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THE STATE AND PROSPECTS OF DIGITAL TRANSFORMATION IN THE AGRICULTURAL SECTORS

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ABSTRACT

The purpose of the study is to analyse trends and directions of digitalisation of agriculture, with a focus on technologies that contribute to improving the efficiency and sustainability of the industry. The methodology includes an analysis of the state of digitalisation of agriculture, key technologies, barriers to implementation, and development prospects based on statistical data and industry reports. The paper analyses the most developed crop and livestock industries in Kazakhstan, such as the production of cereals, oilseeds, dairy, and beef cattle, with a focus on the use of drones, the Internet of Things, artificial intelligence, and blockchain. The technical features of technologies, implementation costs, payback periods, and infrastructural requirements are considered. A comparative analysis of digitalisation in Kazakhstan and other countries is conducted, which identifies the main barriers, such as high costs, insufficient infrastructure, and a low level of digital literacy. It is determined that drones contribute to optimising field monitoring and accurate resource allocation, the Internet of Things provides data collection and analysis for real-time process management, artificial intelligence is used for forecasting and automation, and blockchain increases the transparency of supply chains. These technologies have improved resource management, increased yields, and minimised environmental impacts. The main barriers hindering the digitalisation of agriculture were high technology costs, insufficient infrastructure, low levels of digital literacy among industry workers, and resistance to change on the part of farmers.

Introduction

Digitalisation of agriculture is an important and rapidly developing process that has a substantial impact on the efficiency and sustainability of the agricultural sector. In recent years, the introduction of modern technologies such as drones, the Internet of Things (IoT), artificial intelligence (AI), and blockchain has increased productivity, reduced costs, and improved the quality of agricultural products. Despite the evident advantages, the process of digital transformation is constrained by financial, infrastructural, and human capital challenges.

For small and medium-sized farms with limited budgets, such investments can be overwhelming. For example, the cost of the DJI Agras T16 agricultural drone is about 3,767,170 tenge (8,370 USD), which is a substantial investment for small farms. In 2025, it is planned to connect more than 100 settlements, providing modern Internet to over 10,000 rural residents (High-speed Internet…, 2025). However, despite these efforts, a substantial part of rural areas still remains without access to high-speed Internet. Organisational barriers hinder the effective implementation of digital technologies in agriculture in Kazakhstan. According to a study conducted by the Union of Field Farmers of Kazakhstan in September-October 2021, about 26% of the surveyed farmers do not use digital technologies. The main reasons are high cost and lack of Internet access (32%). Thereby, 20% of respondents identified both of these reasons as the main barriers preventing the introduction of modern technical solutions in their farms (Digital technologies in field cultivation in Kazakhstan, 2021).

The implementation of ICT technologies is particularly difficult for small farms, which, according to the classification of the Ministry of Agriculture of the Republic of Kazakhstan, include farms with less than 200 hectares of cultivated land or fewer than 50 livestock units High-speed Internet comes to villages in Kazakhstan, 2025). These farms typically operate with limited financial and human resources and rely on traditional methods of production. According to national statistics, small farms account for approximately 65% of all registered agricultural entities, yet their access to digital tools remains minimal due to cost, infrastructure, and training barriers.

Nazarov et al. (2022) noted the high costs of technology implementation as a critical obstacle, especially for small and medium-sized farms. Sultanova (2020) identified key problems, including low productivity and limited access to innovation and financing. It is necessary to stimulate cooperation between the government, agricultural holdings, and technology companies to jointly finance digital solutions.

The next problem that exists in the field under study is related to the limitations that hinder the effective digitalisation of agriculture. In the study by Ligonenko et al. (2021), it is emphasised that despite the obvious advantages of digitalisation, such as increased production efficiency, lower costs, and improved resource management, there are substantial obstacles. Alipbeki and Alipbekova (2019) analysed the prospects of using these technologies to increase yields, reduce resource costs, and minimise environmental impacts. It is necessary to explore ways to accelerate the deployment of digital infrastructure in rural areas, including 5G networks and satellite Internet.

The problem in the industry under study is related to the insufficient adaptation of digital technologies to solve environmental and sustainable agricultural problems and the impact of digitalisation on the behaviour of enterprises. Xie et al. (2022) established that digital transformation promotes more environmentally responsible behaviour of agricultural enterprises. Dayıoğlu and Turker (2021) reviewed the concept of "Agriculture 4.0", which includes the use of IoT, big data, artificial intelligence, and automation to increase the sustainability of the industry. Gaps requiring additional study include the need to analyse the environmental impact of digitalisation, develop affordable technologies for small farms, and explore educational programmes to raise environmental awareness.

Another problem in the industry under study is the absence of integration of modern digital solutions, such as the Internet of Things, into agriculture, which limits the possibilities for effective monitoring and management of production processes. Lima et al. (2021) examined how IoT can improve the efficiency of agricultural production, improve monitoring of soil, plants, and animals, and optimise the use of water (Mog, 2023) and fertilisers. A study by Zhou et al. (2022) focused on how environmental norms and requirements can be integrated into digitalisation processes to increase the sustainability and productivity of agriculture. It is important to explore how IoT can be effectively integrated with other technologies such as artificial intelligence, machine learning, and data analytics to create integrated management systems in agriculture.

The purpose of the study was to examine the current trends in the digitalisation of agriculture and identify technologies that contribute to improving the productivity and sustainability of this industry. Within the framework of the set goal, the following tasks were identified:

1. Assess the main barriers and challenges faced by farmers in the implementation of digital technologies.
2. Evaluate the impact of digital technologies on agricultural processes.
3. Development of recommendations for overcoming the identified barriers.

Materials and Methods

In the first stage of the study, an overview of the current state of digital transformation in agriculture in Kazakhstan was conducted. For this purpose, the analysis of reports and data provided by the Ministry of Agriculture of the Republic of Kazakhstan and other public and private sources was conducted. Key innovative technologies are considered: artificial intelligence, the Internet of Things, drones, and robotics. The volume of their use and the results they produce are analysed, and the main problems and trends related to the digitalisation of agriculture are determined. In the course of the study, scientific and industry publications, reports, papers, and statistics related to digital transformation in agriculture were examined.

