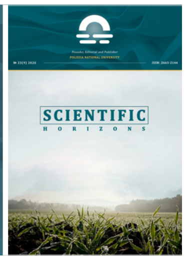
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(8), 206-219

UDC 631.152:631.5

DOI: 10.48077/scihor8.2025.206



The economic efficiency of the introduction of resource-saving technologies in crop production in Kazakhstan

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Article's History:

Received: 2.02.2025

Revised: 1.08.2025

Accepted: 27.08.2025

Abstract. The purpose of this study was to determine whether the implementation of resource-saving technologies in crop production in Kazakhstan during 2021-2024 led to statistically significant improvements in economic efficiency at the level of farming enterprises. The main focus was on the practical results of the application of innovative technologies, such as precision agriculture, Global Positioning System-monitoring, digital crop management, drip irrigation, remote sensing and the use of drones. The

Suggested Citation:

Bayandin, M., Bekmurzayeva, A., Yessymkhanova, Z., Bayandina, G., & Soltangazinov, A. (2025). The economic efficiency of the introduction of resource-saving technologies in crop production in Kazakhstan. *Scientific Horizons*, 28(8), 206-219. doi: 10.48077/scihor8.2025.206.

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study found that the implementation of these technologies allowed to reduce fuel costs by up to 60%, fertilisers by 18-22%, and labour costs by 15-20%. At the same time, wheat yield increased by 50% compared to 2023 and amounted to 1.38 t/ha. The introduction of drip and sprinkler irrigation on an area of about 84 thousand ha allowed to reduce water consumption by 20-40% and increase crop stability in drought conditions. Economic efficiency was confirmed by a high level of payback: typical terms of return on investment in these technologies were 3-5 years with state co-financing of up to 80%. The regression model showed high explanatory power ($R^2 = 0.948$), with the most significant influencing factors being subsidies for drones (+106.51) and digital platforms (+7.29), while direct funding per 1 ha was not statistically significant (coefficient -0.0004; $p = 0.685$). The results confirmed the economic feasibility of innovative approaches to agriculture in Kazakhstan and proved that the effectiveness of state support depends on its targeting and integration into the institutional environment. The results of this study can be practically applied by government agencies to optimise subsidy policies, by agricultural enterprises to justify investments in digital technologies, and by international donors to support scalable, cost-effective solutions for sustainable agriculture

Keywords: innovation; sustainability; yield; precision farming; profitability

INTRODUCTION

Increasing the efficiency of the agricultural sector of Kazakhstan in the face of climate change, depletion of natural resources and rising costs of material and technical resources is one of the key challenges of modern agriculture. Crop production is increasingly faced with problems of reduced soil fertility, water shortages, high energy intensity of technological processes and dependence on imported fertilisers and fuel. In such conditions, the introduction of resource-saving technologies becomes an effective means of ensuring the stability of production, reducing costs and increasing the competitiveness of products. Inefficient use of agricultural land in Kazakhstan, limited implementation of innovations and the lack of a unified approach to the organisation of agricultural enterprise territories make it difficult to achieve sustainable results. This was investigated by Y. Anarbayev *et al.* (2024), who proved that the transition to internal land management, taking into account the experience of the USA, China, Japan and the EU, contributes to increased profitability and rational use of resources. They proposed public-private partnerships, subsidies and digital systems as effective tools. However, there is still a lack of local data on the economic efficiency of such solutions in different regions and unified assessment methods.

Limited adaptation of agricultural practices to climate change, low application of water-saving technologies, and reliance on traditional methods reduce yield stability (Shahini, 2024). Modelling approaches, as demonstrated by A. Tkacheva *et al.* (2024), suggest that adjusting sowing dates and crop structures can help mitigate the negative impact of climate change on grain yields, although the authors did not explore the economic feasibility of such measures at the farm level. he potential of digital tools like Internet of Things and Geographic Information System for improving yield forecasting and cost management was emphasised by M. Toguzova *et al.* (2023), who also pointed to the lack of infrastructure and trained personnel as major barriers to their adoption. High energy intensity of production and dependence on external resources reduce the economic sustainability of the agricultural sector in Kazakhstan. X. Luo and A. Kaiyrbayeva (2024) studied the impact of green energy on the efficiency of agricultural production, noting that the use of solar and wind installations reduces costs and promotes greening. At the same time, the study did not consider the economic payback of such solutions and regional limitations for their scaling. Low environmental efficiency of agricultural production and resource depletion complicate sustainable development. Similarly, the work of N. Suleimenova *et al.* (2021) underlined the importance of combining economic incentives and state support to promote green practices in agriculture, though practical mechanisms and their cost-effectiveness across different farm types remained unaddressed.

