

SECURITY OF SUSTAINABLE DEVELOPMENT OF THE AGRICULTURAL SECTOR OF THE REGION BASED ON DIGITALIZATION AND CIRCULAR ECONOMY: A CASE STUDY OF UKRAINE

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The article examines the features of ensuring the security of sustainable development in the region's agro-industrial complex through digitalization and circular economy principles. It considers contemporary challenges and threats facing the regional agricultural sector, including climate change, resource limitations, and economic instability. The study proposes approaches to increasing resource management efficiency by introducing digital technologies and circular economy models, which help minimize waste, reuse resources, and reduce the negative impact on the environment. The key aspects of ensuring the security of sustainable development in the agricultural industry, such as the digital transformation of management processes, optimization of natural resource use, and enhancement of environmental protection, are identified.

Keywords: agricultural sector, digitalization, digital transformation, environmental safety, circular economy, digital technologies.

1 Introduction

The sustainable development of the regional agro-industrial complex is becoming one of the most critical issues in the modern economy, especially in the context of increasing globalization, climate change, and limited natural resources. Simultaneously, the need to ensure food security and environmental sustainability, while maintaining competitiveness in the agricultural sector, demands new approaches to production organization and resource management. In such conditions, traditional farming methods often prove ineffective given the growing dynamism of the business environment, jeopardizing the stability of both individual enterprises and entire regions.

One of the primary challenges is the scarcity of resources, which requires a rethinking of their practical use. Constant anthropogenic pressure on natural resources from intensive agricultural production leads to soil degradation, depletion of water resources, and increased greenhouse gas emissions. In recent years, climate change has significantly exacerbated these processes, negatively impacting the yield and stability of agricultural production. It is important to note that these effects are especially critical for regional farm producers.

At the same time, digitalization and the adoption of circular economy models offer new solutions to these challenges. However, despite the active development of digital technologies, their implementation in the agricultural sector has yet to reach a significant scale. Infrastructure deficiencies, a lack of awareness, and resistance to change among enterprises are slowing the digital transformation process. Nevertheless, using digital tools, such as big data, the Internet of Things, and automation, can substantially improve the efficiency of agricultural production and resource management, reducing both costs and environmental impact [12].

Additionally, the concept of the circular economy, which emphasizes the efficient use of renewable resources and waste minimization, holds vast potential for the agricultural sector. However, its practical implementation faces several barriers, including regulatory and legal restrictions, limited financial

resources for agricultural producers, and low awareness of new technologies among farmers. Therefore, systemic support at the regional economic policy level is needed to facilitate the transition to a circular production model.

Thus, the security of sustainable development in the agro-industrial sector largely depends on producers' ability to adapt to new conditions through the adoption of innovative technologies and management models. It is crucial to recognize that both the digitalization process and the shift to a circular economy represent technical and managerial challenges. This transition requires new approaches to planning, coordination, and control at all levels of agricultural sector management. Therefore, only a comprehensive approach—combining technological innovation with a shift in the management paradigm—can ensure the long-term sustainability of the regional agro-industrial complex in the face of modern challenges.

2 Literature Review

The study of sustainable development issues in the agro-industrial complex, based on digitalization and the circular economy, reflects the growing attention of researchers to the adoption of innovative technologies and environmentally responsible production models. The primary research focuses on using digital technologies to enhance the efficiency of the agricultural sector and developing circular solutions to reduce the environmental impact of farming systems.

Significant contributions to the study of the digitalization of the agro-industrial complex have been made by M. Dziamulych [1-8], S. Koliadenko [10], and M. Rudenko [14], who analyzed the impact of digital technologies on agricultural production, particularly the role of big data, the Internet of Things, and business process automation in agrarian resource management. These studies highlight that using big data and digital analytics can substantially improve decision-making processes in the agricultural sector, ensuring more efficient resource use. Additionally, the development of precision farming technologies at the regional level is noted for its potential to minimize losses, optimize yields, and increase the resilience of agricultural systems to climate change.

