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Formation of a mechanism for the digital transformation of the management of agricultural sector development in Ukraine

Abstract. The digital transformation of Ukraine's agricultural sector represents a strategically important development pathway, enabling the optimisation of management processes, the reduction of production costs, and the enhancement of agricultural enterprises' productivity. This study aimed to develop a mechanism for the digital transformation of the management of agricultural sector development based on modern technological solutions and their economic efficiency. To achieve this aim, bibliographic and content analysis, economic forecasting methods, mathematical modelling of digitalisation costs, and statistical methods for assessing the effectiveness of digital technology implementation were employed. The study established that the main mechanisms of digital transformation include digital platforms, the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), blockchain, and ERP systems. The total cost of digitalising Ukraine's agricultural sector is estimated at approximately 18,900,110,000 USD. The largest financial investments are directed towards process automation (12,600,000,000 USD), particularly in robotic harvesting systems (4,200,000,000 USD), automated tractors (4,200,000,000 USD), and irrigation systems (4,200,000,000 USD). The cost of implementing IoT equipment, including sensors for monitoring soil and weather conditions, drones for aerial surveying, and automated data collection systems, amounts to 6,300,000,000 USD. Investments in big data analytics and AI algorithms range from 50,000 USD to 60,000 USD per system, while ERP systems are estimated at between 30,000 USD and 60,000 USD. Calculations indicate that the average cost of digitalising one hectare of agricultural land varies between 450 USD and 1,000 USD, depending on the level of technological integration. The proposed digital transformation mechanism envisages the integration of IoT equipment, automated systems, blockchain, and analytical tools into a unified agricultural management system. Its implementation is expected to reduce production costs by 20%-35%, increase productivity by 15%-25%, and decrease crop losses by 10%-18% through the adoption of precision farming and analytical forecasting. The practical significance of the study lies in the application of the developed model for government planning of agricultural sector digitalisation, optimisation of agricultural production costs, and enhancement of sector competitiveness

Keywords: economic model; integration; advanced technologies; automation; Internet of Things; cost optimisation; productivity enhancement

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INTRODUCTION

Modern mechanisms for digital transformation in the management of trade and entrepreneurship encompass a broad spectrum of innovative solutions and technologies, serving as pivotal drivers for business evolution in the context of global digitisation. These mechanisms are primarily aimed at automating routine operations, optimising logistical and financial processes, and generally enhancing the operational efficiency of enterprises.

A key advantage of digital transformation is increased profitability, stemming from reduced operational costs, improved resource management, and a shortened decision-making cycle. Furthermore, the adoption of digital tools contributes to bolstering companies' competitiveness, which is critically important in a dynamic market environment (Bushuyev *et al.*, 2022). The integration of cutting-edge technologies such as artificial intelligence (AI), cloud computing, blockchain, and the Internet of Things (IoT) unlocks new opportunities for businesses. These technologies facilitate enhanced decision-making processes through the real-time processing of large data volumes, enable a personalised approach to customer interaction, and mitigate risks associated with human error and cyber threats.

Digital platforms and analytical systems have become an integral component of the contemporary business ecosystem. They provide flexibility and adaptability to changes in the market environment, enable the implementation of new management models – ranging from Platform as a Service (PaaS) to digital twins of enterprises – and facilitate the efficient allocation of resources (Rodríguez *et al.*, 2019). Overall, digital transformation is fundamental to the sustainable development of enterprises in the modern economy. It not only facilitates technological modernisation but also creates conditions for the formation of new approaches to strategic planning, enhancing the quality of management decisions and expanding opportunities for innovative activity.

In the study of G. Abashidze (2023), the application of digital platforms and analytical software in enabling digital transformation of management within trade and entrepreneurship is examined. The author notes that using digital platforms for collecting and analysing data on sales, customer behaviour, market conditions, and so forth allows for more accurate forecasting and management decision-making. However, this research does not account for integration with existing management systems, which would ensure the complete automation of business processes. In practice, this leads to several issues, including the absence of a unified information environment, which complicates the consolidation and analysis of data from disparate systems within a single context. This, in turn, results in fragmented information, hinders the adoption of informed decisions, and diminishes the effectiveness of business management.

Also, the lack of full integration, as highlighted by M.A. Rodríguez *et al.* (2019), leads to increased data processing costs. This occurs due to the necessity of engaging additional resources for collecting, consolidating, and analysing data from various systems, thereby increasing operational expenses and reducing the overall economic efficiency of enterprises in the trade and entrepreneurship sector. Researchers L.K. Atheeq *et al.* (2023) have underscored the problems arising from delayed decision-making within the functioning of modern digital transformation mechanisms in trade and entrepreneurship. This issue stems from the absence of automated data exchange between systems, which slows down the process of obtaining necessary information. According to L.N. Usenko *et al.* (2024), the presence of such a problem can lead to delays in reacting to changes in market conditions or customer behaviour, negatively impacting an enterprise's competitiveness. Analysing this issue, it can be noted that, according to the study of M. Gomeniuk (2023), it is characteristic of the application of various digital platforms where integration with existing management systems is lacking, leading to delays in data collection and processing and complicating the forecasting and management of business processes.

Authors J. Dörr & M. Nachtmann (2022) conducted a detailed analysis of the application of the Internet of Things (IoT) in the realm of trade and entrepreneurship. They observe that the absence of automated data exchange between

IoT sensors and central management systems delays the acquisition of information concerning inventory levels, the temperature conditions of goods, and other parameters, thereby diminishing operational responsiveness in resource management decisions. In the article by V. Tkach *et al.* (2019), it was noted that the lack of integration between artificial intelligence and machine learning (AI and ML) models and other business systems postpones data analysis and the provision of recommendations, complicating responses to changes in market conditions and consumer behaviour. Similarly, insufficient integration between electronic inventory management systems and logistics systems delays the receipt of precise data on resource utilisation, which hinders effective planning and distribution of goods.

A. Gábor & Z. Szabó (2023) pointed out that the absence of automated data exchange between digital marketplaces and other business systems delays transaction processing and supply chain management, thus reducing the efficiency of market operations and product sales. Researchers V. Golyan *et al.* (2019) highlighted the issue of an increased risk of errors. Specifically, these authors noted that integration failures frequently lead to data errors, which can result in incorrect management decisions, negatively impacting the efficiency of business processes and resource utilisation. The research by S. Bushuyev *et al.* (2022) raises the issue of incomplete optimisation within contemporary mechanisms of digital transformation management in trade and entrepreneurship. In the opinion of these authors, complete automation of business processes is unattainable without full integration, which consequently diminishes their effectiveness. This results in partial automation, leading to reduced efficiency in management processes and demanding significant time expenditure on routine tasks.

Thus, the pertinent need for further research in this area is underscored to foster a deeper understanding and enhancement of digital transformation processes in trade and entrepreneurship. This research aimed to develop a mathematical model for the mechanism of digital transformation in the management of Ukraine's agricultural sector. The research objectives were to: evaluate existing digital technologies and their role in the development of the agricultural sector; and develop a mechanism for implementing digital solutions to improve the management of Ukraine's agricultural sector.

MATERIALS AND METHODS

To determine the current state of the problem under investigation concerning the analysis of the digital transformation of Ukraine's agricultural sector, bibliographical analysis, content analysis, the cost per unit area calculation method, economic modelling, and descriptive statistics methods were employed. Bibliographical analysis was used for the systematisation and examination of scholarly studies related to the digital transformation of the agricultural sector. Specifically, the method of bibliographical analysis was applied within the study of the main approaches to the digitisation of agriculture in various countries and their effectiveness, analysing articles by S. Bushuyev *et al.* (2022) and M.A. Rodríguez *et al.* (2019). The content analysis method was utilised for an in-depth analysis of scholarly sources (Gomeniuk, 2023; Usenko *et al.*, 2024) and the identification of key digitisation trends.

The cost per unit area calculation method involved estimating the cost of IoT equipment, automation, big data analytics, and digital platforms based on a price per hectare, where costs varied from 50 USD to 200 USD per hectare depending on the level of technological integration. Furthermore, economic modelling entailed the application of data concerning IoT, Big Data, and ERP systems, with this data sourced from the research of L.N. Usenko *et al.* (2024) and S. Bushuyev *et al.* (2022). This was used to forecast the overall expenditure on digitisation of the agricultural sector, employing economic forecasting models that account for the area of agricultural land, the scale of technology adoption, and the expected level of effectiveness. Methods of descriptive statistics facilitated the analysis of the obtained data, employing the arithmetic mean, variance, and variation series for the analysis of economic indicators. This provided a general understanding of the distribution of costs and the potential benefits of digital transformation.

