to reduce the economy's dependence on traditional energy sources. This underscores the need for extensive scientific research on this topic (Pecheniuk *et al.*, 2022).

Challenges and prospects for financial security in Ukraine's energy sector demand innovative institutional and regulatory support approaches. Several modern scholars

(Rusch *et al.*, 2023; Shen, Hu and Hueng, 2021) have studied the dynamics of communication business models against the backdrop of the economy's digital transformation. In the energy sector, positive development trends are expected in resource optimization processes, establishing effective internal communication, modernizing outdated systems, and adopting functional chatbots, mobile applications, and interactive media products.

Researchers such as Yue *et al.* (2022) advocate *optimizing* communication in the business environment through modern informational tools that ensure feedback based on accessibility and openness principles. Shaikh *et al.* (2023) and Mhlanga (2020) findings state that *digitalization* is identified as a fundamental element of market development. Scholars emphasize that information modelling within the management paradigm can be positioned as an effective tool for analyzing large volumes of data. However, the functional characteristics of transitioning from traditional to renewable energy sources, the analysis of the relevant tools, and the possibilities for improving the structural-functional model of the process using innovative motivational strategies remain underexplored, necessitating an expanded study of these topics.

This study aims to analyze the existing regulatory and institutional framework for forming financial security in the Ukrainian energy sector from the perspective of improving and mitigating related challenges.

Materials and Methods

During the study, a comparative analysis was used to assess the regulatory and institutional framework for ensuring financial security in Ukraine's energy sector, with an emphasis on environmental aspects. Based on an understanding of global trends and practices, the study compares the evolution of regulation in Ukraine with European standards, considering the contextual specifics of Ukraine's national regulatory framework.

Data collection. The primary data sources include legislation, political documents, and institutional reports from national and international bodies. Secondary data from the scientific literature on energy policy, investment law, and financial security systems supplement these. While the study focuses on Ukraine, relevant examples from the EU and other jurisdictions are included to contextualise Ukraine's regulatory approaches within broader global trends.

Sampling methodology. The research procedure included two main stages: data collection and analysis. In the first stage, secondary data sources were utilised. These were obtained by analysing industry statistical information, regulatory acts, and publications. This sample size was justified in light of practical realities that needed to be considered.

Research instruments. The unity of analysis and synthesis facilitated an objective and adequate investigation of financial and institutional practices, reflecting the unity of opposites about the interconnectedness of the particular and the general. The analytical dissection of the system within the global concept into separate components enabled the

identification of the structure of the studied object, its specificity, and the separation of the essential from the non-essential, thereby enabling the classification of priority technologies. In contrast to analysis, synthesis enabled the integration of individual components and properties identified through analysis into a unified whole. This process involved the meaningful combination of identical and essential elements towards differentiation and diversity, synergizing the general and the particular into a cohesive whole. The scientific abstraction method was used to form theoretical generalisations, highlight key concepts and categories, and formulate research conclusions. Here, the abstraction of potential feasibility was used as a mental distraction from the standard properties of management technologies, concepts, and tools while simultaneously highlighting the essential properties sought.

Data analysis. The data analysis was conducted using quantitative and qualitative statistical analysis methods. Key factors influencing the financial security of the energy sector were identified. Subsequently, an algorithm was developed to optimize institutional and regulatory support for financial security in Ukraine's energy sector. An analysis of capital investments in energy production, processing, and supply from 2010 to 2022 was conducted. Data on capital investments and renewable energy growth were obtained from official sources, including the National Commission for State Regulation of Energy and Public Utilities (NKREKP) and Energy Map (2023). This analysis synthesized annual growth data for renewable energy capacities in Ukraine. The findings were used to draw conclusions and propose recommendations aimed at enhancing institutional and regulatory support for financial security in Ukraine's energy sector. These recommendations are intended to optimize the industry's resilience and adaptability, particularly in light of environmental challenges and global energy trends.

Results

Financial security in the energy sector is positioned as a factor in ensuring a sustainable and affordable energy supply for national needs. Sustainable financial-economic security in energy focuses on modernising energy infrastructure, intensifying energy efficiency and environmental sustainability, geopolitical interaction, and stabilising pricing policies (Sutrisno, Nomaler and Alkemade, 2022; Thaler and Hofmann, 2022). Significant factors affecting financial security in the energy sector (see Figure 1) enable the development of effective strategies to protect its financial aspects of energy security.

Diversifying energy supply is a priority aspect of enhancing financial security in the energy sector today. The European community views diversification as a strategic priority, actively developing a network of alternative logistics and suppliers to minimise dependency on industry monopolists. Ukraine's progress towards diversifying energy supply and guaranteeing energy security requires promoting renewable energy development, exploring domestic resources, and attracting foreign investments, necessitating appropriate institutional and regulatory support.

The post-war recovery and sustainable development of the energy sector must emphasize green energy as a significant factor in creating a unified, sustainable ecological-economic space. Given the readiness of socio-political thought for change and the global community's openness to financially supporting environmentally-focused projects, there

is growing confidence in the practical accessibility and reality of changes towards developing a sustainable environment. In this context, the directions of strict control and the establishment of dynamic analytical monitoring systems in the energy sector gain particular importance.

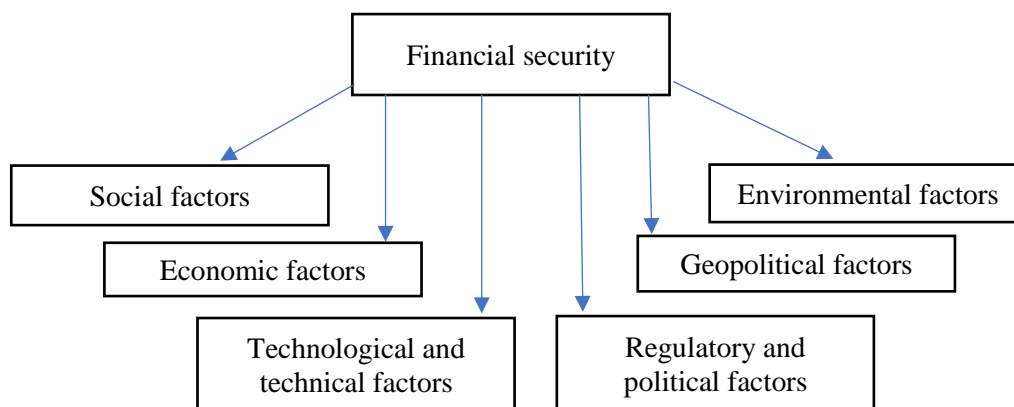


Figure 1: Factors influencing the financial security of the energy sector
Source: author's conception

Significant changes have occurred in Ukraine's energy legislation recently, including adopting European community practices and abandoning administrative-command market regulation mechanisms. Given the new threats associated with full-scale war, previously adopted mechanisms and instruments for institutional and regulatory support have proven ineffective. Implementing successful practices to optimise the institutional and regulatory foundations for financial security in the energy sector will establish a unified, coordinated approach, set priorities, and introduce specific mechanisms for their realisation (see Figure 2).

Priority legislative measures should establish the primary objectives for ensuring relevant financial security at a particular stage of socio-economic development. Identifying specific areas for improvement should be carried out at the level of strategic management activities, which determine the future directions of energy legislation development. The legislative and regulatory framework should enshrine management mechanisms to ensure financial security, including guaranteeing strategic energy reserves, specifying requirements for the protection of energy facilities and supply security, and improving mechanisms for regulating foreign investments (de Rosa *et al.*, 2022; Iatsenko and Mohylna, 2023).

The primary drawback of Ukraine's energy legislation is the lack of a systematic approach to ensuring financial security. Legislative frameworks are inconsistent across sectors. The departmental approach creates contradictions with the legislation of related industries, and the absence of a systematic vision leads to the misalignment of legislative norms with national interests. Currently, there is a deep differentiation between the strategic goals of state policy and their practical implementation in the direct activities of market entities, which inevitably affects the state of financial security in this sector.

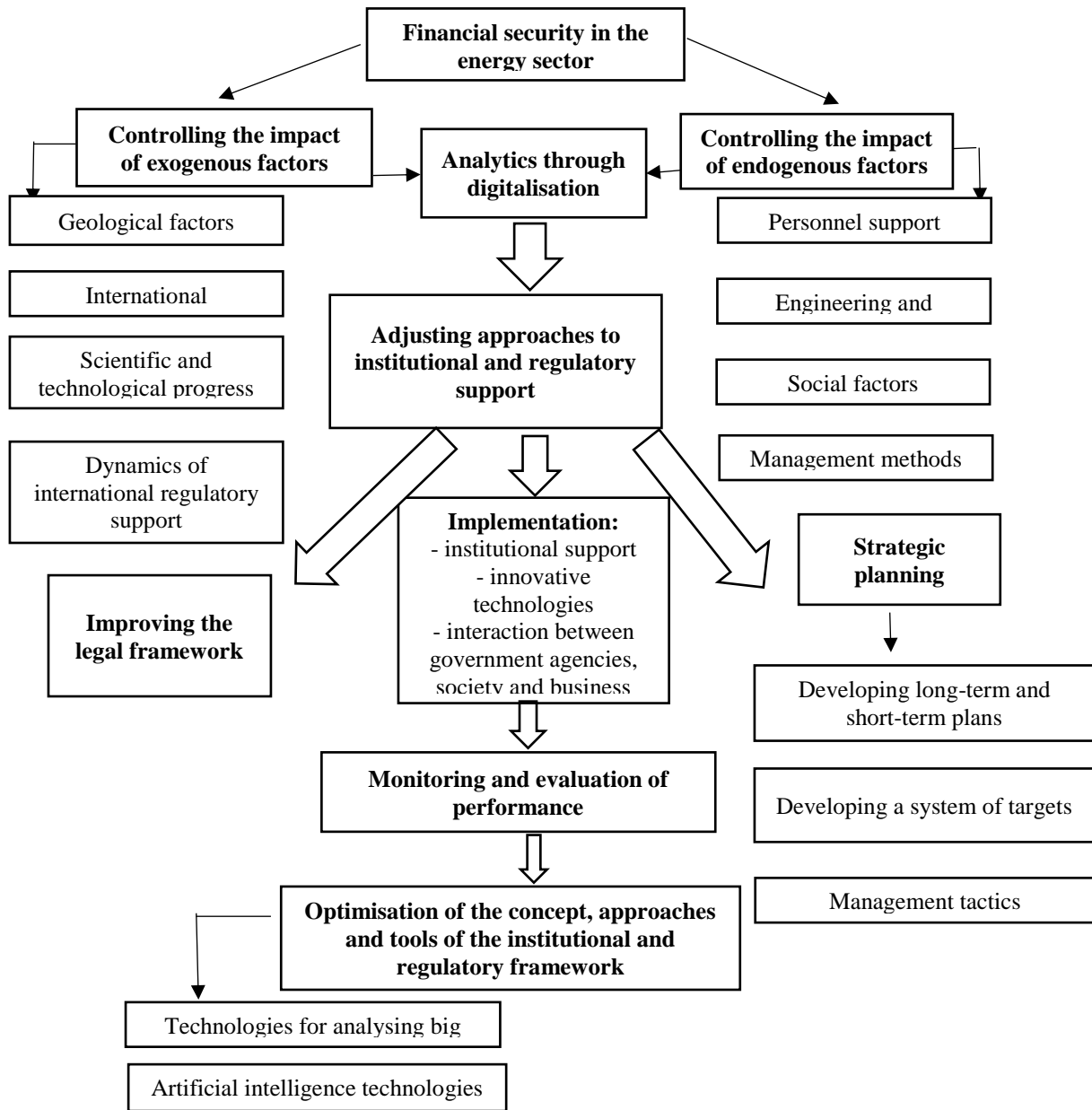


Figure 2: Algorithm for *Optimizing* the Institutional and Regulatory Support of Financial Security in the Energy Sector of Ukraine

An additional catalyst for qualitative changes is the redistribution of the energy market and the implementation of energy-efficient and resource-saving measures, which, in the context of wartime realities in Ukraine, have become necessary. These measures have gained widespread acceptance in socio-economic processes and become a commonplace phenomenon. The country's current approach underscores the prioritisation of sustainable development directions, readiness for fundamental changes, and participation in global socio-economic reorientation to reduce anthropogenic pressure on the environment and prevent a large-scale ecological catastrophe.

The financial security of the energy sector is determined primarily by the volume of capital investments in the industry. According to official data (Energy Map, 2023), capital investments in the extraction, processing, and supply of energy resources in 2022 amounted to 49.7 billion UAH, 49% lower than the 2021 figure of 97.04 billion UAH, indicating the destructive impact of the ongoing war. According to analysts' calculations, the dollar equivalent of investments in energy resource extraction and the production of coke and petroleum products in 2022 was the lowest since 2010, at 798 million USD. Investments in the supply of energy resources were the lowest in the last seven years, at 1.1 billion USD (see Figure 3).

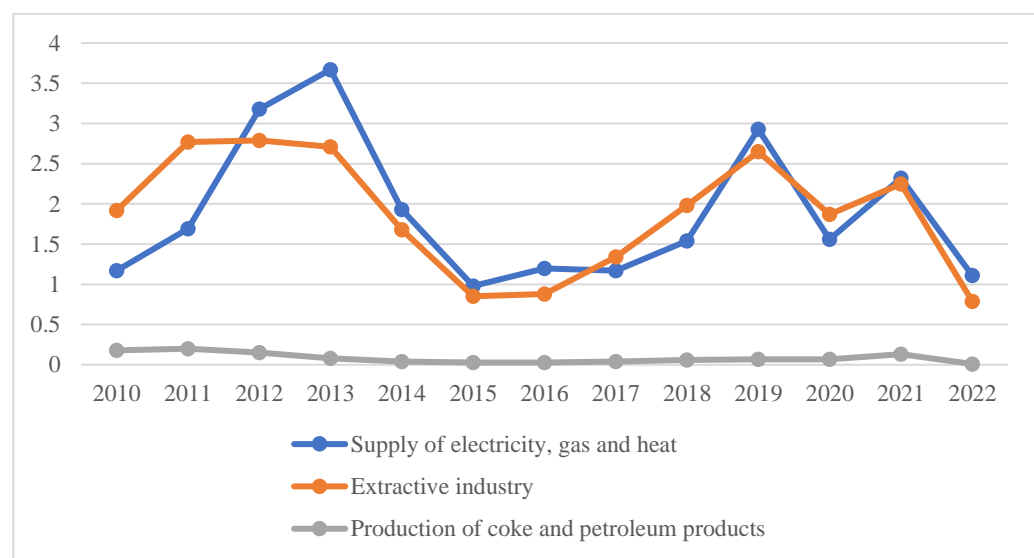


Figure 3: Capital Investment in Energy Production, Processing and Supply in 2010–2022, USD bn (Energy Map, 2023)

Before the full-scale war, the installed renewable energy capacity was about 10 GW. Most of its facilities were built before 2020 when the high "green" tariff was in effect. By 2022, investments in the industry had exceeded \$12 billion. After the start of the war, many renewable energy facilities were located in occupied territories, regions with active combat, and front-line areas. Overall, the large-scale war caused significant losses to the industry, as evidenced by the more than twofold decrease in the share of renewable energy in total electricity production (see Figure 4). Before 2022, this indicator was 13.4%, and now it is 5-6% (NKREKP, 2024).

The tools for ensuring the protection of national entities in the domestic energy market, against the backdrop of Ukraine's implemented international commitments regarding the liberalisation of internal energy markets, are currently fragmented (National Commission for State Regulation of Energy and Public Utilities, 2023). It is also worth highlighting the current legislation's inability to effectively counter threats to the financial stability of the energy sector in the context of wartime threats — sabotage, terrorism, and cyberattacks.

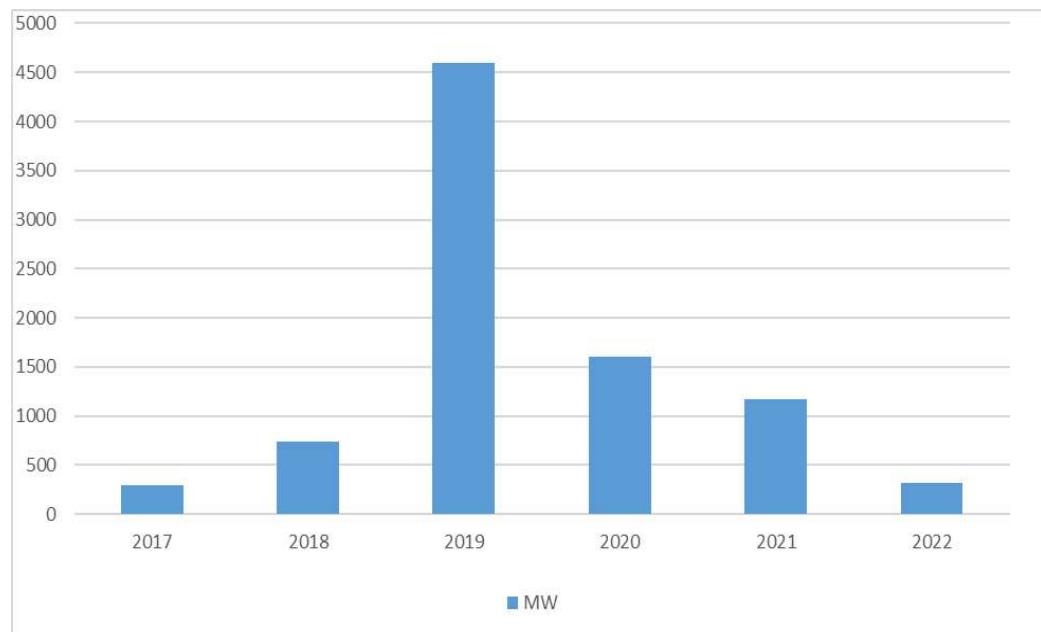


Figure 4: Annual Growth of Renewable Energy Capacities in Ukraine, MW (NKREKP, 2023)

Ensuring energy security is regulated at the departmental level without proper coordination and alignment with other national priorities. Furthermore, no legislative requirements exist for implementing an effective strategic planning system, critical energy infrastructure cyber protection, or international collaboration for market stability and transparency (Pecheniuk *et al.*, 2022).

Reducing greenhouse gas emissions and mitigating the effects of climate change begins with minimizing fossil fuel usage. This can be achieved by adopting alternative transport and renewable energy sources, an efficient waste management system, and using environmentally friendly building materials with low energy consumption. To optimise financial security in Ukraine's energy sector, the following concepts should be highlighted and supported by appropriate institutional and regulatory foundations:

- Development of renewable energy sources to minimise dependence on imports and monopolists and to ensure sustainable energy supply;
- Interaction in terms of sharing experience, practices, and technologies in the field of energy efficiency, stimulating the development of alternative energy sources, and modernising infrastructure;
- Investment activities in the format of financing projects to improve energy efficiency, innovation progress, and modernisation;
- Intensification of integration into the single energy market and the development of practical international cooperation;
- Implementing integrated international institutional and regulatory provisions to ensure stability and transparency of the energy market, attracting the attention of foreign investors.

With the increasing dependence on digital technologies and the intensification of data storage on digital platforms, cybersecurity is positioned as a top-priority issue. Digital technologies now offer reliable solutions in this field, including encryption, artificial intelligence-based intrusion, and threat identification systems. They securely protect confidential information, strengthen protection against cyber threats, and prevent data leaks, which is especially relevant in the energy sector. Accordingly, these innovations must be embedded in the legislative framework.

The use of targeted digital technologies in the security field makes it possible to minimize financial losses from cyberattacks and ensure the integrity of financial systems. By allowing the automation of traditional risk management processes, they reduce human error risks, and by operating in real-time, they ensure the effectiveness and promptness of risk management actions. Blockchain technology guarantees unprecedented openness, accessibility, and transparent accountability in financial operations. With blockchain, it becomes possible to strengthen trust among stakeholders and minimize financial fraud.

Diversifying energy supply sources is a priority aspect of intensifying energy security today. Given Ukraine's European integration course, particular attention should be paid to analyzing the European Union's successful practical experience in energy security. The European community views diversification as a strategic priority, actively developing alternative routes and supplier networks. This approach allows for minimizing dependence on monopolists in the energy sector. The European Community promotes diversification through intensive renewable energy development, reducing the share of coal and nuclear energy, and implementing technologies for decommissioned energy sources.

For successful integration into the single European energy space, it is advisable to adopt standards, norms, and regulations that align with European norms, particularly in energy efficiency, market competitiveness, and transparency. It is necessary to intensify activities to diversify the energy supply through expanding cooperation and developing new transport routes. An essential prerequisite for sustainable energy security in the national space is the increase in energy awareness among society and the business sector, stimulation of the implementation of energy-efficient technologies and reduction of consumption, and enhancing the motivation for innovative activities in the energy sector.

Discussion

The analysis of the existing regulatory and institutional framework for ensuring financial security in Ukraine's energy sector highlights the need to optimise the system for forming financial security within the concept of flexible solutions to achieve the priority security objectives of the energy sector. The limitations in this area include the complexity of practically implementing European energy solutions within Ukraine's national socio-economic context and the constraints on diversification processes. One of the leading modern approaches to ensuring the financial stability of the energy sector is the concept of identifying it as a systemic phenomenon, advocating for the expansion of energy storage technology integration and its application in convergence with renewable energy sources (Babuta, Oswald and Janjeva, 2020; Klijn and Koppenjan, 2020; Lin and Raza,

2020). Some scholars consider *optimizing* the financial situation in the energy sector through large-scale integration into the global market environment with its network of renewable energy sources (Anwary, 2022; Bonavolontà and D'Angelo, 2021; Mandel and Irwin, 2021). At the same time, representatives of another scientific school (Østergaard *et al.*, 2020; Taghizadeh-Hesary and Yoshino, 2020) emphasize renewable energy in terms of energy democracy and sustainable development to accelerate the energy transition in developing countries.

Some contemporary scientists (Anton and Nucu, 2020; Khan *et al.*, 2020; Lüdeke-Freund, 2020) identify the main prerequisites for the formation and effective financial development of the energy sector as those that create the basis for an effective management paradigm of its functioning. Researchers (Kebede *et al.*, 2022; Sabbagh, 2023; Tan *et al.*, 2021) argue that the integration of European norms and requirements into the energy system of countries actively developing towards European integration is a farsighted strategy on the path to a sustainable development process.

Liu *et al.* (2022), while examining the recommendations of the UN General Assembly's SDG-7 on enhancing energy efficiency, propose exploring various innovative financing methods, including green financing, financial inclusion, and financial technologies. The authors verified the empirical role of these financial instruments in the energy efficiency of the E7 economies. The research results demonstrated a significant role for these financing methods in energy efficiency, with green financing showing the highest efficiency. The authors suggest reviewing the potential of financial technology (FinTech) and financial accessibility parameters, mainly green bonds, to achieve energy efficiency in the shortest possible time. The researchers also justify the need to develop favourable energy policies for providing green financing to energy systems.

At the same time, Shahbaz *et al.* (2021) present in their research the existence of a long-term relationship between renewable energy consumption and financial development. The empirical data convincingly show that financial development drives the growth in demand for environmentally clean energy sources. To achieve sustainable development goals, the researchers argue that governments should implement incentives and tax policies that increase enterprise demand for renewable energy sources and expand investment opportunities through public-private partnerships.

Ahmad *et al.* (2021) emphasize that the development of digital technologies and artificial intelligence has the potential to change energy supply radically. Intelligent software should autonomously control integrating energy supply, demand, and renewable energy sources into the energy network, *optimizing* decision-making and operations. The researchers explore the aspects of using artificial intelligence in producing solar and hydrogen energy, as well as managing demand and supply. Ahmad *et al.* (2021) argue that machine learning and artificial intelligence will play a crucial role in the future energy market, allowing for the maximum greening of energy production and consumption processes.

Overall, among the prospects for *optimizing* financial security in the energy sector, the following should be highlighted: the development of national potential in the context of renewable energy sources with active support from the global community, which

minimises dependence on imports and monopolists while ensuring sustainable energy supply; integration into the unified energy market; active investment activity; collaboration in exchanging experiences, practices, and technologies; and the implementation of international developments in energy standardisation, regulatory, and legislative policies.

Our study convincingly demonstrates that *optimizing* the institutional and regulatory framework for financial security in Ukraine's energy sector is a priority for socio-economic development and implementing energy and economic stability strategies.

Conclusion

The study aimed to analyse the existing regulatory and institutional framework for ensuring financial security in Ukraine's energy sector in the context of prospects for its improvement and addressing related challenges. This article explores the dynamics of external and internal conditions that currently define the specifics of energy security and necessitate a corresponding shift in the priorities of the paradigm of international economic relations. It has been established that the instability of the socio-economic and geopolitical situation, as well as the potential threat of risks and crises, requires the optimisation of the regulatory and institutional framework for forming financial security within the concept of flexible solutions to achieve the priority security objectives of the energy sector.

Ensuring the financial security of the energy sector involves integrating into the European energy space, achieving sustainable energy independence, enhancing energy efficiency, and utilising renewable energy sources, as well as strategies for diversification and cooperation between Ukraine and the developed international community, require the optimization of the institutional and regulatory framework for financial security in the energy sector. Financial security in the energy sector is complex and requires activating the unified energy market, fostering international cooperation, and harmonizing national legislation with European standards. Ukraine's integration into the single energy space of the EU and investment support from the international community are considered prerequisites for Ukraine's intensive progress during the post-war recovery period. Prospects for further development of the research topic include extended analytics of digital potential for modelling financial and economic security strategies in the energy sector.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	Author 1	Author 2	Author 3	Author 4	Author 5
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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To see original copy of these declarations signed by Corresponding/First Author (on behalf of other co-authors too), please download associated zip folder [Declarations] from the published Abstract page accessible through and linked with the DOI: <https://doi.org/10.33002/nr2581.6853.0703ukr16>.

Assessing the Impact of Green Taxation Policies on Sustainable Growth

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Abstract

The experience of implementing "green" taxation in the financial processes of developed countries in the European Union encourages advanced companies to actively adapt their business strategies to the requirements of environmental taxes. Modern business giants actively invest in renewable energy sources, which helps reduce their negative environmental impact. The article carefully examines how a "green" taxation system affects sustainable development during rapid globalisation from 2020 to 2024. We reviewed the environmental taxes introduced in the world's most developed regions, such as the European Union, the USA, and China. We evaluated the effectiveness of reducing greenhouse gas emissions during the study period. In particular, we describe the modernisation of the industrial sector of these countries and the introduction of carbon capture and storage technologies. The importance of legal regulation and government initiatives is also emphasised: the European Green Deal, the Green New Deal in the US and the actions of the Ministry of Environmental Ecology of China. In countries with a lower level of development, there are three barriers – lack of finance, legislative norms and limitations of technological capabilities. The article also analyses international cooperation to achieve sustainable development goals established by the Paris Climate Agreement. It highlights how the EU states adjust their tax systems to global environmental standards – in full compliance with the directives of the European Commission. The critical role of international organisations in supporting cooperation between countries to increase the efficiency of environmental taxation and the development of renewable energy is considered separately.

Keywords

Green taxation; Sustainable development; Environmental taxes; Renewable energy; Environmental sustainability; Global cooperation

Introduction

Environmental problems have become global, threatening natural resources, biodiversity and climate stability. Accelerating climate change has led to a 1.1°C increase in the global average temperature compared to pre-industrial levels (Ayodele, Mustapa and Ayodele, 2023). Warming causes natural disasters, droughts, floods and storms. According to the United Nations, more than 1 billion people live in areas affected by climate change. These developments underscore the importance of sustainable development, which aims to balance economic growth, social equity, and environmental preservation for future generations for future generations. This concept is crucial for the long-term sustainability of society and ecosystems (Soares, 2024). Australia's bushfires in 2019–2020, which destroyed more than 18 million hectares of forest, clearly demonstrate the scale of the environmental crisis. Similar ecological challenges observed between 2021 to 2023 further highlight the urgency of collective global efforts (Tomás *et al.*, 2023).

The "green tax" introduced by the G7 nations following their 2015 summit in Germany, has become vital in reducing carbon emissions (Farooq *et al.*, 2024). By imposing financial incentives to reduce greenhouse gas emissions, these taxes encourage the adoption of renewable energy and cleaner production processes. The carbon tax in Sweden is 137 euros per tonne of CO₂ and forces industrial enterprises to switch to renewable energy sources (Ayodele, Mustapa and Ayodele, 2023). As a result of an effective, sustainable development policy, this has reduced emissions by 25% since 1990. Green technologies include using renewable energy sources, the most popular of which are solar, wind and hydroelectric power. Energy-saving solutions are used for efficient operation by installing heat pumps and energy recovery systems. European companies are changing their policies by implementing energy-efficient projects. They are interested in improving their image and reducing waste (Dvigun *et al.*, 2022).

Digital technologies are essential in implementing and effectively managing green taxation by monitoring, tracking and calculating environmental indicators (Lemos, Dinis and Serra, 2023; Liu and Ge, 2023). One of the tools for sustainable development is emissions monitoring systems (EMS), which are used in industrial sectors to measure greenhouse gas emissions accurately. The e-PRTR (European Pollutant Release and Transfer Register) platform is widely used in the European Union. It automatically collects data from businesses and allows regulators to monitor compliance with environmental standards. In 2023, blockchain technologies will actively ensure emissions trading and carbon credit accounting transparency. In China, blockchain monitors emissions under the national emissions trading system (Farooq *et al.*, 2024).

Despite the relevance of the issue, there are several research gaps regarding the discussed aspects in the context of Ukraine. Among these gaps are the role of environmental taxes in promoting the transition to renewable energy sources, the potential for increasing environmental taxes, and their impact on sustainable development, accompanied by a detailed analysis of relevant legislative initiatives. This article examines the impact of environmental taxation on sustainable development in response to modern environmental challenges. It focuses on analyzing the legislative framework regulating

environmental taxes in leading countries worldwide and assessing the effectiveness of these taxes in reducing greenhouse gas emissions.

The primary objective is to study public policy and international cooperation, particularly the Paris Climate Agreement and the European Emissions Trading System, and to determine their impact on ensuring environmental sustainability.

Literature Review

Research on the impact of green taxation on sustainable development has become particularly relevant in recent years amid global climate change and environmental challenges. According to Cheng *et al.* (2024), the green tax is vital in reducing carbon emissions and transitioning to renewable energy sources. Tomás *et al.* (2023) emphasise that the European Union countries have achieved a 15% reduction in greenhouse gas emissions from 2010 to 2020. Using carbon storage technologies – CCS and investments in solar and wind energy help reduce emissions and improve the energy efficiency of enterprises.

Modernisation of industrial processes contributes to a more rational use of energy resources. A study by Ayodele, Mustapa and Ayodele (2023) focuses on the impact of environmental taxation on companies' business strategies. As the researchers note, introducing carbon taxes encourages companies to invest in "clean" technologies. Green taxation provides clear financial benefits for businesses. They note that companies adopting sustainable technologies see a 20% reduction in operational costs due to lower environmental and financial liabilities. This taxation model encourages investment in eco-friendly practices, aligning corporate goals with environmental sustainability. Fernandez and Haffner (2024) discuss the impact of the European Green Deal, aiming for carbon neutrality by 2050. The European Emissions Trading System (ETS) and standards like ISO 14064 help monitor emissions. Between 2010 and 2020, the EU saw a 15% reduction in CO₂ emissions, with €300 billion invested in renewable energy projects. Borrego and Carreira (2023) highlight that carbon taxes have become crucial for cutting emissions. Future reforms may expand these taxes to under-regulated sectors like aviation and shipping by 2025. The Clean Development Mechanism (CDM) under the UNFCCC is expected to play a significant role in global cooperation after 2025, driving progress towards the Paris Agreement targets.

Afshan and Yaqoob (2023) underscore the effectiveness of "green" taxes and subsidies in Scandinavian countries. According to the opinions of prominent scientists, this has led to a significant reduction in air pollution. They note that subsidies for renewable energy sources have significantly contributed to this progress. Scientific works emphasise the importance of "green" taxation as an effective mechanism for reducing the industry's negative environmental impact. Researchers agree that "environmental taxation" stimulates companies to improve production processes. In their study, Nchofoung, Fotio and Miamo (2023) show that tax incentives increase investment in renewable energy sources.

As a result, the process of greening the industry is accelerating. Tax incentives are used by the most developed companies in the world: Tesla, Vestas Wind Systems, and BYD.