Regarding the circular economy in the agricultural sector, key insights are offered in studies by authors such as N. Horobets [9], V. Kostiuk [11], T. Shmatkovska [15], and others, who examine models of resource reuse in agriculture and their impact on the ecological sustainability of regional agricultural systems. Additionally, closed-loop practices are analyzed, where organic waste is used to produce bioenergy or fertilizers, reducing dependence on chemical inputs and contributing to the restoration of natural ecosystems. Research also indicates that the circular economy has the potential to significantly reduce the negative environmental impact of agricultural enterprises; however, institutional and financial incentives, along with support from state and regional authorities, are essential for its widespread adoption.

Moreover, several researchers, including I. Mazniev [13] and O. Zghurska [18], focus on the integration of digital technologies and the circular economy within the context of sustainable development of the agro-industrial complex. These studies highlight that digital technologies can substantially facilitate the implementation of circular models by enabling more precise and efficient resource management. Furthermore, it is emphasized that the combination of digitalization and the circular economy is crucial to achieving sustainable development in agricultural regions, as it not only improves productivity but also reduces the negative environmental impact.

Thus, the existing body of research indicates that ensuring the sustainable development of the agricultural sector through digitalization and the circular economy is a relevant area of scientific inquiry. However, further study is required to identify the specific strategies for implementing these approaches to enhance agricultural production efficiency and ensure food security at the regional level.

3 Materials and Methods

The research methodology is based on a comprehensive approach, incorporating methods of logical generalization, comparison, analysis and synthesis, and expert evaluation. The selection of these methods is driven by the complexity of the subject, which encompasses not only economic and technological aspects but also environmental, social, and institutional factors related to the agricultural sector.

The primary method used in the research is logical generalization, which enables the formation of a comprehensive understanding of the processes underlying the sustainable development of the region's agro-industrial complex in the context of digitalization and the adoption of the circular economy. Logical generalization involves the systematization and interpretation of theoretical and practical aspects of agricultural security, drawing on existing research and data. The application of this method allowed for the exploration of key concepts such as sustainable development, the digitalization of the agro-industrial complex, and the principles of the circular economy. This, in turn, facilitated the identification of critical factors influencing agricultural production safety and the formulation of general conclusions regarding their interrelationship.

The comparison method was employed to analyze the experiences of different regions in implementing digital technologies and circular economic models within the agricultural sector. This approach made it possible to identify the advantages and disadvantages of each model and determine best practices that can be adapted for specific regions. The comparison was conducted between regions with varying levels of digital infrastructure development, which allowed for the identification of factors that either promote or hinder the advancement of the circular economy and digitalization in the agro-industrial complex.

Analysis and synthesis are key methods in evaluating the security of the agricultural sector and developing recommendations for its improvement. The analysis involved a detailed examination of elements related to the impact of digitalization on production processes, the potential for optimizing resource use through circular approaches, and the assessment of risks associated with environmental safety and socio-economic factors. Special emphasis was placed on analyzing contemporary challenges faced by regional agro-industrial systems, as well as the increasing demands for the environmental sustainability of production.

The synthesis method enabled the integration of individual analytical components into a cohesive understanding. Based on this, comprehensive conclusions were drawn regarding the interaction between digital technologies, the circular economy, and the security of the agro-industrial complex, taking into account the specific characteristics of the region [17]. Synthesis was also employed to develop practical recommendations for improving management processes in the regional agricultural sector, aimed at achieving sustainable development.

The use of the expert evaluation method allowed for a more precise and in-depth understanding of the potential risks and benefits of implementing circular and digital approaches in the agricultural sector. This facilitated not only a theoretical assessment of their impact but also the generation of practical recommendations for minimizing risks and maximizing the positive effects of innovations on the regional agricultural industry.

Overall, the research methodology provided a thorough and comprehensive study of the topic, utilizing various methods of analysis and evaluation to ensure the reliability and applied relevance of the results obtained.