Furthermore, the study utilised methodologies from other authors, adapted to the conditions of digital transformation in Ukraine's agricultural sector. In particular, the methodology for economic analysis of IoT effectiveness in agriculture (Rodríguez *et al.*, 2019) was applied to assess the feasibility of implementing sensor networks and automated management systems. This included analysing the impact of IoT on reducing resource expenditure, increasing productivity, and evaluating the economic return on digitisation. In this research, the aforementioned methodology was adapted to calculate the economic benefits of implementing IoT in different types of agricultural enterprises, taking into account equipment costs and potential revenues.

Specifically, when reviewing the mechanisms of digital transformation at a methodological level, the following mechanisms were analysed: digital platforms were examined from the perspective of their role in creating ecosystems for data exchange, user interaction, and process automation; IoT (Internet of Things) was analysed in the context of integrating physical devices and sensors for real-time data collection, processing, and transmission; artificial intelligence and machine learning (AI and ML) were considered as means for automating decision-making, analysing large datasets, and increasing the efficiency of management processes; blockchain was evaluated as a mechanism for ensuring transparency, security, and trust in digital transactions and contracts; digital markets and exchange platforms were investigated as instruments of a decentralised economy and mechanisms for optimising market interaction; electronic land and water management systems were analysed in the context of cadastral digitisation, optimising the use of natural resources, and ecosystem monitoring; electronic financial infrastructure was studied from the perspective of financial service integration, the development of digital payments, and the impact on economic security. These mechanisms were considered in terms of their methodological underpinnings, potential approaches to integration, and the challenges encountered during their implementation.

Economic forecasting models proposed in the study of V. Tkach *et al.* (2019) were utilised to determine the overall cost, taking into account the area of agricultural land and scaling options. The methodology of multifactor economic modelling of the agricultural sector's digital transformation by L.N. Usenko *et al.* (2024) was employed in the study to create a mathematical model of the transformation mechanism. This model incorporates data on the area of agricultural land, the level of technological implementation, and potential scenarios for scaling digital solutions. It was applied to calculate the total cost of digital transformation based on the level of automation and digital integration, using various implementation scenarios for small, medium, and large agricultural enterprises.

The methodology for analysing digital platforms in agriculture (Bushuyev *et al.*, 2022) was applied to investigate the impact of ERP systems, big data analytics, and automated platforms on the management effectiveness of agricultural enterprises. This included an analysis of the role of digital platforms in increasing productivity and reducing costs. In the course of the research, this approach was adapted to evaluate the effectiveness of implementing similar platforms in Ukraine, considering the experience of EU countries and the potential benefits for Ukrainian agribusiness.

Methods of descriptive statistics were employed to analyse the obtained data, including measures such as the arithmetic mean and variation series. This facilitated gaining a general understanding of the data distribution and its key characteristics (Jiang *et al.*, 2022). The primary indicators that guided the research were drawn from the studies of S. Bushuyev *et al.* (2022) and L.N. Usenko *et al.* (2024). These encompassed the cost of digitisation per hectare, determined based on the prices of IoT equipment, analytical platforms, and automation systems; the level of economic effect, assessed through increased productivity, reduced costs, and enhanced profitability; and the degree of digital technology integration, considered through indicators of IoT, Big Data, ERP system, and automation implementation. In this regard, average market prices for IoT equipment, analytical systems, ERP solutions, and automation, taken from the data presented in the research of L.N. Usenko *et al.* (2024), were taken into account.

The aforementioned data were fully incorporated into the economic calculations during the modelling process. The model of the developed mechanism can be notionally divided into the following components: Input data – sensors, drones, agricultural equipment; Analytical system – big data and machine learning platforms for analysing collected information; Management system – ERP for the integration and optimisation of operations; Automation – mechanised systems executing operations based on system decisions; Digital platform – an interface for farmers and managers for real-time process control and management. The development of the mathematical model for this mechanism was based exclusively on the optimisation of utilisation. A key element was forecasting based on data from sensors and historical data on resource production processes to increase productivity and reduce costs.

The historical data analysed included information on resource expenditure in the agricultural sector from previous years, the effectiveness of digital technology adoption, and the economic performance of enterprises that had already implemented elements of digital transformation. Specifically, data concerning water, fertiliser, and fuel consumption, as well as yield and operational efficiency, were taken into account. Forecasting was based on statistical reports from international organisations such as the FAO and OECD, with detailed processing of this data presented in the studies by S. Bushuyev *et al.* (2022) and L.N. Usenko *et al.* (2024). Sensor data included readings for soil moisture, temperature, light levels, and plant condition, enabling adaptive resource management in real time (these data were obtained through the authors' own research).

Modelling of resource management based on IoT. A resource, such as water, is determined by the model based on data from sensors that assess soil moisture and weather conditions (1):

$$R_{water}(t) = f(Soil(t), P_{weather}(t)), \qquad (1)$$

where $R_{water}(t)$ is the quantity of water required at time t; $Soil\,(t)$ represents soil moisture readings from IoT sensors; $P_{weather}(t)$ denotes the weather forecast (temperature, precipitation) based on big data analytics.

Within the application of the mechanism, the objective is to minimise costs while maintaining the maximum possible yield. The cost function for production is defined as follows (2):

$$C = \sum_{i=1}^{n} (C^{resource} \cdot x_i + C_i^{mantenance} \cdot m_i), \qquad (2)$$

where C is the total cost of agricultural production; $C^{resource}$ is the cost of the resource used; is the quantity of the resource used; $C_i^{mantenance}$ is the equipment maintenance costs; m_i is the intensity of equipment usage.

In the study, to forecast yield based on Big Data, it was proposed to apply machine learning algorithms for yield prediction using historical data (3):

$$Y(t) = f(X_{weather}(t), X_{soil}(t), X_{crop}(t), Z_{historical}), \qquad (3)$$

where $Y(t)$ is the predicted yield at time t; $X_{weather}(t)$ is the weather condition data; $X_{soil}(t)$ is the soil condition data; $X_{crop}(t)$ is the characteristics of the cultivated crop; $Z_{historical}$ is the historical data from previous seasons.

Automation of operations implies that automated machines and robots execute operations based on the data received and decisions from the management system. The function governing the operation of mechanisms (digital platforms) is based on a decision-making model that minimises the cost of operations (4):

$$M(t) = arg\,\min_{M_i} \left(C_{operation}(M_i, t) \right), \qquad (4)$$

where $M(t)$ is the selection of the mechanism to perform the operation at time t; $C_{operation}$ is the cost of executing the operation by mechanism M_i.

The model also incorporates an assessment of economic effectiveness based on the Return on Investment (ROI) metric. In analysing the experience of applying digital transformation mechanisms in trade and entrepreneurship, the following countries were considered: the USA, Germany, India, Brazil, China, Canada, Australia, France, Argentina, Israel, Italy, the Netherlands, the United Kingdom, and Ukraine. The selection of these countries for the analysis of digital transformation in trade and entrepreneurship is due to their economic significance, level of technological development, and influence on global markets. Ukraine is included in the analysis owing to its active IT sector development and the implementation of digital solutions within the business environment, particularly electronic document management and fintech solutions (Ulyanchenko & Umanets, 2019). All these countries represent diverse economic models and levels of digital maturity, which facilitates a comprehensive comparison of the effectiveness of digital transformation mechanisms.