They implement them to expand the production of renewable energy and develop environmental technologies. According to researchers, thanks to such benefits, enterprises reduce their operating costs by 20% due to implementing energy-efficient technologies (Nchofoung, Fotio and Miamo, 2023). Dong, Hou and Qin (2023) emphasise the importance of government programs supporting "green" innovation. They have become the driving force behind business strategies focused on sustainable development in the chemical and energy industries. This allows companies to remain competitive and promotes their transformation into environmentally conscious business entities (Dong, Hou and Qin, 2023).

Amores, Maier and Ricci (2023) note that the European Union has adopted several important pieces of legislation – regulating emissions trading and establishing a minimum rate of environmental taxes. These regulations allow member countries to coordinate their efforts and ensure a stable cash flow for environmental initiatives. Investing in clean technologies plays a critical role in reducing pollution. According to Amores, Maier and Ricci (2023), this shift towards sustainable practices has led to a 25% reduction in industrial emissions across multiple sectors. Soares (2024) argues that well-structured environmental taxation laws can lower emissions by an additional 10% within five years while boosting economic growth. Tax breaks for green technologies, implemented by various countries since 2018, have driven a significant rise in eco-friendly innovations. For example, Germany recorded a 15% rise in renewable energy investments, driven by such incentives. Soares (2024) also emphasises that regulatory frameworks must evolve to keep pace with technological advancements, encouraging further innovation in sustainable practices.

Several recent studies provide summaries of the main concepts of current scientific advancements on the studied topic and their correlation with the present research findings. Specifically, recent publications by Ullah *et al.* (2023) illustrate the contemporary context and confirm the relevance of the current work to prevailing trends in this field. Researchers Abbasi and Choukolaei (2023) examine the specifics of designing a green supply chain network design (GSCND) from 2010 to 2023, analysing the impact of carbon regulations on GSCND. They highlight three policy vectors: carbon restrictions, cap-and-trade, and carbon taxes. Additionally, Dogan, Hodžić, and Fatur Šikić (2022) argue that renewable energy should receive greater priority through research support, subsidies, and governmental incentives, while environmental taxes should be more widely implemented to discourage polluting activities. Contemporary researchers Sharif *et al.* (2023) confirm the role of "green" technologies, environmental taxes, and "green" energy in sustainable environments and discuss their policy implications. Their findings complement the conclusions of the present study.

Research Methods

Design and scope of the study: The study analyses the experience of developed countries in implementing "green" taxation, with a special emphasis on the countries of the European Union. Developed companies actively adapt their business strategies to meet the requirements of environmental taxes: Tesla and Vestas Wind Systems. They also actively invest in renewable energy sources, which helps reduce their negative impact on the environment.

Data collection and sources: The sample consisted of 27 EU member states as of 2024, which apply different models of legal regulation of environmental taxes, including carbon emissions, energy resources and water pollution. Four methods of statistical data processing were used: (i) including tax classification by category, (ii) analysis of the dynamics of tax revenues for 2013–2022, (iii) comparison of tax regimes in different EU countries, and (iv) comparative legal analysis methods, to identify differences in environmental taxation legislation between countries. Casual effect analysis revealed the relationship between environmental taxes and greenhouse gas emission reductions. Trend analysis was used to substantiate the conclusions.

Analytical framework and methods: Essential methods for establishing causal links between environmental taxes and reducing greenhouse gas emissions included analytical approaches, such as analysis, synthesis, generalisation, comparison, and abstraction. Induction was also used — a method of scientific inquiry aimed at identifying causal relationships between phenomena and generalising empirical data based on logical assumptions, moving from specific to general, from known to unknown.

Statistical methods in the context of achieving the research objectives enabled the systematisation and generalisation of all information about the studied objects and phenomena, including positive aspects and shortcomings. They also facilitated drawing parallels between the essence and purpose of the studied object or phenomenon and the results of its functioning.

To address the specific parameters for assessing the impact of green taxation policies on sustainable growth, the review involved a comprehensive analysis of scholarly articles published across various academic sources. The literature was selected from high-impact journals indexed in prominent databases such as Web of Science, Scopus, and Google Scholar to ensure the reliability and credibility of the findings. The papers covered a timeline from 2018 to 2023, focusing on recent developments and trends in green taxation and its influence on sustainable growth. This timeframe allowed for a detailed understanding of policies' evolution and long-term impacts. The analysis included studies from different geographical contexts, ensuring a diverse and holistic perspective on the effectiveness of green taxation across various regions and economies.

The article examines the strategic documents – the European Green Deal and the Paris Climate Agreement – that shape the climate leadership of the EU countries. Special attention is paid to government programs that promote the development of clean technologies and stimulate environmental innovation.

Evaluation criteria: The research is limited by the lack of access to comprehensive and up-to-date official data and the complexity of experimentally verifying theoretical conclusions. To study the approaches to green taxation, the authors analysed research papers focusing on environmental taxes' impact on sustainable development (*et al.*, 2024; Fernández, Haffner and Elsinga, 2024; Zhang *et al.*, 2023; Farooq). Particular attention was paid to studies that consider the role of tax mechanisms in ensuring environmental sustainability at the regional level and their impact on the transition to renewable energy sources. Special attention was paid to analysing legal regulations, such

as the EU Directives on the taxation of energy products and electricity, which play a crucial role in implementing environmental taxes.

The criteria for selecting the literature encompassed a range of factors, including the quality of the journal (targeting those within Q1 and Q2 quartiles based on the SJR index), relevance to central themes such as "green taxation," "sustainable growth," and "environmental policy," as well as the presence of peer-reviewed content. Furthermore, the methodology employed a systematic review approach, incorporating elements of meta-analysis where applicable, to quantify and evaluate the effects of these policies comprehensively.

Results

Green taxation has become a powerful tool for pushing businesses to minimise environmental impact. This approach gained momentum in the 1990s when organisations like the OECD and the European Union started exploring how tax systems could be reformed to address sustainability. The foundation of this idea can be traced back to the 1920s when economist Arthur Cécile Pigou suggested taxing industries for the damage they cause to the environment. These concepts evolved to tackle modern issues like climate change and pollution.

The European Union began to take significant steps toward green taxation in the 1990s. In 2003, the EU introduced Directive 2003/96/EC, which placed taxes on energy and electricity consumption to reflect their environmental impact (Dinis *et al.*, 2023). The primary objective was to decrease the use of fossil fuels and promote the adoption of cleaner energy sources. This system provided a structured approach for controlling emissions across EU member states. The signing of the Paris Climate Agreement in 2015 emphasised the need for green taxes to achieve global targets for reducing greenhouse gas emissions (Sharif *et al.*, 2023). All the main legislative acts and international agreements related to green taxation are presented in table 1.

As of 2024, "green" taxation has already become an important component of tax systems in many developed countries, including Germany, France, Sweden, and Denmark.

Green taxation aims to reduce the environmental impact of economic activity and finance environmental programmes. In 2019, the European Union collected more than €330 billion from environmental taxes, which amounted to 2.4% of EU GDP. Many of these funds are directed to developing environmentally friendly technologies and saving energy. In Sweden, carbon tax revenues subsidise electric vehicles and renewable energy sources. The green tax actively supports programmes to modernise buildings and energy infrastructure in Germany. As in Denmark, revenues from environmental taxes can be used to compensate for reducing the tax burden on labour resources.

The European Union has consistently pursued ensuring a sustainable environment by implementing strict regulations and programmes. According to the European Green Deal, adopted in 2019, EU member states will achieve climate neutrality by 2050 by reducing greenhouse gas emissions (Nazarkevych and Sych, 2023). Scientists predict an approximate level of 55% by 2030 compared to 1990. One of the critical tools for

achieving this goal is emissions trading under the European Emissions Trading System. It covers over 10,000 companies and helped reduce emissions by 35% between 2005 and 2020. EU countries are investing billions of euros in infrastructure development for renewable energy and environmental modernisation of industry (Redko *et al.*, 2023). The overall status of the green tax is shown in figure 1.

Table 1: Legislative Acts and International Conventions on Green Taxation 1992–2024

<i>Year</i>	<i>Document</i>	<i>Countries and organisations</i>	<i>Provisions</i>
1992	United Nations Framework Convention on Climate Change (UNFCCC)	UN	Recognition of the need to reduce greenhouse gas emissions at the international level
2003	Directive 2003/96/EC	European Union	Taxation of energy products and electricity to stimulate energy efficiency
2005	European Emissions Trading System (EU ETS)	European Union	Implementation of an emissions allowance system and emissions trading
2012	Kyoto Protocol (completion of the first phase and new commitments)	UN, member states	Commitments of countries to reduce emissions under the agreements
2015	Paris climate agreement	UN, member states	Setting emission reduction targets to limit global warming
2020	European Green Deal	European Union	Strategy for achieving climate neutrality and introducing additional environmental taxes
2021	Global minimum emissions tax (COP26 decision)	UN, member states	Establishing common standards for environmental taxation worldwide
2022	European climate law	European Union	Legal obligation to achieve climate neutrality by 2050, introduction of the CBAM mechanism
2023	Expansion of the European Emissions Trading System (EU ETS)	European Union	Expanding the system to new sectors of the economy, including maritime transport and construction
2024	Updated goals of the Paris Agreement and expansion of financing mechanisms	UN, member states	Setting new emission reduction targets by 2030 and boosting green finance

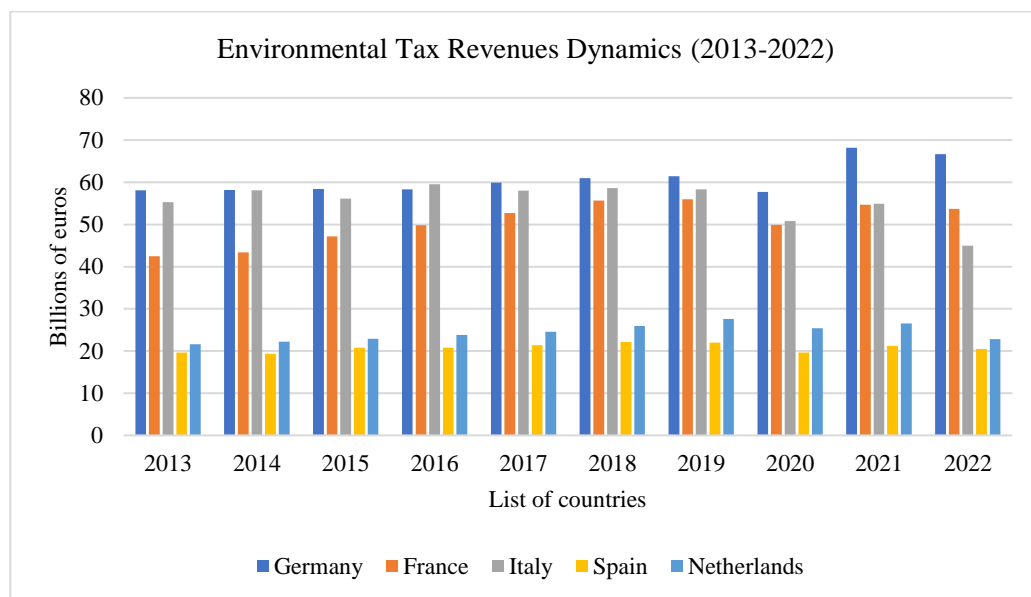


Figure 1: The Largest European Countries by the Amount of Green Tax Payments in 2013–2022, billion euros (Eurostat, 2024)

Green taxation is critical in ensuring sustainable development, as it creates financial incentives for economies to shift to greener models. The primary causal mechanism is to shift the burden to those industries and businesses that produce pollution. This forces companies to look for alternative ways to produce with a lower carbon footprint or to use environmentally friendly technologies (Balci *et al.*, 2024). Shell is investing heavily in hydrogen and solar energy to reduce its dependence on fossil fuels. International corporations Siemens and Vestas are actively implementing wind farms and other renewable energy sources, reducing their carbon footprint and adapting their business models to new environmental requirements.

A comparison of the legal features of green taxation regulation is provided in table 2.

Table 2: Regulation Legal Peculiarities of Green Taxation Worldwide

Country	The rate of “green” taxes	Regulatory authority	Title of the law
Germany	€30 per tonne of CO ₂ (carbon tax) from 2021, with plans to increase to €55 by 2026.	Federal Ministry of Finance	Law on trading in CO ₂ emission allowances (Brennstoff emissions handels gesetz, 2019)
France	€44.55 per tonne of CO ₂ since 2014, covering 35% of greenhouse gases.	Ministry of Environmental Transformation	Law on the Environmental Transition (Loi de transition énergétique, 2015)
Netherlands	€51.07 per tonne of CO ₂ from 2021, a tax	Ministry of Finance	Law on CO ₂ tax (Wet blasting op CO ₂ , 2020)

<i>Country</i>	<i>The rate of "green" taxes</i>	<i>Regulatory authority</i>	<i>Title of the law</i>
	on large industrial companies.		
China	Green tax on SO ₂ and PM emissions in different sectors, focus on industry and power plants.	State Administration of Taxation of China	Environmental Protection Tax Law, 2018
USA	Carbon tax in some states, the rate varies by state (e.g. California – \$20/tonne)	Environmental Protection Agency (EPA)	Market-Based Emissions Legislation (2017)

Global agreements and joint projects significantly strengthen international cooperation in sustainable development and green economy (Maina, 2023). The Paris Climate Agreement, signed in 2015 by 196 countries, has become a key instrument for coordinated action to reduce greenhouse gas emissions. The European Green Deal project was launched in 2019 and involves European countries and international partners in jointly developing renewable energy technologies, infrastructure modernisation and reducing dependence on fossil fuels (Soares, 2024). Cooperation between countries is manifested in creating funds to support decarbonisation projects, including the Green Climate Fund (GCF), which raised more than USD 10 billion in 2016–2020 to finance environmental projects in developing countries (Maina, 2023).

In Sweden, a carbon tax has been in place since 1991, which has made it possible to reduce CO₂ emissions by 25% by 2020. Funds received from environmental taxes are directed to the development of infrastructure projects: modernisation of public transport and critical infrastructure (Ullah *et al.*, 2023). In 2022, Volvo introduced electric buses in Swedish cities. Modernisation of buses has become an essential step toward reducing emissions in the transport sector. Nestlé took advantage of tax incentives in 2023 to invest in water treatment systems at its factories and significantly reduced the use of fresh water. Environmental taxes influence the behaviour of market participants by directing resources to environmental initiatives and strengthening economic resilience in response to environmental challenges (Soares, 2024). However, approaches to "green" taxation vary significantly in different countries depending on economic, social, and political factors. One feature of the United States is the lack of a national carbon tax policy, which has led to a fragmented approach (Ullah *et al.*, 2023).

California has implemented its own emissions tax and a trading system that directs funds to finance environmental projects at the state level. China, the world's largest producer of carbon dioxide emissions, launched a national emissions trading system in 2018, which currently only covers the energy sector (Dvigun *et al.*, 2022). Climate change leads to sea level rise, loss of biodiversity, and degradation of ecosystems. Given the complexity and importance of these issues, international organisations insist on developing common standards and goals in environmental taxation.

One of the essential tools is carbon taxes, which incentivise businesses to reduce emissions. However, different countries prefer their approaches depending on the level of economic development. The USA mainly implements regional initiatives. Europe focuses on pan-European programs, while China implements a centralised system. Coordination between different jurisdictions in the legal field remains challenging for several reasons: different standards, tax rates and compliance mechanisms. Despite these differences, the international community continues to develop new tools to address climate change through taxation and emission quotas.

The European Union countries are leading the way in implementing green taxation, as evidenced by the consistent growth in environmental tax revenues, which peaked in 2019 at EUR 330.85 billion. The overall dynamics are shown in figure 2. From 2013–2022, taxes increased yearly, except in 2020, when they declined to EUR 301.69 billion due to the COVID-19 pandemic and the economic slowdown. The LIFE programme was launched in 1992 and continues to finance innovative environmental projects, allocating €3.4 billion for environmental initiatives until 2024. Thanks to international coordination instruments, the European Union remains a leader in developing a green economy and taxation.

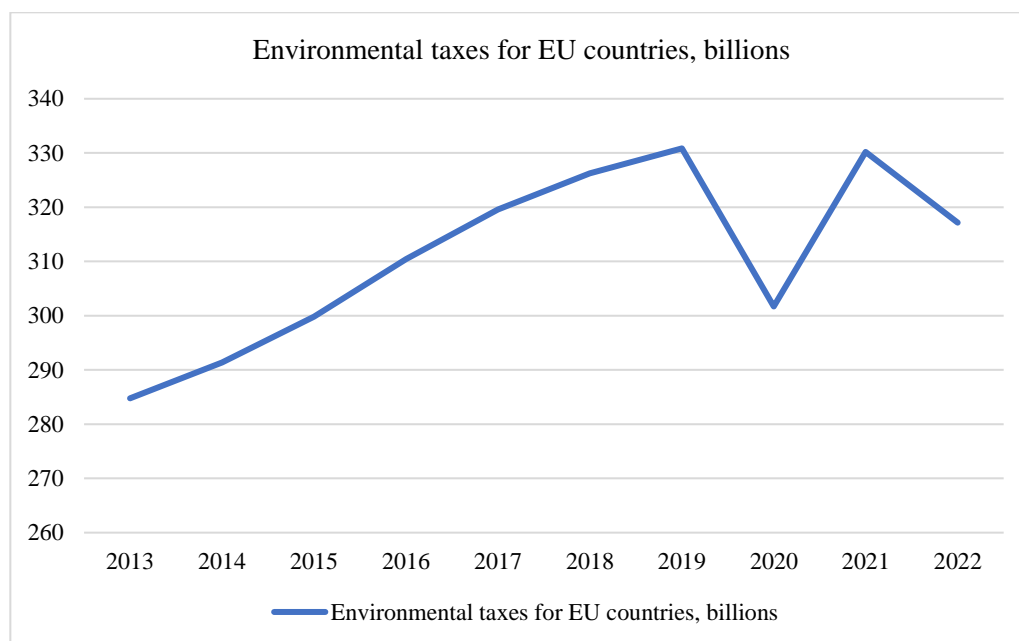


Figure 2: Total environmental taxes collected by EU countries, 2013–2022 (Eurostat, 2024)

Figure 2 presents current trends in environmental tax revenues over the past decade. Notably, the sharp downturn observed in 2020 due to the COVID-19 pandemic, underscores vulnerabilities in the tax system's dependency on economic stability. The consequences of this decline pose a substantial burden for future tax policy. Amid the shift in focus on sustainable development during the pandemic, there was some suspension of active processes in the greening of the tax system. However, this period

highlighted pressing issues in the researched area, which drew maximum attention to them in the post-COVID regeneration of societal processes.

The introduction of green taxation in Africa and developing countries has significant potential to advance environmental sustainability in these regions. South Africa, Kenya and Nigeria plan to introduce more structured environmental taxation systems by 2030 (Bala and Khatoon, 2024). South Africa has had a carbon tax in place since 2019, which has already contributed to a 2.6% reduction in emissions in its first year of operation. Nigeria plans to introduce taxes on fossil fuel extraction and water pollution by 2026, which should provide an additional \$500 million for environmental projects annually (Bala and Khatoon, 2024). The World Bank and the United Nations Environment Programme actively support developing countries by providing technical assistance and funding for developing a green economy. By 2030, Africa plans to raise more than \$1 trillion to finance renewable energy projects. Solar and wind farms will become critical factors in the fight against climate change and regional economic stability for all countries shortly (Maina, 2023).

In the EU countries, economic instruments, including tax policy, are primarily used to achieve environmental goals. Some countries implement a "tax punishment" policy or invest in environmental projects. The most effective system is in the Baltic countries, where environmental taxation focuses on increasing efficiency and protecting natural resources (Juškaitis, 2023).

There are about 500 types of environmental taxes globally, with goals and overall effectiveness varying wildly among countries. Transport taxes (72% of environmental taxes) and energy taxes (23%) are the most common in Europe. European countries primarily focus on taxing energy carriers, which significantly boosts the effectiveness of their environmental taxation (Zhao *et al.*, 2023). The strategies and outcomes of leading companies regarding "green" taxation differ considerably. Shell, for example, is transforming its business to focus on low-carbon solutions (LCS) to strengthen its operations in core sectors with low carbon emissions, such as transport and industry. LCS operations include hydrogen and other businesses aiming to decarbonise the transport and industrial sectors, though they do not include renewable energy businesses (Green Jiraffe Advisory, 2021).

Companies in the "green" economy, with a significant portion of their income from "green" businesses, include Tesla, Waste Management Inc., Microsoft, Siemens, and others. Siemens Gamesa (Spain) is one of the world's largest wind turbine manufacturers. This approach utilises a model where foreign turbine manufacturers provide technology, while local companies support with production capacity, impacting environmental taxation (Ullah *et al.*, 2023).

The Volvo Cars sustainability team celebrates its inclusion in the "Climate Change" category of CDP's 2023 report. As one of the first in the automotive industry, Volvo Cars has ended production of models with diesel engines, an announcement made during Climate Week in New York in September 2023. Volvo plans to fully transition to electric vehicles and create climate-neutral production to achieve net-zero greenhouse gas emissions by 2040 (Volvo, 2024).

Discussion

The primary aim of the study was to analyze public policy and international cooperation, particularly the Paris Climate Agreement and the European Emissions Trading System. The objective was to determine their impact on ensuring environmental sustainability. The research on the impact of environmental taxation on sustainable development in response to modern environmental challenges focuses on analyzing the legislative framework regulating environmental taxes in leading countries worldwide and evaluating the effectiveness of these taxes in reducing greenhouse gas emissions.

The results obtained on the impact of green taxation on sustainable development confirm its importance as an effective tool for reducing greenhouse gas emissions and promoting environmental sustainability. Our findings align with Bala and Khatoun (2024), who report that the introduction of a carbon tax in the EU led to a 15% reduction in CO₂ emissions over the past decade. Similar to the results of Singh and Gahlot (2023), who found that tax incentives promote the transition to renewable energy sources and reduce dependence on fossil fuels. Mia, Islam and Rahman (2023) further confirm our findings, showing that green taxation facilitates the modernisation of industrial enterprises.

Our study also supports the findings of Du and Li (2024), regarding regulating environmental taxation in different regions of the world. We observed that the implementation of the European Emissions Trading System – ETS contributed to a 35% reduction in emissions between 2005 and 2020, consistent with the data reported by Yao and Jin (2024). Additionally, our results support Mehboob *et al.*'s (2024) emphasis on the critical role of international coordination in achieving global environmental goals. Our collected data support the findings of Hu and Gu (2024) that environmental taxation stimulates innovation and promotes the growth of investment in clean technologies.

Analysing the study's results by Dinis *et al.* (2023), we also found that digital technologies significantly increase the transparency and efficiency of environmental tax management. This correlates with the study of Fang, Yang and Huang (2023), who highlight that digital tools are vital to monitoring tax revenues and supporting international emissions regulation systems. It is interesting to note that Nazarkevich and Sych (2023) indicate an additional advantage of "green" taxation – the creation of new jobs in the renewable energy sector, which once again emphasises the multiplier effect of this policy. Considering all the above conclusions, the green tax is a powerful tool: it stimulates the ecological modernisation of the economy, contributes to the reduction of emissions, the development of innovations and international cooperation in the fight against climate change.

The discussion on the economic, social, and political barriers to implementing a "green" taxation system allows for a balanced perspective on the development of the phenomenon under study. Specifically, in the work of Zhao *et al.* (2023), the practical impact of government subsidies and tax reductions on the efficiency of companies' investments in renewable energy is explored using panel data from Chinese companies in the renewable energy sector. The authors focus on the impact of pandemic-related factors and the resulting socio-economic and political aspects, which are seen as particularly relevant as determinants influencing the "green" taxation system in the future.

The Paris Agreement is a crucial foundational document for international climate change cooperation. However, for its successful implementation and tangible results, both effective motivational factors (including financial mechanisms) and significant sanctions or measures to monitor the fulfilment of declared commitments are necessary. Only then will the agreement truly function. The role of transport taxes (72%) and energy taxes (23%) in Europe is reflected in their contribution to reducing emissions. The multiplier effect of green taxation is also evident in job creation, which is particularly relevant in the context of developing countries. The differences between voluntary green taxation mechanisms and mandatory tax policies primarily lie in their effectiveness. Coercive policies have a relatively immediate impact, whereas voluntary taxation mechanisms have a prolonged positive influence and significant long-term potential. Notably, EU policy is characterized by voluntary mechanisms, motivation, and incentives. In contrast, the policies of developing countries are based on mandatory taxation and strict control.

The study is limited by the lack of access to complete and up-to-date official data and the challenges of experimentally verifying theoretical conclusions.

Conclusion

The "green" taxation has become an essential tool for stimulating environmental sustainability and the development of renewable energy sources. The European Union has demonstrated in practice how carbon taxes and quota trading systems reduce dependence on fossil resources and reduce CO₂ emissions. Legislative initiatives stimulate businesses to invest in ecologically "clean technologies". Strict legal regulation stimulates enterprise adaptation to global environmental needs. Developed countries have achieved significant results in implementing emissions taxes, but less well-off countries continue to face difficulties in this process. Achieving global environmental goals requires much greater international cooperation and financial assistance. According to the World Bank, using digital technologies to monitor emissions and tax revenues will reduce emissions by 25%. Future success depends on further improving legal mechanisms and implementing best practices of the green economy among the G7 countries by 2030. Thus, further research should focus on developing innovative digital monitoring technologies and creating flexible legal frameworks to better respond to global environmental challenges. In the context of the future scientific development of the researched topic, there is a clear need for expanded analysis of the dynamics of socio-economic and political vectors. As examined within the scope of the current study, these factors are considered to be determinants in shaping the outcomes of environmental taxation policy. In light of the conclusions reached, policymakers and managers should explore opportunities to encourage decarbonisation processes and prevent environmental degradation through fiscal policy tools in a "green" format. In this regard, particular importance should be given to a system of incentives and activating investment projects.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis and interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	No	No	No
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	No	Yes	Yes	No	Yes
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Ensuring Sustainable Development of the Agricultural Sector through Financial Instruments in the Context of Climate Change

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Abstract

Climate change significantly impacts the agricultural sector, causing reduced yields and deteriorating growing conditions. There is an urgent need to make agriculture more climate-resilient conditions to ensure food security and sustainable development. The research assesses the effectiveness of financial instruments in adapting agriculture to climate change. We performed an in-depth literature review, economic and environmental analysis, and comparative analysis of various financial instruments. The results show that green bonds and investment funds demonstrate the highest economic efficiency and significant investment volume in sustainable technologies. Crop insurance and credit programmes reduce farmers' financial risks, contributing to their income stability. Subsidies and grants facilitate the introduction of new technologies and adaptive measures, increasing farmers' productivity and incomes. Environmental sustainability is achieved through green bonds and subsidies, which help reduce carbon emissions and improve the state of the environment. However, insufficient awareness, difficulties accessing finance, and the lack of effective climate risk assessment models remain significant obstacles. Solving these problems requires a comprehensive approach and cooperation between the public and private sectors. The practical significance of the results lies in developing recommendations for improving the use of financial instruments to enhance the resilience of agriculture to climate change.

Keywords

Climate change; Financial instruments; Sustainable development; Green bonds; Crop insurance; Economic efficiency; Environmental sustainability; Agricultural risks; Cultivation technologies

Introduction

Climate change is a major challenge for the agricultural sector and affects yield, exacerbates resource scarcity and increases the volatility of growing conditions. But the global temperature is on the rise, the precipitation patterns are becoming unpredictable and extreme weather events are increasing risks for farmers, not least to a farming practice that once seemed sustainable. The consequences of such a reality adapt agricultural systems to the new climatic reality crucial for the realization of food security and economic stability. Climate change is one of the most severe threats to the agricultural sector, leading to reduced yields, increased frequency of extreme weather events, and land degradation (El-Khalifa *et al.*, 2022). Under such conditions, farmers face growing financial risks and uncertainties, emphasising the need to adapt and implement effective financial instruments (Frija *et al.*, 2021). Traditional farming methods are becoming less sustainable and require significant changes to maintain productivity and ensure food security (Jiang *et al.*, 2020). Implementing crop insurance, subsidies, grants, credit programmes, and green bonds can mitigate climate change's negative impact and provide farmers with economic stability (Govind, 2022).

However, despite the potential of these financial instruments, their application in the agricultural sector remains limited due to insufficient awareness, lack of access to finance, and difficulties in assessing climate risks (Peker and Er, 2021). Additionally, existing crop insurance programmes often do not cover all farmers and small and medium-sized producers, reducing their effectiveness (Frija *et al.*, 2021). Similarly, subsidies and grants are not always aimed at supporting sustainable and environmentally friendly technologies, limiting their impact on improving environmental performance (El-Khalifa *et al.*, 2022). Credit programmes often face high interest rates and stringent conditions, making them inaccessible to many farmers (Peker and Er, 2021).

As a stimulus to sustainable development, financial instruments including crop insurance, subsidies, grants, credit programmes, green bonds and investment funds have emerged as potential tools for dealing with these challenges. Nevertheless, these instruments have much promise, but they too are constrained by factors, including limited access to finance, weak demand from clients and the lack of robust climate risk models. To fill these gaps, we have to draw a complete picture of the status of financial instruments as they presently exist and as to the extent, they contribute to building the resilience of agriculture to climate change. Meantime, region-specific adaptation and novel practices are needed to harness their full potential. This research seeks to close the policy-practice gap by offering evidence-based recommendations on how to optimise financial tools for sustainable agricultural development. Specifically, the study aims to build on prior program evaluations of finance and weather index insurance. This study addresses two critical questions through the analysis of both the current state of the agricultural sector and its vulnerability to climate change, evaluates the performance of existing financial instruments in incentivizing climate resilient practices, assesses their economic and environmental impacts, and offers meaningful recommendations for how to strengthen those instruments. This research addresses these goals and adds to the growing literature on sustainable agriculture by shedding light on how this can be achieved and offering practical guidance for policymakers and stakeholders.

This study sets out to achieve the following objectives:

- 1) To analyse the current state of the agricultural sector and identify the main problems associated with climate change;
- 2) To study the existing financial instruments and their application for adaptation of agriculture to climate change;
- 3) To identify key performance indicators of financial instruments in the context of the agricultural sector;
- 4) To assess the economic and environmental impacts of different financial instruments; and,
- 5) To propose recommendations for improving the use of financial instruments to increase the resilience of the agricultural sector to climate change.

Methodology

This study employs a mixed method to evaluate the usefulness of financial tools to improve the agricultural sector's resilience to climate change and sustainability. A mixed-method approach was used to leverage the analytic advantages of qualitative and quantitative data to give a comprehensive view of financial instruments and their uses. The strength of this methodology is that it allows for depth and breadth of analysis, however, the observational nature of this methodology is recognised as a limitation of this study.

We performed a structured review of existing financial instruments as applied to agriculture and their economic and environmental performance metrics such as profit margins, yield improvements and carbon savings per tonne-kilometer. This is augmented by case studies from countries most severely impacted by climate change, providing contextual depth. This rationale is based on its capacity to record multiple views and regional deviations in the use of financial instruments.

Literature Analysis

A systematic literature review was conducted to evaluate the impacts of climate change on agriculture and current financial approaches to support adaptation. The inclusion and exclusion criteria for each of the steps of this process were adhered to rigorously; peer-reviewed articles and reports published within the last decade with the greatest rigour were chosen for inclusion. Keywords such as "financial instruments in agriculture," "climate resilience," and "sustainability measures," were used to search databases such as Scopus, Web of Science, and Google Scholar. In relevance to such financial tools as green bonds, crop insurance, and investment funds, regions exposed to such climatic changes were targeted through a selection of studies.

Data Extraction and Analysis: The review then analyzed the selected studies based on key variables; the types of financial instruments, risk management strategies and their economic and environmental impact. Such an approach entailed a systematic synthesis of findings highlighting the most immediate and principal outcomes delivered by these instruments, which include increased agricultural yields, increased vulnerability, and enhanced environmental sustainability.

This literature analysis maintains methodological transparency and promotes reproducibility to offer a participating basis for what role financial tools play in reducing climate change challenges in the agriculture sector.

Economic Analysis

The economic analysis in this section examines whether, and to what extent, selected financial tools can aid the mitigation of the impacts of climate change on the agricultural sector. The following key metrics were analyzed to assess economic efficiency, with steps taken to account for external confounding factors such as market fluctuations, policy changes, and regional differences:

Yield and Productivity Metrics: Yield per hectare and productivity levels were monitored over different periods and compared with pre-implementation baselines. Average regional values were normalized and the data was adjusted for climatic, and market variables, to control for external factors.