A review of technologies aimed at improving the efficiency of agricultural processes was conducted. This included investigating soil analysis technologies such as the Soil Scout and John Deere FieldSense systems, which are used to measure moisture, temperature, and soil composition. The role of animal health monitoring systems, such as Allflex and DeLaval, which monitor the activity and diet of livestock and help in the early diagnosis of diseases, was also considered. An important aspect was the examination of the use of platforms for livestock accounting and productivity analysis, such as ZTags and Smartbow. In addition, attention was paid to the use of drones, such as the DJI Matrice 300 RTK and DJI Phantom

4 RTK, for monitoring pasture conditions and herd management, and agronomic applications, such as AgriData and Sentera, for analysing plant conditions and improving the accuracy of decision-making in agronomy. Platforms such as CowManager and BovControl, which use sensors and mobile applications to monitor livestock health and productivity, are also considered.

During the second stage of the study, technologies were categorised by areas to systematise and in-depth analyse the digital solutions used in agriculture. For this purpose, the main directions of technologies used in the agricultural sector of Kazakhstan, such as drone technologies, IoT, AI, blockchain, and robotic systems, were first established (Sagandykova et al., 2024; Pletsch et al., 2025). For an accurate search, key queries were used covering the main technological areas, such as "digital agriculture", "precision farming technologies", "IoT in agriculture", "AI applications in agriculture", "drones in agriculture", "blockchain in supply chains", "robotics in farming". After collecting the articles, they were filtered based on certain criteria. The inclusion criteria were the relevance of materials to digital technologies in agriculture, the availability of examples of technology application in real conditions, and the availability of empirical data confirming the impact of technology on production processes and the economy of the agricultural sector.

An important aspect was the assessment of the practical application of technologies, which allowed understanding how they were implemented in real conditions and what results they brought. Based on the analysis, conclusions were formulated aimed at identifying the most promising technologies for implementation in the agricultural sector, and optimising the implementation processes, considering the specifics of agriculture. In addition, potential barriers and difficulties that farmers could face in implementing these technologies were revealed.

Data collection and analysis methods were used, which helped identify key problems and trends affecting the digital transformation of agriculture to achieve the goals. Based on the information collected, the identified problems were systematised, which were classified into technical, financial, organisational, and social barriers. The study also examined Climate FieldView, Ag Leader, John Deere Operations Center, and FarmLogs platforms, which provide data collection and analysis from fields, resource optimisation, and real-time monitoring of agricultural operations using IoT devices and sensors.

A comparative analysis of the barriers to digitalisation in agriculture was conducted, which provided for identifying unique aspects characteristic of agriculture, and the possibility of borrowing successful solutions. The results of this stage of the study served as the basis for a subsequent analysis of the prospects for digital transformation and the development of recommendations to overcome the identified barriers. Special attention was paid to creating conditions for improving farmers' digital literacy and developing new educational programme formats.

Results and Discussion

The state and prospects of digitalisation of agriculture in Kazakhstan

The introduction of artificial intelligence and other technologies is actively taking place in Kazakhstan's agriculture, which leads to improvements in various aspects of the agro-industrial complex. For example, chatbots with artificial intelligence automatically check applications for subsidies, which reduces the number of refusals due to errors in documents. Intelligent soil analysis systems reduce manual work by 80% and increase the accuracy of agricultural recommendations by up to 95%. Drones with artificial intelligence help to control pests, reducing crop losses by 25-30%. These measures are aimed at increasing the transparency and effectiveness of government support measures and the rational use of land and pastures (Digital technologies are being introduced.., 2025).

The introduction of digital platforms has substantially improved farmers' access to government services and simplified the process of obtaining subsidies. Electronic services provide transparency, speed up the application process, and minimise bureaucratic barriers. For example, using field monitoring data to justify subsidy applications allows farmers to confirm their losses and receive compensation based on objective indicators (Kozybaeva, 2025).

As of 2020, there were more than 20 digital farms and about 170 advanced farms in the country. The number of advanced farms was expected to reach about 4,000 by 2023. It was planned that by this time, 100% automation of processes and public services in the agro-industrial complex would be provided (Digital transformation of the agro-industrial complex..., 2020). However, these goals were not fully achieved, and most of the innovations were not related to the digitalisation of the agricultural sector. In 2022, due to state support, 227 investment projects worth 214 billion tenge (475.6 million USD) were commissioned, and by the end of the year, it was planned to increase their number to 237. Therewith, 5.2 million hectares of agricultural land were returned to state ownership, and in 2023, it was planned to return another 5 million hectares (Results of 2022 in Kazakhstan..., 2022). In 2024, it was planned to digitise 7 more public services in the field of geology and subsurface use on the public services platform and hold open auctions for subsurface use. There were 2,343 registered users on the platform, who submitted 1,941 exploration applications and 59 production applications. Of these, 66 licences were issued (Kazakhstan's main achievements..., 2023).

In order to illustrate the practical application of digital technologies, a case study was conducted on an advanced farm in the Almaty region (Ishanov, 2024). This farm has implemented a precision farming system integrating DJI Matrice drones, Soil Scout sensors, and the John Deere Operations Center platform. Interviews with the farm manager revealed that the introduction of these systems led to a 20% reduction in fertiliser use and a 15% increase in crop yield within two years. The main challenges identified included the initial investment costs (over 12 million tenge (26,670 USD)) and the lack of trained personnel for system maintenance. However, the farm benefited from state subsidies covering approximately 30% of capital costs.