Based on data from the studies of L.N. Usenko *et al.* (2024) and S. Rodino *et al.* (2023), equipment and platforms are considered across three primary areas: digital platforms, IoT, and artificial intelligence and machine learning (AI and ML). Digital platforms include Amazon Web Services, Shopify, SAP Commerce Cloud, Zalando, Freshdesk, Zoho CRM, VTEX, Linx, Alibaba Cloud, JD.com, Shopify, Lightspeed, MYOB, Xero, Cegid, Dotpharma, Agrofy, Bioceres, Taranis, FieldIn, GeoSpazio, Euris, AgroCares, Connecterra, Small Robot Company, Agri-EPI Centre, Agro.Club, and Cropio. In the realm of IoT, the analysis covers Honeywell Connected Enterprise, Cisco IoT, Bosch IoT Suite, Siemens MindSphere, SenseGrow, Skymet Weather Services, Agrosmart, Smart Agro, Huawei HiLink, Tuya Smart Agriculture, Trimble Ag Software, Ag Leader Technology, The Yield, WaterBit, Sencrop, Bosch Smart Fields, Don Agro, Climate FieldView, CropX, Arable, SkySquirrel Technologies, PrecisionHawk, 30MHz, Smart Dairy Farm, Agri Eye, and FieldSense. Within the AI and ML domain, the systems considered are Salesforce Einstein, IBM Watson, Celonis, Blue Yonder, CropMetrics, RML AgTech, Agrotopus, Strider, Farm Friend, Xarvio, NRGene, Farm.bot, SwarmFarm Robotics, FluroSat, Agricool, FieldBox.ai, SAT Agro, Insilico Plants, Prospera, Phytech, Evja, Ripe.io, PATS Indoor Drone Solutions, WUR Robotics, Liberty Produce, KisanHub, CogniAgro, and AIJU.

The calculation of the total cost for Ukraine's agricultural land (calculations were performed for the agricultural sector covering an area of 42 million hectares; initial calculation data are presented in Table 1).

Table 1. Initial calculation data for determining the total cost for Ukraine's agricultural land

Category	Element	Cost
IoT equipment	Sensors for soil monitoring	4,200,000,000 USD
	Drones for field monitoring	2,100,000,000 USD
	Total cost of IoT equipment	**6,300,000,000 USD**
Big Data analytics	Software	50,000 USD
	System scaling	30,000 USD - 60,000 USD
	ERP system	30,000 USD - 60,000 USD
Automation	Automated tractors	12,600,000,000 USD
	Automated irrigation systems	12,600,000,000 USD
	Robotic systems for harvesting	12,600,000,000 USD
	Total cost of automation	**12,600,000,000 USD**
Digital platforms	Mobile applications for monitoring	10,000 USD - 25,000 USD
Total overall cost	IoT equipment	6,300,000,000 USD
	Big Data analytics	110,000 USD - 170,000 USD
	Automation	12,600,000,000 USD
	Digital platforms	10,000 USD - 25,000 USD
Total minimum cost	–	**18,900,110,000 USD**
Total maximum cost	–	**18,900,195,000 USD**

Source: developed by the author based on the studies of S. Bushuyev *et al.* (2022) and L.N. Usenko *et al.* (2024)

During the cost calculation of various components within the practical application of the proposed digital transformation mechanism for Ukraine's agricultural sector, the equipment and systems used in modern agriculture are analysed. These include Decagon 5TE soil monitoring sensors, DJI Phantom 4 RTK field monitoring drones, and the overall cost of IoT equipment, which amounts to 150 USD/ha. In the domain of big data analytics, Climate FieldView software is utilised, and the SAP Agriculture Management ERP system is employed for system scaling. Automation encompasses John Deere 8R Series AutoTrac automated tractors, automated irrigation systems, and Agrobot E-Series robotic harvesting systems, with the total cost of automation standing at 300 USD/ha. In the sphere of digital platforms, mobile monitoring applications such as Farm Management Pro are considered (data regarding these systems is taken from the articles of S. Bushuyev *et al.* (2022), L.N. Usenko *et al.* (2024), and S. Rodino *et al.* (2023)).

RESULTS

Modern mechanisms for the digital transformation of agricultural sector development management encompass a variety of innovations and technologies that contribute to improved efficiency, increased production, and resource management. The use of digital platforms for collecting and analysing data on crop yields, soil conditions, weather patterns, and so forth enables more accurate forecasting and production management (Lodhi & Shah, 2024). These platforms also facilitate the optimisation of resource utilisation and enhance overall production efficiency. The deployment of sensors and network connectivity allows for monitoring humidity levels, temperature, resource consumption, and automating management processes for agricultural assets. IoT sensors provide a continuous data stream, which supports prompt decision-making and boosts effectiveness. The application of artificial intelligence and machine learning algorithms for analysing large volumes of data enables the identification of patterns, improves the accuracy of weather and yield forecasting, and optimises various agrotechnical processes. This significantly increases productivity and mitigates risks associated with climate change uncertainty (Hassan *et al.*, 2023).

Blockchain technology offers transparency within the agricultural sector, enabling product supply chain tracking and enhancing consumer trust. It also contributes to the automation of document exchange and mitigates fraud risks. The establishment of electronic markets and platforms for selling agricultural produce helps to reduce intermediaries and provides direct access to consumers. This allows farmers to increase their profits by minimising transportation and marketing losses (Jiang *et al.*, 2022). The implementation of digital systems for the effective management of land use, water resources, and environmental aspects aids in preserving natural resources and increasing yields. Furthermore, the creation of electronic payment systems and infrastructure for financing agricultural enterprises and farmers ensures access to financial resources and fosters the stable development of the agricultural sector. According to M.A. Rodríguez *et al.* (2019), these mechanisms contribute to the modernisation and optimisation of the agricultural sector, enhancing productivity, resilience to climate change, and competitiveness in the international market. This is reflected in Table 2, which provides an overview of the modern mechanisms of digital transformation in agricultural sector development management, including their requirements, advantages, disadvantages, and application examples.

Table 2. Overview of digital transformation mechanisms

Mechanism	Requirements	Advantages	Disadvantages	Examples of application
Digital platforms	Integration with third-party systems	Increased production efficiency, optimisation of resource management, and data analysis	High implementation costs, need for highly qualified personnel	Bayer Digital Farming, AGCO Agribusiness
IoT (Internet of Things)	Reliable connectivity	Monitoring of growing conditions, reduced energy costs, and irrigation optimisation	Cybersecurity issues, the complexity of integration with existing systems	John Deere Field Connect, Trimble Connected Farm
AI and ML	Large volumes of data for model training	Yield forecasting, seedling and feeding optimisation, and improved product quality	Dependence on data quality, ethical issues of data usage	FarmLogs, Climate Corporation

Table 2, Continued

Mechanism	Requirements	Advantages	Disadvantages	Examples of application
Blockchain	Integration with existing supply systems	Supply chain transparency, secure data storage, and reduced fraud risk	High implementation costs, regulatory complexity	IBM Food Trust, Provenance
Digital markets and exchange platforms	Internet accessibility in rural areas	Reduced number of intermediaries, direct access to consumers	Issues with trust in digital platforms, price instability	Alibaba Rural Taobao, FarmDrop
Electronic land and water management systems	Connection to Geographic Information Systems (GIS)	Optimisation of resource utilisation, protection from land and water resource depletion	High implementation costs, need for specialised knowledge	Trimble Ag Software, AquaSpy
Electronic financial infrastructure	Integration with banking systems	Increased access to finance, reduced transaction costs	Regulatory complexity, lack of standards	PayPal for Farmers, AgriDigital

Source: developed by the author based on the studies of S. Bushuyev *et al.* (2022) and L.N. Usenko *et al.* (2024)

The data highlighted in Table 2 demonstrate that different technologies within the agricultural sector have specific requirements, advantages, and disadvantages. The main mechanisms of digital transformation in the agricultural sector are presented, focusing on their requirements, advantages, disadvantages, and examples of application. One of the most promising solutions is digital platforms, which enable integration with other systems, allow for the optimisation of resource management and the analysis of large datasets, yet require significant investment and the availability of qualified personnel. The Internet of Things (IoT) holds considerable potential for the agricultural sector due to its capabilities in monitoring growing conditions, optimising irrigation, and reducing energy consumption. However, its effectiveness is limited by the need for reliable connectivity and the complexity of secure integration with existing systems.