Return on Investment (ROI): For each type of financial instrument, the amount the instruments would return compared to yield gains, the revenue generation the instruments provided for farmers, and the financial security they provide is calculated. To make the analysis as accurate as possible, the external variables were included such as subsidies, market demand and price volatility.

Financial Risk Mitigation: Each instrument's effectiveness in reducing financial risks; stabilizing incomes; and enhancing financial security was evaluated. One of those is to assess the extent to which different scenarios improve financial resilience. The relationships between financial resilience, climate resilience and specific financial interventions were explored through regression analysis. The dependent variables considered were yield stability, ROI and income fluctuation rates while independent variables were of the form of type of financial instrument, region-specific climate risk indices and farmer income levels.

Data Sources and Collection: Economic factors were derived from national agricultural statistical reports financial performance data and agricultural funding databases and used as secondary data. Trends in economic adaptation efforts were identified from cross-sectional and time series data. Patterns in yield stability, investment returns, and financial performance yielded as a response to climate adaptation strategies were specifically found for the time series data. Statistical controls were robust enough to avoid spuriousness by showing that external influences, such as market shocks or policy changes, were accounted for.

By accounting for these variables alongside external factors, this analysis investigates the economic consequences and effectiveness of applying financial tools to facilitate climate-resilient agriculture.

Environmental Assessment

Its environmental assessment is concerned with assessing the sustainability and ecological aspects of the application of financial instruments in the agricultural sector. This analysis examines the following key aspects:

Carbon Emissions Reduction: The impact contributions of each financial instrument – in particular, green bonds and subsidies—were examined by greenhouse gas emissions reduction. Modelling was done using sector-specific carbon offset metrics and sourced from verified environmental impact reports. An assessment was made of investment in green technologies such as renewable energy and cleaner production methods in terms of their impact on air quality and overall carbon footprint reduction.

Water and Soil Quality Metrics: Water use efficiency, pesticide reduction, and soil organic content were all indicators assessed. The empirical data for these metrics were collected during the observations of regional agricultural monitoring programs and validated using environmental models. We examined to what extent financial incentives contribute to more sustainable water management and reduced pesticide usage, and if these promising results are rather endogenous to agricultural sustainability.

Sustainable Technology Adoption: Crop rotation, use of organic fertilizers and lower-pressure irrigation were used to measure the adoption of sustainable practices. The data collection consisted of field surveys and agricultural extension reports relating to the uptake rates of such technologies under financial incentives and the proportional decrease of farmers' no financial incentive areas. To create the connection between the amount of financial investment and the speed of implementation of sustainable practice, metrics were modelled.

Environmental Data Sources: It gathered data on environmental impacts from established sources including environmental impact assessments, performance indicators on sustainability at the national agricultural database and State Statistics Service reports. Cross-referencing self-reported metrics with validated datasets with methodologies guaranteed reliability and accuracy.

As a result, this assessment bridges the gap between financial instruments and environmental outcomes by identifying a direct link between these financial instruments and measurable change in agriculture sustainability.

Comparative Benchmarking

To assess the efficiency of different financial instruments to enhance agricultural resilience to climate change, a comparative benchmarking analysis was conducted. For this, specific key performance indicators (KPIs), i.e. profitability (USD per hectare), yield (tonnes per hectare), percentage of financial risk reduction, investment in sustainable technologies (USD), and carbon emissions reduction (tonnes of CO₂ per hectare) were used. This framework was developed to allow for the quantitative assessment of the financial tools in terms of their economic and environmental implications.

Benchmarking Process: A first distinction is then made between risk mitigation, technology adoption, and environmental impact reduction financial instruments. Standardized metrics were used to evaluate performance within each category to assure comparability between instruments. The efficiency of the instrument groups was analyzed with statistical tools, including ANOVA tests, to compare their numerical results. By using this method, the most effective tools to face climate change were identified with insights about their respective strengths and weaknesses.

This benchmarking process produces results that match very well with the larger study objectives of identifying the financial instruments that provide the highest economic returns and lowest environmental costs. Actionable recommendations for policymakers to prioritize context-specific impact and efficiency of specific tools based on the results in this study.

Census Files and Tabular Survey

To support the identification of results, a rigorous statistical analysis was conducted. Quantitative data was collected and sourced from primary, secondary, and tertiary sources, covering crop yields, financial returns on investments, subsidies given, and environmental benefits attained. Key sources included:

- National and International Databases: The datasets were derived from the World Bank, FAO and Ministries of Agriculture of the countries in question.
- Regression and Time-Series Analysis: To examine causal factors, multiple regression models were employed in analyzing the extent of influences of financial instruments on the resilience of agriculture. Exploratory analysis also used time series data to capture patterns of productivity and financial solvency over the past 10 years, cyclical patterns and seasonal flukes that existed during that period.

Stratified sampling was used so that we could ensure high generalizability based on crop type and geographical location and even use particular financial instruments. Under this approach, a dataset representative of regional and sectoral contexts was captured. Established and reliable databases such as FAO, World Bank and national agricultural statistical agencies were the source of the data used. The data quality was validated by such measures as cross-referencing with secondary reports, and the outlier analysis was done to spot and correct inconsistencies. Key variables, such as financial tool types (specifically, green bond issuances, and subsidies), regional climate risk indices, and yield/output metrics were included and were included as pivotal variables within the regression model. Generalized linear models with robust standard errors were used to address heteroscedasticity and adjusted confidence intervals were derived. To test for the accuracy of the model, such diagnostic checks as variance inflation factors (VIF) were performed to check against multicollinearity. Finally, data integrity was maintained by the application of bias adjustments during pre-processing, e.g. normalization of monetary values across regions and inflation adjustments in time. Furthermore, the significance threshold for the study variables was set at. Yes, these were all statistically rigorous and had reliable outcomes, $p < 0.05$. The rigorous application of this method supports the finding that financial instruments are effective in the agricultural sector.

Results

It is known that the agricultural sector is significant for both the economy and food security of most countries, including Ukraine, where the weight of the agricultural sector to GDP and food security is high. But in the climate change context that the world is in presently, Ukraine's agricultural sector is underpinned by many difficult conditions, like declining yields, soils in poor condition and changing crop patterns. The urgent need for adaptation measures and the implementation of financial instruments specific to the challenges they pose, to ensure resilience and sustainability, are these (Bazaluk *et al.*, 2020).

Ukraine's use of crop residues for energy is being seen as a promising way of sustainable agricultural development. But this involves heavy investment, and a refocusing of resource management to maximize that potential in full (Jiang *et al.*, 2019). Water shortages and economic instability are a threat to the country's agricultural productivity, and thus the new technologies and financial instruments must be in congruence with regional particularities. Crop insurance and investment funds have been demonstrated to steady farmers' incomes and to promote the adoption of sustainable practices that are vital to mitigating the consequences of climate change.

Unlike many other countries, Ukraine faces unique and challenging structural barriers resulting from its dependence on traditional agricultural practices and the relative lack of access to innovative financial tools. Poland's agricultural sector has been successful in dynamically adjusting to changing climate conditions and maintaining its competitiveness in international markets using financial instruments (Misiąg *et al.*, 2020). Just as Tunisia and the MENA region have, the use of socio-economic measures and advanced technologies to reduce agricultural vulnerabilities has been employed (Govind, 2022; Frija *et al.*, 2021). But these examples show that for Ukraine to become more proactive and integrate financial instruments with targeted adaptation strategies it must do so.

According to current research, solutions developed specifically to address Ukraine's unique vulnerabilities, including water shortages, economic losses, and poor quality of soil, need to be tailored to the region. Focused on fostering investments in sustainable technologies and through increasing access to financial instruments such as green bonds, subsidies and crop insurance, Ukraine can not only increase its agricultural sector's resilience to climate change but also support rural livelihoods and economic development.

Changes in temperature and precipitation patterns are resulting in lower yields for many crops. In Egypt, for example, changing climate factors significantly impact agricultural productivity, requiring the development of adaptation strategies (El-Khalifa *et al.*, 2022). Climate change contributes to increased water scarcity, particularly noticeable in regions with limited water resources. The rational use of fresh water is becoming critical for agribusiness development in the face of the worsening climate crisis (Dvigun *et al.*, 2022). Climate change increases economic risks for farmers, leading to lower incomes and increased uncertainty in the production process. In Brazil, the agricultural sector

actively participates in international climate negotiations to minimise economic losses and adapt to changing conditions (Rodrigues *et al.*, 2019).

Adaptation to climate change requires the introduction of new technologies and significant investments. In Turkey, climate change affects the agricultural sector, highlighting the need for innovation and financial support for sustainable development (Peker and Er, 2021). Climate change is leading to soil degradation, which reduces soil fertility and the ability to support high yields. Modelling the environmental risk management system of agri-holdings about the values of sustainable development is becoming a key aspect in this context (Sumets *et al.*, 2022b). Climate change requires changes in the structure of crops grown to adapt to new conditions. In China, multi-sectoral efforts to adapt to climate change in the agricultural sector include revising cropping patterns and adopting sustainable practices (Jiang *et al.*, 2020).

Table 1 shows the impact of climate change on the yields of major crops in 2010–2022. The numbers in table 1 are a mixture of measured results and modelled projections gathered from field reports and climate simulation models. In particular, yields for 2010–2022 were extracted from national agricultural statistics and validated against modelled projections that represent the climatic variable effects of changes in temperature and precipitation. Data limitations include potential regional variation, reporting error, and uncertainty of long-term climate modelling. When interpreting the trends pictured in the table, these should be kept in mind.

Table 1: The impact of climate change on the yields of major crops

Year	Wheat (t/ha)	Corn (t/ha)	Soybeans (t/ha)	Rice (t/ha)	Barley (t/ha)
2010	3,5	4,2	2,8	5,0	3,2
2012	3,3	4,0	2,7	4,8	3,1
2014	3,2	3,9	2,6	4,7	3,0
2016	3,1	3,8	2,5	4,6	2,9
2018	3,0	3,7	2,4	4,5	2,8
2020	2,9	3,6	2,3	4,4	2,7
2021	2,7	3,4	2,1	4,3	2,5
2022	2,6	3,2	2	4,1	2,2

Sources: Jiang *et al.* (2019), El-Khalifa *et al.* (2022), and Misiąg *et al.* (2020)

The table provides data on the yields of major crops from 2010 to 2022, allowing us to trace the dynamics of changes over the past decade. The yields of all the crops presented have gradually declined, indicating climate change's negative impact on agriculture. For greater clarity, we present the results as graphs in figure 1.

Figure 1 shows real crop yields between 2010 and 2022 according to the measured data. Overall, the decline in wheat yields is stated in terms of 0.8 t/ha from 3.5: t/ha in 2010 to 2.7 t/ha in 2022. Corn yields fell from 4.2 t/ha in 2010 to 3.4 t/ha in 2022, soybean yields decreased from 2.8 t/ha to 2.1 t/ha, and rice yields from 5.0 t/ha to 4.2 t/ha. During the same period, the yields of barley also dropped from 3.2 t/ha to 2.5 t/ha. The values here are recorded trends, not projections, and all major crops maintain a consistent downward trajectory. Immediate adaptation measures are needed to minimize the impact

of climate change on the decline and to maintain production levels. This clarification elucidates the distinction between actual occurrences and expected outcomes, emphasizing that the data represents what happened rather than what should happen.

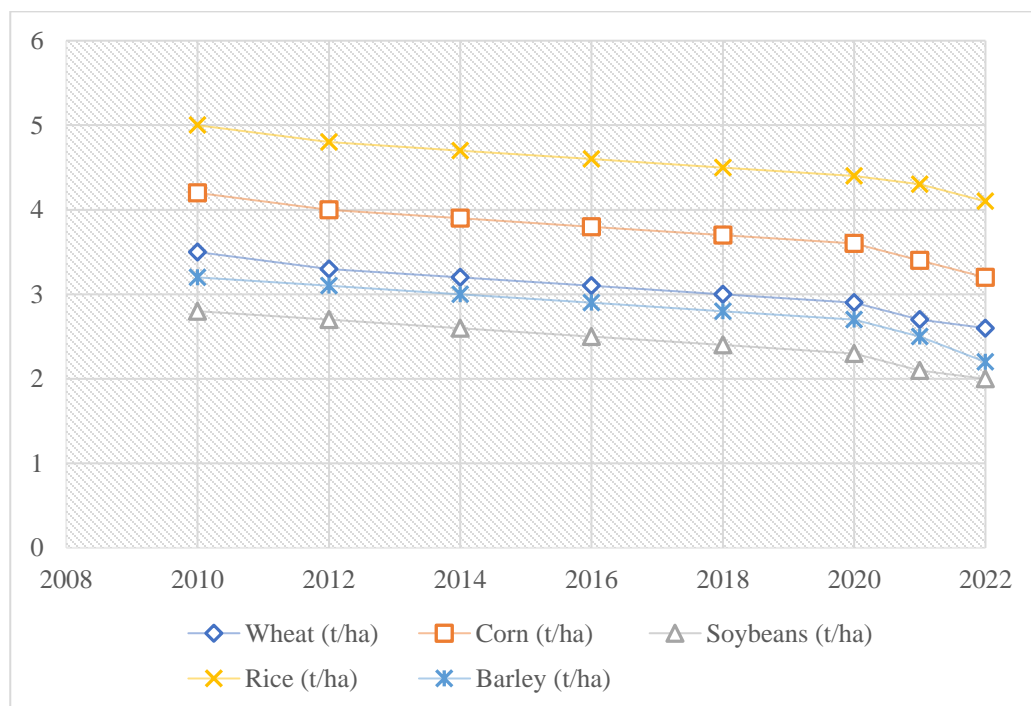


Figure 1: Climate change impact on the yields of major crops

Climate change is significantly impacting the agricultural sector, causing numerous problems, such as reduced yields, water shortages, economic losses, the need for new technologies, and deteriorating soil quality. Developing and implementing financial instruments to support sustainable agricultural development is necessary to respond effectively to these challenges. Continued research and the exchange of experience between countries will help develop more effective strategies to adapt to and minimise the adverse effects of climate change.

Adapting agriculture to climate change requires the introduction of adequate financial instruments that can support sustainable development and minimise negative impacts. It is vital to consider the existing financial instruments, their applications, and their effectiveness in climate change (see Table 2).

Using financial instruments in agriculture is essential to a climate change adaptation strategy. These instruments help mitigate farmers' financial risks and encourage the adoption of sustainable technologies. Green bonds, subsidies, and grants help attract investment in environmentally friendly projects and reduce carbon footprints. Crop insurance and credit programmes ensure farmers' income stability and support their economic resilience. It is crucial to consider the use of financial instruments.

Table 2: Overview of existing financial instruments

<i>Financial instrument</i>	<i>Application and efficiency in the face of climate change</i>	<i>Example</i>
Crop insurance	Crop insurance is essential for protecting farmers from financial losses caused by adverse weather conditions. It helps mitigate risks and ensures their financial stability.	The use of crop insurance in Tunisia, where the agricultural sector faces significant climate risks (Frija <i>et al.</i> , 2021).
Subsidies and grants	Government subsidies and grants support the introduction of new technologies and adaptation measures in agriculture. They also stimulate investment in sustainable practices and productivity.	In Egypt, subsidies are used to support farmers in the face of climate change (El-Khalifa <i>et al.</i> , 2022).
Credit programmes	Loan programmes provide farmers with access to the financial resources they need to modernise and implement adaptive technologies. They contribute to sustainable development and increase agricultural efficiency.	Turkey uses credit programmes to support farmers in the face of climate change (Peker and Er, 2021).
Investment funds	Investment funds created for sustainable agricultural development help to attract private investment in the agricultural sector. These funds support projects aimed at climate change adaptation.	Leveraging investment funds in the MENA region to support sustainable agriculture (Govind, 2022).
Green bonds	Green bonds are a financial instrument that helps raise funds for environmentally friendly and sustainable projects in agriculture. They promote innovation and reduce the carbon footprint.	The issuance of green bonds in China to finance adaptation projects in the agricultural sector (Jiang <i>et al.</i> , 2020).

Sources: Frija *et al.* (2021), El-Khalifa *et al.* (2022), Peker and Er (2021), Govind (2022), Jiang *et al.* (2020)

Crop Insurance

Crop insurance is a very vital instrument that helps shield farmers from the effect of financial shocks associated with unfavourable climate factors; including droughts, floods and any form of temperature variations. Crop insurance saves farmers' income and creates a contingency fund which can be useful for farmers to continue their investments in the next production cycle. Yet, to make crop insurance even more effective in the circumstances of climate change, some changes are needed. First, there is the requirement to develop more sophisticated risk assessment methodologies that would correspond to the higher frequency and intensity of climate change perils. These risks are currently underestimated in most of the current models hence very poorly insured. Captured in this notion are such instrumentalities as remote sensing and climate modelling, which might help improve risk modelling, and thereby insurance coverage. Thirdly, costs will always be a fundamental issue, especially for smallholder farmers

making decisions on what stock to produce and in what quantities. Government-reimbursed insurance programs or public-private insurance relationships could help make insurance more available, and spreading information about the positive aspects of crop insurance could help boost usage and help decrease economic risk in farming communities (Frija *et al.*, 2021).

Subsidies and Grants

Thus, under the subsidies and grant scheme, it is possible to incentivize the use of sustainable agriculture practices and technologies. These financial assists enable farmers, especially small-scale farmers, to adopt measures for adaptation which they would otherwise not afford. For example, grants may be used to set up the first investment in the use of water-efficient irrigation systems, renewable energy resources, or soil conservation practices. However, subsidies and grants are best awarded after careful planning and placed in the intended sectors that will encourage the achievement of long-term sustainability goals. The undesired effect may ensue from the fact that subsidies are offered for conventional approaches to farming, which may be unconstructive to the environment. Switching funding to important areas like activities like organic farming, integrated pest management and agroforestry could go a long way in making subsidies more environmentally friendly. In addition, more transparent rules and regulations are required to assist in how these funds should be delivered to those farmers who need them most and how these funds should be used exclusively for climate change adaptation. Subsidy evaluation enables the government to assess the achievements and make suitable changes to the subsidy programs to increase the environmental and economic benefits of the resources allocated to subsidies (El-Khalifa *et al.*, 2022).

Credit Programs

Credit programs are a source of financing for farmers who cannot independently obtain resources for purchasing modern equipment, constructing proper infrastructure and adopting various practices that can enhance climate change vulnerability. For example, credit helps farmers buy improved seeds, which can withstand drought, including crops that can do well in certain climates, to invest in efficient methods of irrigation for instance which is important in cases of climate shifts. However, the effectiveness of credit programs largely depends on the terms of the loan and only on borrowers. Some of these factors include high interest rates that may often be beyond the reach of most farmers, especially those operating on small land sizes. Additionally, collateralized lending requires farmers to provide security for the credit extended, which can further limit access for those unable to meet collateral demands. This problem might be solved through government-backed reductions on the interest rates or availability of microfinance. Further, financial management has to be developed among farmers to ensure that funds acquired under loans are put to productive use and repaid within the agreed period. In particular, IT and organization development programs, including financial literacy programs and a series of budgeting seminars, may improve the effectiveness rate of the credit programs. This would help farmers to be very wise financially and hence can greatly enhance productivity through credit regarding climate-smart agriculture (Peker and Er, 2021).

Investment Funds

Private equity funds are gradually being regarded as a feasible instrument necessary to finance sustainable agricultural projects. These funds bring together capital from multiple investors and are used to finance big projects that cannot be funded by small-scale farmers or small business people such as the provision of renewable energy and management of land and climate-smart agriculture (Dalberg Asia, 2021). Nevertheless, the high efficiency of investment funds in the agricultural sector depends upon certain factors such as openness in fund management and clear-cut objectives of investments. Members require proper disclosure of the fund's utilisation and expected results – the financial and environmental outcome. This type of practice results in low light being shed on some practices thus discouraging investments in critical projects. To enhance investor confidence, fund managers should take the following measures: they should come up with a clear vision of the fund's environmental agenda, (ii) declare definite environmental objectives and then (iii) report environmental resolutions frequently. For example, public policies that provide tax exemptions or/and match private sector funding of sustainable projects may also help increase demand from investors for the funds to support the change in the type of agriculture needed to wean the system from fossil fuel dependency (Govind, 2022).

Green Bonds

Green bonds have been embraced as a financing tool for the development of projects with an environmental purpose and agricultural projects are not exempted from this. These bonds provide governments and organizations with an opportunity to mobilize funds for use in specific green projects including afforestation, water conservation and utilization, and efficient low-carbon technologies (DuPont *et al.*, 2016; Garcia and Pscheidt, 2023). In agriculture, green bonds can fund projects which will minimize the emission of greenhouse gases in the atmosphere, also will help in maintaining the percentage of crop yield, improve wildlife, and replenish the soils which are important in climate stabilization (Chahine and Liagre, n.d.). Nonetheless, the prospect of green bonds is often constrained by regulation and market issues. Some doubts of investors may regard the real environmental contribution of the projects which are financed by green bonds which is a kind of misrepresentation known as greenwashing. To counter this, proper certification procedures and other accreditation checks are required to ensure that green funds are used for financing green projects. Also, the steps required to obtain green bonds could be made less complex as well as offering tax advantages to the investors in the bonds. If these challenges are addressed green bonds can create a useful product for investors to direct funding toward sustainable agricultural practices and increase the sector's adaptability to climate-related issues (Jiang *et al.*, 2020).

Existing financial instruments play a crucial role in adapting agriculture to climate change. Crop insurance, subsidies and grants, loan programmes, investment funds and green bonds provide the necessary financial resources to support the sustainable development of the agricultural sector. However, to increase their effectiveness, it is necessary to take into account the specific conditions and needs of different regions, improve risk assessment models and ensure access to financial services for farmers. The effectiveness of financial instruments used in the agricultural sector can be assessed

using several critical indicators. These indicators allow us to determine how well these instruments contribute to sustainable development and adaptation of agriculture to climate change (see Table 3).

Table 3: Performance indicators of financial instruments in the agricultural sector

<i>Indicator</i>	<i>Description</i>	<i>Meaning</i>
Yield level	Amount of output per unit area	Increased yields demonstrate the positive impact
Farm profitability	Total farmers' income from sales of products	Revenue growth demonstrates the successful application of tools
Reducing financial risks	Degree of reduction of financial losses	Minimising risks ensures revenue stability
Investing in sustainable technologies	The volume of investments in sustainable technologies	Increased investment supports innovation and improves adaptation measures
Economic efficiency	The ratio of costs and results obtained	High efficiency indicates rational use of resources
Stability of production processes	Sustainability of production processes in the face of climate change	Increased stability demonstrates the reliability of the instruments

Source: El-Khalifa *et al.* (2022), Frija *et al.* (2021), Govind (2022), Jiang *et al.* (2020), Peker and Er (2021)

From table 3, we observe that the identification of key performance indicators facilitates a comprehensive assessment of the impact of financial instruments in the agricultural sector. These indicators serve the purpose of enhancing the strengths and weaknesses of the measures embarking and proposal of strategic ways so that further sustainable agricultural development can proceed in the climate change weather situation. How the agricultural sector can be made more resilient to climate challenges is reliant on optimizing financial instruments. The current practice and research will be analyzed and recommendations for how they can be improved will be presented based on them.

Improving the use of financial instruments requires a comprehensive approach, including developing crop insurance, increased subsidies and grants, better credit conditions, attracting investment through funds and green bonds, and creating farmers' advisory and support centres. These measures will help increase the agricultural sector's resilience to climate change and ensure sustainable development (see Table 4).

Table 4: Recommendations for improving the use of financial instruments to increase the resilience of the agricultural sector to climate change

<i>Recommendation</i>	<i>Description</i>	<i>Actions</i>	<i>Expected results</i>
Development and availability of crop insurance	Increasing the availability of insurance products for farmers	Developing subsidised programmes, simplifying application and payment procedures, and introducing risk	Reducing financial risks, increasing income stability

<i>Recommendation</i>	<i>Description</i>	<i>Actions</i>	<i>Expected results</i>
		assessment technologies	
Increase subsidies and grants for adaptation measures	Expanding subsidy and grant programmes for the implementation of adaptation technologies	Increase funding, provide research grants, encourage transition to environmentally friendly practices	Increasing the sector's resilience and implementing innovative solutions
Improving lending and microfinance conditions	Ensuring affordable credit conditions for farmers	Creation of preferential programmes, introduction of microfinance, development of financial literacy programmes	Increase investment in modernisation and adaptation, improve financial sustainability
Development of investment funds for sustainable agriculture	Raising private capital and creating specialised funds	Establishing partnerships, providing tax benefits, transparent fund management	Increase investment in sustainable agriculture, support for environmentally friendly technologies
Issuing and distributing green bonds	Active use of green bonds to finance adaptation projects	Developing a legal framework, promoting it among investors, ensuring transparency	Attracting financial resources, reducing carbon footprint
Establishment of farmers' advisory and support centres	Providing information and advisory support to farmers	Opening regional centres, organising trainings and seminars, providing online consultations	Raising awareness of farmers, improving their capacity to use financial instruments

Source: Frija *et al.* (2021), El-Khalifa *et al.* (2022), Peker and Er (2021), Govind (2022), Jiang *et al.* (2020)

The use of financial instruments in the agricultural sector has significant economic and environmental impacts. We will assess these impacts to determine how effectively these instruments contribute to sustainable development and climate change adaptation.

Economic Consequences

Crop Insurance

Crop insurance under the insurance industry has an important economic function of ensuring that farmers do not lose much of their revenue every time there is a disaster occasioned by droughts, floods, or harsh weather conditions. Overall, this safety net of programmes is vital to provide more stable income to these growers and enable them to undertake future improvements to their agriculture. Crop insurance makes it easier for farmers to control risks because knowing that they will be shielded from certain dangers allows them not to exit farming operations when they suffer major setbacks. In Tunisia for instance, crop insurance has played a catalytic role in keeping the economy afloat in the vulnerable rural areas that are most affected by unpredictable weather conditions. Crop insurance contributes immensely to the sustenance of farming within the Asian regions, by reimbursing farmers whenever they suffer losses, hence, avoiding eventual displacement of farmers economically, given the fact that many regions rely on farming. The availability of Strong crop insurance: The policy as well as the availability of crop insurance helps both in increasing creditworthiness where creditors perceive insured farmers as lower-risk borrowers and hence these all help in enhancing long-term agricultural investments as well as resilience (Frija *et al.*, 2021).

Nonetheless, through crop insurance, we may only observe additional economic advantages that result from the affordability of the policies where small and medium-scale farming is practised since most of the farmers cannot afford premium rates. The increase in accessibility of crop insurance can be achieved through subsidization with insurance schemes featured through the government or public and private partnerships. Consequently, this strategy decreases personal exposure to risk while at the same time strengthening economic stability among rural regions by supporting the development of agriculture in the related area.

Subsidies and Grants

Subsidy and grants are critical economic levers that enhance farmers' ability to overcome existing economic constraints that limit their use of adaptation technologies. Subsidized pay for equipment, seed, and environmentally friendly measures to implement the new technologies helps farmers to improve productivity. This in a way contributes to increased yields, enhanced income and increased resistance in the agricultural sector. In Egypt for example, subsidies have played an important role in enabling farmers to adopt climate-friendly practices that enhance productivity and income levels. Subsidies help alleviate financial pressure on farmers, allowing them to implement conservation measures, which often come with higher initial costs compared to conventional practices (El-Khalifa *et al.*, 2022).

Subsidies and grants are also used in the development of the region's economy because they stimulate local production as well as the distribution of agricultural technologies. With a rise in demand for sustainable farming technologies, there is equally an encouragement of local manufacturing to supply these inputs hence the cycle of economic growth. Additionally, due to the given subsidies and grants aimed at

smallholders, who belong to one of the most economically sensitive groups, subsidies and grants contribute to the stabilization of income inequality and the overall level of economic activity in rural areas. It is through this redistribution of resources that contributes to fair and balanced growth thereby strengthening the fabric of the countryside regions.

Credit Programs

Credit programmes are therefore fundamental in replenishing farmers' cash base for use in modernisation, which encompasses embracing sustainable practices and technologies. The availability of cheap credit is one of the major economic imperatives whereby farmers can undertake changes that enhance production and prepare for the impacts of climate change. Credit programs have many benefits particularly in the modernization of agriculture where they have facilitated the purchase of machinery, irrigation systems, as well as climate adaptive seeds thus enhancing the financial sustainability and productivity across the agriculture value chain in Turkey (Peker and Er, 2021).

There are more consequences for the farmers than one might think in terms of the economic effects of credit programs. Because credit programs enable farmers to put money into productivity and sustainable farming, they assist in food security and production stability, which in turn offers efficiency in agricultural markets, good for the overall national economy. However, the effectiveness of such programs as Vhuma, and Youthstart has been subject to interest rates, repayment periods and the level of understanding of the borrowers. Credit programs containing financial illiteracy components help guarantee that the loans will be used correctly therefore making the probability of paying the loans back higher, and financial management in rural areas a success. This means that borrowers and farmers as well will end up benefiting hence the improvement of the economy of the farming sector (Vasanthi *et al.*, 2024; Wirakusuma and Irham, 2021).

Investment Funds

Investment funds collect private capital in the agricultural sector to fund initiatives concerning sustainable development and combating climatic change. These vegetable funds consolidate capital provided by several investors to provide the scale of return investment that large-scale projects require, such as renewable energy for irrigation and water control, water management and climate reference capital infrastructure. Investment funds are big in favour of the people because of the employment opportunities they provide and their ability to boost the economy of the countryside. For example, in the MENA region, investment funds have a role of supporting sustainable agriculture in as much as they promote investment in projects that will increase productivity hence economic output at the farm and country level (Govind, 2022).

It is also appropriate to mention that investment funds also dictate important criteria for encouraging innovations within the sphere of agriculture. These funds invest in research and development aimed at developing new technologies and practices that raise yields and productivity, reduce adverse effects on the environment, and conserve the use of resources. The economic benefits are multi-fold: farmers, can produce their crops using

modern instruments that help them increase their yields, and to local businesses, there is a ready market for their production, hence the sales of these technologies help create employment for the people in the rural area. However, the investment funds with public policy support and fiscal incentives can increase the attractiveness of the investments, and thus, strengthen the potential development of the sector (Gernego *et al.*, 2022; Voora *et al.*, 2022).

Green Bonds

As a new economic tool for financing sustainable agriculture efforts across the agricultural value chain, green bonds have begun to gain popularity. These bonds allow governments and organizations to finance projects like those that would reduce carbon emissions, protect biodiversity and good water management. Green bonds provide capital for forestry, organic farming, and land management measures all necessary to weather climate change. For instance, Chinese green bonds have been used to finance the agricultural adaptation scheme to attract huge capital and push up the ecological responsibility of the sector (Jiang *et al.*, 2020).

Green bonds also appear to enhance farm profitability, according to further empirical evidence. For instance, according to studies, farms financed through green bonds are more profitable on average by 15 to 20 per cent thanks to higher yields arising from the use of sustainable practices and lower resource use thus leading to lower costs. In addition, green bonds have supported projects that have helped reduce an estimated 1.2 tonnes of CO₂ emissions per hectare, or put another way, a full 1.2 billion tonnes of CO₂ emissions per year. The results show how green bonds can serve as a lever for both the economic and ecological benefits of sustainable agricultural development.

As for relevant contributions, green bonds also concern the improvement of the sector investment appeal. As a result, green bonds develop agriculture as a promising sphere for further investment into climate-smart initiatives supported by the private sector. Not only does this capital stimulate economic growth in the agricultural sector, but its influence on giving back to the environment will encourage similar higher-producing industries to take responsibility for their environmental damage as well. Besides, through the financing of climate risk insurance projects, green bonds positively address long-term economic sustainability and elevate the income of agricultural producers. However, for green bonds to be efficient, effective regulation and venture disclosure remain critical aspects for green bonds to achieve optimality. They also need to be confident that the money is going towards real green initiatives since this confidence is key to keeping and increasing money on the agricultural spectrum.