Thus, the digitalisation of agriculture in Kazakhstan has developed unevenly due to differences in the amount of financing, the availability of technology, and the scale of farms. Therefore, the plan to create 4,000 farms using digital technologies across the country by

2021 has not been fully implemented (Twenty digital and 4000 advanced farms to be created..., 2018). If in 2019 there were 10 digital farms and 114 advanced ones in the country, then by November 2024, the number of digital farms exceeded 200 (Ishanov, 2024). However, despite this progress, the indicators achieved are still below the initial goals, although there is a positive trend in the development of digital technologies in agriculture in Kazakhstan.

The pace of digitalisation of the agricultural sector also varied. According to data for 2021, the level of digital technology adoption in large agricultural enterprises is about 40%, while among small and medium-sized farms, this figure does not exceed 15% (Mustafina and Bimurzina, 2021). These differences are due to different levels of financing: crop production and grain farming receive more attention from the state and private investors, while livestock and small farms lack the funds to implement modern technologies. The depth of digitalisation implies the degree of integration of digital technologies into various aspects of agricultural production, including the use of GPS navigation, automated control systems, sensors for monitoring soil and plant conditions, and the use of big data and artificial intelligence to optimise processes (Abiri et al., 2023).

Digitalisation is becoming part of management in large agricultural companies with financial and technical capabilities (Kropyvko et al., 2020). The seeding, watering, fertilising, and harvesting are automated here using digital technologies. Innovative field monitoring devices offer real-time soil moisture, plant health, and crop production forecasts. This improves job efficiency and lowers expenses, especially on large farms with lots of acreage. Thus, small farms confront many barriers to digital adoption. High hardware and software costs are a major issue. Drones, sensors, and specialised software are typically too expensive for small farms with restricted resources.

Digital technology adoption also depends on infrastructure accessibility (Yuan et al., 2024). In rural places, unstable Internet connectivity or inadequate mobile communications make using IoT or cloud platforms nearly difficult. Even farmers wanting to engage in digitisation confront infrastructure constraints. Social factors also influence digital technology adoption. Many farmers, especially older ones, are apprehensive of new technologies and prefer traditional ways. Insufficient digital literacy and absence of specific farmer education programs limit digital change.

Digital technology training for farmers is being offered by Danone Kazakhstan. Despite such endeavours, only a small audience is trained, indicating a lack of organised educational programs for farmers nationwide (Danone wants to launch “Schools for farmers” in Kazakhstan, 2023). The 2017 Atameken Schools for Farmers project taught farmers about current technologies, including digital tools. The project was local and not broadly diffused, demonstrating the limitations of specific educational courses (School for farmers: Training stimulates development, 2017). Kazakhstan's most developed agricultural sectors – cereals and oilseeds, dairy, and beef cattle breeding – are most affected by digitalisation. These sectors are adopting drones, precision farming, the Internet of Things, and computerised farm management systems. Digitalisation varies by economy, funding, and infrastructure.

Kazakhstan is one of the largest producers of grain crops, especially wheat, which occupies about 70% of all sown areas (Lyagusha, 2024). Kazakhstan is actively developing the production of oilseeds. In particular, the production of sunflower, soybeans, and rapeseed is growing, which is associated with an increase in demand for vegetable oils and other products derived from these crops. Kazakhstan's dairy cattle sector also has positive trends, with dairy exports growing. The strategy is aimed at improving the quality of dairy products and increasing production capacity and the number of dairy farms. Beef cattle breeding is also actively developing, which is related to the needs of the domestic market and export potential. Kazakhstan has become an important player in the production of beef and meat from other animals, with an emphasis on improving livestock genetics and developing the feed base (Syzdykova and Eszhanov, 2025).

Animal husbandry in Kazakhstan occupies an important place in the economy, especially dairy and beef cattle breeding. The main problems of the industry remain low productivity, seasonal fluctuations in feed and a shortage of qualified specialists (Montayeva et al., 2023). Digital technologies help automate herd management, increase productivity, and monitor animal health. In dairy cattle breeding, cow health monitoring systems using sensors, such as Allflex or DeLaval, are widely implemented. These systems monitor the activity of animals, analyse their diet, and help detect diseases at an early stage. The implementation of such technologies requires equipment, including animal sensors, server equipment for data collection and analysis, and monitoring software, such as CowManager or BovControl. The cost of implementing such systems can be about 5 million tenge per farm (11,110 USD), and the payback period is from 2 to 3 years, subject to optimised feeding and increased yields.

Beef cattle breeding actively uses feeding management technologies and systems for cattle identification using RFID tags (Radio Frequency IDentification). Platforms such as ZTags or Smartbow allow keeping accurate livestock records and analysing productivity. This requires equipment for reading RFID tags, server software for data analysis and forecasting of feed needs, and a drone for monitoring the condition of pastures. The cost of implementing such technologies is about 3-7 million tenge (6,670-15,560 USD), and the payback period is usually from 1 to 2 years, depending on the scale of technology use and savings on feeding.

Drones for monitoring pastures and herds, such as the DJI Matrice 300 RTK, allow shepherds to track the location of livestock in real time, look for possible threats (such as diseases or loss of animals), and monitor the condition of pastures. The cost of implementation for a farm using drones and related monitoring software can range from 2-5 million tenge (4,445-11,110 USD). Payback period: from 1 to 3 years, depending on the efficiency of using drones. Nevertheless, the digitalisation of agriculture creates new prospects for improving the efficiency and sustainability of the industry. Among the most popular technologies are drones, the Internet of Things, artificial intelligence, and blockchain (Figure 1).