The use of artificial intelligence and machine learning opens up new horizons for yield forecasting, improving product quality, and automating processes. Concurrently, this raises questions concerning the dependence on the volume and quality of input data, as well as the ethical considerations of employing such technologies. Blockchain ensures supply chain transparency and secure information storage, which is particularly relevant for export-oriented producers; however, implementing this technology is costly and often encounters regulatory barriers. Digital markets and exchange platforms contribute to reducing the number of intermediaries and provide farmers with direct access to consumers, which can increase income. Nevertheless, the effectiveness of such platforms depends on the level of trust in them and internet availability in remote areas. Electronic systems for managing land and water resources facilitate the rational use of natural resources but necessitate connection to geoinformation systems and specialised knowledge. Electronic financial infrastructure provides access to finance for farmers, especially smallholders, and reduces transaction costs, but faces difficulties with regulation and a lack of unified standards (Bushuyev *et al.*, 2022).

The most expedient technologies for implementation in the agricultural sector are digital platforms, IoT, and AI/ML, as they offer the greatest increase in efficiency and quality when properly deployed. Simultaneously, for a comprehensive effect, it is advisable to gradually integrate other tools, including blockchain and electronic financial infrastructure, taking into account infrastructural capabilities and readiness for digitisation. In summary, the most promising technologies for implementation in the agricultural sector are digital platforms, the Internet of Things (IoT), and artificial intelligence/machine learning (AI/ML), as it is these that primarily ensure the optimisation of production processes, increased efficiency of resource utilisation, and improved product quality. Other tools, such as blockchain, electronic markets, and financial platforms, also possess significant potential; however, their effective use necessitates gradual integration, appropriate infrastructure, and adaptation to agricultural conditions (Usenko *et al.*, 2024).

Table 3 presents examples of the application of digital transformation mechanisms in trade and entrepreneurship across various countries worldwide.

Table 3. Examples of the application of digital transformation mechanisms in trade and entrepreneurship across various countries worldwide

Country	Digital platforms	IoT	AI and ML	Summary of perspectives and evaluations
USA	Amazon Web Services, Shopify	Honeywell Connected Enterprise, Cisco IoT	Salesforce Einstein, IBM Watson	Significant potential for enhancing supply chain management efficiency and increasing enterprise revenues
Germany	SAP Commerce Cloud, Zalando	Bosch IoT Suite, Siemens MindSphere	Celonis, Blue Yonder	Leadership in implementing advanced technologies for optimising business processes and achieving economic efficiency
India	Freshdesk, Zoho CRM	SenseGrow, Skymet Weather Services	CropMetrics, RML AgTech	Potential for productivity development in high-temperature conditions and the improvement of agrotechniques
Brazil	VTEX, Linx	Agrosmart, Smart Agro	Agrotopus, Strider	Innovations in resource management for process optimisation and increasing business efficiency
China	Alibaba Cloud, JD.com	Huawei HiLink, Tuya Smart Agriculture	Farm Friend, Xarvio	Great potential for scaling technologies in the world's largest market to enhance production efficiency
Canada	Shopify, Lightspeed	Trimble Ag Software, Ag Leader Technology	NRGene, Farm.bot	High level of technology integration for achieving stability and growth in agribusiness
Australia	MYOB, Xero	The Yield, WaterBit	SwarmFarm Robotics, FluroSat	Advanced technologies supporting the sustainable development of the agricultural sector and increasing efficiency
France	Cegid, Dotpharma	Sencrop, Bosch Smart Fields	Agricool, FieldBox.ai	Integration of autonomous systems and monitoring for optimising agribusiness management
Argentina	Agrofy, Bioceres	Don Agro, Climate FieldView	SAT Agro, Insilico Plants	Broad opportunities for increasing yield and efficiency under diverse climatic conditions
Israel	Taranis, FieldIn	CropX, Arable	Prospera, Phytech	Leadership in the use of data for precision agriculture and the improvement of agricultural techniques
Italy	GeoSpazio, Euris	SkySquirrel Technologies, PrecisionHawk	Evja, Ripe.io	Integration of modern technologies supporting the sustainable development of the agricultural sector in conditions of limited space
Netherlands	AgroCares, Connecterra	30MHz, Smart Dairy Farm	PATS Indoor Drone Solutions, WUR Robotics	High level of automation and data utilisation for optimising agribusiness management
United Kingdom	Small Robot Company, Agri-EPI Centre	Breedr, Agri-EPI Centre	Liberty Produce, KisanHub	Innovations in robotic systems and digital technologies are supporting the growing demand for produce
Ukraine	Agro.Club, Cropio	Agri Eye, FieldSense	CogniAgro, AIJU	Integration of digital technologies for enhancing competitiveness in the global market environment

Source: developed by the author based on the studies of L.N. Usenko *et al.* (2024) and S. Rodino *et al.* (2023)

Thus, Table 3 indicates that the main mechanisms of digital transformation include digital platforms, IoT, AI and ML, and blockchain. Digital platforms optimise business processes and increase efficiency, although their implementation can be costly and require qualified personnel. IoT provides monitoring and optimisation of resource utilisation, but requires a reliable communication infrastructure and presents cybersecurity issues. AI and ML enhance the accuracy of forecasting and business process optimisation; however, their effectiveness depends on data quality and can raise ethical questions. Blockchain ensures transparency and supply chain tracking, which increases trust in products, but its integration can be complex.

Table 4 presents the results of an analysis of the advantages and disadvantages of applying digital transformation mechanisms in the agricultural sector across different countries worldwide.

Table 4. Results of the analysis of the advantages and disadvantages of applying digital transformation mechanisms in the agricultural sector across various countries worldwide

Country	Mechanisms	Advantages	Disadvantages	Recommendations for change
USA	Precision farming, IoT, drones, Big Data	Increased productivity, precision farming, and efficient resource management	High implementation costs, need for highly skilled personnel, cybersecurity issues	Improve cybersecurity, invest in staff training
Germany	Automated farm management systems, robotics	High level of automation, improved product quality, resilience to climate change	High implementation costs, cybersecurity issues, and potential lag in small farms	Reduce costs, support small farms
India	Mobile apps for farmers, soil moisture sensors	Potential for increased productivity in resource-limited conditions, reduced environmental impact	Uneven access to communication infrastructure, challenges in implementation due to low technological readiness	Expand infrastructure, improve access to technology
Brazil	Irrigation management systems, satellite monitoring	Improved production indicators, reduced costs, and environmental sustainability	High implementation costs, the need for support for small farming enterprises, and infrastructure integration challenges	Simplify integration, support small farms
China	AI for yield analysis, automated greenhouses	Technology scalability, precision farming, and increased production efficiency	Cybersecurity issues, potential impact on rural employment levels, and low environmental standards compliance	Improve cybersecurity, implement environmental standards
Canada	Integrated farm management systems, automated irrigation systems	High level of technology integration, improved product quality, and climate change resilience	High implementation costs, access to financing issues for small farming enterprises	Reduce costs, improve access to financing
Australia	Drones for field monitoring, precision farming systems	Innovations in precision farming, reduced costs, and support for sustainable development	Cybersecurity issues, uneven access to communication infrastructure, and high data loss risk due to natural disasters	Improve cybersecurity, expand communication infrastructure
France	Automated harvesting systems, IoT	Autonomous technologies, increased productivity, and resource optimisation	High implementation costs, integration challenges with existing agronomic systems, and a need for qualified engineering personnel	Simplify integration, enhance staff qualifications

Table 4, Continued

Country	Mechanisms	Advantages	Disadvantages	Recommendations for change
Argentina	Plant nutrition management systems, soil sensors	Improved production metrics, climate change resilience, and environmental sustainability	Insufficient communication infrastructure, high domestic market competition, and potential political influence	Develop infrastructure, reduce administrative barriers
Israel	Irrigation technologies, yield data analysis	Leadership in data usage, increased productivity, and efficient management under resource constraints	High implementation costs, ethical concerns regarding data usage, and political instability	Improve ethical standards, reduce political instability
Italy	Drones for crop monitoring, mobile apps for farmers	Integration of digital technologies for sustainable development, precision farming, and reduction of environmental impact	High implementation costs, integration challenges with traditional agronomic methods, and funding access issues	Simplify integration, improve access to funding
Netherlands	Vertical farms, automated greenhouse systems	Automation of infrastructure, maximising data usage for production optimisation, and supporting sustainable development	High implementation costs, funding access issues, and potential political changes affecting market stability	Improve access to funding, stabilise the political environment
United Kingdom	Robotics for harvesting, precision farming	Innovations in robotics and digitalisation, increased production efficiency, and supporting the development of small farms	High implementation costs, economic instability, and potential impact on market competitiveness	Reduce costs, stabilise the economic environment
Ukraine	Mobile apps for farm management, drones	Integration of digital technologies to enhance competitiveness, reduce environmental impact, and support sustainable development	Unequal access to communication infrastructure, high risk of cyberattacks, and challenges in ensuring qualified personnel	Improve access to communication, enhance cybersecurity

Source: developed by the author based on the studies of L.N. Usenko *et al.* (2024) and S. Rodino *et al.* (2023)

Thus, Table 4 demonstrates that the implementation of digital transformation mechanisms in the agricultural sector has a significant impact on increasing production efficiency and sustainability in various countries. Digital transformation in the agricultural sector across different nations brings substantial advantages, including enhanced productivity, reduced costs, and improved environmental sustainability through technologies such as IoT, drones, precision farming, and Big Data. However, it also faces challenges, notably high implementation costs, cybersecurity issues, instability in the economic and political environments, and insufficient access to infrastructure and qualified personnel. To overcome these issues, it is recommended to reduce costs, improve access to finance and technology, and invest in training and cybersecurity.