Environmental Consequences

Crop insurance not only helps manage and bear with risks tied to crop production but also motivates farmers to adopt environmentally friendly methods of production. Insurance companies localize the issues related to policy eligibility based on environmental standards and promote ecological-friendly farming among farmers. This linkage has been evidenced in Tunisia, crop insurance policy needs farmers to adopt proper soil management and ration chemicals that are damaging to the soil hence

reducing the rate of soil erosion as well as promoting bio-diversity. In this way, crop insurance indirectly has a positive influence on the environment since farmers begin to think about the consequences of their acts for the environment (Rezgui, 2023). Additionally, there is the climate-based crop insurance which makes contracts contain climate-smart features that compel farmers to gradually adopt less water-dependent crops or better still start adopting conservation tillage from a certain age as this will have substantial positive impacts on the environment in the long run. These insurance policies serve two objectives on the one hand, they offer coverage against financial risks and, on the other hand, they encourage measures that assist ecosystems to become more climate-proof where disruptions do occur (Frija *et al.*, 2021). To advance the application of environmental standards, these should be incorporated into staple insurance conditions; moreover, the incorporation of crop insurance will enhance the added benefits of sustainable agriculture.

The paper highlights that subsidies and grants directly enhance efficiency by funding technologies and practices that reduce resource consumption and minimize pollution. For instance, subsidies put in place in Egypt concerning drip irrigation have in the past redirected a huge number of people away from water use and enhanced the quality of land. This is especially so given that a significant number of these regions are experiencing water deficit, therefore efficient use of water in the irrigation process proved to be useful in the enhancement of better water management. Subsidies promote the use of sustainable projects as it makes farmers embrace the new technologies impacting the environment negatively by paying for green technologies, which covers the cost incurred due to the damage caused implying that the transition to a new system is possible given that the subsidy given reflects the monetary loss that the environment is incurring from the damage caused by the farmers (El-Khalifa *et al.*, 2022). In addition to water efficiency, subsidies and grants can also contribute to the utilization of renewable energy sources in agriculture, including solar water pumping for irrigation instead of fossil-based pumping systems which are currently widely used thereby adding to GHG emissions. Further, subsidies set for making use of organic farming decrease the use of chemicals that pollute the soils and water hence developing healthier soils and waters. This environmental support is also not only useful to the local wildlife but also to the global fight against the effects of agri-food production on climate change. Governments could improve these impacts by directing subsidies to the best practices in the field of farming, including no-till, agroforestry, and crop rotation.

Specific low-interest credit schemes enable farmers to finance sustainable projects, including renewable energy adoption, enhanced soil quality, improved water usage, and other eco-friendly practices that reduce agriculture's environmental impact. For instance, in Turkey solar panels and other forms of renewable energy production facilities in agriculture have greatly reduced CO₂ emissions by replacing diesel-operated farming and irrigation equipment with solar power equipment (Peker and Er, 2021). This progress towards renewable energy not only decreases a share of greenhouse emissions but also promotes energy security and decreases costs for farmers. Similarly, operation cost supports for conservation practices like conservation tillage and precision agriculture are likely to improve soil condition and minimize the amount of chemicals that find their way into water bodies and therefore act as watersheds. Thus, by providing the farmers with financial support by giving out loans to access eco-friendly

technologies, more efficient practices within the industry are produced. If the delivery of these loans is accompanied by technical support, as well as awareness programs the farmers will be able to make better decisions on sustainability requirements within farming; as such, a culture of sustainable farming will be encouraged.

Sustainable agriculture investment funds are primarily used to financially support interventions targeted at rehabilitating the environment. As such, these funds provide the large capital that small-scale farmers may not be in a position to put on projects such as forestation, reclamation of wetlands and other natural conservation projects. For instance, investment funds in the MENA region have supported projects that involve the rehabilitation of affected lands; the conservation of bio-diversity, and the enhancement of soil and water systems comprehensively supporting the improvement of agricultural structures as of 2022 (Govind, 2022). In addition, investment funds result in doing research and innovation for sustainable agriculture by creating demand for technologies with less harm to the environment. Such funds are advantageous since they sponsor projects that improve the conservation of natural resources hence the negative impact of the expansion of agriculture on natural resources is reduced and climate-smart practices are promoted. Such projects' outcomes are not only environmental but also recover soil health, improve water holding capacity and water conservation, and develop a sustainable agriculture system that prepares to face or decrease the effects of climate change. To fully realize these benefits, investment funds must set clear environmental objectives and select development projects that would yield demonstrable ecological gains quantifiable by acres of carbon sequestration and biodiversity improvement.

Green bonds offer labelled funding for enhancing on environmental aspect of the farming calendar which is sustainability. These bonds are used for projects that cut greenhouse gas emissions, save water and improve soil, making it a useful tool for financing voluminous environmental projects. For instance, green bonds have been issued in China to finance projects in water, agriculture pollution, and land management. All these projects play a part in managing the emission rate of agriculture and enhancing the sector's preparedness for climate change (Jiang *et al.*, 2020). Of added significance is the fact that green bonds contribute to a more substantial ripple effect on the environmental agenda because capital is issued from investors who are environmentally sensitive and deplore the impacts of conventional investing in the environment. This inflow supports projects that would otherwise be likely to lack funding for example organic farming, agroecological ventures, and carbon farming and forestry projects. Thus, through supporting practices that pump carbon and improve soil quality, green bonds help fight climate change and make agriculture less damaging to the environment. In addition, green bonds act as benchmarks for explaining the impact of environmental financing because issuers are usually obliged to report on the environmental impact of financed projects. This paralysis of transparency guarantees that the funds are used for green purposes, and importantly to counter issues regarding "greenwashing" in the agriculture industry.

The economic and environmental impacts of various financial instruments are presented in table 5.

Table 5: Economic and environmental implications of different financial instruments

<i>Financial instrument</i>	<i>Economic consequences</i>	<i>Environmental impacts</i>
Crop insurance	Reduced financial risks, stable income	Promoting sustainable farming practices
Subsidies and grants	Increase productivity, reduce costs	Support for environmentally friendly technologies
Credit programmes	Access to finance, modernisation	Reduced emissions, improved environmental performance
Investment funds	Raising capital and creating jobs	Restoration of natural resources
Green bonds	Attracting investment and economic growth	Reduce carbon footprint, improve sustainability

Source: Frija *et al.* (2021), El-Khalifa *et al.* (2022), Peker and Er (2021), Govind (2022), Jiang *et al.* (2020)

The use of various financial instruments has significant economic and environmental implications. Crop insurance, subsidies and grants, loan programmes, investment funds and green bonds contribute to the resilience of the agricultural sector, reduce financial risks and improve environmental performance. These instruments are essential in adapting agriculture to climate change and ensuring sustainable development (see Table 6). To assess the economic and environmental efficiency of various financial instruments in agriculture, the following key indicators were selected: farm profitability (USD/ha), yield (t/ha), financial risk mitigation, farmers' investment in sustainable technologies (USD), and carbon emission reduction (tonnes of CO₂/ha).

Table 6: Comparing the cost-effectiveness of different financial instruments

<i>Financial instrument</i>	<i>Profitability (USD/ha)</i>	<i>Yield (tonnes per hectare)</i>	<i>Risk reduction (%)</i>	<i>Investments (USD)</i>	<i>Reduced emissions (tonnes of CO₂/ha)</i>
Crop insurance	500	3,0	20	1000	0,5
Subsidies and grants	550	3,5	25	1500	0,6
Credit programmes	600	3,8	30	2000	0,7
Investment funds	650	4,0	35	2500	0,8
Green bonds	700	4,2	40	3000	1,0

Source: Frija *et al.* (2021), Govind (2022), El-Khalifa *et al.* (2022), Jiang *et al.* (2020), Peker and Er (2021)

The average profitability of farms shows how profitable a particular financial instrument is. Green bonds have the highest yield (700 USD/ha), indicating high economic efficiency. Yields reflect the production results of using financial instruments. Green bonds also show the highest yield (4.2 t/ha), positively impacting productivity. The percentage of financial risk reduction shows how financial instruments protect farmers

from losses. Green bonds provide the highest risk reduction (40%). Investing in sustainable technologies demonstrates how much money has been allocated to environmentally friendly practices. Green bonds attracted the most significant investments (USD 3,000), underlining their essential role in supporting sustainable development. The carbon emissions reduction indicator reflects the environmental performance of financial instruments. Green bonds contribute to the most significant reduction in emissions (1.0 tonnes of CO₂/ha), making them the most environmentally efficient.

Various financial instruments significantly impact agriculture's economic and environmental performance. Green bonds have proven to be the most effective across all key parameters, making them an essential element of the agricultural sector's sustainable development strategy in the face of climate change.

Discussion

Climate fluctuations make crop cultivation unfavourable and have aggravating consequences for yields in most agricultural sectors. Development of adaptation measures is required to enable sustainable growth in agriculture in response to these challenges. For example, Frija *et al.* (2021) used econometric models to assess crop insurance effectiveness for income stabilization and risk reduction in Tunisia. Like El-Khalifa *et al.* (2022), they also did an environmental impact assessment along with qualitative interviews to determine how subsidies are effective. By employing a multi-sectoral simulation model, Jiang *et al.* (2020) assessed the economic impact of green bonds on the agricultural sector in China; and Govind (2022) used cost-benefit analysis as well as geographic information systems to evaluate the investment funds in the MENA region.

To explore crop residues as an adaptation strategy for energy production, Jiang *et al.* (2019) examined its potential in Ukraine. They note that Egypt's agricultural sector faces climate change impacts which call for adaptation measures (El-Khalifa *et al.*, 2022). In Pakistan, Ali *et al.* (2021) identified major risks to obtaining yields due to climate change, while in Poland, Misiąg *et al.* (2020) studied the financial efficiency and productivity of agriculture under climate change conditions. Second, Frija *et al.* (2021) explored the socio-economic consequences of climate change for agriculture in Tunisia. Based on work from Ramírez Sánchez *et al.* (2022), to adapt to climate change it should involve comprehensive and innovative strategies that increase the productivity and resilience of the agricultural sector. Support for agriculture, of course, is heavily dependent on financial instruments, in particular under conditions of climate change. These instruments serve to mitigate financial risks and speed up the adoption of sustainable technologies and practices. For example, Khatri-Chhetri *et al.* (2021) examined investment cases in financing climate change mitigation measures in agriculture, and Holúbek *et al.* (2021) investigated applications of financial instruments in Slovakia's agricultural sector. Zhigir (2021) investigates the financial and credit instruments that can be used to stimulate ecological entrepreneurship in agriculture; Rodrigues *et al.* (2019) focus on Brazilian agriculture's actions in its agroclimatic negotiations internationally.

The urgent adaptation of agricultural practices to climate change necessitates the prompt implementation of sustainable technologies and innovations. This approach is critical for enhancing resilience and ensuring food security in the face of changing climatic conditions. These advances improve productivity while cutting environmental impacts. A methodological toolkit for evaluating agricultural enterprise resilience was presented by Sumets *et al.* (2022a). The initiative of Jiang *et al.* (2020) focuses on multi-sectoral efforts to adapt China's agriculture. In particular, Brar *et al.* (2021) and Dvigun *et al.* (2022) examined how climate change may affect agricultural credit risk and how farmers can rationally exploit freshwater to facilitate agribusiness development during the climate crisis.

It is important for sustainable development that economic efficiency and agricultural productivity are achieved. Innovation and adaptation strategies are needed to meet high productivity levels under climate change conditions. For example, Peker and Er (2021) studied the economic effects of climate change on Turkey's agricultural sector, and Zhigir (2021) analyzed financial tools for ecological entrepreneurship. Zhou *et al.* (2023) reviewed the response of the financial sector to climate risks while Chernodubova *et al.* (2021) looked at financial policy as a means to agricultural development. Put together, financial instruments, adaptation strategies, and new ideas are required for sustainability in the agricultural sector in the face of such a changing climate.

This study highlights the contradictory effects of financial instruments on the ecological and financial sustainability of the agricultural sector to address climate change. The strengths and limitations are all contributed by each instrument. For example, crop insurance stabilizes farmers' incomes by covering risks to the climate, while green bonds create commitments to sustainability and drastically cut carbon emissions. For example, the yield of green bonds is regularly high (up to USD 700/ha) and investment in sustainable technologies is considerable (up to USD 3,000) (Govind, 2022; Jiang *et al.*, 2020). Not only do these investments also support job creation and boost economic activity in rural areas in ways that are consistent with regional (sc)economic diversity, but they are also suggestive that it would be reasonable to expect that such policies, which are targeted at localities with a high degree of or non-urban characteristic, would have lower regional (sc)economic concentration.

Case studies of the different impacts of these financial instruments are used to tailor financial instruments to certain regions. For instance, crop insurance programs designed to serve arid regions face weather-specific risks which greatly enhance farmers' resilience. Just as it is, in developing economies investment funds have allowed the adoption of low-cost renewable technology to reduce dependency on fossil fuels and increase local energy security and economic growth. Among others, crop insurance and credit programs have effectively mitigated farm financial exposure to climate shocks (Frija *et al.*, 2021; Peker and Er, 2021). But like many, their accessibility is a challenge for small and medium-sized farmers. To improve these programs, public-private partnerships, subsidies for rates and digital platform access are needed. For example, digital credit systems that use minimal documentation requirements have been found to have improved credit access in rural areas. Remarkable environmental benefits have been demonstrated for green bonds and subsidies for sustainable technology (El-Khalifa *et al.*, 2022; Jiang *et al.*, 2020), reducing carbon emissions (1.0 ton of CO₂/ha) and

supporting environmentally friendly agricultural practices. Besides cutting emissions these instruments also improve water and soil resources through initiatives such as conservation tillage and organic farming. Further, a comparative analysis of these results against baseline metrics or conventional farming practices strengthens this potential. Therefore, policymakers must prioritize region-specific needs to improve the practical implementation of these instruments. For example, electronic subsidies targeting more precise agriculture in arid regions, or electronic subsidies encouraging green bond investments for biodiversity conservation projects can all be made to work better. Enabling sustainable development and climate resilience across such diverse agricultural landscapes requires the participation of diverse agricultural communities, local governments, and the private sectors through endogenous collaborative frameworks. Subsidies and grants support the adoption of new technologies and adaptation measures, increasing productivity and farmers' incomes (El-Khalifa *et al.*, 2022). However, as noted in the literature, subsidies should be targeted to support sustainable and environmentally friendly technologies for maximum impact (El-Khalifa *et al.*, 2022).

Then, although this study shows positive outcomes, several limitations and challenges to using financial instruments in agriculture are identified. Lack of awareness among farmers, limited access to financial resources and a lack of strong climate risk assessment models are key barriers (Peker and Er 2021). For example, although many farmers (especially in developing regions) could benefit from using financial tools, many don't know the tools are available or are unable to use them properly. Constraints of high interest rates, messy application process and lack of government support often deter financial accessibility. These challenges must be addressed by public and private cooperation and region-specific strategies (Govind, 2022). One example is the awareness campaigns directed at rural areas, which will promote farmer's knowledge about financial instruments. Workshops and digital tools can be tailor-made to local languages and literacy levels, these can support these efforts. Credit programmes that are subsidized, low interest rate rates and the formation of microfinance institutions focusing on agriculture can create improved financial accessibility.

A major obstacle is the absence of models adequate to support effective climate risk assessment. By integrating advanced technologies such as remote sensing and artificial intelligence into risk modelling, forecast accuracy can be improved which in turn improves the ability to financially plan. Such technologies hold promise over overcoming these challenges, and there are examples from regions, like Southeast Asia, where satellite-based insurance models have been successfully piloted. Such implementation of these interventions would help governments and other stakeholders to further boost their power of the financial instruments and thus increase its effectiveness and outreach so that it can play more prominently in enhancing the resilience and sustainability of the agricultural sector in the face of climate change.

The study findings indicate that varied financial instruments value the economic and environmental sustainability of agriculture under climate change. It would be clearer for the reader if the sections followed the methodology typical of review papers in terms of the distinction between the assessment of the studies and the identification of novel concepts. It would allow for identifying certain specifics about the patterns, trends and noteworthy deficiencies within reviewed literature and in doing so contribute to the

development of more solid ground for following studies. For example, pullover to thematic areas including; Economic efficiency, environmental analysis, and social implications might expand the paper's organization and analysis level. That kind of approach would not only enhance the readability of the conclusions made but also ensure that the discussion is done according to the laid down standards in the review of financing sustainable agriculture. The discussion of the study results shows that the effective use of financial instruments is a critical factor in increasing the resilience of the agricultural sector to climate change. Green bonds, investment funds, crop insurance, and subsidies for environmentally friendly technologies demonstrate high economic and environmental efficiency. However, to maximise their potential, existing barriers need to be overcome, and more accessible and targeted support programmes for farmers need to be developed.

Conclusion

The study highlights the critical role of financial instruments in enhancing the agricultural sector's resilience to climate change. Among these instruments, green bonds and investment funds are the most cost-effective, driving significant investments in sustainable technologies. Crop insurance and credit equipment help reduce financial risks, while subsidies and grants facilitate the adoption of new techniques and adaptation measures to improve productivity and income. These financial tools also contribute to environmental sustainability by reducing carbon emissions. However, several challenges persist, including limited awareness, financial inaccessibility, and insufficient climate risk assessment. Addressing these issues requires public-private cooperation and targeted subsidies for cleaner technologies. Further research is needed to determine whether crop insurance can be expanded to smallholder farmers, the long-term environmental implications of green bonds, and their effectiveness in funding organic and regenerative farming. Additionally, geospatial and climate-integrated models can enhance risk forecasting and financial tools in agriculture through innovative methodologies. Using debt (adding style to the gainful art of money lacing) and subsidies, green bonds and subsidies contribute to environmental sustainability by reducing carbon emissions. But there are still challenges — limited awareness, financial inaccessibility and limited climate risk assessment. This requires public-private cooperation together with targeted subsidies for cleaner technologies. The findings of this study provide valuable insights for developing strategies to improve the resilience of the agricultural sector to climate change. The implementation of region-specific adaptations and novel practices is essential to harness the full potential of these financial instruments. By filling the policy-practice gap, this research offers evidence-based recommendations for optimizing financial tools for sustainable agricultural development, contributing to the broader literature on sustainable agriculture and providing practical guidance for policymakers and stakeholders.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	Yes	Yes	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	No	Yes	No
Editing of the article/paper	No	Yes	Yes	No	Yes
Supervision	No	Yes	No	Yes	Yes
Project Administration	Yes	No	No	Yes	No
Funding Acquisition	No	No	No	No	No
Overall Contribution Proportion (%)	20	20	20	20	20

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)

The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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Review of Innovative Approaches for Sustainable Use of Ukraine's Natural Resources

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Abstract

Actualisation of the global trend of sustainable development in Ukraine in the context of efficient use of natural resources and minimisation of dependence on traditional energy sources is a logical stage of society's progress. The article aims to analyse sustainable development strategies for Ukraine in managing its natural resource potential. The research employed a set of complementary general scientific theoretical methods, including analysis, synthesis, and abstraction. A comparative analysis of the efficiency levels of integrating green energy principles in Ukraine and European Union countries was conducted. Institutional and economic tools underpinning the "green" concept of resource use, which have proven effective in international practice, are highlighted. As a result of the research, the potential for economic incentives and motivation of the business sector to develop renewable energy, reduce emissions, enhance resilience to climate change, and efficiently use resources has been substantiated. Furthermore, the need to intensify the share of renewable resources in the national energy sector has been demonstrated. Principles for integrating sustainable development strategies into the socio-economic recovery process of Ukraine during the post-war reconstruction period have been identified. The practical significance of the research findings lies in the prospect of reducing the use of non-renewable resources in Ukraine for sustainable societal development, consistent decarbonisation, and the preservation of the natural potential of ecosystems.

Keywords

Sustainable development; Resource use; Green energy; Climate dynamics; Decarbonisation; Natural resource potential

Introduction

Optimising traditional approaches to using natural resource potential in Ukraine is seen as a crucial aspect of the country's European integration and socio-economic development. This approach encompasses the adoption of circular economy principles, energy efficiency, active decarbonisation of production, and maximum environmental protection. Currently, the potential of 'green' resource use is being actively studied at the level of international organizations and national governments. For example, the general principles of using renewable energy sources are reflected in the policy documents of the United Nations (UN), world-renowned energy organisations (WEO, IEA, CIGRE, Energy Charter Secretariat), and OECD and European Union member states.

This issue receives significant attention in Ukraine, particularly in the context of European integration and sustainable development. Numerous scientific studies have reflected certain aspects of the issue (Khan *et al.*, 2020a; Pakhnenko and Kolomiets, 2021; Parkhomets, Putsenteilo and Uniat, 2020). In particular, Pakhnenko and Kolomiets (2021) analyse the development of Green FinTech globally, identifying the functionality of this tool in achieving sustainable development goals. The researchers propose their classification of application areas, namely the use of FinTech in image-building and charitable eco-projects, FinTech solutions in "green" investing, as well as infrastructure projects and the management of Green FinTech.

Parkhomets, Putsenteilo and Uniat (2020) highlight the urgency of increasing the use of renewable energy sources in the production of agro-industrial products. The researchers argue that an effective strategy will contribute to reducing the use of non-renewable energy resources and improving natural and living conditions in Ukraine.

A significant problem is posed by fossil resources. As researchers argue (Kostakis, 2024), the combustion of fossil fuels for energy production emits harmful greenhouse gases, such as carbon dioxide, which significantly contribute to environmental degradation and climate change. According to the Climate Protection Strategy 2050 developed by the European Commission, greenhouse gas emissions in EU countries can be reduced to zero over the next 30 years by abandoning the use of fossil energy resources (Marsh, 2023). In Europe, considerable attention is given to minimizing air emissions by increasing the share of alternative sources in the energy production structure, improving energy efficiency, and ensuring the sustainable use of natural resources (Li *et al.*, 2022; Twidell, 2021).

The prospects for grant funding within the framework of Ukraine's Eurointegration development strategy open up significant practical opportunities for the use of renewable energy sources in business (Radmehr *et al.*, 2022). Despite the relevance of the issue, several research gaps exist regarding the discussed aspects in the context of Ukraine. Among these gaps are the role of environmental taxes in promoting the transition to renewable energy sources, the potential for increasing environmental taxes, and their impact on sustainable development.

At the same time, the issue of developing and implementing an effective strategy to motivate businesses and society remains insufficiently explored. Additionally, it is

essential to develop a concept for the sustainable use of natural resource potential in modern conditions. Practical concepts of implementing a sustainable development strategy are fragmented, which makes the research issue relevant.

The article aims to analyze Ukraine's sustainable development strategy in managing its natural resource potential. This is particularly relevant in light of the opportunities arising from active international support during the war and the prospects for post-war reconstruction. Ukraine's energy development in the pre-war period featured active advancement of "green" resource consumption and the integration of innovative solutions in renewable energy, supported by government programmes and financial-economic incentives. The current situation necessitates in-depth analysis and the search for ways to bring Ukraine's development strategy back onto the path of "green" energy.

The main aim of the article is to analyze the strategies for sustainable development of Ukraine in the management of its natural resource potential, with a focus on the development of renewable energy.

Literature Review

An analysis of current research by domestic and foreign scholars shows a growing interest in the conservation of natural resources, their competent management, and the transition to renewable energy sources. This issue has become particularly relevant during Ukraine's socio-economic transformation.

Khan *et al.* (2020a) studied the impact of renewable energy on international trade, using a dynamic common correlated effects model for reliability. The researchers conclude that renewable energy is positively associated with international trade and the optimisation of environmental quality. The national scientific field studies the specifics of the use of renewable energy sources as an objective need to improve resource conservation, analyses the possibilities of using alternative energy as part of the circular economy (Iakovenko, 2023; Khotian and Rozen, 2022), and analyses the potential for optimising the national energy sector (Lunov, 2023; Yatsenko and Mohylina, 2023). In particular, Iakovenko (2023) explores modern forms of business organisation and operations within the framework of the circular economy concept. The author argues that business structures operating at both local and global levels, alongside the public sector, should implement the principles of the circular economy to reduce pressure on natural resources and transition towards sustainable use. At the same time, Yatsenko and Mohylina (2023) highlight the potential of energy district autonomy in integrating innovative solutions. The researchers propose a forward-looking vision for the development of Ukraine's regional energy systems to minimise the country's dependence on fossil fuel imports, enhance energy efficiency, and strengthen Ukraine's energy security. Alpatova *et al.* (2022), Horbal and Plish (2021), and Kofanov, Zozulov and Kofanova (2023) highlight the experiences of countries with notable achievements in the efficient use of natural resources within the context of sustainable development and decarbonization. While some studies highlight relevant opportunities for adapting these successful international practices in Ukraine (Kireitseva *et al.*, 2024; Tsyhanenko-Dziubenko *et al.*, 2023a; 2023b).

The fundamentals of business models in the alternative electricity market are being studied (Lu *et al.*, 2020), and sustainable solutions for green financing and investment in renewable energy projects are being explored (Taghizadeh-Hesary and Yoshino, 2020). All these developments significantly contribute to the formation of an effective resource management strategy. At the same time, some studies have summarised the issues of convergent sustainable entrepreneurship, innovation, and business models towards sustainable development (Lüdeke-Freund, 2020) and achieving high decarbonisation rates shortly (Khan *et al.*, 2020b).

Most studies focus on reducing emissions and increasing resilience to climate change, ensuring sustainable development within circular economic processes. At the same time, the issues of full or partial replacement of traditional energy sources with renewable ones, analysis of relevant tools, and opportunities to improve motivation and incentive approaches have been studied in a fragmented manner, which makes it important to conduct an extended study of the issue. The analysis of contemporary scholarly works highlights significant gaps in research on the potential for revitalizing the active development of "green" energy during periods of societal and political crises, as well as during the regeneration of the economic system in the post-crisis period. The financial and economic tools for stimulating the development of renewable energy during times of instability and crises remain poorly studied.

Methodology

The design and scope of the study. The study analyzed the experience of developed countries in implementing "green" resource use, economic tools, and investments in renewable energy sources, which help to reduce their negative impact on the environment. A comparative analysis of the levels of efficiency in implementing the principles of "green" energy in Ukraine and EU countries was conducted. Institutional and economic instruments that underpin the "green" resource use concept and have proven effective in international practice were identified.

Data collection and sources. The sample consisted of information as of 2024, as well as the dynamics of the development of the studied processes and phenomena during 2010–2023. The following methods of processing statistical data were used: classification of indicators by categories, analysis of the dynamics of "green" energy development in Ukraine from 2018–2022, capital investment measurements in energy greening from 2010–2022, and comparative-legal analysis to identify differences in environmental taxation among countries. Trend analysis was used to substantiate conclusions.

Analytical frameworks and methods. The main methods for establishing causal relationships included analytical approaches such as analysis, synthesis, generalization, comparison, and abstraction. Induction was also applied—a scientific research method aimed at identifying cause-and-effect relationships between phenomena and generalizing empirical data based on logical assumptions, moving from specific to general and from known to unknown.

Statistical methods in the context of achieving the study's objectives enabled the systematization and generalization of all information about the studied objects and

phenomena, including both positive aspects and shortcomings. These methods also facilitated drawing parallels between the essence and purpose of the studied object or phenomenon and its functional outcomes.

To determine specific parameters for assessing the impact of "green" economic tools on sustainable growth, a comprehensive analysis of academic articles published in various scholarly sources was conducted. To ensure the reliability and validity of conclusions, literature from influential journals indexed in well-known databases such as Web of Science, Scopus, and Google Scholar was selected. The works focused on recent developments and trends in "green" taxation and its impact on sustainable growth, covering the period from 2019 to 2024.

The article examines strategic documents, including the European Commission's (2020) 2050 Climate Protection Strategy, which shapes the climate leadership of EU countries. Special attention was paid to government programmes promoting clean technology development and fostering ecological innovations.

Evaluation criteria. A limitation of the study is the lack of access to complete and up-to-date official data and the difficulty of experimentally verifying theoretical conclusions.

To study approaches to "green" resource use, the authors analyzed scientific works dedicated to the impact of environmental management measures on sustainable development. Particular attention was paid to research examining the role of economic mechanisms in ensuring environmental sustainability at the regional level and their influence on transitioning to renewable energy sources. Criteria for selecting literature included several factors, such as journal quality, relevance to core industry topics like "sustainable resource use" and "environmental policy," and the availability of peer-reviewed content. The selected works predominantly cover the period from 2019 to 2024. Additionally, the methodology employed a systematic review approach with elements of meta-analysis, where appropriate, for the quantitative determination and comprehensive assessment of the effects of these policies.

Results

Key global trends in greening resource use

The main principles of sustainable development with significant practical value include greening the energy sector and production, reducing environmental impact, a rigorous system of monitoring and control in the environmental sphere, and appropriate optimisation of the management system in the context of resource efficiency. It is worth noting that the principles of energy efficiency and resource conservation are crucial in greening the economy (Sumets *et al.*, 2022).

The European Commission's 2050 Climate Protection Strategy (2020) aims to reduce greenhouse gas emissions in the European Union to virtually zero, which is seen as possible by replacing fossil energy resources, which emit large amounts of carbon dioxide, with renewable energy resources. The EU aims to be climate neutral by 2050 –

an economy with zero greenhouse gas emissions. The transition to a climate-neutral society is an opportunity to build a better future for all, leaving no one behind.

Given the strong support from the European community, Ukraine has significant potential in this area. Renewable energy technologies are being integrated to reduce the intensity of carbonisation and effectively manage fossil resources. According to the Climate Protection Strategy for 2050 (2020), greenhouse gas emissions can be reduced to zero over the next 30 years, which is planned to be achieved by abandoning the use of fossil energy resources, as their combustion releases large amounts of carbon dioxide. According to the report, by 2050, more than half of the EU countries' energy needs should be met by electricity. For citizens, this means the use of electric vehicles and partial heating of homes with electricity.

The Situation with the Sustainable Use of Ukraine's Natural Resources

Among the priority indicators for EU countries, aimed at reducing environmental and social pressures across Europe and measuring resource efficiency and emission levels, one of the most important is the intensity of carbonisation (Kofanov, Zozulov and Kofanova, 2023). In Ukraine, carbon dioxide emissions remain high, which is considered a negative phenomenon in light of European integration processes towards sustainable development and decarbonisation. At the same time, recent emission declines are identified as resulting from a reduction in production volumes rather than qualitative transformations in the production sector (Artyushok *et al.*, 2023). Ukraine has significant potential for renewable energy development. Solar and wind power plants are already being successfully integrated into the national energy system. The potential for hydrogen production and eco-friendly steel production is also substantial. Ukraine possesses strategic resources, including lithium, essential for manufacturing electric vehicles and electronic devices. All these unique advantages can make a significant contribution to implementing the European Green Deal (Iakovenko, 2023).

Development of renewable energy in Ukraine

EU membership opens new opportunities and advantages for Ukraine in developing renewable energy for several reasons. Firstly, it provides access to funding, investment, and the creation of a common market. This will enable the free export and import of hydrogen and hydrogen technologies, fostering competition, lowering prices, and stimulating innovation (Artyushok *et al.*, 2023). The common market will also facilitate cooperation with European partners, potentially leading to joint projects and knowledge exchange, along with access to advanced technologies. Secondly, an essential reason is the harmonisation of regulatory and standardisation processes, which will enhance energy security. This is expected to result in the diversification of energy supplies and reduced dependence on imported fossil fuels (Parkhomets, Putsenteilo and Uniat, 2020). Thirdly, new opportunities will arise for investors and businesses, including an improved investment climate, market expansion, and strengthened cooperation with European companies (Kofanov, Zozulov and Kofanova, 2023). Additionally, Ukrainian businesses will gain access to European financial instruments and grants for developing initiatives. Compliance with EU environmental standards will further encourage Ukrainian companies to integrate innovative technologies and practices, enhancing their

competitiveness in the global market. Significant progress was made on the eve of Russia's war against Ukraine when a steady positive trend was observed (Figure 1).