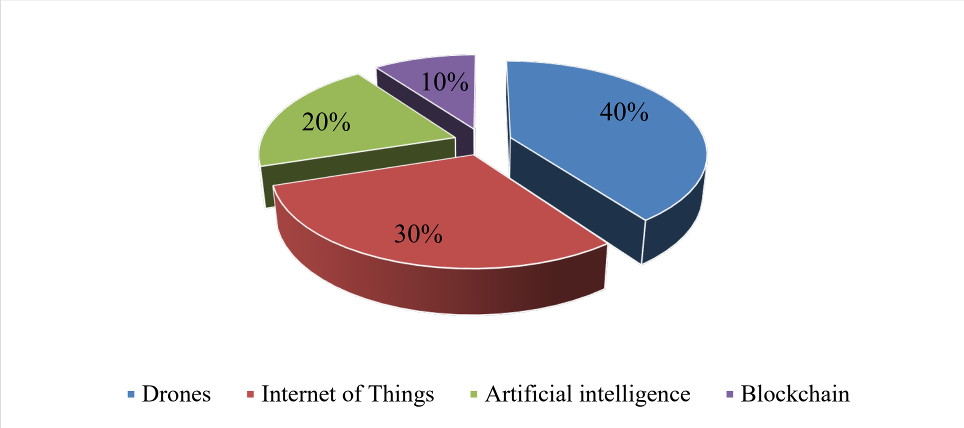

Figure 1. Digitalisation technologies in agriculture of Kazakhstan (quantity)

Source: compiled by the authors based on (Zhumaxanova, et al., 2019)

Drones allow quickly collecting data on the state of the soil, vegetation, and yield, which helps to make more informed decisions about the time of harvest and the use of fertilisers. IoT systems allow you to monitor soil moisture, air temperature and other parameters, optimising irrigation and fertilisation processes. Blockchain technology represents a critical component of digital transformation in agriculture, particularly in ensuring transparency, data integrity, and trust throughout the agri-food supply chain (Bisenovna et al., 2024). Its application allows for immutable tracking of agricultural inputs, certifications (e.g., organic, fair trade), and product movements from farm to consumer, which is especially relevant in export-oriented sectors such as grain and meat production. Table 1 presents a comparative overview of blockchain adoption in agriculture across selected countries, highlighting both the benefits and constraints relevant to Kazakhstan's future implementation efforts.

In Kazakhstan, however, blockchain adoption remains limited to pilot projects due to legal, technical, and organisational challenges. For example, the Ministry of Agriculture launched a pilot blockchain traceability system for meat exports in 2023 in collaboration with a private tech firm (Abiri et al., 2023). The system enables real-time verification of product origin, health certification, and compliance with veterinary regulations. Early results indicate increased efficiency in customs clearance and reduced cases of data fraud.

Blockchain platforms such as AgriLedger, TE-FOOD, and Provenance have been implemented globally to address issues of food fraud and ensure secure data sharing among stakeholders (Rehman et al., 2023). These platforms demonstrate how distributed ledgers can enhance the traceability of crops, improve supply chain efficiency, and meet international food safety standards. The integration of blockchain with IoT devices allows for real-time automated recording of production and environmental data, further increasing trust and auditability in supply chains. Despite these benefits, challenges in Kazakhstan include limited legal regulation of distributed ledger technologies, lack of technical expertise among farmers and supply chain actors, and insufficient digital infrastructure to support decentralised data networks. Addressing these limitations requires regulatory innovation, technical capacity-building, and integration with existing national data systems.

Table 1.
Comparative overview of blockchain applications in agriculture

Country	Key Applications of Blockchain in Agriculture	Benefits Observed	Challenges Encountered
Kazakhstan	Pilot traceability system for meat exports; experimental platforms for grain certification.	Faster customs clearance; reduced documentation fraud; improved traceability in livestock sector.	Legal uncertainty; low digital infrastructure in rural areas; lack of farmer awareness.
Netherlands	Blockchain for fresh produce tracking (e.g., tomatoes, flowers); integration with RFID and cold chain logistics.	Full transparency from farm to supermarket; reduced food waste; consumer trust.	High implementation costs; need for interoperability across actors.
USA	Platforms like IBM Food Trust and AgriDigital for grain, dairy, and vegetable traceability; integration with IoT.	Improved food safety compliance; data auditability; supply chain resilience.	Complex regulations; concerns about data ownership and standardisation.
China	Blockchain-enabled smart contracts for agricultural subsidies; pork supply chain traceability.	Reduction in subsidy fraud; enhanced consumer confidence in food safety.	Lack of unified platform; rural areas face internet access problems.
Australia	AgriDigital platform for grain trading, real-time contracts, and quality assurance.	Increased market transparency; faster payments; simplified transactions.	Limited use beyond grains; education needed for widespread adoption.

Source: compiled by the authors based on AgriDigital (2025), IBM Food Trust (2023), Abdulaev et al. (2020)

Digital technologies in agriculture, similarly to Industry 4.0 and 5.0 (Grabowska et al., 2024), improve the accuracy and efficiency of resource management (Duncan et al., 2021). Optimising water and fertiliser use is key. Sensors in the soil allow exact humidity and temperature management, helping farmers optimise watering and fertilisation. This decreases resource costs and sustains agricultural productivity. Digital technologies automate processes, lowering operating expenses. Robotic sowing, harvesting, and tillage technologies reduce human labour and labour expenses, enhancing agricultural output efficiency. Digitalisation boosts agricultural product quality and quantity. Farmers may get high-quality photos and crop health data from drones with cameras and sensors. This permits early detection and rapid treatment of plant diseases and nutrient deficits, improving yields and lowering plant protection expenses. AI helps anticipate crops and optimise harvest time. Data on weather, soil, and other factors can accurately estimate when plants will attain optimal maturity, preventing premature or late harvesting losses (Shahini and Shahini, 2025).

Blockchain technology reduce losses and boost consumer confidence by providing transparency and data security. Such technologies improve agricultural accounting and management, ensuring information dependability and protection, which is crucial for large data-intensive agricultural operations. Drone systems and AI detect plant diseases, nutrient deficits, and insect infestations quickly, increasing yields and lowering plant protection expenses. AI predicts and reduces risks, helping farmers make better decisions and save losses. Process optimisation includes IoT-controlled irrigation and blockchain-based data security and transparency, which boosts consumer confidence (Fountas et al., 2020).