The low efficiency of agricultural production in Kazakhstan is due to weak infrastructure, lack of irrigation, and limited access to technology (Taishykov *et al.*, 2025). Digitalisation is often proposed as a solution, and R. Gabdualiyeva *et al.* (2024) explored its potential through tools like Global Positioning System (GPS), drones, sensors, and Artificial Intelligence (AI), showing their capacity to enhance precision and reduce operational costs. However, widespread adoption remains hindered by poor internet coverage, absence of unified standards, limited digital literacy, and farmer reluctance. Despite the presence of over 20 digital and 170 advanced farms, weak internet coverage, lack of standards and digital skills, and farmer caution remain constraints. Further research is needed into the incentives and conditions for scaling up digital solutions. The challenge of low productivity and underutilisation of innovation is further complicated by risks to food security, as discussed by Z. Ospanov *et al.* (2024), who stressed the benefits of precision farming and sustainable resource management, though without addressing feasibility for smaller farms or regional disparities. At the same time, there is no analysis of the economic feasibility for small-scale producers and regional specificities of implementation. Limited access to innovation, inefficient management, and staff shortages are holding back agricultural productivity gains. G. Abdikerimova *et al.* (2024) showed that digital technologies, such as sensor monitoring and remote sensing, increase planning efficiency and reduce costs. However, the study does not cover the economic feasibility of implementation for small farms and ways to overcome barriers to digitalisation.

Based on the analytical differences in the implementation of innovative agricultural technologies between regions of Kazakhstan, this study hypothesised: the implementation of precision agriculture in the regions of Kazakhstan provides a statistically significant increase in the profitability of agricultural production at the farm level. The purpose of this study was to explore the impact of precision agriculture and resource-saving technologies on the economic performance of Kazakhstan's crop production sector during 2021-2024, with a focus on identifying measurable improvements in input efficiency, profitability, and investment returns at the enterprise level. The main objectives of the study were: to analyse the indicators of yield, costs and profitability in farms that use resource-saving solutions; to assess the impact of the use of such technologies on reducing the cost of production and increasing production efficiency.

MATERIALS AND METHODS

The study was analytical in nature and covered the period 2021-2024. The study examined the concepts and classifications of resource-saving technologies in agriculture in Kazakhstan with the results of analytical sources (Kazakhstan Adopts Water..., 2025). The methodological support of the study was focused on empirical verification of the specified hypothesis regarding the impact of precision agriculture on changes in the profitability of agricultural production in certain regions of Kazakhstan. Innovative approaches such as precision agriculture, GPS monitoring, digital crop management, drip and sprinkler irrigation, remote sensing and the use of drones were analysed (Food and Agriculture Organization, 2023). The main attention was focused on the practical results of the application of these technologies in the context of regions, in particular the northern region (North Kazakhstan, Akmola, Kostanay and Karaganda regions), where precision agriculture technologies are most actively used. The Eastern cluster, which includes Pavlodar and East Kazakhstan regions, is marked by the gradual introduction of Geographic Information System. In the southern and south-eastern regions (Turkestan, Kyzylorda, Zhambyl, Almaty regions), the key focus has been on modernising growth in response to water scarcity (Nurmaganbetova, 2025; Sowing Campaign 2025..., 2025; Revolutionizing Kazakhstan's Agriculture..., n.d.).