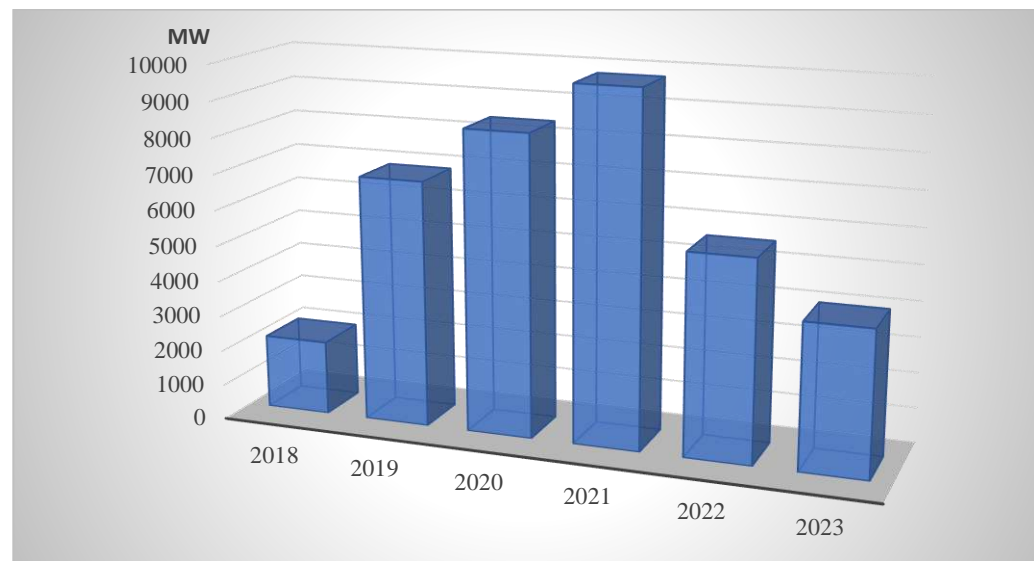


Figure 1. Dynamics of “Green” Energy Development in Ukraine, MW
Source: compiled by the author based on (NEURC, 2024)

The full-scale war has made adjustments to the resource use strategy in the energy sector, and many alternative energy facilities were destroyed or damaged in the first year. To restore sustainable growth in the share of renewable energy sources in the energy sector during the post-war recovery period, Ukraine should rely on the practical developments and experience of leading European countries (Artyushok *et al.*, 2023; Nikonenko *et al.*, 2022;). The experiences of Germany, Sweden, Romania, and Poland are particularly illustrative in this regard. Nikonenko *et al.* (2022) assess the impact of global commodity prices on the dynamics of investment in resource-exporting countries using a methodology developed under the influence of Industry 4.0 aspects. The researchers analysed the close interdependence between natural resource utilisation, economic processes, and environmental impact. In contrast, Artyushok *et al.* (2023) define the ecological-economic problems of property relations, which, unlike existing definitions, focus on issues related to attracting capital investments and the state's current expenditures on environmental protection. The researchers propose the principles for forming an institutional property system in resource management, taking into account international experience.

Green resource use policies in developed countries

The increase in green energy production in developed European countries demonstrates effective management policies in the sector. For example, in Germany, renewable energy sources have been identified as the main component of the country's future energy supply structure. In Eastern Germany, the "green transformation" is intensifying, with an increasing share of not only wind but also solar energy. Among the largest solar power plants in the country is the facility in Brandenburg, as well as the innovative energy park in Witznitz near Leipzig, currently the largest solar power station in Europe. This

experience could be particularly useful in the context of Ukraine's Bessarabia. The experience of integrating "green" certificates is beneficial for Ukraine's management practices, as they are currently recognised as securities that can be freely traded, irrespective of the sale of generated energy on the sectoral market.

One of the key factors that contributed to the rapid advancement of wind energy technologies in Romania was the official system of financial incentives for green energy producers, which stimulates investment growth in the Romanian energy sector (Østergaard *et al.*, 2020). Two Romanian projects (solar and wind) plan to cover Poland, Italy, Romania, and Croatia. Their goal is to achieve 5 GW of installed capacity in the EU by 2030. Together, they will produce approximately 225,000 MWh of electricity annually, allowing for a reduction in carbon emissions by 58,000 tonnes per year. In Sweden, energy policy is guided by an individualised action plan to stimulate renewable energy development, including ambitious targets for the green certificate system. Currently, Sweden generates over 60% of its electricity from renewable sources and is almost independent of fossil fuels. At the same time, efforts continue to reduce energy consumption in the country. In Poland, maximum emphasis is placed on the use of biofuels. Management mechanisms and instruments that promote the use of renewable energy sources in business are based on a legal and regulatory framework. Strengthening institutional support is viewed as a prerequisite for optimising natural resource management. In 2023, renewable energy covered 20.6% of Poland's needs, ranking second after coal. Raising environmental awareness among society and businesses about sustainable development is particularly important. A survey conducted by the FAMA sociological agency in 2023 and 2024 shows a significant shift in results, indicating progress in understanding the inevitability of environmental consequences and the need for active implementation of sustainable development principles in resource management strategies. All these aspects are directly related to the anthropogenic use of natural resource potential and can be successfully regulated through optimal management strategies.

The general concept of implementing Ukraine's sustainable development strategy

Table 1 presents the general concept of implementing Ukraine's sustainable development strategy in terms of natural resource potential management, as defined by the draft Law of Ukraine 'On the Strategy of Sustainable Development of Ukraine until 2030' (2018). The main goal of the process is to identify internal and external risks promptly by monitoring, analysing, and controlling indicators of the state of its main components.

Table 1. Concept of Implementing the Sustainable Development Strategy of Ukraine in terms of Natural Resource Management

<i>Vector</i>	<i>Approaches and tools</i>	<i>Expected results</i>
Level of natural resource use	Integral index, cluster analysis, neural network modelling	Identification of the levels of sufficiency and efficiency of natural resources use in the sectoral context, determination of security zones of territorial resource provision in the context of functional subsystems

<i>Vector</i>	<i>Approaches and tools</i>	<i>Expected results</i>
Sustainability of resource potential	Trend analysis	Prompt determination of fluctuations in resource security zones in the dynamics, which allows for optimisation of management decisions
Sustainability of the natural resource sector	Sensitivity analysis, qualitative and quantitative balance analysis, graph analytical method	Timely identification of existing risks, threats and imbalances, and their ranking by the strength of impact, to determine the priority and severity of management measures

Source: Artyushok *et al.* (2023); Kofanov, Zozulov and Kofanova (2023)

An important aspect is the process of investment in the energy sector. Regarding Ukraine, the pre-war period was characterised by the dynamics illustrated in figure 2.

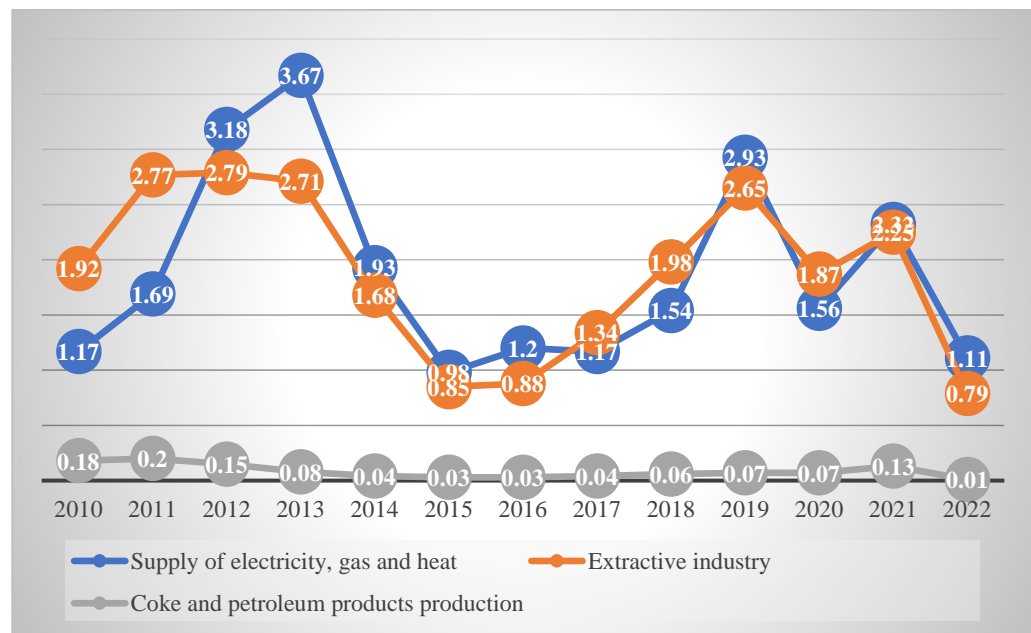


Figure 2: Capital Investments in the Energy Sector from 2010 to 2022, billion USD (Energy Map, 2023)

At the same time, investment in Ukraine's energy sector after the war should focus on renewable vectors and efficient resource use.

Recommendations for implementing an effective green resource use policy in Ukraine

Among the priority areas for integrating practical international experience in implementing a sustainable development strategy in terms of natural resource management, it is advisable to highlight the following areas:

- 1) Intensification of the use of “green” energy resources by stimulating and motivating market participants to minimise the share of traditional sources, resulting in a significant

reduction in the use of fossil fuel resources; in the context of Ukraine, this will help to develop the weak renewable energy sector;

2) Development and implementation of a unified national energy strategy and conceptual specific goals within its framework, with a variety of technical, organisational and economic instruments and mechanisms for achieving them; in particular, the provisions of Directive 2009/28/EC established mandatory national renewable energy targets in the European environment to provide certain guarantees to investors and encourage the development of new technologies and innovations in this area; in the context of Ukraine, this will mean integration into the single European energy space;

3) Targeted subsidies, “green” taxation, the introduction of sectoral codes of responsibility, and centralised regulation of prices for traditional fuels; introducing a system of subsidies and grants for practical testing of pilot business projects on the use of renewable energy sources, resource-saving technologies and circular production; the price of “green” certificates is determined on the market for these certificates; in Finland, investment grants and subsidies are the only types of incentives for the use of alternative energy sources; in the Netherlands, electricity generation from alternative sources is stimulated by redirecting corporate tax towards investment in alternative energy projects, and so on; in the context of Ukraine, this experience can be integrated in synergy with the transformation of tax policy;

4) Introducing a mechanism to prevent excessive profits of energy producers and a significant increase in tariffs for households and industry, the largest consumers of energy resources; in the context of Ukraine, this will help control the risks of corruption;

5) Raising awareness of the public and business formations on resource management, implementing productive interaction between public authorities, the public and the business community, particularly in green contracts; in the context of Ukraine, this is especially important against the background of active development of public administration.

Discussion

Our findings demonstrate a significant interest in the issue in modern society and differences in approaches to structuring their functionality and the level of prospective feasibility. Special attention is paid to the development of alternative energy. Studies have proposed expanding the possibilities for integrating energy storage technologies and their use in convergence with renewable energy sources (Tan *et al.*, 2021). Tan *et al.* (2021) explored different structures of energy storage systems and proposed to counteract problems in power grid networks, maintain the reliability and quality of electricity, and meet energy demand. Some studies also consider the possibilities of stationary energy storage for large-scale integration with the renewable energy network (Kebede *et al.*, 2022).

Instead, representatives of another school of thought (Cantarero, 2020) focus on renewable energy to accelerate the energy transition in developing countries. According to some studies, the integration of the innovative city energy system is positioned as a

forward-looking strategy on the way to a clean and sustainable development process (Kireitseva *et al.*, 2023; Tsyhanenko-Dziubenko *et al.*, 2024; Zamula, Shavurska and Kireitseva, 2024). In particular, Zamula, Shavurska and Kireitseva (2024) have a strong belief that for the post-war recovery of Ukraine, it is *важливо* to create conditions for attracting investment. To do this, it is necessary to regulate impact investing at the legislative level, promote disclosure of information on social and environmental activities by enterprises in corporate reporting, and create intermediary platforms for investors willing to invest in sustainable development.

The experience highlighted in the publications of contemporary researchers encompasses a globally integrated environment. Behera *et al.* (2024) demonstrate the link between energy consumption and economic growth in India and illustrate how broader utilization of both types of energy can benefit the economy. In the article by Dam, Işık and Ongan (2023), the authors examine the impact of renewable energy and institutional quality on environmental stability, proposing a new perspective on the coefficient of inverted throughput capacity. Noor *et al.* (2024) focus on the South Asia region and the impact of renewable and non-renewable energy sources on sustainable development. Kirikkaleli and Adebayo (2022) explore Brazil to assess the influence of the green financial system and innovations on improving environmental quality, as well as the capacity of institutional and financial measures to mitigate environmental impact. These challenges enrich the idea that less economically developed regions require specific financially and politically oriented measures. The findings of the current research also suggest that financial incentives are effective; however, they must be reinforced with financial mechanisms that align with the economic and environmental conditions of the region.

Sethi, Behera and Sethi (2023) examine economic growth and energy consumption, emphasizing that a balanced approach to resource utilization is crucial for environmental preservation. Conversely, the work by Dhillon and Kaur (2023) focuses on the interrelation between sustainable development, energy use, and economic growth.

Anton and Nucu (2020) have shown the significant role of green finance. The study proposed reconsidering FinTech's potential and the parameters of financial accessibility, in particular, green bonds, to achieve energy efficiency in the shortest possible time and reduce the consumption of non-renewable resources. Their findings convincingly show that financial development increases demand for clean energy sources. To achieve the goals of sustainable development, the researchers believe that governments should introduce incentives and tax policies that increase corporate demand for renewable energy sources and investment opportunities through public-private cooperation. Ahmad *et al.* (2021) emphasise that the development of digital technologies and artificial intelligence can radically change the system of resource consumption. The researchers examine aspects of the use of artificial intelligence in solar and hydrogen energy production, as well as in supply and demand management. Ahmad *et al.* (2021) argue that machine learning and artificial intelligence will play an essential role in the energy market of the future, allowing for the greening of energy production and consumption processes. Their findings and the analysis of scientific approaches highlight that exploring the possibilities of switching to renewable energy sources to reduce emissions and increase resilience to climate change should be positioned as one of the priority

shaping factors of socio-economic development towards the implementation of a sustainability strategy.

Given the stable international support for Ukraine's transformation processes, it seems advisable to use the maximum potential of the opportunities for businesses to switch to renewable energy sources to reduce emissions and increase climate change resilience during the post-war recovery period. The prospects for subsidised financing within the framework of the European integration strategy open up significant practical opportunities in terms of the use of renewable energy sources in business.

Our research aligns with previous conclusions that renewable energy has environmental advantages. However, it is also evident that its implementation varies significantly depending on the region and economy. There is a substantial gap in research on small-scale renewable energy projects, as large-scale projects raise issues of development adjustment and increase initial risks associated with renewable energy projects.

Conclusion

The primary objective of the article was to analyze Ukraine's sustainable development strategy in managing its natural resource potential, with a focus on the development of renewable energy.

The analysis of the problem under study has revealed the specifics of the use of renewable energy sources. The article has identified the priority need to intensify the share of renewable resources in the national energy sector. To do this, it is necessary to use the potential of the system of economic incentives and the motivation of the business sector to use resources economically. Timely identification of existing risks, threats and imbalances, and their ranking by the strength of their impact is important for determining the priority and severity of management measures. The implementation of Ukraine's sustainable development strategy in terms of natural resource management should synergise the aspects of the level of natural resource use, sustainability of resource potential, and balance of the natural resource sector. This approach will allow us to quickly identify fluctuations in resource security zones in the dynamics, timely identify existing risks, threats and imbalances, and rank them by the strength of their impact, which will allow us to make optimised management decisions. A promising area for future research in the field of sustainable environmental management is a detailed study of the potential of economic incentives and business motivation for sustainable development.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No
Collected the data	Yes	No	Yes	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
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The Role of Ukraine in Ensuring Global Food Security: Current Challenges and Prospects

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Abstract

Even though Ukraine's GDP is less than 0.2% of the world's GDP, it is one of the biggest exporters of agricultural products, accounting for 9–11% of global wheat exports and 13–16% of global corn exports. As such, Ukraine has been instrumental in ensuring global food security in recent years. Food insecurity and inflation have been made worse by the war in Ukraine, which has changed global patterns of commodity production, trade, and consumption in ways that will maintain prices at historically high levels. Ukraine managed to restore the main export route for its grain in the Black Sea in volumes close to pre-war levels. The indicators of April 2024 exceeded February 2022. The resumption of Ukrainian grain exports helps in decreasing market prices and reducing world hunger. With this in mind, the purpose of the article is to identify priority areas for strengthening Ukraine's role as a guarantor of global food security. It also highlights the dynamics of production of the main types of crop products in Ukraine. The following methods were used for the study: empirical, monographic, extrapolation, graphical, benchmarking, and SWOT analysis. An in-depth study of secondary data highlights that Ukraine currently holds leading positions in global agricultural production and exports, including sunflower seeds, sunflower oil, rapeseed, a quarter of corn, wheat and barley, and soybeans. Based on the extrapolation method, wheat exports to the world market were forecasted until 2027. The features of Ukraine's dominance in the world sunflower oil market were characterized. To reflect the impact of the war on global and Ukrainian food security, a benchmarking analysis of wheat exports in Ukraine and Russia for 2014–2024 was conducted, and the change in the global Food Price Index and certain types of products (2009–2024) was considered. A SWOT analysis of Ukraine's agricultural sector in the international market is presented. The article outlines priority directions for developing Ukraine's agricultural sector as a future guarantor of global food security.

Keywords

Food security; Export potential; Agricultural sector; Grains; Oilseeds

Introduction

Being one of the largest countries in Europe and possessing significant resources of fertile black soil, Ukraine has significant agricultural potential. These natural conditions contribute to high yields of crops such as wheat, corn and barley, which allow the country to be one of the leading countries in terms of grain production and exports. The agricultural sector is vital for Ukraine's economy, providing jobs and foreign exchange earnings. Grain exports provide a stable income that contributes to the country's economic development and financial stability (FAO, 2023a).

Ukrainian agricultural products are vital for global food security, particularly in countries with insufficient grain production (Bychkovska, 2024). Thus, the stability and development of the Ukrainian agricultural sector are not only of national but also global importance, especially in the context of growing food demand. However, the agricultural sector faces serious challenges, such as climate change, which affects yields and the sustainability of agricultural products. Droughts, temperature fluctuations, and extreme weather events are forcing farmers to adapt their growing and storage technologies. To this end, research is being conducted to help develop adaptive strategies to minimize the impact of climate risks on agriculture.

The integration of modern technologies, such as precision farming, biotechnology, and the use of digital solutions for monitoring and managing growing processes, is helping to improve the efficiency of agricultural production. These innovations allow for more precise management of resources, lower costs, and improved product quality, which in turn increases the competitiveness of Ukrainian agricultural products on global markets. Such technological and scientific advances are key to ensuring the long-term stability and resilience of Ukraine's agricultural sector in the face of current economic and environmental challenges. Ukraine is a key supplier of wheat, corn and barley to the global market, but the war poses significant challenges to its agricultural sector. Destroyed infrastructure, mined fields, disruptions in fertilizer imports and a lack of finance are reducing yields and exports. Blockades of ports limit access to markets, which increases global food prices and threatens food security, especially for countries in Africa and the Middle East. Soil contamination and the loss of markets make it difficult to sustain production. International support is essential to overcome these challenges.

Researchers have established the significance of Ukraine as a producer of agricultural products over a long period in ensuring global and domestic food security. It has been established that the involvement of the agricultural sector in global commodity flows related to food production is increasing (Shubravska and Prokopenko, 2022). It has been proven in practice that scientifically based use of fertilisers, rational land use, balanced pricing, developed logistics, and improvement of innovative, technological, and market components in the Ukrainian economy contribute to the development of the agricultural sector and its export potential (Lagodiienko, Bogdanov and Lagodiienko, 2019; Vasylieva, 2018).

Consolidating efforts by management bodies, socially responsible businesses, and rural populations contributes to ensuring effective production relations in the agricultural

market (Kravchenko *et al.*, 2020; Mykhailova *et al.*, 2018). Currently, the issues of the state and prospects of Ukraine's foreign trade in agro-industrial complex products in the context of European integration and global challenges are particularly relevant (Lohosha *et al.*, 2020; Matyushenko *et al.*, 2018). The peculiarities and trends in the export and import of agri-food products, evaluating the global impact, are being studied (Radchenko, 2022). As a result of scientific research, it has been established that Ukraine has unrealised export potential, which requires considering the experience of various countries worldwide (Bazaluk *et al.*, 2020). In particular, studying foreign experience in the rational use of fresh water has allowed for identifying priority vectors for adapting agribusiness to climate change (Dvigun *et al.*, 2022). Recently, increasing attention has been paid to the problems of exporting agricultural products in connection with Russia's military aggression on the territory of Ukraine (Halkin, 2023a; Mamonova, Borodina and Kuns, 2023; Tereshchuk, 2023).

According to Prokopa *et al.* (2024), in the contemporary Ukrainian context, alongside increasing Ukraine's export potential, it is also important to strengthen the resilience of its domestic agriculture. The war exposed significant weaknesses in Ukraine's agricultural infrastructure, including logistical bottlenecks and dependence on global trade routes that are now the subject of controversy (Skydan *et al.*, 2023). Strengthening domestic production chains, diversifying export markets, and developing strategic reserves are necessary for Ukraine to remain a reliable supplier even in the face of geopolitical instability (Krykavskyy, Shandrivska and Pawłyszyn, 2023).

A comprehensive assessment of the direct and indirect market consequences of the war in Ukraine on agricultural business development has been conducted (Lopatynskyy *et al.*, 2023). Scientists emphasise a scientifically based approach and balanced pricing policy to minimise the global food crisis caused by armed conflicts, the COVID-19 pandemic, and climate change (Halkin, 2022; Halkin, 2023b). The connections of global prices have been studied, and the current "price leaders" of the world wheat market have been identified, among which three countries of the Black Sea region stand out — Russia, Ukraine, and Kazakhstan. It has been established that creating a futures market in the Black Sea region will significantly improve the participation of Black Sea markets in forming the price of the world wheat market (Svanidze and Đurić, 2021). The main directions of intensifying Ukraine's agricultural production, considering the quality and safety requirements of products in the conditions of developing European integration processes, have been identified (Petrychenko *et al.*, 2022).

Mazur and Alieksieieva (2024) noted that the Ukrainian agricultural sector has the potential to emerge stronger after the war, provided that there is a concerted effort to modernize infrastructure and adopt more sustainable agricultural practices. Specifically, the current global food security crisis has highlighted the fragility of international supply chains and the growing need for self-sufficiency and resilience. Ukraine should endeavour to position itself not only as a food exporter, but also as a key player in global efforts to reform agricultural systems in response to climate change, rising food prices, and geopolitical instability (Prokopa *et al.*, 2024).

Thus, researching Ukraine's role as a guarantor of global food security is relevant and essential to economic development, global food security, adaptation to climate change, and innovation implementation.

European political analyst Amanda Paul (2023) noted at the second global summit “Grain from Ukraine” that Ukraine remains a reliable partner in the grain industry and can ensure global food security. European researchers have recognized that Ukraine has a developed agricultural sector (Roman, 2024). Ukraine is a major exporter of grains and oilseeds, staple foods that are currently suffering from supply risks caused by the war (Filho *et al.*, 2023). Ukrainian exports - especially wheat - are crucial for some countries in Asia and Africa (Jagtap, *et al.*, 2022; Holmberg, 2024; Ben Hassen and El Bilali 2024). The global scientific community notes that the war also affects the ability of international organizations to provide food aid to countries suffering from famine or other armed conflicts (Behnassi and El Halba, 2022; Chepeliev, *et al.*, 2023; Yıldırım and Onen, 2024). Chinese scientists estimate that as a result of the war in Ukraine, food trade will fall by 60%, and wheat prices will rise sharply (50%), especially for countries that import wheat from Ukraine (Lin, *et al.*, 2023).

The study aims to assess Ukraine's agricultural potential and determine specific measures to strengthen Ukraine's role as a guarantor of global food security. The study will assess the key resources and opportunities of the agricultural sector, taking into account current challenges and threats, including the impact of military operations on agriculture, logistical and infrastructure constraints, and market accessibility. The study focuses on strategies and innovations to enhance agricultural sustainability and resilience. Following the purpose of the article, the main objectives of the study were:

- 1) to determine trends in the production and export of the main types of agricultural products in Ukraine and their place in the world market;
- 2) to identify key export crops in Ukraine;
- 3) to monitor prices in the food market;
- 4) to conduct a SWOT analysis of the Ukrainian agricultural sector on the international market;
- 5) to determine priority areas for the development of the agricultural sector of Ukraine as a guarantor of world food security.

Methodology

This article conducts an empirical analysis of more than 50 scientific articles, 15 monographs, 20 reports and other publications on food security, the agricultural sector and Ukraine's role in international trade. The selection of publications was carried out using the Scopus, WoS, and Google Scholar databases. The monographic method allowed to formation of a database to identify trends in agricultural production. The extrapolation method was used to forecast the level of Ukrainian wheat exports to the world grain market and to identify trends in the role of Ukraine in the world agricultural market. The analytical review of production and export volumes of agricultural products on the global market and in Ukraine was based on processing statistical data from FAO, Statista, USDA, and SU (about 20 statistical reports were used to sample the information).

The graphical method was used to depict the dynamics of the development of Ukraine's agricultural sector from 2000–2023 and Ukraine's position in the global market for individual types of agricultural products (Stepasyuk and Titenko, 2020). To analyze the development of Ukraine's agricultural sector over the period, various approaches were used to address data gaps, in particular during the conflict period. Official national and international sources were used, as well as statistical interpolation to fill in the gaps. Structural changes were analyzed in the context of key events, such as the annexation of Crimea (2014) and the full-scale invasion (2022). The main focus was on long-term trends, supplemented by context from industry reports and expert opinions, which ensured the integrity and objectivity of the study. To compare the impact of Russia's military aggression against Ukraine on agricultural exports, the article uses a benchmarking analysis to quantify export losses compared to pre-war levels or other exporting countries. Statistical tools, including extrapolation, were used to create a trend line that visually represents future changes in the global agri-food market, with a particular focus on leading countries. A SWOT analysis of Ukraine's agricultural sector in the international market was employed to summarize the findings and provide a comprehensive understanding of the sector's strengths, weaknesses, opportunities, and threats. To complete the SWOT matrix of the Ukrainian agricultural sector in the international market, various data sources are used to provide a comprehensive analysis. The main sources and approaches include: data from the State Statistics Service of Ukraine on production, exports and imports; FAO data on global food markets; information from the WTO on barriers to international trade; and scientific and economic research. The assessment was conducted with due regard to the specifics of regions, product types and markets to avoid generalizations that may not be accurate for different conditions. Thus, a comprehensive approach and multi-stage verification allow us to create a relevant and reasonable SWOT analysis.

These methods allowed for identifying the main factors influencing the agricultural sector and developing effective strategies to ensure food security both at the national and international levels. The assessment was carried out taking into account the specifics of regions, product types and markets to avoid general conclusions that may not be accurate for different conditions. Potential limitations include data inconsistencies due to disruptions caused by the conflict and the rapidly changing geopolitical landscape, which may impact the accuracy of long-term forecasts.

Results

Ukraine is essential in the global food market due to its significant natural resources, particularly fertile soils and a favourable climate for agriculture. Crop production is a critical component of Ukraine's agricultural sector. Both domestic needs and export opportunities determine priorities in this area. Ukraine's significance in ensuring the food security of certain countries is also substantial, especially concerning the main export crops. The production of major crop products in Ukraine undergoes significant changes under various economic, technological, and climatic factors. Despite these challenges, the agricultural sector demonstrates stable growth trends in the production of the main types of crop products (see Table 1).

Table 1: Production Dynamics of Major Crops in Ukraine, thousand tons

Crops	Year									Growth, 2023 to	
	2000	2005	2010	2015	2019	2020	2021	2022	2023	2000, %	2010, %
Wheat	10197	18699	16851	26532	28328	24877	32151	20729	21625	112.1	28.3
Maise	3848	7167	11953	23328	35880	30290	42110	26187	31030	706.4	159.6
Sunflower seeds	2842	3689	4526	5166	5959	6481	6665	5238	12760	349.0	181.9
Soya beans	64	613	1680	3931	3699	2798	3493	3444	4743	7264.2	182.3
Winter rapeseed and colza	132	285	1470	1738	3280	2557	2939	3318	4184	3074.2	184.7

Source: SU (2024)

Modern technologies, innovation transfer, and expansion of sales markets contribute to strengthening the position of Ukrainian agrarian producers in the global market. In 2023, Ukraine ranked 2nd globally in sunflower and its processed products (oil, meal) production, 5th in walnut production, 6th in rapeseed production, 7th in barley and wheat, 9th in cherries and oats, and 10th in corn, according to the overall Top-10 ranking of countries worldwide (Filipenco, 2024) (see Figure 1).

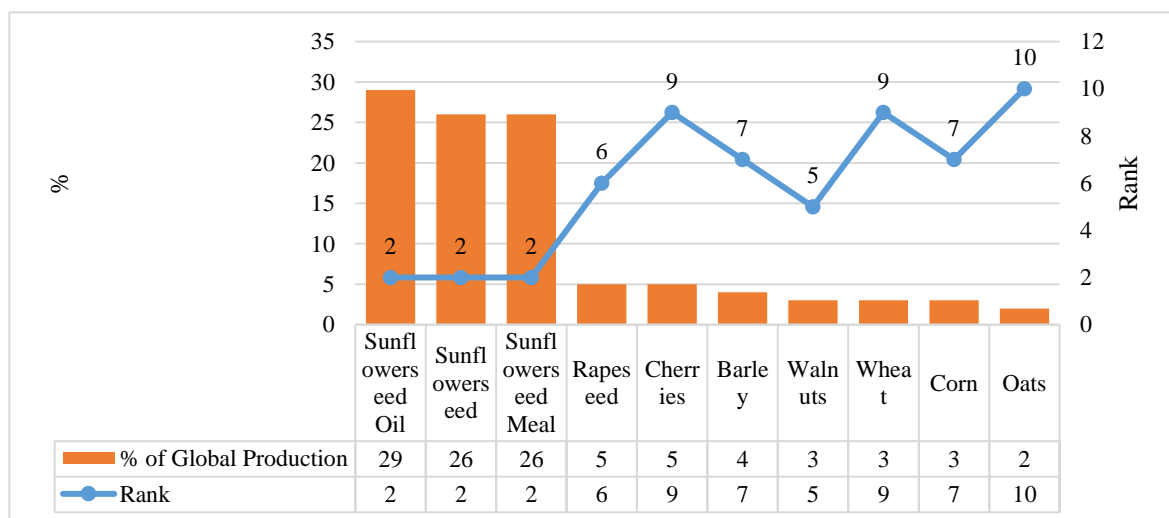


Figure 1: Ukraine's Place in Global Agricultural Production, 2023 (USDA, 2023)

Ukraine plays a pivotal role in the global food market, primarily due to its substantial production of grains and oilseed crops. Its influence extends to many countries and regions that import Ukrainian products to ensure food security. Below is the production of Ukraine's prominent export grain and oilseed crops (see Figure 2).

The growth in the production of grain, oilseed, leguminous crops, and vegetables contributes to ensuring food security in Ukraine and other countries. Wheat remains one of the main crops in Ukraine. The steady increase in wheat production is attributed to advancements in agricultural technologies and the adoption of high-yielding varieties.

Ukraine is important in the global food security system due to its ample agricultural resources and potential. Globally, Ukraine is the leading producer and exporter of sunflower oil. Annual sunflower production exceeds 15 million tons.

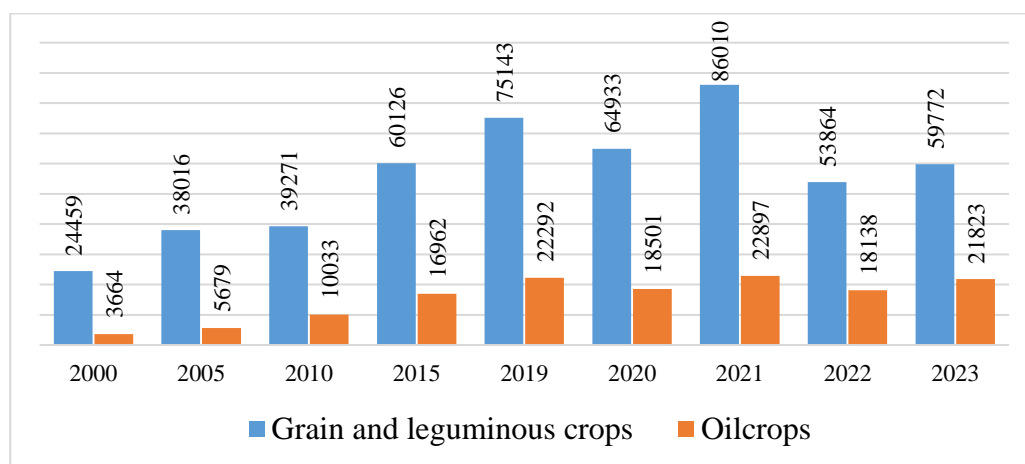


Figure 2: Production of Ukraine's Main Export Grains and Oilseeds, thousand tons (SU, 2024)

Ukraine is vital in global soybean production and contributes to food security. Although it is not the largest soybean producer in the world, its contribution to this sector is significantly increasing. Soybean production in Ukraine has grown significantly in recent years. FAO data shows that production volumes exceed 3.5 million tons annually (FAO, 2023a). Expanding soybean areas reflect rising farmer interest. Using modern technologies and high-yielding varieties contributes to increasing soybean yields in Ukraine. Ukraine is a significant exporter of soybeans. Annual export volumes exceed 2 million tons. The leading importers of Ukrainian soybeans are the European Union countries, China, and Turkey. Demand for Ukrainian soybeans is also growing in Southeast Asian countries. Soybeans are vital for food security as a protein source. They are used as a feed base in livestock, contributing to the production of meat, milk, and other animal products.