Technology application reduces operating expenses, especially in water resources management, fertiliser use, and plant protection. Precision agricultural technology, including sensors and drones, reduce chemical and water use, saving money (Shahini et al., 2025). Since AI and robotic systems can work 24/7 and perform jobs accurately, they boost agricultural production efficiency. This is crucial given worker shortages and rising productivity needs. Digital tools forecast yields and detect plant problems, helping farmers adjust to changing climates. This reduces drought and frost concerns. Digitalisation has a good ROI despite significant initial expenses. Lower labour costs, resource efficiency, and higher yields boost agricultural business profitability and sustainability.

Digital technologies contribute to increasing the efficiency and sustainability of the agricultural sector. For example, by the end of 2025, it is planned to develop a digital map of agricultural land, which will allow using land resources more efficiently and improve land management in regions such as the Almaty region (Kudryashova, 2023). In addition, modern digital solutions are being introduced in the country, including artificial intelligence for crop forecasting, climate risk management, and irrigation optimisation, which will increase the accuracy of decision-making and improve results in the agricultural sector.

Farmers can better plan their activities and reduce weather risks by using artificial intelligence to predict climate risks, yields, and market prices (Kazakhstan is introducing digital technologies..., 2025). AI analyses soil, weather, and plant data to automate irrigation and fertilisation, maximising resource consumption and yields (Digital technologies are being adopted..., 2025). AI algorithms forecast breakdowns and optimise routes to decrease operating costs and boost tractor and combine productivity. Systems that track livestock activities assist diagnose diseases and change diets in animal management.

The digital transformation of agriculture substantially affects the socio-economic situation in the industry, including employment and professional competencies of employees. Automation of processes, the use of artificial intelligence to predict yields and optimise irrigation, and the use of drones and robotics create a demand for highly qualified specialists. For example, in the field of precision agriculture, where drone systems and AI are used, data processing specialists and operators of complex equipment can expect to receive a salary increase.

In the United States, the digitalisation of agriculture has led to substantial productivity growth and a change in employment patterns. The introduction of automated systems and artificial intelligence technologies has increased the demand for specialists with skills in working with data and controlling robotic technology. Modern agricultural machines are equipped with computerised monitoring systems, GPS navigation, and automatic control programmes, which make them more accurate and economical in using resources. These technologies allow one farmer to provide food for more than a thousand people, which substantially exceeds the figures of the last century (Kenney et al., 2020).

Kazakhstan has also seen an increase in salaries in the agricultural sector, where digital technologies are being actively introduced, especially for specialists working with high-tech equipment and data analysis. According to the data, over the past five years, the wages of agricultural workers have increased from 95,163-184,830 tenge (212-411 USD). However, despite this growth, wages in the agricultural sector remain among the lowest compared to other sectors of the economy (Salaries in agriculture remain the lowest in Kazakhstan, 2023). The introduction of technologies such as automation, artificial intelligence, the Internet of Things, and robotics is changing the nature of work, creating new opportunities but also challenges for workers, especially in traditional agricultural sectors. The main challenge is the need to retrain employees, as many of them must learn new skills in working with technology and software. This can lead to difficulties for those who do not have the necessary knowledge or are not ready to learn. Furthermore, reducing the need for manual labour may cause job losses in traditional fields. Finally, there is a risk of social inequality, as access to new technologies and training may be limited in some regions.

The introduction of automated systems and robotic solutions can substantially reduce the need for labour resources, especially in such labour-intensive processes as sowing, harvesting, and tillage (Rehman et al., 2023). Digitalisation can reduce the need for labour in traditional professions such as agricultural labour, where previously large numbers of people were needed. However, on the other hand, digitalisation creates new jobs that require highly qualified specialists. In particular, there is a need for IT specialists, data analysts, robotics engineers, and data processing specialists. These new professions require highly qualified workers and specific knowledge in the field of technology, which opens up employment opportunities in more high-tech sectors.

Professional competencies are also undergoing substantial changes in the context of digital transformation. Agricultural workers should learn new skills related to the use of digital tools, such as soil and plant monitoring systems, drone technologies, and skills in working with big data and analytical platforms (Venuraj et al., 2024). It is important that these skills are accessible to a wide range of workers, including in rural areas where there is often a shortage of educational resources. Thus, digital transformation requires substantial investments in education and staff training.

Digitalisation also helps to increase labour efficiency and productivity, which can lead to an increase in the incomes of workers employed in high-tech segments of agriculture. However, this requires the creation of an infrastructure that will provide access to new knowledge and technologies for all employees in the industry. Otherwise, some workers may have difficulty adapting to new conditions, which will increase the problem of inequality in access to technology.

Digital transformation of agriculture in Kazakhstan: Challenges, barriers, and opportunities

Online platforms that facilitate direct sales of agricultural products and reduce dependence on intermediaries are actively developing in Kazakhstan. For example, the platform

Baibolsyn.kz provides farmers with the opportunity to manage and promote their products online and place ads for the sale of agricultural goods and services. Due to category filters such as location and price range, users can efficiently find the right products or services.

In other countries, such as the Netherlands and the USA, farmers are actively using platforms with data analysis and forecasting functions, which allows them to adapt to market changes and optimise production. In Kazakhstan, it is recommended to introduce such platforms with integrated functions of demand forecasting, trend analysis, and logistics optimisation so that farmers can plan production more accurately and effectively manage supply chains. This is especially important for the southern regions of Kazakhstan, such as the Turkestan and Zhambyl regions, where the demand for vegetables and fruits varies substantially depending on the season and yield. Variable demand, with an increase in sales during the harvest period and a decrease in the off-season, creates challenges in logistics and inventory management. As part of the digital solutions research, successful examples of platforms such as AgriDigital in the Netherlands and FarmLead in the USA can be noted. These platforms help manage the supply chains of agricultural products by predicting shortages or oversupply of goods on the market, which allows farmers to make informed decisions on the sale and purchase of products, minimising the risks associated with fluctuations in the market.