4 Results and Discussion

The modern regional agricultural sector faces numerous challenges and threats resulting from resource limitations and economic instability. Additionally, climate change exacerbates these issues by causing unpredictable weather patterns, which negatively affect farm productivity and soil quality. These factors increase the risks of crop failure and reduce overall agricultural productivity, thereby threatening regional food security. Resource constraints, including the depletion of water and land, further complicate efficient agricultural management, compelling farmers to seek new approaches. Concurrently, economic instability, driven by the devastating impact of the war on Ukraine's agricultural sector, intensifies these threats by restricting access to financing, investment, and the new technologies required to modernize agricultural production. As a result, the economic and ecological stability of rural regions is in decline.

Improving resource management efficiency in the region's agro-industrial complex is crucial to ensuring sustainable development under these modern conditions. The adoption of digital technologies and circular economy models in agricultural production helps minimize waste, reuse resources, and reduce the negative environmental impact of agriculture. This is particularly relevant for farming enterprises that must address the dual challenge of increasing productivity while conserving natural resources. One of the key strategies for enhancing resource management efficiency is the implementation of a circular economy, which promotes closed-loop production cycles. The circular economy is grounded in principles of rational resource use, material reuse, and waste minimization, making it an effective tool for mitigating the environmental impact of the agro-industrial complex. This model shifts away from the traditional linear production approach, in which resources are consumed and waste is discarded, toward a system where resources are reused or transformed into new products, reducing losses and preserving natural resources.

It is important to highlight that among the various aspects of digitization in the agricultural sector, several stand out for their significant impact on improving enterprises' economic security. Prospective areas of digitization and their influence on financial security are outlined in Table 1.

Table 1: The influence of promising directions of digitalization on the economic security of agricultural enterprises

Factors of economic security	Directions of digitization	Impact on the economic security of the enterprise
Productivity growth	precision farming; introduction of drones (spraying; aerial reconnaissance; visual monitoring of resources)	reduction of costs for fertilizers and resources; increasing productivity;
Resistance to external influences	weather and climate change monitoring systems; automated security systems; means of cyber security and information protection	increasing resistance to threats; optimization of security costs
Ensuring stable production	digital platforms for process planning and control; systems of electronic document circulation	increasing planning efficiency; optimization of document flow; reducing the risk of information loss
Financial stability	digital accounting tools; reporting automation; systems of financial forecasting	reduction of financial risks; strengthening of financial stability
Risk management	electronic and hardware monitoring tools; IoT devices and sensors; video surveillance systems	risk reduction and prevention; acceleration of detection and response to economic threats

Source: [10]

One of the primary issues in traditional agriculture is the high consumption of water, land, and energy resources, as well as the significant amount of waste generated throughout the

agricultural production cycle—from the cultivation of raw materials to their processing and transportation. Adopting the principles of the circular economy addresses these problems by transitioning to more closed-loop systems, where the waste from one process becomes resources for another. For instance, utilizing organic waste to produce biofertilizers or bioenergy not only reduces waste but also creates added value by generating resources that can be reintegrated into the production cycle. Such solutions enhance environmental sustainability and improve economic efficiency by lowering waste disposal costs and securing new resources. Moreover, they lessen dependence on external resource supplies, which can be crucial during global economic and political crises. In the context of increasing market instability and resource limitations, circular approaches are becoming increasingly attractive to agricultural enterprises, as they help mitigate risks and bolster resilience to external shocks. Additionally, the adoption of innovative solutions in Ukraine's agricultural sector has been steadily growing in recent years, particularly evidenced by the rising amount of financing for agricultural start-ups (see Fig. 1).