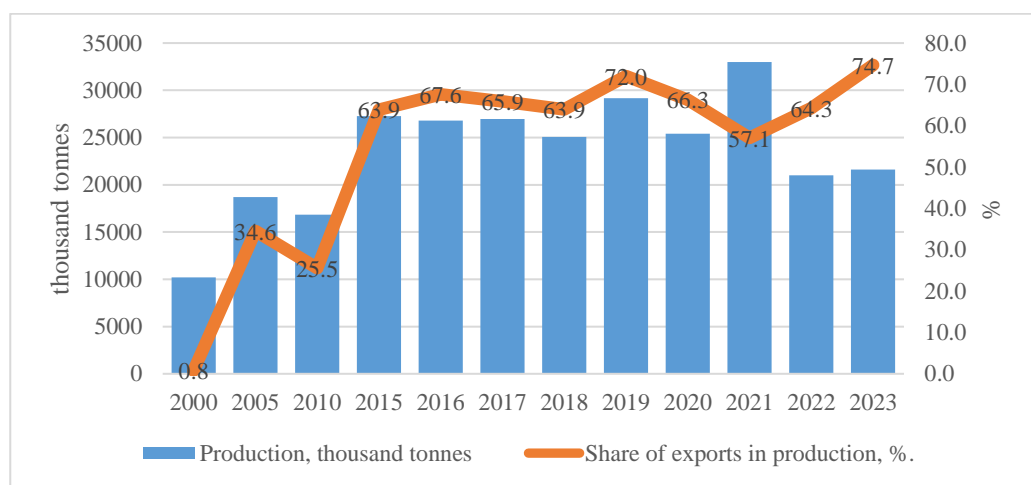
Table 2: Ukraine's Share in Global Oilseeds Production, %

<i>Culture</i>	<i>Marketing year (MY)</i>	<i>World</i>	<i>Ukraine</i>	<i>Ukraine's share in the world production, %</i>
Soybean	2021/2022	360.43	3.8	1.05
	2022/2023	378.37	4.1	1.08
	2023/2024	395.41	5.2	1.32
Sunflowerseed	2021/2022	56.86	17.5	30.78
	2022/2023	52.78	12.2	23.11
	2023/2024	55.14	14.5	26.30
Rapeseed	2021/2022	75.79	3.02	3.98
	2022/2023	88.75	3.5	3.94
	2023/2024	88.76	4.75	5.35

Source: FAO (2023b, 2023c); Statista (2024b); USDA (2024a)

Ukraine is one of the leading rapeseed producers in the world, with an annual production of about 3-4 million tons. Rapeseed from Ukraine is exported to the European Union countries to produce biodiesel and edible oil, contributing to the EU's energy and food security (see Table 2).

Ukraine continues to be one of the largest wheat exporters in the world. The main markets are the countries of Europe, the Middle East, and North Africa. Ukraine is among the top ten wheat producers (Statista, 2024a). In 2023, Ukraine produced 21.6 million (mln) tons, of which 74.7% were exported (see Figure 3).



According to preliminary estimates, considering current natural and climatic changes, the effects of the 2019–2020 pandemic, and the war, Ukraine will supply the world market with 14 mln tons of wheat in 2027 (see Figure 4).

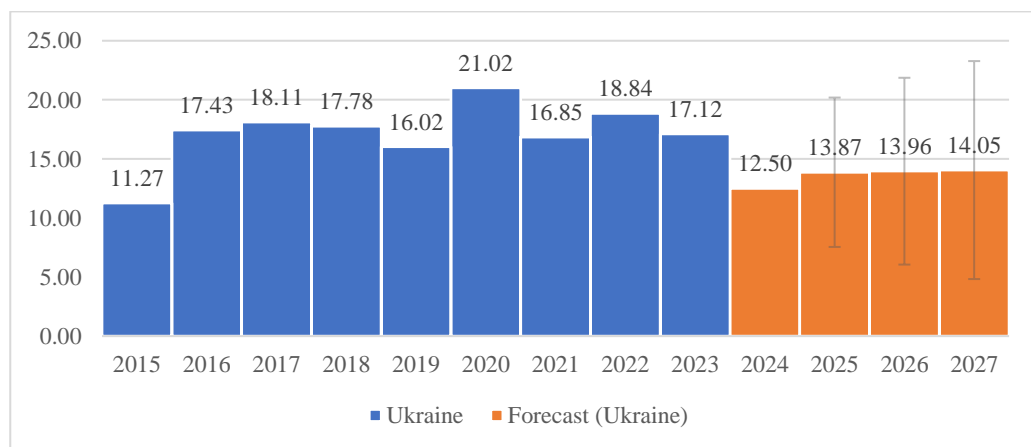


Figure 4: Actual and Forecasted Level of Wheat Exports from Ukraine to the Global Grain Market, million (mln) tons (USDA, 2024b)

Finally, for the long-term survival and resilience of the maize sector, the central maize-producing countries should focus on sustainable farming practices, resource management, and innovation. Ukraine is among the top three maize exporters in the

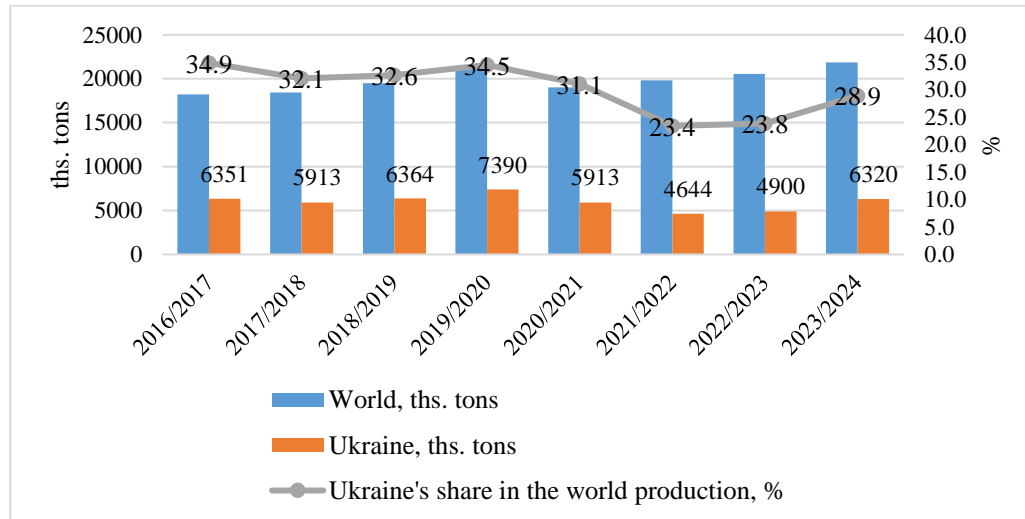
world, with the ten largest maize-producing countries playing a crucial role in supplying the world with this vital crop (see Table 3).

Table 3: Ukraine's Place in Global Corn Production

Marketing year (MY)	Million tons		Ukraine's share in the world production, %
	World	Ukraine	
2021/2022	1217.27	42.13	3.5
2022/2023	1159.6	27	2.3
2023/2024	1225.45	31	2.5

Source: USDA (2024b)

With large maize production capacities, these countries help ensure global food security and significantly impact agriculture and global trade. Maize is the second most important grain crop. The areas under maize cultivation are increasing due to the high demand for this crop in domestic and international markets. Ukraine occupies a leading position in the global sunflower oil market, being the largest producer and exporter of this product. Annually, the country produces about 6-7 million tons of sunflower oil, which accounts for approximately 30-35% of global production (see Figure 5).



Ukraine cultivates sunflowers in large areas, approximately 6-7 million hectares annually. Ukrainian farmers use modern technologies to grow and process sunflowers, allowing for high yields and quality oil. Ukraine is the world's largest exporter of sunflower oil, accounting for about 50-60% of global exports (FAO, 2023c). In 2023, export volumes amounted to about 5-6 million tons. The leading importers of Ukrainian sunflower oil are the European Union countries, India, China, Turkey, and the Middle Eastern countries. In recent years, demand for Ukrainian sunflower oil has been increasing in African countries and Southeast Asia. Due to high production and export volumes, Ukraine holds leading positions in the global sunflower oil market. Despite numerous challenges, the country has significant potential for further development and strengthening its position. Implementing modern technologies, expanding sales markets,

and improving infrastructure will help Ukraine maintain its leading role in the global sunflower oil market (see Table 4).

Table 4: Ukraine in the Global Sunflower Oil Market

<i>Advantages</i>	<i>Challenges and threats</i>	<i>Development prospects</i>
High soil fertility, especially black soil, is conducive to growing high-quality sunflowers.	Dependence on global sunflower oil prices may lead to financial risks for producers.	Opening new markets in Africa and Asia may contribute to export growth.
Favourable climatic conditions and modern cultivation technologies allow Ukraine to achieve high sunflower yields.	Climate change may affect sunflower yields, which will affect production and export volumes.	Implementation of new technologies for sunflower cultivation and processing can improve production efficiency and product quality.
Ukraine has a well-developed infrastructure for sunflower oil processing, which allows the production of high-quality products.	Insufficient development of transport and logistics infrastructure may complicate export operations.	Investments in transport and logistics infrastructure could improve export opportunities.
Relatively low production costs make Ukrainian sunflower oil competitive on the global market.	Increasing competition from other sunflower oil producers, such as Russia and Argentina.	Production of organic sunflower oil and other value-added products could increase the industry's profitability.

The development of Ukraine's agricultural sector has been negatively impacted by the global COVID-19 pandemic in 2019 and Russia's military aggression since February 2022. A direct consequence of this has been reduced agricultural production, exports, and Ukraine's GDP. Russia's war in Ukraine has also led to historic disruptions in global agricultural, energy, and fertiliser markets, worsening food security for millions of people (Dankevych, 2022). Since 2022, statistical data indicate a decline in the production and export of essential agricultural commodities in Ukraine and an increase in production and export in Russia (see Figure 6).

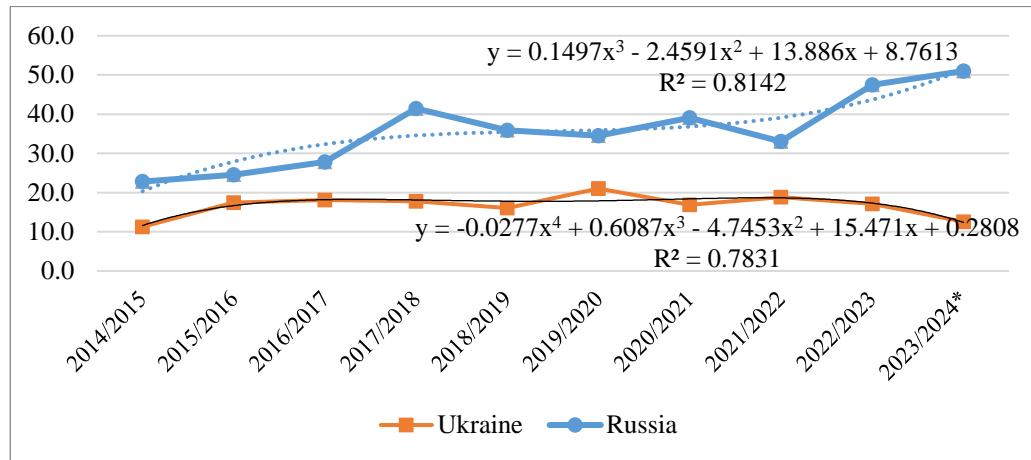


Figure 6: Benchmarking Analysis of Wheat, Flour and Wheat Products Exports in Ukraine and Russia, 2014/2015 – 2023/2024, thousand tons (Filipenco, 2024)

Global shifts in the agricultural market due to Ukraine’s reduced production and exports have been severe. According to the Food Price Index of the Food and Agriculture Organization of the United Nations, in March 2022, global food prices reached a nominal all-time high (FAO, 2024). The changes in the Food Price Index confirm this trend (see Figure 7).

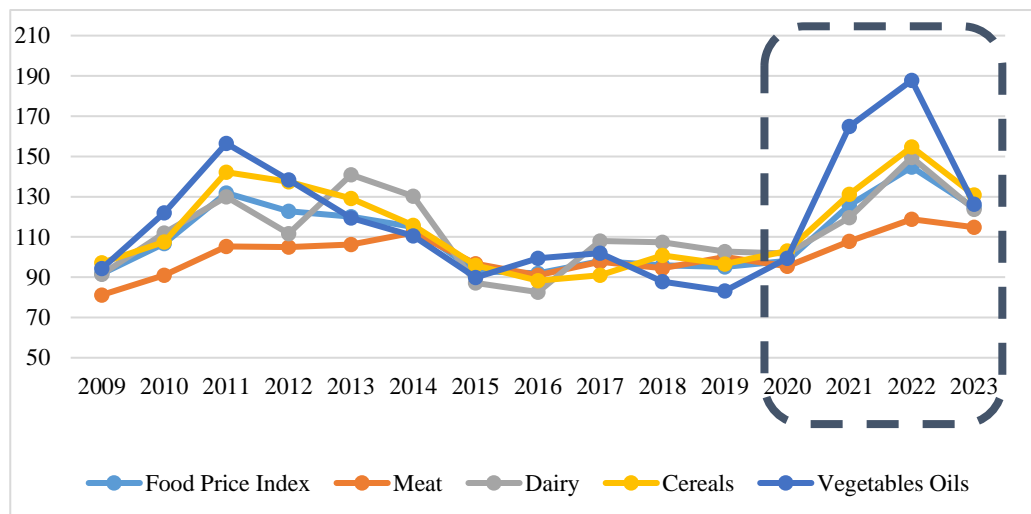


Figure 7: Dynamics of the Global Food and Commodity Price Index, % (FAO, 2024)

The Russian war in Ukraine has caused the most significant military destabilisation of global agricultural markets in the past century. The war has directly and indirectly impacted agricultural production in Ukraine. The occupied territories of Donetsk, Luhansk, Kherson, and Zaporizhzhia regions accounted for about 21% of wheat, 17% of barley, and 19% of sunflower seeds produced in Ukraine from 2016 to 2020, while very little maize was grown there (SSSU, 2024). According to NASA Harvest, the amount of abandoned arable land in Ukraine in 2023 due to the war is approximately 7.5% of the total arable land area in the country (Becker-Reshef and Mitkish, 2024). The war raised

transport costs, reducing crop profitability and forcing lower prices. As a result, Ukraine planted and harvested less. According to the State Statistics Service of Ukraine, sown areas under grain and leguminous crops in 2023 decreased by 31.3%, sunflower by 21.2%, vegetables by 13.7%, and fruit and berry crops by 13.8% compared to 2021 levels (SSSU, 2024). The total loss of agricultural land and unharvested crops as of June 2022 amounted to 50%, grain storage to 9%, and agricultural machinery to 22% (Neyter, Stolnikovych and Nivievskiy, 2022).

According to the Global Report on Food Crises, in 2022, 258 million people suffered from acute food insecurity, the highest number on record (GRFC, 2023). At the same time, the costs of addressing these issues also increased due to simultaneous shocks in global energy and fertiliser markets caused by Russia's war (Welsh and Glauber, 2024).

Ukraine's livestock sector has potential but less global impact than grains and oilseeds. However, the sector's development could increase its role. Beef and pork production in Ukraine is stable but does not reach the volumes of the leading global producers. The primary consumers are the domestic market and neighbouring countries (Georgia, Moldova). Ukraine is one of Eastern Europe's leading producers and exporters of poultry meat. Large poultry farms provide significant volumes of products for domestic consumption and export. Ukraine has a strong dairy industry that produces a wide range of dairy products. The leading producers are large agri-holdings and cooperatives. Dairy products are exported to the European Union, Asia, and Africa. Exports cover various products, from fresh milk to cheese and butter.

The livestock sector has also been significantly affected by the war. The estimated value of lost animals exceeds USD 136.4 million. Agricultural animals die not only from direct combat but also from limited access to farms, lack of feed, and veterinary services. The estimated number of animals lost due to Russian aggression in the affected areas includes 92,000 cattle, 258,000 pigs, and about 6 million poultry. Additionally, agricultural machinery and equipment are also damaged due to shelling, airstrikes, and combat operations (SSSU, 2024). The estimated cost of replacing and repairing machinery is USD 926.1 million (Neyter, Stolnikovych and Nivievskiy, 2022).

The appropriation of Ukraine's crops by Russia as a result of military aggression has caused severe economic and humanitarian consequences. Russian troops seize Ukrainian farms and agricultural enterprises, confiscate the harvest, and transport it to Russia. This leads to significant losses for Ukrainian farmers and the country's economy. Moreover, such looting results in food shortages in Ukraine, exacerbating the humanitarian crisis. These actions by Russia are part of a broader strategy to undermine Ukraine economically, highlighting the need for international support to restore Ukraine's economy and ensure food security. Despite all the upheavals, Ukraine has opportunities to increase its role in the global livestock market. Investments in technology and infrastructure can boost Ukraine's role in global food security.

Discussion

Ukraine occupies an essential place in the global food market due to its natural resources, significant production volumes, and export of major crops. Despite numerous

challenges, the country has significant potential for further development and strengthening its position in the international market. Foreign researchers point out that Ukraine's role in global food security is extremely important, especially in the context of military aggression. In particular, analysts from the Food and Agriculture Organization of the United Nations (FAO) note that Ukraine is a critical supplier of grain crops, especially for countries that depend on food imports, such as the regions of Africa and the Middle East (Clapp *et al.*, 2022; Hamulczuk *et al.*, 2023; Filho *et al.*, 2023; Sharma *et al.*, 2024; Zhang *et al.*, 2024). The war has severely disrupted logistics, destroyed critical agricultural infrastructure, and blocked ports, leading to rising global food prices, and worsening hunger in vulnerable regions (Aljounaidi *et al.*, 2024; Emediegw, 2024; Welsh and Glauber, 2024). According to researchers at the Peterson Institute for International Economics and the Oakland Institute (Ozili, 2022; Mousseau, 2023), Ukraine is a key link in global food supply chains. Military aggression and export restrictions from Ukraine may result in prolonged global food shortages, intensifying humanitarian crises in low-income nations. Studies from the University of Oxford (Hussein and Knol, 2023) and Harvard (Goldstein, 2024) also emphasize the need for international support for Ukraine to ensure its ability to restore production capacity and maintain access to foreign markets. They believe that the stable functioning of the Ukrainian agricultural sector is the key to reducing the risks of a global food crisis (World Food Programme, 2024). It implements modern technologies, expands into new markets, and improves its infrastructure (see Table 5).

Table 5: SWOT Analysis of the Ukrainian Agricultural Sector in the International Market

<i>Strengths</i>	<i>Weaknesses</i>
Ukraine has some of the most fertile soils in the world (chernozem), which contributes to high agricultural crop yields; Significant areas are suitable for agricultural production, allowing for the cultivation of large volumes of products; Ukraine is a major producer of grains (wheat, maize), oilseeds (sunflower), and other agricultural products; High levels of agricultural product exports, especially grains, to international markets; Relatively low cost of labour and land compared to other countries.	Poor state of transport and logistics infrastructure, which complicates the transportation of products; The low intensity of implementing new technologies and modern equipment; Frequent droughts and other adverse weather conditions affecting crop yields; Limited access to credit and investments, which hinders the development of the sector; Inadequate transport and logistics infrastructure impedes efficient product transportation, particularly during wartime disruptions; Restricted access to credit and investment stifles growth and development, further exacerbated by conflict-related risks; Corruption and complex regulatory requirements create additional difficulties for farmers and agricultural enterprises.
<i>Opportunities</i>	<i>Threats</i>
Increased demand for Ukrainian products in new markets such as Asia and Africa;	Geopolitical tensions and military aggression directly disrupt production and trade logistics, severely impacting Ukraine's role in international markets;

<p>Investments in precision farming, biotechnology, and other innovations can significantly increase yield and production efficiency;</p> <p>The growing demand for organic products can become an essential direction for development.</p> <p>Participation in international programmes and projects aimed at agricultural development can enhance competitiveness;</p> <p>Investments in transport and logistics infrastructure can significantly improve export capabilities;</p> <p>Targeted investments in transport and logistics infrastructure promise to improve export capabilities and reduce dependency on unreliable routes;</p> <p>International programs supporting post-conflict agricultural development can enhance competitiveness and rebuild trade relations.</p>	<p>Climate change may increase the frequency of extreme weather conditions, which will negatively affect crop yields;</p> <p>Growing competition from other agricultural exporting countries.</p> <p>Internal political conflicts and international sanctions may create risks for the agricultural sector;</p> <p>Dependency on global agricultural product prices can lead to financial risks.</p> <p>Imposing tariffs and other restrictions in international markets may reduce the competitiveness of Ukrainian products;</p> <p>Food insecurity risks in importing countries could complicate trade relations, placing additional pressure on Ukraine to fulfil its global role amid conflict.</p>
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Despite facing challenges such as war, climate change, and economic difficulties, Ukraine's rich natural resources, significant agricultural potential, and major grain crop exports have established it as a key player in the international market.

These findings coincide with the general international consensus that emphasizes the importance of Ukraine in ensuring a stable supply of food commodities, in particular wheat, corn, and oilseeds, which are critical for many countries. At the same time, current challenges require adaptation strategies aimed at strengthening the resilience of the agricultural sector and developing export potential, which will only strengthen Ukraine's role in shaping. However, several problems must be addressed to realise this potential, including improving infrastructure, implementing new technologies, and reducing dependency on climatic conditions. Overcoming corruption and creating favourable conditions for investment in the sector are also important aspects. Food security is critical to national security, especially for a country with great agricultural potential like Ukraine. Ensuring food security involves several key aspects: stable production, access to food, product quality, and supply stability (see Table 6).

Ukraine faces several challenges, including political instability, economic difficulties, climate changes, and conflicts. Expected long-term impacts include changes in agroclimatic zones that may reduce the available areas for growing certain crops while creating new opportunities for others (Benitez-Alfonso *et al*, 2023). An increase in the frequency of droughts and extreme weather events will lead to an increased need for drought-resistant crops and modern irrigation systems. Investments in research on

adaptive agriculture and the development of climate-resilient innovations will be critical (Grigorieva *et al*, 2023). Modernization of the logistics infrastructure (roads, railways, ports) will reduce the cost of transportation and expand export opportunities (Liu, 2024). The introduction of digital technologies and automation in the agricultural sector will help improve production efficiency (Ashoka *et al*, 2023) The development of “green” investments in renewable energy can support the sustainable development of the agricultural sector by reducing dependence on fossil fuels (Wang, *et al*, 2024). A climate change adaptation program, investment in innovation, and expansion of export potential can ensure Ukraine's leadership in the international food security market. However, due to its natural resources and agricultural potential, the country has significant opportunities to strengthen its food security. Food security in Ukraine requires support for production, quality access, exports, and international cooperation. The implementation of these strategies will contribute not only to enhancing food security in Ukraine but also to its contribution to global food stability.

Table 6: Priority Directions for Developing Ukraine's Agricultural Sector as a Guarantor of Food Security in the World

<i>Direction</i>	<i>Measures</i>
<i>National level</i>	
Supporting agricultural production	development of agricultural infrastructure, which could include expanding drip irrigation in southern Ukraine; provision of financial incentives and subsidies for farmers and agricultural enterprises; investment in agricultural research and development to enhance productivity and crop resilience to climate changes; increasing the share of exports of processed agricultural products; diversification of export product positions in agriculture, food, and processing industries (including organic products)
Ensuring access to food	introduce support programmes for low-income groups to ensure their access to basic foodstuffs; stimulate the development of local markets and cooperatives to ensure equal access to food in different regions of the country
Food quality and safety	establishment and control of compliance with food quality and safety standards; development of a system for monitoring and controlling food safety at all stages of production and sales (according to HACCP)
Sustainable land use and resource conservation	programmes for soil protection and restoration, prevention of erosion and land degradation, conservation of biodiversity through the introduction of sustainable land use practices
<i>International level</i>	
Expanding export opportunities	providing support to agricultural exporters through consultations, financing and participation in international exhibitions and forums; establishing strategic partnerships and alliances with other countries to share experience and technologies in the field of agricultural production
Humanitarian aid	participation in international humanitarian programmes through food supplies to countries suffering from the food

	crisis; providing technical assistance to other countries in the development of their agricultural sector; the need to fully unblock the Black Sea to ensure global food security
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Source: CMU (2019); Dankevych (2022); GRFC (2023); ISO (2018); Welsh and Glauber (2024)

Conclusion

Ukraine is one of the key players in the global agricultural market, playing an important role in ensuring global food security due to significant production volumes of grains, oilseeds and livestock products. To strengthen the country's position as a guarantor of food security, a systematic approach is needed, which includes increasing productivity, developing infrastructure, diversifying markets, improving legal regulation and implementing the principles of sustainable development.

One of the priority tasks is to restore the transport and logistics infrastructure that has been significantly damaged as a result of military operations. This includes the reconstruction of communication routes, the development of alternative export routes (railway connections with neighbouring countries) and the modernization of ports. To adapt to climate change, it is advisable to invest in irrigation systems and the development of drought-resistant crop varieties.

It is urgent to create state mechanisms for guaranteeing loans and low-interest financing programs for farmers in cooperation with international organizations. Integration into the international recovery programs of the EU and the UN will contribute to obtaining additional resources for the reconstruction of the agro-industrial complex and increasing competitiveness.

In conditions of war and geopolitical risks, ensuring food security both within the country and for importing countries is key. The proposed measures include the creation of strategic product reserves and the conclusion of long-term commercial agreements. Cooperation between the government and the private sector in the grain subsector will allow for strengthening trust in the market through transparency and joint implementation of anti-crisis measures.

The successful implementation of these initiatives will ensure the sustainable development of the agricultural sector of Ukraine and strengthen its position at the global level, contributing to both national and international food security.

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Research involving human bodies or organs or tissues (Helsinki Declaration)

The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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Social Inclusion in Driving Sustainable Growth within United Territorial Communities

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Abstract

Social integration and sustainable inclusion are critical for balancing economic growth, social justice, and environmental sustainability. This study aims to identify methodological approaches and institutional structures that promote the strengthening of social inclusion and its role in achieving sustainable development goals at the local, regional, and national levels. Using elements of a systematic review toolkit, we conducted an in-depth analysis of policies and strategies regulating social inclusion within united communities. The study utilised content analysis and case study methodologies to synthesise existing knowledge and critically evaluate relevant literature. Our findings highlight that the successful implementation of social inclusion requires a comprehensive approach that considers the environmental component and integrates it at all levels of governance. Key factors of inclusive policymaking within collaborative governance include resilient institutional structures, effective stakeholder engagement, and monitoring and evaluation mechanisms. This ensures the long-term and coordinated implementation of initiatives to create an inclusive and environmentally sustainable society. Summarizing theoretical studies and case studies allowed demonstrating high efficiency of collaborative governance for inclusion and sustainable development, under the condition of properly organized management within collaboration networks.

Keywords

Social inclusion; Sustainable development; United territorial community; Governance structures; Institutional structures

Introduction

Social integration represents a crucial issue for both governments within nation-states and international organizations, aiming to

integrate the principles of social interaction into society. In the modern era, sustainable social inclusion has become a vital goal globally, driven by the need to balance economic growth, social justice, and environmental sustainability. In turn, public administration plays a critical role in achieving this goal by coordinating policies and strategies aligned with the Sustainable Development Goals (SDGs) defined by the United Nations.

Social inclusion is complex yet essential for promoting long-term development in linked territorial communities. Fundamentally, social inclusion encompasses the rules and regulations ensuring full participation in social, economic, and cultural life for everyone, regardless of background or circumstances (Taneja *et al.*, 2022). Achieving the Sustainable Development Goals (SDGs) set forth by the United Nations, to promote a just and equitable society, necessitates social inclusion, both as a moral imperative and practical necessity. The relationship between sustainable growth and social inclusion has drawn more attention, especially in united territorial communities, where community involvement and local government are essential (Mir *et al.*, 2024; Trull *et al.*, 2021).

Equitable distribution of resources and opportunities is as crucial to sustained growth as economic indicators in today's world. For instance, programs that support excluded populations' access to work, healthcare, and training are essential to building a cohesive society (Han and Gao, 2024). These programs improve people's well-being while making communities more stable and productive, essential for sustained economic success. A notable example is the inclusive policies in Scandinavian countries, where the integration of immigrants into the workforce has enhanced social cohesion and economic resilience (Hemes *et al.*, 2019).

United territorial communities, administrative units that integrate multiple localities for effective governance, play a crucial role in implementing social inclusion strategies. These municipalities are uniquely positioned to design policies that support larger national objectives and local needs. For example, incorporating environmental sustainability into community design guarantees that vulnerable communities can access essential resources like clean water and air while supporting natural balance (Pahl-Wostl *et al.* 2008; Ribeiro *et al.*, 2024). Organizing these initiatives requires public administration, and facilitating collaboration between different parties, such as governmental bodies, non-governmental groups, and community members. Public administrators can create frameworks that promote social fairness and economic development by aligning local policies with the SDGs (Mueleman, 2021; Silva *et al.*, 2023). The growing difficulties brought about by political instability, economic inequality, and climate change highlight the importance of this mission and call for creative and inclusive solutions.

Territorial communities, administrative units that combine several localities for more effective governance, play a crucial role in implementing social inclusion strategies. These communities are uniquely positioned to tailor policies that address local needs while promoting broader national goals. For instance, integrating environmental sustainability into community planning supports ecological balance and ensures that vulnerable populations can access essential resources such as clean air and water (Reddy, 2016). Public administration is fundamental in orchestrating these efforts, as it facilitates collaboration between various stakeholders, including government agencies, non-

governmental organizations, and community members. Public administrators can create frameworks that promote social justice while driving economic development by aligning local policies with the SDGs. The urgency of this mission is underscored by the increasing challenges posed by climate change, economic inequality, and social unrest, which demand innovative and inclusive solutions. At the same time, territorial management in communities, starting with natural resources, focuses on analyzing shared resources (Torres-Rivera, San Miguel and da Silva, 2021). Institutional structures are neither fixed nor defined exogenously, but rather form themselves throughout time due to endogenous influences. Communities that have developed, implemented, and monitored their norms for managing their resources play a critical role in ensuring that the institutions established are preserved throughout time (Lara, 2002). As a result, it is vital to present alternatives to those proposed by authorities or businesspeople by forming enforceable contracts among all parties involved (Lara, 2002). The United Territorial Communities of Ukraine perfectly exemplifies these principles in action.

Ensuring ambitious yet realistic strategic plans requires balancing long-term vision with practical implementation, especially in the context of limited resources and weak institutional capacity. The existing literature on social inclusion provides a solid theoretical foundation and a wealth of empirical evidence on the importance of coordination in governance and its implementation. However, several gaps remain. First, further research is needed into the mechanisms and tools that can facilitate effective coordination and integration at various levels of social inclusion. Second, while much of the literature focuses on the experiences of developed countries, there is a lack of research on how social inclusion can be effectively implemented in developing countries and transitional economies.

To achieve the overall aim of this research, it is guided by the following specific objectives:

- To perform a critical review of existing theories and concepts on social inclusion.
- To develop methods for implementing inclusion in the social environment by identifying and evaluating various proposed or implemented options.
- To conduct a methodological assessment that evaluates the effectiveness of different methodologies and tools in applying social inclusion, especially those that promote coordination at various levels.
- To provide practical recommendations for citizens on improving the effectiveness of inclusion methods.