The cost of drones and IoT devices creates financial constraints. Small farms in Kazakhstan, especially around Almaty, sometimes lack finances for such developments. In Germany, government subsidies and loans for farmers help offset some of the costs. Farmers in distant areas like East Kazakhstan have little digital literacy, which creates organisational difficulties (Zabelina et al., 2020; Baubekova et al., 2020). Not knowing how to use technologies like farm management systems makes adaption harder. Australia is offering farmers free digital platform courses to boost innovation. Legal obstacles include weak data protection and inadequate legislation. Kazakhstan has inadequate agriculture technology cybersecurity, which puts farmers at danger. The EU's rigorous GDPR standards protect farm data and encourage secure technology development (GDPR: What is it, what industries is it relevant for? 2022). Table 2 categorises Kazakhstan's digital transformation challenges in agriculture.

In order to understand the regional disparities in digital adoption, a comparative analysis was conducted between two regions with contrasting levels of digital development—North Kazakhstan (high adoption) and Kyzylorda region (low adoption). Data from regional Departments of Agriculture and interviews with local farming cooperatives revealed that in North Kazakhstan, over 40% of large farms use IoT and satellite monitoring systems, while in Kyzylorda, this figure does not exceed 7%. The main factors explaining this gap are differences in Internet infrastructure, availability of public subsidies, and access to training. The findings support the hypothesis that regional inequalities substantially affect the digitalisation process in agriculture (Twenty digital and 4000 advanced…2018).

The main obstacles are limited access to the Internet, high cost of technology, lack of specialists and educational programmes, and problems with legislative regulation. It is necessary to improve infrastructure, support small farms, develop farmers' digital skills, and improve legislation to overcome these barriers.

Table 2.
Problems and barriers of digital transformation in agriculture

Category	Challenges and barriers	Description	Examples from Kazakhstan
Technical barriers	Insufficient infrastructure (Internet access)	Rural areas often lack stable and fast internet, making it difficult to use technologies that require constant connectivity.	Many rural areas of Kazakhstan, especially remote ones, have limited Internet access.
	The complexity of technology maintenance and support	Modern digital solutions require regular maintenance and updates, which can be difficult for farmers without technical education.	The lack of qualified specialists in rural regions of Kazakhstan creates difficulties in servicing new technologies.
Financial barriers	High cost of technology (drones, sensors, monitoring systems)	Small and medium-sized farms often cannot afford the purchase and maintenance of expensive technologies.	In Kazakhstan, small and medium-sized enterprises have difficulty accessing expensive digital solutions.
	Uncertainty about the return on investment	Farmers face uncertainty when implementing technologies due to the impact of market conditions and climate risks. Although the payback calculation is quite accurate due to analytical tools, difficulties may arise due to a lack of data or their misinterpretation.	Despite the analytical tools, the lack of data in Kazakhstan creates difficulties in calculating the payback of digitalisation.
	Lack of government support for small farmers	In some regions, there are no programmes to subsidise or support digitalisation for small farms.	For example, there are not enough specialised grants for digitalisation in remote regions of Kazakhstan.
Organisational barriers	Low level of digital literacy among farmers	Many farmers, especially the older generation, do not have the necessary knowledge to work with new technologies, which slows down their implementation.	The problem of low digital literacy is relevant for most regions of Kazakhstan.
	Resistance to change by employees and managers	Adherence to traditional working methods and concerns about job losses due to automation can hinder the adoption of new technologies.	Some farmers in Kazakhstan are afraid of the introduction of technology for fear of layoffs.
	Lack of educational programmes for farmers	There is a lack of specialised courses and training on digital technologies for farmers, which complicates mastering new solutions.	In Kazakhstan, there is a shortage of educational programmes for farmers on the development of digital technologies.

Category	Challenges and barriers	Description	Examples from Kazakhstan
Legal barriers	Insufficient legislation to regulate digital technologies in agriculture	In some countries, legislation lags behind technological innovations, which creates legal uncertainty in the use of new technologies.	In Kazakhstan, work is underway to improve the legislative framework, but some aspects remain unregulated.
	Problems with legal regulation of data (protection of personal information, GDPR (General Data Protection Regulation))	Data protection issues, especially in the context of collecting information on soil conditions, yields, and other aspects, require compliance with data protection standards, which can be difficult for small farms.	Farmers face difficulties in complying with Law of the Republic of Kazakhstan No. 94-V “On Personal Data and Their Protection” (2013).
	Cybersecurity and cyberattack risks	The use of digital technologies increases the risks of cyber-attacks, data leaks, and financial losses, especially among farmers who are unaware of possible threats.	Kazakhstan has developed measures to increase the level of cybersecurity in the agricultural sector.

Source: compiled by the authors based on (Resolution of the Government of the Republic of Kazakhstan No. 269 “..., 2023; Law of the Republic of Kazakhstan No. 94-V.., 2013; Tiwari et al., 2024)

Recommendations on the development of digital technologies in agriculture in Kazakhstan

To digitalise agriculture in Kazakhstan, innovative solutions in all aspects of production, such as robots and autonomous machines, must be introduced (Mendes et al., 2022). Autonomous tractors and drones can sow, fertilise, and harvest without human intervention, reducing labour costs and improving accuracy. Robots for harvesting and plant care are efficient, especially in labour shortages. These technologies should become more accessible to farmers of all levels as they evolve.

Expanding cooperation between IT companies and the agricultural sector is also a promising area. IT companies offer farmers specialised software solutions, such as platforms for data analysis, field monitoring, and yield forecasting. In turn, the agricultural sector provides unique opportunities for testing and adapting innovative technologies. This interaction allows accelerating the implementation of digital solutions and improving their effectiveness.

Furthermore, alongside plans for the active implementation of innovative solutions like robots and autonomous machines and the enhancement of collaboration between IT firms and the agriculture industry, it is imperative to concentrate on numerous supplementary factors. Firstly, it is worth paying attention to improving digital literacy among farmers, especially in remote regions, where many do not have the necessary skills to work with new technologies. The creation of educational programmes and courses aimed at increasing awareness and skills in using digital solutions, which will help farmers to innovate more effectively and reduce resistance to change, can be proposed for this purpose.