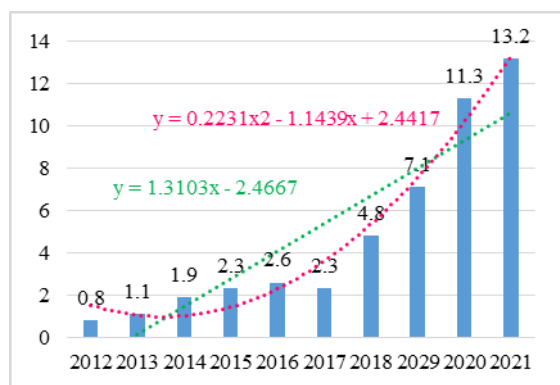


Figure 1. Correlational assessment of the dynamics of start-up financing in Ukraine's agricultural sector (2012-2021), in billion USD.

Source: calculated by the author based on [16]

The results of the correlation evaluation indicate that the linear trend parameters reveal a clear upward trajectory in the financing of start-ups in agriculture over the analyzed period. Specifically, the absolute increase in this indicator was calculated at \$1.3103 billion USD. Conversely, the polynomial trend analysis shows that the actual annual change in financing volume is \$1.4149 billion USD, compared to an initial growth of \$0.2231 billion USD.

In agriculture, it is essential to consider the interactions among various resources such as water, energy, soil, and biodiversity. To enhance resource management efficiency, it is crucial to ensure their rational use and recovery, a fundamental principle of sustainable development. The circular economy provides methods to minimize water use by reusing treated wastewater for irrigation or implementing closed-water supply systems, thereby reducing the strain on natural water resources. Additionally, the circular economy emphasizes optimizing energy use in agro-industrial processes. Traditionally, the agricultural sector consumes substantial amounts of energy, leading to higher costs and increased greenhouse gas emissions. Utilizing renewable energy sources, such as bioenergy, can reduce reliance on conventional energy sources and lessen the environmental impact of agricultural production. For instance, biogas derived from organic waste can serve as an energy source for agricultural enterprises, thus closing the energy production loop within the farm and minimizing emissions.

Another important aspect is the minimization of product and resource losses in the supply chains of the agro-industrial complex. At various stages, including harvesting, processing, storage, and transportation, losses can become significant, increasing the environmental burden and reducing the economic efficiency of production. Employing innovative approaches to

mitigate these losses enables optimized resource use and waste reduction. For instance, improving product storage conditions, modernizing logistics, and employing food waste processing methods can substantially reduce losses—an essential factor in the sustainable development of Ukraine's agro-industrial complex.

One of the main challenges in implementing the circular economy is the need to change management approaches within enterprises. Transitioning to new models necessitates investments in new technologies and processes, as well as the development of infrastructure for recycling and reusing resources. This requires close cooperation between businesses, governments, and communities to create the conditions necessary for implementing circular solutions. Government support, through incentives, financial programs, and regulations, also plays a crucial role in facilitating the transition to sustainable agricultural production. Additionally, investments in digital technologies within the agro-industrial complex are becoming increasingly important (see Fig. 2).

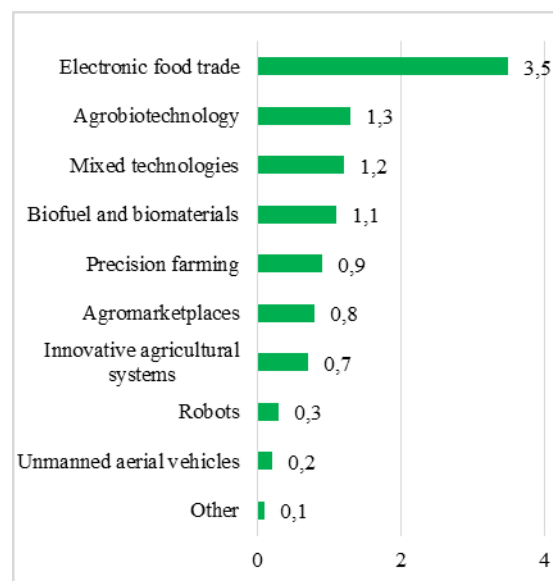


Figure 2. Funding volumes of digital projects in the agricultural sector of Ukraine in 2021, billion USD.