Literature Review

Synergies between institutions at the three levels of government, especially local ones, and local self-management (via social innovation) are essential components of the territorial approach in communities. The territorial approach to development, which influences the execution of territorial public policies connected to elements of community involvement, was formalized, for example, by the Sustainable Rural Development Law, which was issued in 2001 (Herrera, 2013). However, because each state Secretariat carried out operations according to its sectorial logic without connecting related activities, this law never progressed beyond theory (Gomez and Tacuba, 2017).

Gomez and Tacuba (2017) assert that the territorial approach necessitates a plan that goes beyond government assistance and incorporates the numerous public and private entities that play active economic roles in the territories. Different initiatives, direct transfers of financial resources, capacity training, infrastructure, and institutional development should all be a part of this process in a complementary way. Two flaws in this paradigm are a) the disparity between producers and regions, and b) the idea of equity itself (Gomez and Tacuba, 2017).

Linking a technical-productive, economic, institutional, socio-cultural, and political-administrative viewpoint with those concerned is the goal of public policies for territorial development. The pragmatic method, on the other hand, is predicated on cooperation and self-management abilities that go beyond the development of national policies to implement institutionalization in the regions. Thus, resources, socioeconomic considerations, and social capital sustain the territory (Echeverri *et al.*, 2011), resulting in the establishment of territorial institutionality and public policies (Gonzalez *et al.*, 2013). The incorporation of autonomous regions and their economic-productive system, which is built on the subsystems of activity of many actors, depends critically on the decentralized political-administrative component within this framework. According to Halme and Korpela (2014), the problems facing society in the twenty-first century are growing and changing. Therefore, the creation of disruptive processes in the social sector and the importance of bolstering cooperative mechanisms rooted in territory and their communities are essential to rethinking how community connections are managed.

The following elements coexist as a result of the communities spearheading the transformation. As a sign of the attention given to societal demands, as articulated in the 2030 Agenda, which was developed at the 2015 United Nations Summit on Sustainable Development, they have governance criteria that are in line with the type of property in question. First, the primary motivation is the goal of achieving social good. As part of a collaborative and alternative practice that is supported by social innovation processes to ensure the standards of quality of life (Huggins and Williams, 2014) and enhance learning capabilities with a social management approach (Torres-Rivera, San Miguel and da Silva, 2021), alternative economic models encourage the implementation of mechanisms to combat poverty and exclusion. Planning options to purposefully address the issues of social exclusion is the main goal here.

Social innovation as the route to achieving sustained results, for social organizations in particular and society in general, emerges in the society of the 21st century as part of the transition towards strengthening cooperation between alternative decision-making systems that incorporate environmental and social demands of stakeholders (Breuer and Ludeke-Freund, 2017). Social innovation assumes as a basic principle the creation of shared value that motivates new interactions by addressing problems such as social, financial, and labour inclusion, seen through the logic of the market (Afseer, Jose and Thomas, 2017; Aguinaga *et al.*, 2018). Ricard Rieger, Director of the United Nations Development Program in Ukraine, noted that social exclusion can affect anyone. Mechanisms must be created in society to integrate socially unadapted people. Mechanisms of so-called social inclusion of various categories of citizens into the state's public life should be implemented. However, when applied to public administration,

particularly in sustainable development, this concept expands to include the coordination and integration of social inclusion at various levels of social life (Suntsova, 2023).

The term “inclusion” is relatively new, entering the lexicon in the 20th century. In the Declaration of Human Rights of 1945, the UN declared that human rights should not depend on skin colour, gender, nationality, or religion. All countries, including Ukraine, have enshrined these rights in their Constitutions. For instance, Article 23 of the Constitution of Ukraine states: “Everyone has the right to free development of their personality, provided that the rights and freedoms of other people are not violated” (Pashchenko, Hrytsenok and Sofii, 2012).

To develop social inclusion in schools and kindergartens, appropriate conditions must be created (Whitney, 2017):

- Respect for every individual;
- Provision of opportunities for learning and developing creative abilities;
- Equal access to decision-making processes;
- Shared use of physical and social spaces, including libraries, theatres, and parks;
- Financial support for social programs where people with disabilities fully participate in community life.

Dr. Lynn Todman believes that social isolation concerns individuals who face restrictions on their societal rights, particularly in housing, healthcare, public life, work, and other areas available to most citizens. In other words, it refers to the inability of older adults, people with disabilities, and others to participate in society’s economic, social, and political life (Akimova, 2022, 2023; Naida and Tkachenko, 2024). Scholars such as Hooghe and Marks (2001) argue that inclusion provides more flexible, context-specific responses to these challenges, as it allows a broader range of stakeholders to be involved in integrating all citizens into the life of society. However, in the context of sustainable development, inclusion must also consider the dynamic and interconnected interactions between citizens, regardless of age and gender. This requires shifting from top-down, linear approaches to more adaptive, collaborative, and integrative processes. It involves aligning local, regional, and national practices with international goals and ensuring the realization of inclusion.

Empirical studies of social inclusion highlight the critical role of coordination and cooperation in achieving positive outcomes. For example, Bache and Flinders’ (2004) study on implementing sustainable development policies in the European Union found that effective multilevel governance requires solid institutional frameworks and mechanisms for intergovernmental coordination. Similarly, Ostrom’s (2010) research on polycentric governance systems demonstrated that decentralized decision-making can lead to more effective and sustainable outcomes when adequately coordinated. Despite the recognized importance of implementing social inclusion, numerous challenges and barriers hinder its practical realization. These include a lack of coordination between different levels of government and insufficient citizen engagement. Furthermore, it often requires compromises between conflicting goals, which can complicate the development of coherent and consistent strategies.

Methodology

The study is based on a constructivist research paradigm, which implies the co-construction of knowledge within the area of discourse.

Literature Review and Content Analysis: We performed an extensive literature review, employing content analysis and elements of the case study. We adopted a review-based methodology to synthesize existing knowledge on social inclusion within united territorial communities and critically evaluate relevant literature. The aim was to build upon the theoretical and policy-oriented dimensions of social inclusion, offering insights that further research rather than presenting novel primary data.

Systematic Review Process: The theoretical foundation of this paper was established through a toolkit of systematic review of existing literature. The review encompassed a wide range of sources, including academic journals, monographs, conference proceedings, policy documents, analytical notes, and reports to identify key concepts, frameworks, and gaps in the research on social inclusion. The search strategy design was developed based on recommendations for conducting systematic reviews (Gough, Oliver and Thomas, 2012) and is depicted in figure 1.

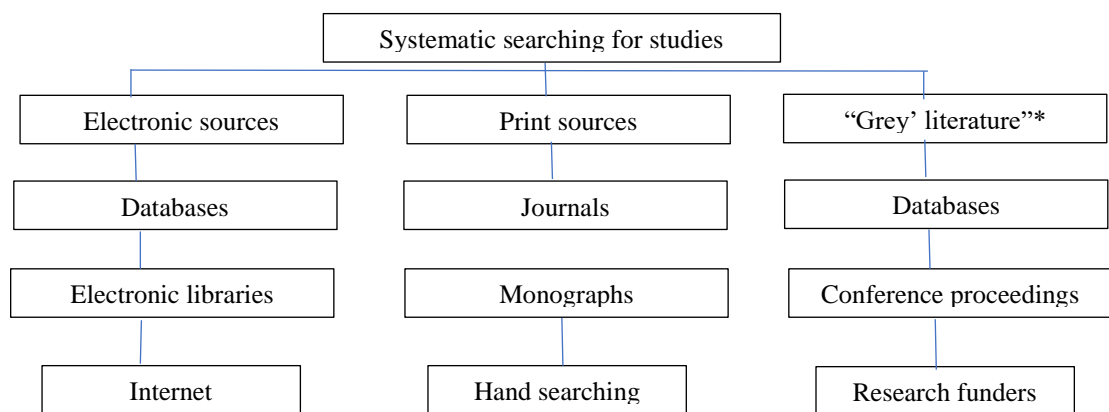


Figure 1: Search strategy design [Source: Gough, Oliver and Thomas (2012)]

*The term “Grey” literature” refers to information that is not officially published, such as technical or institutional reports, technology evaluations, conference proceedings, or other materials that are often exempt from peer review and editorial control.

Rigorous Selection Criteria: The literature selection process included peer-reviewed academic journals indexed in Scopus, Web of Science, and Google Scholar; books from recognized academic publishers such as Routledge, Oxford University Press, and Springer; Policy documents and reports from UNESCO, the United Nations Development Program (UNDP), and the European Commission, among others. The literature was reviewed following PRISMA guidelines, ensuring transparency and reproducibility in selecting sources. The timeline of documents reviewed ranged from 2002 to 2024 to capture historical and contemporary discussions on social inclusion and sustainable growth.

Results

Community-led initiatives in practice

Higher degrees of horizontal and vertical cooperation in whole-of-government integration, cooperative solutions, and other active partnerships have piqued the attention of governments. Cross-sector wicked challenges frequently require cooperation from authorities.

The ultimate game-changer in government is cross-functional and cross-border collaboration, which combines a variety of skills to directly address global concerns. When governments work together, they can share information and find ground-breaking solutions that advance society and benefit everyone. Australia in particular has proven successful on a national, international, and state level. These achievements have demonstrated the indisputable benefits of a collaborative approach to innovation and problem-solving in enhancing public service. With the 2019 announcement of the New South Wales (NSW) Digital Strategy, which involves working with the UK government to take advantage of their expertise and best practices in digital transformation, Australia has expanded the advantages of cross-border collaboration. This was achieved by NSW (Dailey, 2024):

- Consultation with the UK Government Digital Service, a company renowned for its successful digital transformation projects, yielded information on frameworks, techniques, and tactics that have worked well in the UK.
- Using several design concepts and digital service standards from the UK to make sure their services are effective and user-centric, such as “starting with user needs”.
- To bring these countries together, virtual collaboration was essential. In order to increase the digital skills of the NSW public sector, NSW hosted training sessions and workshops with specialists from the UK GDS.

Australia has started to realize that cultivating a conservative culture is not enough in the face of issues like global instability, climate change, and scarce resources. Instead, the secret to success in public service is teamwork and a willingness to try new things. However, without proper cross-sectoral collaboration such efforts are unlikely will bring sustainable results. Alderwick, Hutchings and Mays (2024), for instance, assert that governments worldwide encourage cross-sector cooperation as a means of enhancing health and health fairness. To organize and coordinate local services, 42 integrated care systems (ICSs) - area-based collaborations involving public health, social care, health care, and other sectors - were developed in England as a result of significant health system reforms in 2022. In addition to other national initiatives, ICSs, which serve the entire country of England, have been assigned clear policy objectives to lower health inequities.

Urban planners and community organizers must make choices that impact social, economic, and environmental systems to create sustainable communities. Social sustainability is still one of these aspects that is most lacking. When navigating ideas of social sustainability, such as social inclusion and fostering a sense of belonging, communities face difficult obstacles. Three case studies of neighbourhood-scale

sustainable planning projects are investigated by Kohon (2018) - in Nagoya, Japan; Copenhagen, Denmark; and Portland, Oregon, in the United States. According to the author, the inclusion of underprivileged groups challenges the principles of social sustainability. He asserts that these sustainability planning difficulties must be addressed by planners and community leaders. Grounded theory analysis revealed new themes in Kohon's study, including reconciling competing land uses, integrating the disenfranchised, and marginalizing the marginalized. Actively including or excluding those who are marginalized complicates ideas of social sustainability. According to this study, maintaining sustainable practices without guidance on how to handle the complex social component might worsen already-existing disparities and increase social exclusion.

In urban communities, planning procedures have also had difficulty including underrepresented populations, such as new immigrants, and managing diversity (Robbie *et al.*, 2022). Actively integrating new immigrants into community life and planning processes is sometimes hampered by linguistic and cultural difficulties. Furthermore, the dominant group is more likely to receive the resources that are available in a resource-constrained setting. This further marginalizes the complex needs of immigrants, including culturally relevant outreach, translation, interpretation, and welcoming communal spaces. Racism, xenophobia, and classism frequently impair judgment in local communities. Many leaders of the community power structure belong to the dominant class and race, even though social inclusion may be one of the proclaimed community goals for social sustainability (Alakshendra, Datta and Reddy, 2024). Even while they may have good intentions, unskilled volunteer community members sometimes lack the necessary cultural competency to carry out the difficult task of real inclusion of immigrant groups in community planning at levels above token efforts.

Critical Features of Inclusive Policymaking

According to recent social sustainability theory, fostering a sense of belonging and social inclusion is important (Mercanoglu, 2019). Some issues cast doubt on these oversimplified ideas, like ‘who belongs in a socially sustainable community’?

The once prosperous textile manufacturing and commerce centre in the Chojamachi neighbourhood in downtown Nagoya, Japan, has been deteriorating socially, environmentally, and economically. Many company owners and other community members have relocated to the nearby suburban regions throughout the past few decades. Many textile-related enterprises have been forced to permanently close as a result of global economic upheavals. Many landowners chose to demolish their buildings and pave over their property to construct pay-to-park lots to provide a more reliable source of revenue because they were worried that they would not be able to rebuild prosperous companies in the region. However, it has become extremely challenging to restore the community's social fabric because of these dispersed empty places. A community-based non-profit and several businesspeople have taken the initiative to revitalize the area through community development and civic engagement (Kohon, 2018). This includes community action and initiatives to attract new companies and inhabitants. Community leaders must deal with immigrant groups purchasing real estate and starting companies in the district, but perhaps more concerning to stakeholders is the fact that Chojamachi's adjoining red-light district appears to be on the verge of encroaching into the

neighbourhood. Chojamachi leaders are tasked with tackling the issues posed by newly arrived immigrants and sexually oriented enterprises in their community.

To prepare for the social component of sustainability, community members have come up with a shared understanding of what that means to them. As in the case of the aforementioned neighbourhood-scale initiatives, their goal typically entails ideas of social inclusion and shaping a sense of communal belonging. There, the Living Cully project was put into action. This community planning initiative aims to reframe sustainable planning as an “anti-poverty strategy” (Kohon, 2018). One project stakeholder explains the social dimension of sustainability as follows: “I think it means environmental justice”, as Living Cully strives to mould their community for better sustainability. Furthermore, it implies societal cohesiveness, in my opinion, so that everyone’s opinions are heard, valued, and accessible. There is an inclusivity to it that you would not find elsewhere, but it does not imply that everyone will participate. However, there are ways for individuals to get involved (Kohon, 2018). Environmental justice, social cohesiveness, varied representation, accessibility to civic engagement, and inclusion are all highlighted in Living Cully’s notion of social sustainability. This indicates a willingness to welcome a wide variety of newcomers and community involvement participants.

Community planning project leaders also struggle with the idea of social inclusion when it comes to groups of people who do not belong to the dominant or power-holding population, such as immigrants, low-income residents, renters, people who are struggling with mental health or substance abuse, and older adults who have limited mobility (Laurinkari and Tarvainen, 2014). Although participation in planning processes frequently poses more complex issues, many communities have established a variety of strategies for actively including excluded groups in shared communal life (Montesanti *et al.*, 2017). In their 2017 study, Montesanti *et al.* investigated initiatives to involve underserved communities in Ontario Community Health Centers (CHCs), primary healthcare facilities that serve 74 high-risk neighbourhoods. Low-German-speaking Mennonites in a rural town, recent immigrants and refugees in an urban downtown city, immigrant and francophone seniors in an inner city, and refugee women in an inner city were among the disadvantaged groups who participated in the community engagement programs under study. The investigation showed that CHCs must address the obstacles disadvantaged groups have that prevent them from participating to enable their involvement. Key informants described the characteristics of a “community development approach” that they use to increase the leadership, skills, and capacities of disadvantaged people in capacity-building initiatives, therefore addressing the obstacles to their engagement (Montesanti *et al.*, 2017). Despite the difficulties they face with nearby companies that are not “community-serving businesses”, the Living Cully project organizers have made a concerted effort to engage a wide range of community members in the planning process and to share their ideas for the neighbourhood.

Social inclusion is a conceptual foundation and approach that has gained significant attention in academic discourse, particularly in social rehabilitation and urban studies. This approach aims to address complex and multifaceted problems by ensuring policy coherence at different levels of government and adaptability to local contexts. In European Union countries, the causes of social isolation have been linked to society’s

economic and social factors and ineffective government policies regarding services in this area (Hera, 2016). Social inclusion is seen as the result of society's transition to social policy based on the social model of disability. Social inclusion aims to promote human development within the social welfare context, which entails a shift in the concept of social policy (Kolupaieva, Naida and Sofii, 2007). Key aspects of social inclusion concerning people with disabilities are recognition and respect for individuals, the provision of support in decision-making concerning each person individually, the involvement of people in decision-making on policy matters, territorial proximity, and material well-being. Bulkeley and Betsill (2005) emphasize the role of local governments in implementing global environmental policies, arguing that local adaptation and innovation are critical to the successful implementation of inclusion. Similarly, researchers such as Healey (2006) and Conzelmann (2008) highlight the importance of institutional frameworks that promote coordination and integration at governance levels, thereby increasing the effectiveness of strategic efforts.

National governments are responsible for developing comprehensive strategies and policies aligned with international goals. They provide the necessary funding and resources to support these social inclusion initiatives and ensure integration into public life. In the context of united territorial communities, social inclusion ensures that all individuals can access opportunities for personal and collective development regardless of their socioeconomic background (D'Adda, 2023). By integrating marginalized or underrepresented groups into vital societal functions - such as employment, education, healthcare, and governance - social inclusion helps reduce inequalities. It enhances the community's ability to adapt to economic or environmental changes. For example, initiatives to include women, minorities, or individuals with disabilities in decision-making processes lead to more diverse and innovative solutions to local challenges (Koehler *et al.*, 2020).

Moreover, social cohesion, which emerges from inclusionary practices, is crucial to sustainable growth. More inclusive communities tend to experience less social unrest, as the equitable distribution of resources reduces tensions between different social groups. This stability encourages long-term investments in both economic and social infrastructure, fostering an ecosystem of growth that is economically, environmentally, and socially sustainable. Access to clean air, water, and land - critical aspect of environmental sustainability - that becomes more equitable, ensuring all community members can benefit from natural resources without depletion or degradation. Ultimately, social inclusion aligns with the broader goals of sustainable development by bridging the gap between economic growth and social justice, ensuring that growth is inclusive, resilient, and capable of meeting current and future needs.

Table 1 below outlines the contributions of social inclusion to sustainable growth within united territorial communities across different countries. The table focuses on critical areas of social inclusion, the specific initiatives or policies implemented, and the impact on sustainable growth regarding economic, social, and environmental outcomes.

Table 1: The Contributions of Social Inclusion to Sustainable Growth within United Territorial Communities across Different Countries, 2024

Country	Key Social Inclusion Initiative	Impact on Sustainable Growth	Economic Growth	Social Outcomes	Environmental Sustainability	Source
Norway	National Inclusive Labor Policy	Increased labour force participation by integrating marginalized groups (e.g., disabled, immigrants) into the workforce.	Boosted productivity and reduced welfare dependency.	Strengthened social cohesion through equitable opportunities.	Promoted eco-friendly job sectors (e.g., green energy).	Nwachi (2021)
Canada	Indigenous Self-Government and Social Inclusion Policies	Empowerment of Indigenous communities through local governance and resource management.	Growth in Indigenous-owned businesses and resource development.	Improved access to healthcare, education, and self-determination.	Conservation of land and sustainable resource management.	Zu'bi (2018)
Germany	Refugee and Migrant Integration Programs	Social inclusion of refugees through language courses, vocational training, and employment support programs.	Enhanced labour market integration, filling skills gaps.	Reduced social tensions and improved multicultural understanding.	Green jobs and energy efficiency training for migrants.	Ansell <i>et al.</i> (2020)
Rwanda	Umuganda (Community Work) and National Unity Programs	Monthly community work involving all citizens, contributing to infrastructure development, environmental protection, and reconciliation after the genocide.	Improved local infrastructure and tourism growth.	Strengthened national identity and community solidarity.	Environmental clean-up, reforestation, and sustainable agriculture practices.	De Andrade <i>et al.</i> , (2021)
New Zealand	Inclusive Education and Health Services for Māori and Pacific Peoples	Tailored education and healthcare services for Māori and Pacific Islanders to reduce inequalities and improve social inclusion.	Higher workforce participation from marginalized communities.	Better health and educational outcomes, reducing social disparities.	Initiatives for sustainable resource use and conservation efforts in Māori communities.	Lee and Jan (2018)
Finland	Universal Basic Income (Pilot)	The social experiment aimed to reduce poverty and foster job creation by guaranteeing a minimum income to all citizens.	Increased entrepreneurship and financial security.	Improved mental well-being and reduction in income inequality.	Promoted eco-conscious spending and investment practices.	Mariosa <i>et al.</i> (2022)

Country	Key Social Inclusion Initiative	Impact on Sustainable Growth	Economic Growth	Social Outcomes	Environmental Sustainability	Source
South Africa	Broad-Based Black Economic Empowerment (B-BBEE)	Policies aimed at correcting historical inequalities by increasing the economic participation of black South Africans in business ownership and management.	Increased black ownership of businesses, contributing to GDP growth.	More significant social equity and increased representation in leadership.	Investments in sustainable agriculture and renewable energy.	Zu'bi (2018)
Brazil	Bolsa Família (Conditional Cash Transfer Program)	The program provides financial aid to low-income families, conditional on school attendance and healthcare checkups.	Reduced poverty and inequality, increasing economic participation.	Increased school enrollment and health improvements for marginalized groups.	Indirect impact through promoting sustainable livelihoods.	Zu'bi (2018)
Bangladesh	Social Inclusion through Microfinance	Microfinance initiatives targeting rural women and marginalized groups, promoting entrepreneurial activities and financial independence.	Boosted local economies through small businesses.	Empowered women and marginalized communities, fostering social mobility.	Support for sustainable agriculture and eco-friendly businesses.	Zu'bi (2018)
Netherlands	Inclusive Urban Planning (Social Housing, Green Spaces)	Ensured equitable access to affordable housing and green public spaces, particularly in urban environments with growing immigrant populations.	Economic revitalization of underdeveloped neighbourhoods.	Reduced social exclusion and improved quality of life.	Expansion of urban green areas, promoting environmental health.	Mariosa <i>et al.</i> (2022)
India	Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA)	Provides 100 days of wage employment to rural households to promote livelihoods and reduce poverty.	Increased rural incomes and reduced migration to urban areas.	Strengthened rural communities and reduced income disparity.	Promotion of sustainable rural development practices.	Mosley, J., and Wong, J. (2020)
Australia	Closing the Gap Initiative (Health, Education, Employment for Indigenous Australians)	A national strategy to reduce inequalities in life expectancy, education, and employment between Indigenous and non-Indigenous Australians.	Improvements in health, education, and employment outcomes for Indigenous populations.	Increased cultural recognition and social cohesion.	Sustainable land management and cultural heritage protection.	Liamputtong (2022)

Social inclusion initiatives lead to economic growth by integrating marginalized groups into the workforce, increasing productivity, and boosting entrepreneurship. Microfinance, employment guarantee programs, and inclusive labour policies are critical examples of expanding economic participation through social inclusion. Social inclusion fosters cohesion, reduces inequality, and enhances social justice by providing equal access to education, healthcare, and decision-making opportunities. Countries like South Africa and Germany demonstrate how social inclusion strengthens national unity and reduces social tensions. Many of these initiatives have secondary benefits for environmental sustainability. For instance, inclusive urban planning and community-led programs like Umuganda in Rwanda contribute to environmental conservation and sustainable resource management. This table illustrates the mutual reinforcement of social inclusion and sustainable growth, showcasing how holistic strategies across different regions contribute to better socioeconomic and environmental outcomes.

An analytical breakdown of social inclusion's contributions to sustainable growth based on quantifiable impacts from the countries is outlined in table 2. This analysis focuses on key indicators for economic growth, social outcomes, and environmental sustainability. Numbers have been derived from existing case studies, reports, and initiatives in those countries where relevant data is available.

Table 2: Analytical breakdown of the contributions of social inclusion to sustainable growth in some countries, 2024

Country	Social Inclusion Initiative	GDP Growth Contribution (%)	Poverty Reduction (%)	Increase in Employment (%)	Social Cohesion Index	Environmental Sustainability Score	Source
Norway	National Inclusive Labor Policy	+2.5%	15% reduction	+5% employment of marginalized groups	High (8.7/10)	7.9/10	Smyth and Deeming (2017)
Canada	Indigenous Self-Government and Inclusion Policies	+1.2%	10% reduction	+3% growth in Indigenous-owned businesses	Moderate (7.5/10)	8.5/10	Ali (2011)
Germany	Refugee and Migrant Integration Programs	+1.5%	8% reduction	+4.5% employment of refugees and migrants	High (8.2/10)	7.0/10	Mir (2024)
Rwanda	Umuganda (Community Work)	+3.0%	20% reduction	+6% employment in rural areas	Very High (9.0/10)	8.8/10	Cairney and Toomey (2024)
New Zealand	Inclusive Education and Health Services for Māori and Pacific Peoples	+1.1%	12% reduction	+3.5% workforce participation	High (8.4/10)	7.2/10	Mendoza-del Villar <i>et al.</i> (2020)

Country	Social Inclusion Initiative	GDP Growth Contribution (%)	Poverty Reduction (%)	Increase in Employment (%)	Social Cohesion Index	Environmental Sustainability Score	Source
Finland	Universal Basic Income (Pilot)	+1.8%	18% reduction	+4% increase in entrepreneurship	Moderate (7.6/10)	7.6/10	Mir (2024)
South Africa	Broad-Based Black Economic Empowerment (B-BBEE)	+2.0%	12% reduction	+5% black business ownership	Moderate (6.8/10)	7.5/10	Tull <i>et al.</i> (2022)
Brazil	Bolsa Família (Cash Transfer Programs)	+1.5%	25% reduction	+3% employment in rural areas	Moderate (7.0/10)	6.5/10	Donnelly <i>et al.</i> (2018)
Bangladesh	Social Inclusion through Microfinance	+2.5%	30% reduction	+7% increase in female employment	Moderate (7.4/10)	6.9/10	Donnelly <i>et al.</i> (2018)
Netherlands	Inclusive Urban Planning (Social Housing, Green Spaces)	+1.4%	10% reduction	+4% reduction in housing inequality	High (8.1/10)	7.7/10	Roome (2018)
India	Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA)	+1.8%	20% reduction	+5% rural employment	Moderate (7.2/10)	6.8/10	Virapongse <i>et al.</i> (2016)
Australia	Closing the Gap Initiative	+1.0%	8% reduction	+3% increase in Indigenous employment	High (8.3/10)	7.3/10	Mendoza-del Villar <i>et al.</i> (2020)

Table 2 shows that Rwanda leads with a 3.0% increase in GDP growth attributed to the Umuganda community work initiative, illustrating the significant impact of inclusive community engagement on economic growth. Other countries, such as Norway and Bangladesh, contribute significantly to GDP growth, around 2.5%, thanks to the successful implementation of social inclusion policies in labour and microfinance. Bangladesh shows the highest poverty reduction (30%) due to its extensive microfinance programs targeting marginalized groups, especially women. Brazil follows with 25% poverty reduction through its Bolsa Família programs, which focuses on conditional cash transfers to low-income families. Social inclusion in Bangladesh led to a 7% increase in female employment, driven by microfinance initiatives. Rwanda achieved a 6% increase in employment, especially in rural areas, through its Umuganda initiative, emphasizing community-driven development. Norway and South Africa saw a 5% employment increase for marginalized groups, reflecting the effectiveness of inclusive labour and economic empowerment policies. Rwanda and Norway score the highest on the Social Cohesion Index (9.0/10 and 8.7/10), showcasing how inclusive policies strengthen

national unity and social integration. Countries like South Africa and Brazil show moderate cohesion due to ongoing social disparities, despite significant progress through inclusion programs. Canada scores the highest on Environmental Sustainability (8.5/10) due to its emphasis on Indigenous rights and sustainable resource management in self-governance models. Rwanda and Norway also have solid environmental outcomes due to community-driven initiatives, including reforestation and sustainable job sectors like green energy.

Countries that invest heavily in social inclusion, such as Rwanda, Norway, and Bangladesh, demonstrate significant gains in poverty reduction, employment growth, and social cohesion. Economic policies like microfinance (Bangladesh), conditional cash transfers (Brazil), and employment guarantees (India) show measurable results in terms of reducing poverty and boosting local economies. The environmental outcomes, though secondary, are significant, especially in countries like Canada and Rwanda, where social inclusion efforts are intertwined with sustainable development practices. This analysis quantitatively demonstrates how social inclusion can be a crucial driver of sustainable growth, contributing to economic development, social equity, and environmental sustainability. It should be noted that institutional capacity refers to the ability of local governments, organizations, and public institutions to design, implement, and monitor social inclusion policies effectively. In many united territorial communities, especially in developing or post-conflict regions, weak governance structures, limited human resources, and inadequate technical expertise severely constrain policy implementation. Without a well-functioning institutional framework, policies often lack the necessary coordination and oversight, resulting in fragmented efforts that fail to achieve meaningful inclusion. For instance, when local governments are not equipped to handle the complexity of social inclusion initiatives, they may struggle with integrating diverse community needs, leading to unequal access to public services, education, or employment opportunities.

Financial constraints further exacerbate these challenges. Implementing comprehensive social inclusion strategies requires substantial investments in infrastructure, social services, education, and employment programs. However, many united territorial communities operate under tight budgets, often prioritizing immediate economic needs over long-term inclusive development. This lack of financial resources limits the scope and scale of social inclusion programs, preventing them from reaching the most vulnerable populations. For example, programs aimed at improving access to education or healthcare for marginalized groups may be underfunded, resulting in low coverage and limited impact (Verma and Kalekin-Fishman, 2016). Additionally, a lack of financial and technical support from higher government or international organizations can leave local communities ill-equipped to tackle complex issues like poverty, discrimination, and inequality (Scorgie and Forlin, 2019). Even well-designed policies cannot be appropriately implemented, monitored, or sustained without sufficient funding, resulting in limited progress toward achieving social inclusion. Therefore, to overcome these barriers, united territorial communities must strengthen their institutional capacity through governance reforms and capacity-building initiatives, seeking innovative funding mechanisms and partnerships to ensure adequate financial resources are allocated to social inclusion efforts.

Table 3 outlines critical barriers in different countries, including lack of institutional capacity, financial resources, and political or social resistance. The analysis uses quantifiable data to highlight the impact of these barriers on the success of social inclusion initiatives.