Second, government subsidies and financial support for small and medium-sized farms will help them buy pricey equipment like drones and sensors. These steps will lower financial barriers and accelerate digitisation. To boost government programme availability, grant and subsidy applications must be simplified and new technologies like drones and sensors must be funded. Educational programmes on digital technologies and agricultural instruments are also needed to help farmers learn new methods and gain confidence. Information centres for farmers and small farm-specific programs will enhance access to government support and technology.

The successful adoption of digital technology requires infrastructure, especially in rural areas where dependable Internet is scarce (Ivanovs et al., 2018). Investment in broadband and Internet connectivity will enable stable access to online materials and aid precision farming systems. It is also worth considering integration with international agricultural digital platforms like Climate FieldView, which collects, analyses, and visualises field data using IoT devices and sensors to improve forecasts, resource optimisation, and experience exchange with developed countries, which will accelerate the introduction of advanced technologies. Precision farming solutions from Ag Leader include machinery control systems and sensors for informed decision-making. Farmers may monitor farm output and condition in real time using data from agricultural machines and sensors at the John Deere Operations Centre. FarmersLogs optimises field management, weather tracking, and soil and crop data analysis. Integration with these platforms and exchange of agricultural technology knowledge with industrialised countries will speed Kazakhstan's adoption of sophisticated solutions and boost farm efficiency. To secure farmers' data, regulate new technology, and encourage agricultural investments, the legislative framework must be updated.

The results obtained are consistent with the studies by Ahmed et al. (2022) and Tzounis et al. (2017), confirming the role of IoT, AI, and blockchain in optimising agriculture. As in their research, cost reduction, higher yields, rational use of resources, and the importance of government support are emphasised. The conclusions about the need for data protection and the problems of the high cost of technology implementation coincide. In contrast to the paper of Ahmed et al. (2022), the focus on climate adaptation and the use of blockchain for supply chain transparency was mentioned only briefly in this study. While Tzounis et al. (2017) pay attention to the technical limitations of IoT, in this study, this aspect was not addressed to such an extent since the main focus was on broader issues of IoT application in agriculture, such as increasing efficiency and reducing costs.

Precision farming technologies, such as sensors for monitoring soil and plant health, play a critical role in reducing costs and increasing agricultural sustainability (Shahini et al., 2023; Skydan et al., 2021). The use of such technologies allows farmers to collect accurate data on soil conditions, moisture levels, nutrients, and other factors that directly affect plant growth and development. Based on these data, it is possible to precisely regulate the amount of water, fertilisers, and other resources, which reduces their overspending and minimises the impact on the environment (Vinyukov et al., 2022). One of the main advantages of such technologies is the reduction of water and fertiliser costs. In traditional agriculture, these resources are often used inefficiently, which leads to unnecessary costs and negative impacts on the ecosystem. Precision farming technologies help farmers precisely control irrigation and fertilisation, which helps to substantially reduce their consumption and reduce soil and water pollution (Palamarchuk et al., 2019; Yeraliyeva et al., 2016).

These conclusions are supported by the findings of Getahun et al. (2024) and Sabir et al. (2024). Both authors stress the importance of using technology to increase the sustainability of agriculture. Getahun et al. (2024) underline environmental sustainability, which is achieved by reducing soil and water pollution, improving soil quality, and preserving biodiversity. Sabir et al. (2024) highlight remote sensing as an important tool for precision agriculture, which contributes both to economic efficiency and the long-term sustainability of agricultural systems in the face of climate change.

Digitalisation opens farmers' access to new markets through e-commerce and online sales platforms (Nurgazy et al., 2019). These tools reduce dependence on intermediaries, allowing farmers to increase profits independently by reducing additional costs. In addition, digital platforms expand the geography of sales, which is especially important for manufacturers of specialised agricultural products whose products are in demand outside their region (Shumka et al., 2021).

Papers by Xie et al. (2020) and Koçyiğit and Demiryürek (2022) confirm the essential aspects of digitalisation discussed above but contain some additional accents and differences. Xie et al. (2020) underscore the importance of analysing market data to improve the efficiency of farming operations, which coincides with a discussion of the role of analytical systems and AI in forecasting demand and optimising stocks. Koçyiğit and Demiryürek (2022) also point out the importance of e-commerce in increasing the entrepreneurial activity of farmers, which echoes the idea of the need to master digital tools to improve business processes in the agricultural sector.

Digitalisation of agriculture creates new jobs in high-tech sectors such as data analysis, robotics, and IT (Bimendiyeva et al., 2018). Data analysis specialists are becoming in demand for interpreting information from sensors and drones, which helps optimise farming processes. Robotics engineers develop and maintain automated systems, including drones and autonomous tractors, adapting them to the needs of farms (Bulgakov et al., 2020; Voloshina et al., 2021). IT specialists play a vital role in creating and maintaining software used for farm management and data analysis. These professions not only promote employment but also open up prospects for professional growth, especially for young people. However, to realise these opportunities, educational programmes are needed that prepare personnel to work with digital technologies. Without this, farmers may have difficulty implementing innovations, which limits their application.

The discussion coincides with the conclusions of Fabregas et al. (2019), noting that digital technologies contribute to the growth of employment in agriculture, including consultants specialising in the use of digital solutions. Li and Zhang (2023) also indicate that the digital economy is expanding the range of jobs, including highly skilled positions, and explore the impact of the digital economy on the redistribution of labour, including the transition to more skilled professions. The introduction of digital technologies in agriculture faces several barriers. Technical constraints, such as the lack of stable internet and necessary infrastructure in rural areas, limit the use of technologies that require constant connectivity. This is especially true for developing countries.

Problems with technical infrastructure and access to Internet services in rural areas are also noted by Ganeshkumar et al. (2023), who point to this as an important barrier to the introduction of Industry 4.0 technologies. Shang et al. (2021) concentrate on the importance of data integration at the farm level and system interaction, which also implies the need for a reliable infrastructure for data exchange, confirming the relevance of the technical infrastructure problem mentioned in the discussion.