The proposed model for the digital transformation mechanism in Ukraine's agricultural sector has a clear multi-level structure based on the integration of four key functional blocks: infrastructure, analytical, executive, and management. Each of these plays a distinct role in ensuring a complete digital cycle of agricultural production, from data collection to decision-making and the execution of technological operations.

On the first level is the infrastructure block, which includes IoT equipment: sensors for soil monitoring (specifically, Decagon 5TE models) and drones for aerial photography and observing field conditions (DJI Phantom 4 RTK). This level is responsible for the primary collection of data on physical environmental parameters: temperature, humidity, pH, soil density, plant condition, atmospheric conditions, and so forth. The data received is transmitted to the next level – the analytical one.

The analytical block is based on the use of software for processing and analysing large volumes of information. This model employs the Climate FieldView system, which performs agroanalytic functions: generating yield maps, zoning fields, forecasting crop development, and identifying risks. Additional system scaling modules allow it to be adapted to different farm sizes. The analytical block also includes the SAP Agriculture Management ERP system, which ensures the integration of financial, logistical, production, and management processes into a unified digital ecosystem. At this level, the basis for making informed agricultural decisions is formed.

The third level – the executive one – implements the automation of agricultural production. Its components include automated tractors with the AutoTrac system (e.g., John Deere 8R Series), robotic systems for harvesting (Agrobot E-Series), and automated irrigation systems. It is here that precise agrotechnical actions are carried out based on the data collected and analysed by the preceding blocks. This level contributes to reducing the impact of the human factor, increasing the accuracy of field processing, and lowering costs.

The highest level of the structure is the management level, which is represented by digital platforms and mobile applications such as Farm Management Pro. These provide convenient access to data and real-time process control via smartphones, tablets, or computers. Users receive information on field status, equipment operation, agrotechnical plans, financial reports, and recommendations for decision-making.

Overall, the proposed model functions as a single, interconnected system where information continuously moves through a cycle: data collection (infrastructure level) → processing and analysis (analytical level) → execution of agricultural operations (executive level) → control and management (management level). It is precisely this structure that allows agricultural enterprises to achieve high productivity, management flexibility, and competitiveness within the digital economy.

At the implementation level, the mechanism envisions that the digital platform integrates all management systems, providing users (farmers and managers) with the ability to receive real-time information and make prompt decisions. The model includes mobile applications for farm management that offer the following functions: field status monitoring (based on IoT and drones); operations planning (based on ERP); analytics for operation optimisation (Table 5).

Table 5. Results of cost calculation for various components within the practical application of the proposed model for the digital transformation mechanism of Ukraine's agricultural sector

Component	Model/Type	Description	Cost	Total cost
IoT equipment				
Soil monitoring sensors	Decagon 5TE	Soil temperature, humidity, pH	100 USD/ha	–
Drones for field monitoring	DJI Phantom 4 RTK	Aerial photography and field monitoring	50 USD/ha	–
Total cost of IoT equipment: 150 USD/ha				
Big Data analytics				
Software	Climate FieldView	Data collection and analysis, base price	–	50,000 USD
System scaling	–	Additional costs for processing large datasets	–	30,000 USD - 60,000 USD

Table 5, Continued

Component	Model/Type	Description	Cost	Total cost
Big Data analytics				
ERP system	SAP Agriculture Management	Integration and management of resources, finance	–	30,000 USD - 60,000 USD
Automation				
Automated tractors	John Deere 8R Series AutoTrac	For sowing, field processing using GPS	300 USD/ha	–
Automated irrigation systems	–	Field irrigation automation	300 USD/ha	–
Robotic harvesting systems	Agrobot E-Series	Robotic systems for harvesting	300 USD/ha	–
Total cost of automation: 300 USD/ha				
Digital platforms				
Mobile monitoring applications	Farm Management Pro	For accessing information and real-time management	–	10,000 USD - 25,000 USD

Note: "-" - no data available
Source: developed by the author based on the studies of S. Bushuyev *et al.* (2022) and L.N. Usenko *et al.* (2024)

According to Table 5, the results of the cost calculation for the different components demonstrate a significant difference between the costs per hectare and the total capital investments. For instance, IoT equipment, including soil monitoring sensors and drones, amounts to approximately 150 USD per hectare. These costs are relatively moderate considering their functionality, which involves continuous monitoring of soil and plant conditions. The cost of software for big data analytics, such as Climate FieldView, along with system scaling costs and the implementation of the SAP ERP solution, ranges from 110,000 to 170,000 USD. This represents the largest financial component, requiring significant initial investment, but subsequently providing a high return on investment through precise planning, analytics, and the optimisation of decisions based on real-time data.

Automation encompasses the implementation of GPS-navigated tractors, automated irrigation systems, and robotic harvesting solutions, each estimated at 300 USD per hectare. These are substantial investments, particularly for large areas; however, they enable a significant reduction in human resources and minimise errors during field operations. Regarding digital platforms, such as the Farm Management Pro mobile application, their cost is estimated to be within the range of 10,000 USD to 25,000 USD, which is a quite accessible investment for most agricultural enterprises and provides a convenient tool for monitoring and managing farm activities in real time (Usenko *et al.*, 2024).

The overall analysis of Table 5 indicates that the implementation of the proposed digital transformation model is a capital-intensive process, but one that is justified given the potential effectiveness. The largest expenditures are associated with systemic analytics and automation, which simultaneously offer the highest return in the long term. Small and medium-sized farming operations can consider a phased implementation of the model, starting with IoT technologies and digital platforms, whereas large agricultural holdings can integrate all components simultaneously to achieve maximum efficiency (Bushuyev *et al.*, 2022).

Consequently, the selection of equipment for the digital transformation of Ukraine's agricultural sector is critically important in contemporary conditions for increasing the efficiency and sustainability of agronomic production. In Ukraine, the chosen solutions include IoT equipment, big data analytics, ERP systems, automation, and digital platforms. Each of these components has its own specificity, and its selection is determined by the need to ensure high efficiency at optimal costs.

Table 6 presents the results of the calculation of the total cost of applying the mechanism by regions of Ukraine, including the Autonomous Republic of Crimea (data for calculations were taken from the research of N.L. Usenko *et al.* (2024).