Source: [18]

Therefore, in addition to embracing the circular economy, developing innovative management approaches that enable agro-industrial enterprises to remain flexible and adaptable to changes in external conditions is crucial for enhancing resource management efficiency. In modern agribusiness, the ability to respond quickly to shifts in market conditions, climatic challenges, or fluctuations in demand is essential. This adaptability is facilitated by advanced information systems and management technologies, which improve the planning and control of resource use, thereby minimizing costs and losses.

Integrating sustainable development strategies into the management of agro-industrial enterprises also requires the development of new forms of cooperation and partnerships among agricultural producers, processors, and consumers. Such collaboration enhances coordination at all stages of production and product supply, contributing to reduced losses and increased resource use efficiency. For example, developing short supply chains, where products are delivered directly from producers to consumers, can reduce transportation and storage costs while minimizing the environmental impact by decreasing greenhouse gas emissions.

In this context, the role of state policy and regulation in ensuring the sustainable development of the agro-industrial complex is vital. There must be state-level mechanisms to support farmers and agribusinesses in adopting the latest technologies and

circular models. This support could include financial subsidies or tax incentives for enterprises that implement innovative approaches to resource management, as well as the development of infrastructure to support the circular economy. For instance, creating conditions for processing organic waste or utilizing biomass for energy production can significantly enhance the efficiency of agricultural systems and aid in resource conservation. Therefore, it is essential to develop a functional algorithm to determine the strategy for integrating digital innovations into the business processes of agricultural enterprises (see Fig. 3).

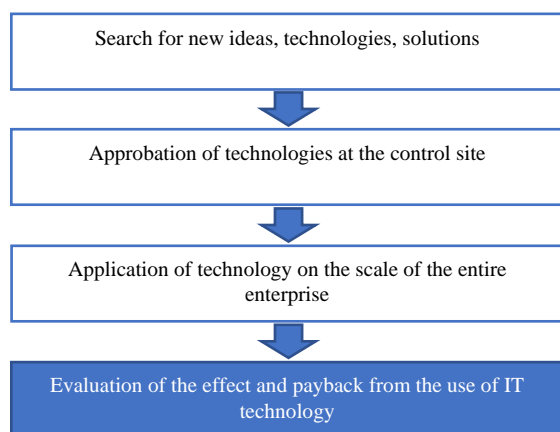


Figure 3. The algorithm for introducing digital technologies to the production strategy of agricultural enterprises
Source: [9]

Therefore, implementing approaches to enhance resource management efficiency in the agro-industrial complex, based on the principles of sustainable development and the circular economy, is essential for ensuring the environmental sustainability and economic stability of rural regions. These approaches help reduce resource losses, optimize production processes, and mitigate the negative impact on the environment. However, their successful implementation requires comprehensive support at all levels—from state policy and regulation to the development of educational programs and international cooperation. Only through this holistic approach can we ensure the long-term growth of agricultural systems that can address modern challenges and preserve natural resources for future generations.

5 Conclusion

Thus, we conclude that the security of sustainable development for the region's agro-industrial complex hinges on integrating digital technologies and circular economy models. Key aspects of ensuring this security include effective resource management, which involves minimizing waste and reusing materials to reduce the environmental burden on the region. The adoption of modern technologies enhances productivity and the agricultural sector's adaptability to climate change. Additionally, the development of the circular economy supports the economic sustainability of agro-industrial enterprises by optimizing the use of natural resources, which is crucial for maintaining environmental and socio-economic stability in the region. Furthermore, to ensure the security of sustainable development in the agricultural industry, it is essential to integrate digital solutions across all stages of the production cycle—from resource monitoring to supply chain management. This integration enables optimization of resource use, thereby reducing costs for agricultural producers. Circular models encourage the efficient use of agricultural waste, converting it into resources such as biogas or fertilizers. This approach lessens dependence on non-renewable resources and promotes the restoration of natural systems. Therefore, to achieve these objectives, the agricultural sector in Ukraine requires support at the state policy level to stimulate innovation and create

conditions for developing a sustainable agricultural economy, addressing contemporary environmental and social challenges.

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