Financial difficulties include the high cost of equipment such as drones and sensors, which makes them inaccessible to small farmers. Lack of confidence in the return on investment also slows down the adoption of technology. Organisational problems are related to the low level of digital literacy among farmers, especially the older generation. Resistance to change on the part of employees and management also inhibits digitalisation. Legal and cybersecurity issues include an insufficient legislative framework for data protection and the risks of cyberattacks, which are especially dangerous for small farmers who do not have the resources to protect information. For the successful implementation of technology, it is crucial to solve problems with infrastructure, finance, education, and legal aspects.

Digitalisation of agriculture is a powerful tool for improving the efficiency, sustainability, and competitiveness of the industry, but its implementation is accompanied by substantial challenges. The benefits, such as increased yields, rational use of resources, lower costs, and increased access to markets, are confirmed by a number of international studies. However, high equipment costs, insufficient infrastructure, technical constraints, and problems with digital literacy among farmers remain major obstacles to widespread technology adoption.

Conclusions

The digitalisation of agriculture in Kazakhstan shows significant potential to improve productivity, resource efficiency, and environmental sustainability. Technologies such as IoT, drones, AI, and blockchain have demonstrated concrete benefits, including a 15-30% increase in crop yields, 20-40% reduction in input costs, and improved traceability and food safety in pilot supply chain applications. However, the adoption remains uneven, with large enterprises integrating technologies up to 40%, while small and medium farms lag below 15%, largely due to financial, infrastructural, and human capital constraints.

Blockchain, although promising for supply chain transparency, remains underdeveloped in Kazakhstan. Its full potential can only be realised through legal reform, technical standardisation, and integration with IoT and national databases. Without substantial improvements in Internet infrastructure and targeted educational programmes for farmers and agri-enterprises, these technologies risk further entrenching inequality rather than alleviating it. Future policy should focus on enabling mechanisms for smallholder access to blockchain-based certification and traceability systems.

The use of digital technologies such as IoT, drones, artificial intelligence, and blockchain helps to improve the accuracy of resource management by optimising irrigation and fertilisation. Process automation reduces operational costs and increases productivity and economic efficiency. Monitoring the condition of plants using AI and drones leads to an increase in yields and product quality by timely identifying problems. Blockchain ensures transparency and security of supply chains, strengthening consumer confidence and increasing product competitiveness. Digitalisation of agriculture creates new opportunities for improving the efficiency, sustainability, and adaptation of the industry to modern challenges. Digitalisation is changing the nature of employment in agriculture. On the one hand, automation reduces the need for traditional manual labour, and on the other hand, it creates demand for highly qualified specialists such as data analysts, robotics engineers, and IT specialists. This requires the creation of educational programmes to retrain workers and eliminate social inequalities.

The key technical, financial, organisational, and regulatory challenges to digital agriculture were examined. Technical issues include rural Internet instability and high-tech equipment maintenance. Digital solutions' high cost and uncertain payoff limit innovation investment. Organisational issues include low digital literacy, workforce resistance to change, and a lack of technology education courses. Legal hurdles include insufficient legal regulation, data privacy issues, and cybersecurity concerns, which hinder industry digitisation.

Innovative technologies, farmer digital literacy, and IT company collaboration are needed to digitalise agriculture in Kazakhstan. Government support for small and medium-sized enterprises and education and infrastructure improvements are crucial. Integration with worldwide digital platforms will speed up sophisticated technology adoption and boost agricultural efficiency.

The study was limited by the insufficient coverage of all digitalisation technologies, especially in the context of biotechnology and innovation, and the lack of a detailed analysis of barriers specific to different regions, especially developing countries. Further research should focus on developing solutions to improve Internet connectivity in rural and remote areas, which is a major obstacle to the widespread adoption of digital technologies.

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STAN I PERSPEKTYWY TRANSFORMACJI CYFROWEJ W SEKTORACH ROLNICZYCH

Streszczenie. Celem badania jest analiza trendów i kierunków cyfryzacji rolnictwa, ze szczególnym uwzględnieniem technologii przyczyniających się do poprawy efektywności i zrównoważonego rozwoju branży. Metodologia obejmuje analizę stanu cyfryzacji rolnictwa, kluczowych technologii, barier wdrażania oraz perspektyw rozwoju w oparciu o dane statystyczne i raporty branżowe. W artykule przeanalizowano najbardziej rozwinięte sektory produkcji rolnej i hodowlanej w Kazachstanie, takie jak produkcja zbóż, roślin oleistych, bydła mlecznego i mięsnego, ze szczególnym uwzględnieniem wykorzystania dronów, Internetu Rzeczy, sztucznej inteligencji i technologii blockchain. Uwzględniono specyfikę techniczną technologii, koszty wdrożenia, okresy zwrotu z inwestycji oraz wymagania infrastrukturalne. Przeprowadzono analizę porównawczą cyfryzacji w Kazachstanie i innych krajach, identyfikując główne bariery, takie jak wysokie koszty, niewystarczająca infrastruktura i niski poziom kompetencji cyfrowych. Stwierdzono, że drony przyczyniają się do optymalizacji monitorowania pól i precyzyjnej alokacji zasobów, Internet Rzeczy umożliwia gromadzenie i analizę danych do zarządzania procesami w czasie rzeczywistym, sztuczna inteligencja jest wykorzystywana do prognozowania i automatyzacji, a blockchain zwiększa przejrzystość łańcuchów dostaw. Technologie te usprawniły zarządzanie zasobami, zwiększyły plony i zminimalizowały wpływ na środowisko. Głównymi barierami utrudniającymi cyfryzację rolnictwa były wysokie koszty technologii, niewystarczająca infrastruktura, niski poziom kompetencji cyfrowych wśród pracowników przemysłu oraz opór rolników przed zmianami.

Słowa kluczowe: technologia, sztuczna inteligencja, blockchain, wdrożenie, sektor rolny