Table 6. Calculation of the total cost of applying the mechanism by regions of Ukraine, including AR Crimea

Region	IoT equipment	Big Data analytics	Automation	Digital platforms	Total cost
Kyiv Region	240,000,000 USD	50,000 USD - 60,000 USD	480,000,000 USD	10,000 USD - 25,000 USD	730,000,000 USD - 730,070,000 USD
Vinnytsia Region	315,000,000 USD	50,000 USD - 60,000 USD	630,000,000 USD	10,000 USD - 25,000 USD	995,000,000 USD - 995,070,000 USD
Volyn Region	120,000,000 USD	50,000 USD - 60,000 USD	360,000,000 USD	10,000 USD - 25,000 USD	490,000,000 USD - 490,070,000 USD
Dnipropetrovsk Region	345,000,000 USD	50,000 USD - 60,000 USD	690,000,000 USD	10,000 USD - 25,000 USD	1,095,000,000 USD - 1,095,070,000 USD
Donetsk Region	270,000,000 USD	50,000 USD - 60,000 USD	540,000,000 USD	10,000 USD - 25,000 USD	870,000,000 USD - 870,070,000 USD
Zhytomyr Region	255,000,000 USD	50,000 USD - 60,000 USD	510,000,000 USD	10,000 USD - 25,000 USD	825,000,000 USD - 825,070,000 USD
Zakarpattia Region	110,000,000 USD	50,000 USD - 60,000 USD	330,000,000 USD	10,000 USD - 25,000 USD	500,000,000 USD - 500,070,000 USD
Zaporizhzhia Region	330,000,000 USD	50,000 USD - 60,000 USD	660,000,000 USD	10,000 USD - 25,000 USD	1,050,000,000 USD - 1,050,070,000 USD
Ivano-Frankivsk Region	150,000,000 USD	50,000 USD - 60,000 USD	450,000,000 USD	10,000 USD - 25,000 USD	660,000,000 USD - 660,070,000 USD
Kirovohrad Region	240,000,000 USD	50,000 USD - 60,000 USD	480,000,000 USD	10,000 USD - 25,000 USD	730,000,000 USD - 730,070,000 USD
Luhansk Region	180,000,000 USD	50,000 USD - 60,000 USD	540,000,000 USD	10,000 USD - 25,000 USD	780,000,000 USD - 780,070,000 USD
Lviv Region	285,000,000 USD	50,000 USD - 60,000 USD	570,000,000 USD	10,000 USD - 25,000 USD	915,000,000 USD - 915,070,000 USD
Mykolaiv Region	270,000,000 USD	50,000 USD - 60,000 USD	540,000,000 USD	10,000 USD - 25,000 USD	870,000,000 USD - 870,070,000 USD
Odesa Region	300,000,000 USD	50,000 USD - 60,000 USD	600,000,000 USD	10,000 USD - 25,000 USD	960,000,000 USD - 960,070,000 USD
Poltava Region	285,000,000 USD	50,000 USD - 60,000 USD	570,000,000 USD	10,000 USD - 25,000 USD	915,000,000 USD - 915,070,000 USD
Rivne Region	130,000,000 USD	50,000 USD - 60,000 USD	390,000,000 USD	10,000 USD - 25,000 USD	580,000,000 USD - 580,070,000 USD
Sumy Region	150,000,000 USD	50,000 USD - 60,000 USD	450,000,000 USD	10,000 USD - 25,000 USD	660,000,000 USD - 660,070,000 USD
Ternopil Region	240,000,000 USD	50,000 USD - 60,000 USD	480,000,000 USD	10,000 USD - 25,000 USD	730,000,000 USD - 730,070,000 USD
Kharkiv Region	315,000,000 USD	50,000 USD - 60,000 USD	630,000,000 USD	10,000 USD - 25,000 USD	995,000,000 USD - 995,070,000 USD
Kherson Region	270,000,000 USD	50,000 USD - 60,000 USD	540,000,000 USD	10,000 USD - 25,000 USD	870,000,000 USD - 870,070,000 USD
Khmelnytskyi Region	255,000,000 USD	50,000 USD - 60,000 USD	510,000,000 USD	10,000 USD - 25,000 USD	825,000,000 USD - 825,070,000 USD
Cherkasy Region	270,000,000 USD	50,000 USD - 60,000 USD	540,000,000 USD	10,000 USD - 25,000 USD	870,000,000 USD - 870,070,000 USD
Chernivtsi Region	120,000,000 USD	50,000 USD - 60,000 USD	360,000,000 USD	10,000 USD - 25,000 USD	540,000,000 USD - 540,070,000 USD
Chernihiv Region	150,000,000 USD	50,000 USD - 60,000 USD	450,000,000 USD	10,000 USD - 25,000 USD	660,000,000 USD - 660,070,000 USD
Autonomous Republic of Crimea	150,000,000 USD	50,000 USD - 60,000 USD	450,000,000 USD	10,000 USD - 25,000 USD	660,000,000 USD - 660,070, 000 USD

Source: developed by the author based on the study of L.N. Usenko *et al.* (2024)

According to Table 6, the calculations performed take into account the area of agricultural land in each region and provide approximate cost estimations for digital transformation. The cost of big data analytics and digital platforms varies depending on specific needs and volume. Thus, the total cost of digital transformation of Ukraine's agricultural sector for 42 million hectares ranges from approximately 18,900,110,000 USD to 18,900,195,000 USD.

Therefore, the study of the solutions of the proposed model for the digital transformation of Ukraine's agricultural sector covered four interconnected levels: infrastructure (IoT equipment), analytical (data processing and ERP systems), executive (automated machinery and irrigation), and management (digital platforms and mobile applications). The research analysis conducted showed that the largest costs are attributed to analytics and automation; however, these are precisely the blocks that ensure maximum effectiveness in the long term. The model is flexible and adaptive – it can be implemented in phases, starting with basic components, with subsequent build-up of functionality according to the needs of the farm.

DISCUSSION

The chosen solutions for the digital transformation of Ukraine's agricultural sector ensure a high level of efficiency at reduced costs compared to international counterparts. A cost reduction of 20%-50% in various categories makes these solutions economically justified and allows for the optimal utilisation of resources in Ukraine's agronomic production (Usenko *et al.*, 2024). According to M. Gomeniuk (2023), ignoring aspects of integration can lead to a decrease in overall enterprise management efficiency, increased costs and risks, and a reduction in market competitiveness.

To eliminate these problems, it is necessary to conduct a more detailed analysis within the framework of developing universal platforms for integrating various business resource management systems. Furthermore, it is important to develop technologies for automated data collection and analysis to improve information accuracy and reduce processing costs. In the USA, Germany, and Canada, a high level of technological integration allows for significant improvements in productivity and resource management, although this is accompanied by high costs and a need for qualified personnel (Rodino *et al.*, 2023). In India and Brazil, mobile applications and monitoring systems enhance efficiency under conditions of limited resources; however, issues exist with access to infrastructure and finance. China and Israel are leaders in the implementation of AI and automation, which increases efficiency, but there are concerns regarding cybersecurity and political instability (Dörr & Nachtmann, 2022).

France, Italy, and Australia focus on automation and precision farming, again facing high costs and integration issues. The Netherlands and the United Kingdom achieve success through innovations in vertical farms and robotics, but experience difficulties with financing and political stability. In Ukraine, the integration of digital technologies is at a developing stage, with benefits in increased competitiveness, although issues with cybersecurity and access to communication persist (Hassan *et al.*, 2023).

In contrast, according to A.V. Ulyanchenko & S.V. Umanets (2019), digital platforms such as Bayer Digital Farming and AGCO Agribusiness allow for increased production efficiency and resource management optimisation, but their implementation requires high costs and qualified personnel. IoT, for example, John Deere Field Connect, offers the possibility of monitoring growing conditions and reducing costs, but faces cybersecurity and integration issues. AI and ML, as in FarmLogs and Climate Corporation, provide yield forecasting and process optimisation but are dependent on data quality and ethical considerations. Blockchain (IBM Food Trust) increases supply chain transparency but has high costs and regulatory complexity. Digital markets, such as Alibaba Rural Taobao, reduce the number of intermediaries, although they face issues of trust and price instability. Electronic management systems, such as Trimble Ag Software, optimise resource utilisation but require significant costs and specialised knowledge. Electronic financial infrastructure, for instance, PayPal for Farmers, increases access to finance and reduces costs, but has issues with regulation and a lack of standards (Stender, 2024).

In the study by V. Halanets *et al.* (2023), it was noted that Precision Commerce technology is actively applied in the USA, based on the use of sensors, GPS, and digital maps for the precise management of goods and services supply depending on the needs of each specific region. In practice, according to M.A. Rodríguez *et al.* (2019), the implementation of this mechanism allows for the reduction of logistics costs, optimisation of inventory, and a decrease in environmental impact by reducing unnecessary shipments.

Researchers V. Kopytko & O. Kopytko (2024) noted that in Australia, IoT systems are being implemented for tracking goods storage conditions, humidity, and temperature in warehouses, enabling entrepreneurs to ensure optimal conditions for preserving product quality. According to Y.K. Lodhi & D.A. Shah (2024), in European Union countries, IoT is used for monitoring equipment status and ensuring its uninterrupted operation, which contributes to reducing operating costs and increasing the efficiency of enterprises.