To assess economic efficiency, generally accepted indicators were used: production costs, profitability, net income, return on investment, resource efficiency (water, fertilisers), labour productivity (Nurmaganbetova, 2025). The calculation was based on collected statistical data and a summary of the results of agricultural enterprises that introduced these technologies, In Akmola, this included companies such as Ivolga Holding (n.d.), Rodina Agrofirm (n.d.), and TNK Agrofirm (n.d.). In Kostanay, key enterprises were Agro-Trade Ltd (n.d.) and Barlau Agrofirm (n.d.). In North Kazakhstan Grain Industry Corporation (n.d.). In Almaty, companies such as Zelenyi Dom (n.d.) and KazBeef Ltd (n.d.). In Turkestan and Zhambyl, Taraz Sugar Factory LLP (n.d.), and K-Agro Holding (n.d.). In Kyzylorda, Baikonur Agroholding (n.d.). These enterprises were selected due to their documented adoption of GPS navigation, smart irrigation systems, and drone-based monitoring during 2021-2024. The indicators of net profit, gross income per hectare, and return on investment in digital platforms and irrigation systems were also analysed. To achieve this objective, a multiple linear regression model was constructed, where the dependent variable represented the level of digitalisation in large and medium-sized agricultural enterprises, expressed as the share of farms using GPS navigation, drones, and electronic field maps. The independent variables included the amount of state support per hectare (in KZT), the availability of irrigation systems (0 – no, 1 – yes), the presence of subsidies for drones (0/1), the introduction of digital platforms (0/1), and a binary variable representing the type of region (0 – northern regions, 1 – southern regions). The selection of these parameters was driven by their documented relevance in national policy reports and previous studies, which highlight the role of targeted support instruments and infrastructure development in advancing digital transformation (Organisation for Economic Co-operation and Development, 2023; United States Department of Agricultural, 2025). The regression equation is (1):

$$\begin{aligned} \text{Digital}_{\text{TechUse}} = 106.51 \times \text{Drones}_{\text{Subsidy}} + 7.29 \times \\ \times \text{Digital}_{\text{Platforms}} - 0.0004 \times \text{Support\_per\_ha} - \\ - 7.49 \times \text{Irrigation} - 7.49 \times \text{Region\_Type} + \varepsilon, \end{aligned} \tag{1}$$

where $\text{Digital}_{\text{TechUse}}$ – share of agricultural enterprises using digital technologies such as GPS navigation, drones, and electronic field maps in a given region; $\text{Drones}_{\text{Subsidy}}$ – presence of a government subsidy program for drones (binary variable: 1 if active, 0 if not); $\text{Digital}_{\text{Platforms}}$ – presence of digital platforms (such as cadastral maps, digital field monitoring tools) (1 = implemented, 0 = not implemented); Support_per_ha – total amount of state support per hectare (in tenge);

Irrigation – availability of government support for irrigation systems (1 = support available, 0 = not available); Region_Type – region classification (1 = southern regions, 0 = northern regions); ε – residual error term of the model.

The dataset used for the model was compiled from aggregated regional information on agricultural support programs and technology implementation rates during the 2020-2024 period. For each region, the digitalisation rate was determined based on the proportion of enterprises that actively utilise precision agriculture tools, while the financial and structural variables were. The regression analysis was conducted using the ordinary least squares method, which allowed for the estimation of the relationship between state policy measures and digitalisation levels, while controlling for regional differences. The rationale for constructing the regression model was to quantify the contribution of various policy instruments and technological enablers to the overall digital maturity of the agricultural sector. By identifying which factors have the most significant influence on the adoption of digital technologies, the model provided a robust analytical framework for evaluating the effectiveness of current government strategies and for proposing more targeted measures.

RESULTS

Theoretical principles for assessing the effectiveness of resource-saving technologies in crop production. The assessment of the effectiveness of resource-saving technologies in crop production combines several conceptual and methodological approaches. In economic research, effectiveness is most often evaluated through profitability indicators, cost reduction, and return on investment. In the context of sustainable agriculture, however, the assessment also includes ecological and operational parameters – such as water use efficiency, input productivity, and climate resilience. Resource-saving technologies in crop production in Kazakhstan demonstrate gradual but steady implementation, supported by both state support and positive economic results. One of the main areas is minimal tillage technologies, in particular no-till, strip-till and reduced tillage. According to 2016 data, the no-till area amounted to more than 2.5 million hectares, which was equal to about 10% of agricultural land. In 2023-2024, the share of these technologies increased slightly, especially in the northern regions – Kostanay and North Kazakhstan regions, where their effectiveness in preserving soil fertility and increasing yields has been proven in practice. At the same time, implementation is hampered by the need for specialised equipment and insufficient awareness among farmers (World Bank, 2024a). By 2024, about 60-75% of agricultural enterprises in Kazakhstan use elements of precision agriculture, including GPS navigation, electronic field maps and satellite monitoring. More than 200 digital farms use drones to analyse soils and crops in real time, which allows them to reduce costs for fertilisers, fuel and water. On average, such technologies allow to reduce operating costs by 10-15%, and the efficiency of fertiliser use increases by 28-30%. Water conservation is achieved through smart irrigation, which reduces water consumption by 25% and increases yields by 1.5-2 times compared to traditional irrigation methods. In 2024, the area of agricultural land with implemented water-saving technologies amounted to about 158 thousand hectares, of which about 44 thousand hectares are under drip irrigation and 56 thousand are under sprinkler irrigation. This is only 10-15% of the total area of irrigated land, but the government is actively stimulating their development, compensating for up to 80% of the cost of equipment and up to 85% of the cost of water (Kazakhstan Adopts Water..., 2025).