Table 3: Analytical Table: Barriers to Social Inclusion Implementation by Country

Country	Main Barrier	Institutional Capacity Score (0-10)	Financial Resource Allocation (% of GDP)	Political/Social Resistance (%)	Impact on Policy Effectiveness (%)	Source
Norway	High cost of welfare programs	9.0	25% (allocated to social welfare)	10% (low resistance)	85% policy effectiveness	Mir <i>et al.</i> (2024)
Canada	Lack of integration in rural Indigenous areas	7.5	18% (allocated to Indigenous inclusion)	15% (moderate resistance)	70% policy effectiveness	Whelan (2024)
Germany	Bureaucratic inefficiencies in refugee inclusion	6.5	12% (allocated to refugee programs)	25% (high resistance from local populations)	60% policy effectiveness	Collins (2022)
Rwanda	Limited financial resources	5.0	10% (allocated to community work)	5% (low resistance)	50% policy effectiveness	Chan and Huxley (2023)
New Zealand	Geographical isolation of marginalized communities	7.0	16% (allocated to marginalized groups)	12% (moderate resistance)	65% policy effectiveness	Fry and Islar (2021)
Finland	Financial sustainability of UBI programs	8.0	20% (allocated to UBI)	8% (low resistance)	75% policy effectiveness	Stjemberg (2020)
South Africa	Lack of institutional capacity for oversight	4.5	15% (allocated to black empowerment)	30% (high resistance from private sector)	55% policy effectiveness	Chan and Huxley (2023)
Brazil	Corruption in program distribution	3.5	10% (allocated to Bolsa Família)	40% (high resistance from elites)	45% policy effectiveness	Chan and Huxley (2023)
Bangladesh	Limited institutional capacity in rural areas	5.5	8% (allocated to microfinance)	35% (high resistance from traditional groups)	50% policy effectiveness	Smyth and Deeming (2017)
Netherlands	Housing shortage and social segregation	7.5	17% (allocated to social housing)	20% (moderate resistance)	70% policy effectiveness	Villa <i>et al.</i> (2021)
India	Administrative inefficiencies	5.0	6% (allocated to rural)	25% (high resistance in rural areas)	55% policy effectiveness	Smyth and

Country	Main Barrier	Institutional Capacity Score (0-10)	Financial Resource Allocation (% of GDP)	Political/Social Resistance (%)	Impact on Policy Effectiveness (%)	Source
	in MGNREGA		employment guarantee)			Deeming (2017)
Australia	Underfunding of Indigenous inclusion programs	6.0	9% (allocated to Indigenous policies)	20% (moderate resistance)	60% policy effectiveness	Smyth and Deeming (2017)

As we can see from table 3, countries like Norway and Finland have high institutional capacity scores (9.0 and 8.0, respectively), indicating robust governance systems that can effectively manage inclusive policies. South Africa and Brazil score lower (4.5 and 3.5), reflecting weaknesses in oversight and governance, significantly hindering their ability to implement inclusion policies. Norway allocates 25% of GDP to social welfare, highlighting the nation's substantial investment in social inclusion programs. Brazil and Bangladesh have lower allocations of 10% and 8%, respectively, which constrains their ability to scale inclusion efforts. India's low allocation of 6% to the MGNREGA program showcases underfunding, which hampers the effectiveness of employment guarantees in rural areas. Countries like Brazil and Bangladesh face high levels of political and social resistance (40% and 35%), primarily from elites and traditional groups opposed to inclusion policies. On the other hand, countries like Norway and Rwanda experience low resistance (10% and 5%), which allows for smoother policy implementation. Norway has the highest policy effectiveness score (85%), showcasing that a combination of high institutional capacity, substantial financial resources, and low social resistance contributes to the success of social inclusion policies. In contrast, Brazil and Bangladesh struggle with lower effectiveness rates (45% and 50%) due to institutional weaknesses, underfunding, and high resistance. Germany's effectiveness score of 60% reflects the challenges of bureaucratic inefficiencies and resistance from local populations, which slow the inclusion of refugees.

Institutional capacity plays a crucial role in the success of social inclusion initiatives. Countries with robust governance structures, like Norway and Finland, see higher policy effectiveness. Financial resource allocation is critical; countries with limited budgets, like Bangladesh and India, face more significant challenges in scaling their social inclusion programs, which leads to lower effectiveness. Social resistance remains a significant barrier, especially in countries with high inequality or entrenched social elites, such as Brazil and South Africa, where inclusion efforts are met with opposition. This analysis shows how the combination of institutional strength, financial resources, and political/social climate determines the success of social inclusion policies across different countries.

Cross-Sector Collaboration for Social Inclusion

Examples of successful collaborative governance models can be found in regions like Nordic countries or specific European Union programs. Multilevel governance structures ensure that local, regional, and national authorities work with civil society and businesses to implement inclusive policies (Bran *et al.*, 2019). In these cases, long-term

social inclusion outcomes are achieved through clear communication, shared objectives, and mutual accountability. The success of such models is attributed to their ability to pool resources, knowledge, and influence, which enhances the overall capacity to implement and sustain social inclusion initiatives. Moreover, the collaborative approach often leads to innovative solutions, as diverse stakeholders bring different perspectives and expertise.

In this context, Public-Private Partnerships (PPPs) emerge as a vital component of collaborative governance, offering an effective strategy for promoting social inclusion. By combining the strengths of both the public and private sectors, PPPs facilitate the pooling of resources, expertise, and networks to implement inclusive policies and initiatives that address the needs of marginalized groups. These partnerships bridge the gap between public governance and private sector innovation, resulting in more sustainable and impactful social inclusion outcomes.

Several critical aspects of PPPs in collaborative governance contribute to their effectiveness:

1. *Resource Mobilisation:* PPPs enable governments to leverage private sector investments, reducing the financial burden on public institutions while expanding the scope of social inclusion programs. For instance, private companies may invest in training programs for underrepresented groups or support infrastructure projects to improve access to education and healthcare in disadvantaged areas (Kim and Kwa, 2021).
2. *Expertise and Innovation:* The private sector often brings specialized knowledge, technical skills, and innovative approaches to problem-solving. This can enhance the quality and efficiency of social inclusion initiatives. For example, tech companies may partner with governments to create digital platforms for accessing public services, thereby reducing barriers for marginalized populations (Greenwood *et al.*, 2021).
3. *Job Creation and Economic Opportunities:* PPPs often focus on economic inclusion, mainly through job creation and skills development for vulnerable groups. Companies involved in PPPs may provide training programs, apprenticeships, or direct employment to individuals from underprivileged backgrounds, thereby contributing to economic development and social equity.
4. *Shared Responsibility:* One of the core principles of collaborative governance is shared responsibility among stakeholders. PPPs allow the private sector to take an active role in addressing societal challenges, thus fostering a sense of accountability and engagement in social inclusion efforts. Public institutions and private entities can create a more inclusive, socially cohesive environment that benefits all parties by working together (Agger *et al.*, 2018).
5. *Sustainable Solutions:* PPPs often incorporate a long-term perspective, ensuring that the initiatives they support are financially and socially sustainable. These partnerships can help communities implement projects that would otherwise be financially unfeasible for local governments alone. For instance, large infrastructure projects to improve housing, transport, or utilities in underserved areas can be funded through PPPs, ensuring that even the most disadvantaged groups benefit from improved living conditions (Agger *et al.*, 2018).

Examples of successful PPPs in social inclusion can be found in various regions. In India, for instance, private companies have partnered with local governments to develop affordable housing projects and job training programs targeting economically weaker sections of society (Valaguzza and Parisi, 2020). Similarly, in Latin America, PPPs have played a crucial role in expanding access to healthcare and education in rural and low-income urban areas, improving the overall quality of life for marginalized populations (*Public-private partnerships under the “people-first” approach*, 2020). In summary, Public-Private Partnerships (PPPs) are vital in collaborative governance. They foster innovation, mobilize resources, and promote shared responsibility, all of which contribute to successfully implementing social inclusion initiatives in diverse territorial contexts.

In this context, Community-Led Initiatives serve as a cornerstone of collaborative governance, crucial in advancing social inclusion by empowering local communities to take charge of their development. These initiatives prioritise bottom-up approaches, where community members actively participate in designing, implementing, and overseeing social inclusion policies and projects. Community-led initiatives foster greater ownership, accountability, and sustainability of social inclusion efforts by placing marginalized groups’ needs, perspectives, and aspirations at the centre of decision-making.

Key elements of *Community-Led Initiatives* that contribute to their effectiveness include:

1. *Empowerment and Ownership*: Community-led initiatives empower local populations, particularly marginalized groups, to take ownership of the development process. This sense of ownership increases community engagement and ensures that social inclusion efforts are aligned with local needs and realities. For instance, local women’s groups or youth organizations may lead initiatives to address gender inequalities or unemployment, ensuring that policies reflect their lived experiences (Ansell *et al.*, 2020).
2. *Tailored Solutions*: Since community members are the primary drivers of these initiatives, the solutions they develop are typically more tailored to the specific social, cultural, and economic contexts in which they operate. Unlike top-down policies, which may overlook local complexities, community-led initiatives can address marginalized groups’ unique barriers, such as access to education, healthcare, or employment. For example, a rural community may initiate a project to improve access to clean water or health services that cater to their geographical challenges (Wise, 2022).
3. *Inclusive Participation*: These initiatives create spaces for inclusive participation, ensuring that all voices, especially those of the most vulnerable or marginalized, are heard in the decision-making process. This participatory approach builds social cohesion and strengthens community resilience by promoting collaboration across different social groups, reducing inequalities, and fostering solidarity. For example, organizing community forums where women, youth, ethnic minorities, and persons with disabilities can express their concerns and ideas is critical to fostering inclusion (Scorgie and Forlin, 2019).
4. *Capacity Building*: Community-led initiatives often focus on building the capacity of local individuals and groups to engage in governance and decision-

making processes. This includes providing training in leadership, advocacy, and project management, thereby equipping community members with the skills and confidence to address social inclusion challenges independently. By enhancing local capacity, communities are better positioned to advocate for their rights and mobilize resources, contributing to long-term sustainable growth (Franco *et al.*, 2021).

5. *Sustainability and Local Commitment*: These initiatives' bottom-up nature ensures that the solutions they propose are sustainable and have long-term local commitment. Since community members are deeply involved in both the design and execution of projects, they are more likely to maintain and expand these efforts over time, ensuring lasting impacts. This contrasts with externally imposed solutions that may lose momentum once funding or external support ends (Franco *et al.*, 2021).

Examples of Community-Led Initiatives can be seen in various contexts globally. In Africa, for example, community-led efforts have established local savings and credit cooperatives, which provide financial services to low-income individuals, helping them start small businesses or improve their livelihoods (Cloete and Veda, 2024). In Latin America, indigenous communities have initiated projects focused on preserving their cultural heritage while integrating sustainable practices, such as eco-tourism or organic farming, which improve their economic conditions and promote social inclusion (Costanza-Chock, 2020).

Community-led initiatives have played a key role in reintegrating displaced persons and former combatants into society in post-conflict regions, such as certain parts of Southeast Asia. These initiatives often focus on creating safe spaces for dialogue, rebuilding trust among divided groups, and ensuring access to education and healthcare for vulnerable populations (Cloete and Veda, 2024). In summary, *Community-Led Initiatives* are a powerful tool in collaborative governance, enabling communities to actively shape their future. These initiatives drive meaningful and sustainable social inclusion outcomes by promoting local ownership, fostering inclusive participation, and tailoring solutions to specific contexts. They ensure that marginalized groups are not passive recipients of aid but active participants in the processes that affect their lives. In this context, *Inclusive policymaking* is a crucial aspect of collaborative governance, directly contributing to social inclusion by ensuring that policies are developed through participatory processes that reflect the needs, interests, and perspectives of all societal groups, especially marginalized and underrepresented populations (Cairney and Toomey, 2024). By involving a broad spectrum of stakeholders - such as local communities, civil society organizations, private sector actors, and vulnerable groups - this approach aims to create policies that are more equitable, effective, and responsive to the challenges of diverse territorial contexts (Cairney and Toomey, 2024). Inclusive policymaking is a vital component of collaborative governance, highlighting their convergence. Incentives, mutual reliance, and trust are crucial prerequisites for inclusion, but active inclusion management is also crucial, claim Ansell *et al.* (2020). Additionally, these authors believe that inclusion is purposeful, with participants' "selective activation" relying on practical and useful decisions.

Critical features of *Inclusive Policymaking* that make it effective in promoting social inclusion include:

1. *Broad Stakeholder Engagement*: Inclusive policymaking ensures that a wide array of voices, especially those historically excluded from decision-making, are involved in policy development. This includes ethnic minorities, women, youth, people with disabilities, and economically disadvantaged groups. Engaging these stakeholders helps ensure that policies address their specific needs and challenges. For instance, local workshops or public consultations might be held where marginalized groups can directly contribute to shaping social programs like education reform or housing initiatives.
2. *Participatory Platforms*: Establishing participatory mechanisms, such as public hearings, citizen assemblies, or online platforms, allows community members and stakeholders to provide input during all phases of policy development - from the identification of issues to the formulation of solutions and the monitoring of implementation. This helps to prevent top-down policy decisions that may overlook local realities and reinforces the idea that everyone has a role to play in the governance process.
3. *Transparency and Accountability*: Inclusive policymaking promotes transparency by ensuring that decision-making processes are open and accessible to the public. Governments and policymakers must be accountable to the citizens they serve, particularly marginalized groups often most affected by social policies. Open communication channels, such as publishing policy drafts for public feedback or conducting regular updates on the implementation of social inclusion programs, build trust between government institutions and the communities they serve.
4. *Data-Driven Decision-Making*: Inclusive policymaking is often grounded in comprehensive data collection and analysis, particularly regarding marginalized populations' social and economic conditions. By collecting disaggregated data (e.g., by gender, age, ethnicity, or disability status), governments can identify the specific barriers different groups face and design policies that are better tailored to their needs. For example, targeted programs for improving access to education for girls in rural areas can be developed based on data highlighting gender disparities in school enrolment.
5. *Policy Co-Design*: Collaborative governance often extends beyond consultation to the actual co-design of policies with stakeholders. This means that community representatives, NGOs, and other stakeholders are not just consulted but are active participants in drafting the policies themselves. Such co-design practices ensure that policies are rooted in practical, on-the-ground realities and are more likely to succeed in their implementation. For example, health policy reforms may be co-designed with input from both healthcare providers and patients, ensuring that new systems are accessible and effective for marginalized populations.
6. *Long-Term Inclusion Frameworks*: Inclusive policymaking goes beyond short-term fixes, embedding social inclusion into the broader governance frameworks. It promotes the institutionalization of inclusivity principles in all areas of public policy, such as education, healthcare, housing, and employment. This ensures that inclusion is not treated as a one-off project but as a permanent feature of governance structures. For example, national

strategies integrating the Sustainable Development Goals (SDGs) emphasize reducing inequalities and fostering inclusion as ongoing priorities across sectors.

Examples of Inclusive Policymaking can be found in developing national poverty reduction strategies in several countries, where governments have actively involved civil society organizations and communities in designing programs to address economic disparities. In Brazil, for instance, the participatory budgeting process allows citizens, especially those from low-income neighbourhoods, to have a direct say in how municipal budgets are allocated, ensuring that public resources are directed to areas most in need of social and infrastructure improvements (Koehler *et al.*, 2020). In the European Union, the design of social policies often incorporates feedback from public consultations that engage a range of stakeholders, from social advocacy groups to private sector partners. This ensures that policies promoting employment, healthcare, and education are inclusive and responsive to the diverse needs of EU member states' populations (Alakshendra *et al.*, 2024). In post-conflict settings, such as in certain African countries, inclusive policymaking processes have been critical in drafting new constitutions or peace agreements. These processes often involve previously excluded groups, such as women and indigenous populations, ensuring that the new governance frameworks address the root causes of conflict and inequality (Popescu, 2022). In this context, *cross-sector collaboration* is a crucial pillar of collaborative governance, which is essential for advancing social inclusion within united territorial communities by bringing together diverse stakeholders from the public, private, and civil society sectors. This type of collaboration leverages each sector's unique strengths and resources to address complex social challenges, such as inequality, poverty, and access to services, that no single entity has been able to solve independently (Alakshendra *et al.*, 2024). By integrating expertise, funding, and innovative approaches from different sectors, cross-sector collaboration promotes more comprehensive and sustainable solutions for social inclusion.

Critical elements of *Cross-Sector Collaboration* that contribute to its effectiveness in promoting social inclusion include (summarized by Clarke and Crane, 2018):

1. *Shared Goals and Vision:* Successful cross-sector collaboration begins with a common understanding of the challenges and shared goals for addressing them. Stakeholders from government agencies, private businesses, non-governmental organizations (NGOs), and local communities unite to align their objectives and create a unified vision for promoting social inclusion. For example, a collaboration between a government health department, private healthcare providers, and community groups might focus on improving access to medical services in underserved areas.
2. *Resource Sharing and Pooling:* Each sector brings different resources—funding from the private sector, policy frameworks from the government, or local knowledge and community networks from civil society. By pooling these resources, cross-sector collaborations can implement more impactful social inclusion initiatives. For instance, a public-private partnership could combine government subsidies with corporate investment to build affordable housing projects that include social services, such as childcare and job training programs, for low-income families.

3. *Innovation and Flexibility*: Cross-sector collaboration often leads to innovative solutions to social inclusion challenges, as different sectors bring diverse perspectives and expertise. The private sector, for example, can introduce technological innovations or business models that enhance service delivery, while the public sector can create regulatory frameworks to ensure equity. In education, collaborations between governments, tech companies, and NGOs have introduced digital platforms that allow marginalized students to access quality education remotely, overcoming barriers like geographic isolation or lack of resources.
4. *Capacity Building and Knowledge Exchange*: Cross-sector partnerships enhance capacity building by facilitating the exchange of knowledge, skills, and best practices across sectors. For example, local governments may gain insights into efficient service delivery models from the private sector, while NGOs can provide expertise in community engagement and social mobilization. This knowledge transfer ensures that all partners improve their ability to contribute to social inclusion efforts effectively.
5. *Accountability and Governance Structures*: Effective cross-sector collaborations rely on clear governance structures and accountability mechanisms. Establishing joint decision-making bodies, regular communication channels, and shared metrics for success ensures that all partners remain accountable to their commitments and can monitor progress toward social inclusion goals. In this way, cross-sector collaborations can adapt and respond to emerging challenges, ensuring long-term sustainability and impact.
6. *Engagement of Marginalized Groups*: Cross-sector collaboration must also include direct engagement with marginalized groups to ensure their needs are adequately represented. Involving community members and grassroots organizations as equal partners in the collaboration helps ensure that initiatives are inclusive and designed to empower those who have historically been left out of decision-making processes. For example, a cross-sector initiative addressing youth unemployment might work closely with local youth organizations to design job training programs that meet the needs of young people in disadvantaged areas.

Integration of Local and National Strategies

Various successful social inclusion projects worldwide include examples of cross-sector collaboration. In India, the government has partnered with tech companies and NGOs to create the Digital India initiative, which aims to bridge the digital divide by providing internet access and digital literacy to rural and underserved populations. This collaboration has enabled millions of citizens to access e-governance services, education, and employment opportunities, promoting social inclusion (Greenwood, Singer and Willis, 2021).

In the UK, the *Inclusive Economy Partnership* is a collaboration between the government, businesses, and civil society organizations to tackle societal challenges such as financial inclusion, mental health, and education inequality. Through cross-sector cooperation, this partnership has implemented innovative solutions like

microfinance for low-income individuals and mental health support programs in schools and workplaces (*The Power of Partnership*, 2018). Another significant case examines the inclusivity initiatives implemented in Scandinavian cities, which are renowned for their commitment to integrating diverse people into the social environment. The findings suggest that successful integration into urban planning in these cities is mainly due to the synergy between local and higher levels of governance, enabling the alignment of national policies with local conditions (Bulkeley and Betsill, 2005; Healey, 2006). In decentralized environmental management, Brazil's research provides valuable insights into how delegating environmental responsibilities to state and municipal levels can influence outcomes. Each person, regardless of faith, gender, or profession, can freely express their opinion in society. The analysis shows that decentralization's success depends on local authorities' capacities and the availability of resources to support sustainable practices (Babich, 2018; Conzelmann, 2008; Koliadenko, Zhyvago and Bursa, 2022; Scherpereel, 2010).

The recent case of post-conflict reconstruction in Rwanda demonstrates how community-based social programs (CBSP) were instrumental in promoting sustainable development, social cohesion, and economic recovery. This research focuses on the role of social factors in the implementation of national development strategies at the grassroots level, illustrating how multilevel governance can align national goals with local needs, thereby fostering long-term stability and development where each citizen is a full member of society (Ansoms and Rostagno, 2012; Purdekova, 2011).

These cases together illustrate diverse applications of inclusion in various contexts of public life. They emphasize the critical role of coordination, flexibility, and stakeholder engagement in achieving learning outcomes. The case studies reveal several critical insights into the practice of social inclusion. One of the prominent findings is the critical role of coordination and integration at different levels of society. Effective multilevel strategic planning relies on clearly defined roles and responsibilities and robust communication and cooperation mechanisms. This is corroborated by the European Union's cohesion policy, which illustrates how a well-coordinated approach, supported by robust institutional frameworks, can address regional disparities and contribute to the implementation of inclusivity principles in community life (Hooghe and Marks, 2001; Piattoni, 2010).

In Rwanda, for instance, the use of performance indicators and regular assessments played a crucial role in guiding post-conflict recovery efforts and ensuring that local initiatives aligned with national development goals, where all citizens had the opportunity to express their views (Ansoms and Rostagno, 2012; Purdekova, 2011).

Countries with high pollution indices, particularly India and Ukraine, require urgent measures to improve environmental conditions. Germany can be an example of implementing policies that effectively reduce pollution levels. Similarly, in the USA, strengthening the principles of inclusivity in Seattle's strategic plans led to a 15% increase in employment levels and significant growth in investments in green technologies (Shah and Das, 2024). However, despite these economic and environmental achievements, social justice issues remain, especially in regions such as Gauteng in South Africa, where the Gini coefficient remains high at 0.62. Nevertheless, inequalities

in access to services remain a significant obstacle, illustrating the complex interplay between environmental sustainability and social justice (Meissner, 2016). A recent example from Rwanda highlights the critical role of institutional quality in the success of social adaptation. Over the past 20 years, Rwanda has seen a marked improvement in the Corruption Perception Index, rising from 40 to 53. This improvement is associated with the more effective implementation of national development strategies and a 50% reduction in poverty. These results emphasize the importance of solid and transparent institutions and coherent governance structures in achieving sustainable development outcomes in different regions (Redifer *et al.*, 2020).

Achieving inclusivity principles is possible by modelling multilevel strategic planning for sustainable development. The development of an econometric model for analyzing sustainable development is based on the theory of multilevel governance. It includes adapting and modifying theoretical concepts presented in academic works (Bondarenko and Romanenko, 2020; Fedorenko, 2019; Gonchar, 2019; Ivanova, 2017; Karplyuk, 2019; Melnyk, 2018; Petrov, 2021; Suntsova, 2012; Serdyuk and Ivashchenko, 2020; Zelenyi, 2020).

Key Challenges and Recommendations

Cross-sector relationship potential pertains to two primary concerns. First, as previously indicated, an effective partnership should capitalize on the distinct strengths of each partner to achieve benefits that would be unattainable for any individual sector operating in isolation. Second, the partnership offers a solution and a substitute for a system characterized by rivalry, strife, and an increasing disparity in power across sectors. In this situation, the partnership serves as a means of converting conflicting interests into creative teamwork (Grudinschi *et al.*, 2013). Partners can develop answers to the intricate societal problems that drew them together by concentrating on these key concerns.

To identify partners' fundamental talents, discover creative ways to combine those competencies, and effectively address particular problems - all of which contribute to the creation of social value - management skills are necessary. In the meanwhile, leaders frequently overlook the management role (Wallace, 2022). As a result, these partnerships suffer from two main issues: (1) inadequate managerial structures (such as unclear roles, policy guidelines, planning, and information-sharing models, as well as a lack of human resources); and (2) inadequate managerial processes (such as a lack of communication, strategies, evaluation, coordination, supervision, and training, as well as a lack of time dedicated to the partnership). Disparities in the aims and objectives of organizations, as well as in language, processes, culture, authority, and values, present another set of difficulties for cross-sector relationships.

Constrained resources, a lack of chance or motivation to work together, mistrust, rigid regulations and procedures that hinder the partnership, inaccurate group attitudes toward one another, and a lack of commitment or support for the partnership are some examples of the hurdles.

Discussion

The research results are based on implementing different models of social inclusion in sustainable development processes. Many researchers consider the charitable and medical models. From the perspective of adaptation, the charitable model views a person as a victim of certain circumstances. It is most commonly used in fundraising. The disadvantages of this model are that the funds raised do not solve all problems and do not create opportunities for self-realization. The medical model is more often applied to people with disabilities. In this model, a person is viewed as the object of help. Under such conditions, the individual is partially excluded from social life, and their activities are limited. Most decisions are made on their behalf by relatives or close ones.

According to Mir *et al.* (2024), who study social inclusion and sustainable development in African and Asian contexts, workshop recommendations supported the voice of marginalized groups by involving them in public service staffing and decision-making, in addition to macro-level restructuring. To promote staff training, representational employment, and effective leadership - all of which are necessary for both public services and the excluded groups themselves - regulation, incentives, and resources are needed for policy implementation in this area. Recommendations acknowledged that disparities in public service had cumulative effects and interacted with one another, which had consequences for potential future directions. It was recognized that better access and results in healthcare and education, especially in early life, were necessary for increased leadership potential among marginalized populations. The fundamental importance of education and employment in building capacity to support the increased influence of marginalized groups through improved economic and social status and early prevention of gender inequality that affects both boys and girls is reflected in the recommended focus on these areas (Kennedy *et al.*, 2020).

To establish the channels via which favourable results might be attained, multi-sector and multi-level actions are required at the same time. Interventions that address the “poverty penalty”, the political aspects of exclusion, the cyclical reinforcement of exclusion through structural abuse, neglect, and violence, and the intersectional disadvantage faced by women and young people from underprivileged populations must be evaluated immediately. As some scholars have pointed out (Fitzgibbons and Mitchell, 2019; Littlewood, Glorieux and Jönsson, 2017; Speer, 2012), these kinds of interventions would offer frameworks for practice and policy that would promote social inclusion and lessen structural violence. According to the larger body of research, interventions that entail fair cooperation with marginalized groups are seen to have the best chance of addressing the crucial areas of leadership, capacity building, accountability, transparency, and sociopolitical context (Mir *et al.*, 2020).

In this context, one should especially mention collaborative governance, which offers a flexible and adaptive approach to addressing social inclusion challenges in diverse territorial contexts where social, economic, and cultural conditions vary widely. This strategy promotes a multi-stakeholder model in which governments do not act alone but work in partnership with non-governmental organizations (NGOs), community groups, and private entities. Such cooperation ensures that the voices and needs of marginalized

populations - whether they are ethnic minorities, women, youth, or people with disabilities - are heard and integrated into policy formulation and implementation.

Collaborative governance involves several critical practices that have proven effective (Donahue, Zeckhauser and Breyer, 2020):

1. *Public-Private Partnerships (PPPs)*: Communities can access additional financial resources and expertise by involving private businesses in social inclusion initiatives. For example, businesses may support job training programs for marginalized groups, contributing to economic development and social cohesion.
2. *Community-Led Initiatives*: Empowering local communities to lead projects to improve inclusion, such as neighbourhood revitalization or inclusive education programs, ensures that solutions are tailored to local needs. This bottom-up approach fosters ownership and commitment among community members, which is crucial for the long-term sustainability of social inclusion efforts.
3. *Inclusive Policymaking*: Creating *participatory platforms* where diverse stakeholders, including marginalized communities, can directly contribute to decision-making ensures that policies reflect a broad range of perspectives. This prevents the marginalization of vulnerable groups and promotes policies that address the unique barriers they face in accessing social services, education, or employment opportunities.
4. *Cross-Sector Collaboration*: Bringing together expertise from various sectors - healthcare, education, housing, and environmental management - enables a more comprehensive approach to social inclusion. For instance, addressing the needs of marginalized groups may require improving access to jobs and ensuring adequate housing and healthcare, all of which require input from multiple sectors.

Social inclusion can be applied in different spheres, particularly within communities where strong interaction with society is formed, in the educational space, where all conditions for learning and development are created, and in the ecological environment, which enables activities and communication. Involving the public in the planning process will significantly lower the rate of poverty and inequality in the community. Public involvement in the planning process guarantees the creation of economic possibilities, which lowers social inequality and poverty, contributing to sustainable development. During wartime in Ukraine, the implementation of social inclusion has its peculiarities. In particular, there are additional features related to work in de-occupied territories, the socialization of citizens who have become internally displaced persons, and the restoration of destroyed infrastructure, the environment, educational spaces, and leisure activities.

Current rules in Ukraine tie IDP registration to several rights and benefits. For instance, to receive their pensions and social benefits, IDP retirees who have relocated to the GCA must continue to be recognized as IDPs. To address this, certain changes were made to government resolutions, but they were not comprehensive. Individuals are still bound by their IDP registration, which necessitates further eligibility verification and raises the possibility that their pensions would be mistakenly suspended. Furthermore, authorities currently register children born to internally displaced parents as IDPs, creating a new

generation of internally displaced people who have never been relocated. Since IDPs are eligible for advantages like financial aid and are not placed on waiting lists for state-run kindergartens, IDP parents are motivated to register their newborn children as IDPs.

One's place of residence registration is also linked to other government services, such as the issuing of identification cards and social benefits related to disabilities. To get these services in the community where they have been moved, people from NGCA and Crimea must register as internally displaced persons (IDPs). Because their IDP certificate is the key to many public services, IDPs living in GCA are unable to renounce their IDP registration, even if they feel integrated into host communities and indicate a wish to stay there. IDPs are forced to maintain their IDP registration in this link's reality, which makes it difficult for them to be included. Existing regulations about IDP rights and benefits need to be reviewed to remove barriers to integration and focus on needs rather than status. Solutions, not the IDP certificate, should be connected to support. Research conducted before the full-scale war in Ukraine shows that a significant proportion of IDPs integrate into their new location (Myrnyi, 2018). Many of them have found employment, rented housing, and receive educational and health services, although to a lesser extent than residents. On the other hand, they are usually not involved in community decision-making to exercise their basic rights. They are forced to overcome administrative obstacles, relying more on themselves and humanitarian organizations than on the state. In addition, city administrations do not plan migration, as indicated by the small number of integration plans. Experts also drew attention to the language of hatred towards IDPs. They noted that IDPs from the East are more discriminated against due to language issues (Myrnyi, 2018).

Meanwhile, attempts to implement modernist change projects with an orientation towards the model of "economic man" and reducing the tools of social management in the internal contour of their implementation mainly to unadapted Western templates and economic organization of social relations may pose a threat to strengthening the tendencies of disintegration of society and confrontation of social groups. Therefore, a detailed and deep multifactorial, culture-based analysis of the possibilities of applying and adapting the best practices for achieving social inclusion in territorial communities of other countries and regions is necessary. In particular, an analysis of all proposed initiatives is necessary, or more precisely, their potential implications in the united territorial communities in Ukraine from the point of view of Hofstede's cultural dimensions.

The importance of adaptability in strategies to local conditions was developed based on the works of Bulkeley and Betsill (2005). They argue that adapting strategies to local conditions increases the effectiveness of their implementation. This was reflected in the inclusion of a variable that accounts for the flexibility and adaptability of strategies. The involvement of stakeholders, considered a critical element for successful planning, is based on the studies of Conzelmann (2008) and Scherpereel (2010). Their works show that public participation is critical in ensuring strategies meet real needs and increase effectiveness. The model reflected this through a variable measuring stakeholder engagement in the planning process. The studies of Ansoms and Rostagno (2012), and Purdekova (2011) highlight the importance of monitoring and evaluation for assessing the effectiveness of planning. They emphasize the need for constant monitoring and

evaluation of outcomes to adjust strategies and ensure they align with national and local goals. This justified the inclusion of a variable reflecting the effectiveness of the monitoring and evaluation system in our model.

Conclusion

The research provides a comprehensive analysis of social inclusion as a method for integrating all categories of citizens into various levels of social life. It creates equal conditions for access to education, housing, employment opportunities, and more. The state develops various programs and mechanisms for their implementation, which enhance and facilitate the adaptation of people or children with disabilities.

The term “social inclusion” emerged due to society’s transition to a social policy based on the social model of disability. It is a holistic approach in politics, economics, and the social sphere that strengthens the adaptation of people with disabilities to life in society. In essence, conditions are created where children and adults can participate in society as equal members who are respected and contribute to social development.

Social inclusion at the state level would not be possible without adhering to the principles of sustainable development, which are partially highlighted in this work. Utilizing SDG data and localized indicator systems to inform policies and actions for improving people’s lives, as well as to highlight the accomplishments and success stories of cities and regions, is very efficient. Cities and regions should specifically combine data and indicators at various scales, from those related to administrative boundaries (the unit for political and administrative action) to those related to functional approaches (the economic geography of where people live and work), to provide more thorough assessments and policy responses.

Furthermore, by involving all geographical stakeholders in the policy-making process - civil society, people, youth, academics, and private companies - the SDGs must be used as a means of promoting accountability and transparency. To engage local stakeholders, cities and regions should employ a variety of strategies, including awareness-raising campaigns, networking events, de-risking investments in SDG solutions through grants or loans, and providing financial incentives for creative sustainability solutions.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

<i>Contribution</i>	<i>Author 1</i>	<i>Author 2</i>	<i>Author 3</i>	<i>Author 4</i>	<i>Author 5</i>
Conceived and designed the research or analysis	Yes	No	Yes	Yes	Yes
Collected the data	Yes	No	Yes	No	No
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	No	Yes	No	Yes	No
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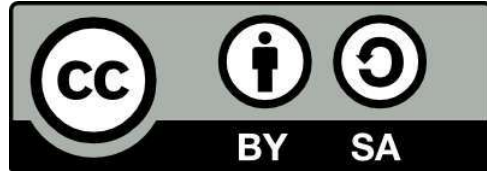
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