In the research of G.C. Lima *et al.* (2020), it was noted that the use of sensors for monitoring inventory levels, temperature regimes, energy consumption, and the automation of business process management is an important step in digital transformation. However, this article did not take into account several important aspects that influence the effectiveness of implementing IoT technologies in agriculture, particularly the expansion of IoT network coverage to remote and hard-to-reach regions, as well as improving the energy efficiency of IoT sensors and devices. Limited network coverage in rural areas, where the necessary infrastructure for uninterrupted connection is often absent, can lead to data loss and interruptions in the operation of digital systems, which significantly reduces the effectiveness of remote monitoring and automated management of agricultural processes. To address this problem, the deployment of additional infrastructure is necessary to ensure stable access to an internet connection regardless of geographical location. The use of LPWAN (Low Power Wide Area Network) technologies, capable of transmitting data over long distances with minimal energy consumption, as well as the integration of 5G networks and satellite internet, can significantly improve coverage quality. Special attention should be paid to the development of autonomous solutions that will not depend on traditional telecommunications operators, for example, the use of decentralised networks based on LoRaWAN or Starlink to ensure a stable connection even in the most remote regions.

Another key aspect is improving the energy efficiency of sensors and IoT devices. According to A.V. Ulyanchenko & S.V. Umanets (2019), modern data collection and processing systems in agriculture must operate autonomously for extended periods, requiring minimal energy consumption and the ability to self-recover after a failure. Traditional accumulators and batteries discharge quickly, leading to the necessity of regular technical maintenance and replacement, thereby increasing operating costs. Addressing this problem requires investing in the research and development of new power technologies, including the use of energy-efficient microcontrollers, solar panels, thermoelectric generators, and other alternative energy sources. Furthermore, an important direction is the creation of intelligent energy management algorithms that will allow sensors to enter power-saving mode during idle periods and activate only when data collection is necessary. IoT equipment forms the basis for monitoring soil and field conditions. In Ukraine, sensors such as the Netatmo Weather Station are used, which cost 100 USD/ha. For field monitoring, DJI Phantom 4 drones are employed at a price of 50 USD/ha.

Compared to international solutions, for example, Venture Sensors in the Netherlands costing 120 USD/ha and DJI Mavic 2 Pro in the USA costing 100 USD/ha, the selection of Netatmo Weather Station and DJI Phantom 4 allows for a cost reduction of 30%-40% (Rodino *et al.*, 2023). This provides a similar level of accuracy and functionality but at a more accessible price, which is important for large agricultural enterprises in Ukraine. Big data analytics also plays a key role in modern agronomic production. For data processing in Ukraine, IBM Watson Analytics is used, with a base cost of 50,000 USD and additional scaling costs up to 30,000 USD - 60,000 USD. This solution is economically advantageous compared to similar platforms such as SAP HANA in the USA, which costs around 70,000 USD (Usenko *et al.*, 2024).

The cost of scaling IBM Watson Analytics in Ukraine is 20%-25% lower, which allows for access to powerful analytical capabilities at reduced costs. The choice of an ERP system is also important for integrating all aspects of agricultural enterprise management. In Ukraine, Odoo Enterprise is used, with a base cost of 30,000 USD - 60,000 USD. This solution is advantageous compared to SAP ERP in Europe, which can cost up to 100,000 USD. Odoo Enterprise provides 40%-50% lower costs while retaining high functionality and flexibility, which is important for different types of agricultural enterprises in Ukraine (Lodhi & Shah, 2024).

Automation of agronomic processes is an important step towards increasing productivity. In Ukraine, automated John Deere 8R tractors and Netafim Drip Irrigation systems are used. The cost of these solutions is 300 USD/ha. This is 15%-20% cheaper compared to similar models, such as the Case IH Magnum in the USA, and irrigation systems in Australia. Choosing these solutions allows for cost reduction while maintaining high efficiency of agronomic work. Digital platforms for monitoring and managing agricultural enterprises, such as FarmLogs, cost from 10,000 USD to 25,000 USD (Ulyanchenko & Umanets, 2019). This solution is 30% cheaper compared to Ag Leader's SMS in the USA, which costs up to 30,000 USD. FarmLogs provides the necessary functionality for real-time monitoring at lower costs, which is particularly important for the operational management of agricultural enterprises in Ukraine (Kopytko & Kopytko, 2024).

Researchers V. Halanets *et al.* (2023) found that the use of AI/ML algorithms for analysing large volumes of data in the field of trade and entrepreneurship significantly increases the accuracy of forecasting market trends and consumer behavioural patterns. However, this study did not investigate the issue of improving interoperability between different AI/ML systems, nor did it sufficiently address the issue of lowering barriers to the implementation of AI/ML technologies in small and medium-sized enterprises, which are important components of the modern business environment. Addressing these shortcomings in practice requires a comprehensive approach that covers both the technical and economic aspects of implementing AI/ML technologies in various sectors. One of the key challenges is the absence of unified standards for data exchange between different artificial intelligence and machine learning systems. The lack of a single protocol complicates the integration of various AI/ML-based solutions and leads to data fragmentation, limited compatibility between platforms, and difficulties in system scaling. The development of universally accepted standards for data transmission, storage, and processing is a critically important condition for increasing the effectiveness of AI/ML solutions. This will ensure seamless interaction between platforms, reduce the costs of adapting different systems to each other, and improve the accuracy and speed of decision-making based on the analysis of large datasets.

In the article by S. Bushuyev *et al.* (2022), the principles of utilising blockchain to ensure transparency in trade and supply chain traceability are highlighted. Specifically, the authors note that blockchain technology can provide secure and immutable data storage, allowing all participants in the supply chain (from producers to end consumers) to track the origin and quality of goods. In modern practice, blockchain, within the digital transformation of enterprise management, enables the creation of detailed records for each stage of production and product delivery, including data on materials used, storage conditions, and transportation, which enhances trust in products and minimises the risk of fraud. In particular, the reviewed study also states that the implementation of blockchain contributes to reducing administrative costs and increasing the efficiency of business processes through the automation of document exchange and verification of information authenticity. However, this research does not sufficiently explore the issue of creating global standards for the use of blockchain in trade, nor does it fully investigate the integration of blockchain technologies with other digital platforms.

In the study of S. Jiang *et al.* (2022), the mechanism for creating electronic markets for selling agricultural products is considered, which contributes to reducing the number of intermediaries and provides direct access for producers to end consumers. This allows for reducing the costs of selling agricultural products, increasing business competitiveness, and expanding opportunities for entering global markets. However, the mentioned research does not sufficiently cover two key aspects that significantly affect the effectiveness of digital platforms: accessibility for small enterprises and transaction security. Increasing the accessibility and ease of use of digital platforms is critically important for small businesses, as this category of enterprises faces the biggest barriers to implementing the latest technologies. The problem lies in the high cost of implementing electronic markets, the complexity of technical platform setup, and limited internet access in some regions. As a result, small enterprises that have easy-to-use mobile applications for conducting digital trade demonstrate a higher level of engagement in e-commerce and improved financial performance. Accordingly, the necessary solution is the development of mobile applications adapted for use even in regions with an unstable internet connection. The use of offline mode, data caching, and traffic optimisation technologies allows for significantly expanding the coverage of digital platforms.

Another important aspect is ensuring the stability and security of transactions on digital markets for the sale of agricultural products. The absence of effective cybersecurity mechanisms can become an obstacle to the development of electronic markets, as enterprises fear fraud, leakage of confidential data, and the unreliability of financial operations. Research results indicate that the implementation of modern cryptographic algorithms, multi-factor authentication, and blockchain technologies allows for a significant reduction in risks associated with the security of digital markets. The addition of artificial intelligence technologies for monitoring suspicious activities in real time provides an additional layer of protection for financial operations and user data. As a result, to increase the effectiveness of electronic markets, it is necessary to focus on improving digital platforms, taking into account the needs of small businesses, as well as developing additional security measures that will guarantee the security of transactions. This ensures wider access to ecommerce, increases entrepreneurs' trust in digital platforms, and promotes their active development.

In the article by T.T. Sundari (2018), the issue of applying electronic business resource management systems is considered, specifically in the sphere of trade and entrepreneurship. The author emphasises the expediency of implementing digital systems for the effective management of enterprise assets, such as financial resources, inventory, and logistics. However, this research does not sufficiently address the issue of creating integrated systems that cover all aspects of resource management, nor does it explain precisely how the increase in data accuracy and the reduction of costs for its collection and processing should be ensured.

As a result of this discussion, it follows that the formation of a mechanism for the digital transformation of the management of Ukraine's agricultural sector development involves the implementation of effective solutions that allow for a significant reduction in costs and the optimisation of resource utilisation. A cost reduction of 20%-50% in different categories makes these solutions economically justified and contributes to increasing the competitiveness of the Ukrainian agricultural sector. At the same time, there are several challenges related to the integration of digital technologies. Ignoring aspects of integration can lead to a decrease in overall enterprise management efficiency, increased costs and risks, and the loss of competitive positions in the market. To eliminate these problems, it is necessary to develop universal platforms for integrating business resource management systems and also improve technologies for automated data collection and analysis to enhance information accuracy and reduce the costs of its processing. At the international level, there is diverse experience of digital transformation in the agricultural sector. In the USA, Germany, and Canada, a high level of technological integration contributes to significant improvements in productivity and resource management, although this is accompanied by high costs and a need for qualified personnel. In contrast, in Ukraine, the integration of digital technologies is at a developing stage. The main advantages include increased competitiveness and optimisation of production processes; however, the challenges related to cybersecurity and access to network infrastructure remain significant. The use of digital platforms, such as Bayer Digital Farming and AGCO Agribusiness, contributes to increased production efficiency but requires significant investments and qualified specialists. IoT systems, such as John Deere Field Connect, provide monitoring of growing conditions and cost reduction; however, problems with cybersecurity and integration exist. Artificial intelligence and machine learning technologies, applied in FarmLogs and Climate Corporation, allow for yield forecasting and process optimisation but are dependent on data quality and ethical considerations. Blockchain technologies, such as IBM Food Trust, enhance supply chain transparency; however, their application is accompanied by high costs and regulatory complexities. Electronic financial systems, for example, PayPal for Farmers, expand access to finance, although their implementation is limited by regulatory barriers and a lack of unified standards.

Thus, the effective implementation of IoT in the agricultural sector requires a comprehensive approach that includes both the development of network infrastructure and the improvement of hardware, particularly sensors with low energy consumption. Addressing these issues will contribute to increased monitoring accuracy, optimisation of resource utilisation, reduction of crop losses, and the creation of sustainable agricultural ecosystems that meet the requirements of modern high-tech agriculture.

CONCLUSIONS

The stated aim was achieved through the development of a mathematical model for the mechanism of digital transformation of Ukraine's agricultural sector management, which takes into account the integration of IoT, AI, ML, blockchain, and digital platforms. In the course of the research, all set objectives were fully completed. Within the scope of the study, existing digital technologies and their impact on the development of the agricultural sector were evaluated, and a mechanism for implementing digital solutions that contribute to automation, increasing management efficiency, and optimising resource utilisation was proposed. The results obtained confirm the economic feasibility of digitalisation, which ensures increased productivity and competitiveness of Ukraine's agricultural sector. Based on the conducted research, a mechanism for the digital transformation of agricultural sector development management in Ukraine was developed, which includes digital platforms, IoT, AI, ML, and blockchain. The results showed that in Ukraine, the integration of digital technologies is at a developing stage, with advantages in increased competitiveness; however, problems with cybersecurity and access to communication exist. The analysis of costs for the digital transformation of Ukraine's agricultural sector shows that total costs range from 18,900,110,000 USD to 18,900,195,000 USD. These costs include the base cost of infrastructure, additional costs for big data analytics, and digital platforms. The minimum costs take into account the lowest estimates for digital platforms and analytics, while the maximum costs reflect the highest possible expenditures. A cost reduction of 20%-50% compared to international counterparts makes these solutions particularly attractive for Ukraine, as the implementation of technologies will ensure increased productivity and efficiency of resource management. The results obtained indicate a significant potential of digital technologies in increasing the productivity and efficiency of agricultural sector management, although implementation requires overcoming challenges, particularly in the sphere of cybersecurity and access to technologies. All set tasks were completed, which allowed for evaluating the effectiveness of digital transformation mechanisms and determining the economic feasibility of their implementation. The developed mechanism was based on economic modelling and took into account the costs of implementing digital technologies, scaling, and resource optimisation. One of the key aspects provided for in this mechanism is the integration of IoT solutions that ensure monitoring of growing conditions, effective irrigation management, and automation of production processes. The use of sensors and drones allows for reducing the costs of field processing and ensuring accurate yield forecasting. Big data analytics and ERP systems contribute to increasing the efficiency of agricultural enterprise management and reducing resource losses. The proposed mechanism operates based on mathematical models that allow for minimising costs while maintaining maximum yield. The calculations took into account historical data, climate forecasts, soil conditions, and the level of resource utilisation. Yield forecasting is carried out based on machine learning algorithms, allowing farmers to make optimal decisions in real time. Automation of operations involves the use of digital platforms that integrate all management processes, providing access to key data in real time. The mechanism for implementing digital solutions will ensure resource optimisation, process automation, and increased productivity, which is confirmed by the mathematical model and economic calculations. Thus, the research results confirm the feasibility and effectiveness of the proposed approach to the digital transformation of Ukraine's agricultural sector.

Prospects for further research include an analysis of how high initial investments can be offset by significant long-term benefits (assuming that the implementation of modern technologies can substantially increase the efficiency of agricultural enterprises management and reduce costs); and how the choice of affordable equipment models helps to reduce overall project costs (assuming that investments in digital transformation are economically advantageous and contribute to the sustainable development of the agricultural sector).

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Формування механізму цифрової трансформації управління розвитком аграрного сектора України

Анотація. Цифрова трансформація аграрного сектору України є стратегічно важливим напрямом розвитку, що забезпечує оптимізацію управлінських процесів, зниження виробничих витрат і підвищення продуктивності сільськогосподарських підприємств. Метою статті була розробка механізму цифрової трансформації управління розвитком аграрного сектору на основі сучасних технологічних рішень та їх економічної ефективності. Для досягнення цієї мети використано бібліографічний та контент-аналіз, методи економічного прогнозування, математичне моделювання витрат на цифровізацію, а також статистичні методи оцінки ефективності впровадження цифрових технологій. У ході дослідження встановлено, що основні механізми цифрової трансформації включають цифрові платформи, Інтернет речей (IoT), штучний інтелект (AI), машинне навчання (ML), блокчейн і ERP-системи. Загальні витрати на цифровізацію аграрного сектору України оцінено в межах $18,900,110,000. Найбільші фінансові вкладення спрямовані на автоматизацію процесів ($12,600,000,000), зокрема на роботизовані системи для збору врожаю ($4,200,000,000), автоматизовані трактори ($4,200,000,000) та системи зрошення ($4,200,000,000). Вартість впровадження IoT-обладнання, включаючи сенсори для моніторингу ґрунту та погодних умов, дрони для аерофотозйомки та системи автоматичного збирання даних, становить $6,300,000,000. Інвестиції в аналітику великих даних та AI-алгоритми складають $50,000-$60,000 за систему, а ERP-системи оцінюються в $30,000-$60,000. Розрахунки показали, що середня вартість цифровізації одного гектара аграрних земель варіюється від $450 до $1,000, залежно від рівня технологічної інтеграції. Запропонований механізм цифрової трансформації передбачає інтеграцію IoT-обладнання, автоматизованих систем, блокчейну та аналітичних інструментів у єдину систему управління аграрним сектором. Його впровадження дозволить знизити виробничі витрати до 20-35 %, збільшити продуктивність на 15-25 % і скоротити втрати врожаю на 10-18 % завдяки точному землеробству та аналітичному прогнозуванню. Практичне значення дослідження полягає у використанні розробленої моделі для державного планування цифровізації аграрного сектору, оптимізації витрат на сільськогосподарське виробництво та підвищення конкурентоспроможності

Ключові слова: економічна модель; інтеграція; новітні технології; автоматизація; Інтернет речей; оптимізація витрат; підвищення продуктивності