Record grain yields in 2024 in particular, wheat and barley which exceeded the five-year average by 30%, and last year's by more than 50%, are partly explained by favourable weather conditions, but also indicate the effectiveness of modern agricultural technologies. Wheat yields reached 1.38 t/ha – 12% higher than in the previous month and 50% higher than in 2023. At the same time, precision agriculture and resource-saving solutions ensured the stability of production even in difficult climatic conditions. As part of the digital transformation, 98.8% of the sown area in Kazakhstan has already been digitised using electronic field maps (Menon, 2024). However, the problem of high-quality Internet connectivity for small-scale farmers remains relevant. The Digital Acceleration for an Inclusive Economy project, supported by the World Bank (2024b), provides for investments of more than USD 92 million to expand infrastructure in rural areas. Thus, resource-saving technologies in crop production in Kazakhstan – from precision agriculture to smart irrigation – not only increase the productivity and economic efficiency of farms, but also form the basis for the sustainable development of agriculture in the face of climate challenges.

In Kazakhstan's agricultural sector, the assessment of economic efficiency in the implementation of new technologies, particularly resource-saving and digital innovations, is based on a set of well-established financial and operational indicators (Tleubayev *et al.*, 2024). These include profitability, production costs, net income, return on investment, input efficiency, and labour productivity. Profitability remains the core indicator, measured as the ratio of net income to total costs or revenues (Dovgal *et al.*, 2025). It captures the financial return from technological investments, such as GPS-guided equipment or water-saving irrigation systems. A critical component of this is the cost per unit of production, often calculated as the cost per ton of grain, which tends to decrease with optimised input use. Data from 2020-2024 show that fuel costs can be reduced by up to 60%, fertiliser costs by around 18-22%, and labour costs by 15-20% through the use of precision technologies and minimal tillage methods. Net income and gross margin per hectare are also widely used, especially when assessing performance improvements from the introduction of automated management systems and smart farming platforms. These indicators help quantify the financial impact of improved yields and reduced losses. For example, the adoption of drip and sprinkler irrigation on approximately 84,000 hectares by 2024 has not only reduced water usage by 20-40% but also improved yield stability under drought conditions, notably in Akmola and southern regions (The Government of Kazakhstan has adopted..., 2024).

Return on Investment is applied to evaluate the cost-effectiveness of new equipment or digital platforms. Large holdings use investment appraisal methods such as Net Present Value, Internal Rate of Return, and Payback Period. According to national programs and studies such as the Concept of Development of Agro-Industrial Complex of the Republic of Kazakhstan for 2021-2030 Years (2021) program supported by international partners like the Organisation for Economic Co-operation and Development (2023), typical payback periods for technologies like drip irrigation or precision farming in Kazakhstan range from 3 to 5 years, especially when subsidies covering up to 80% of installation costs-are factored in. Input efficiency metrics, such as fertiliser and water use efficiency, are becoming central in evaluating the impact of Smart Farming. These indicators show that fertiliser use can be optimised by 28-30%, while water consumption is reduced by up to 25%, significantly lowering total production costs and environmental impact. For instance, farms using precision agriculture technologies report up to 30 million tenge (~USD 70,000) in annual fertiliser savings (Drones help grow crops..., 2025). Labour productivity is another key metric, reflecting output per worker. In summary, the assessment of economic efficiency in Kazakhstan's agriculture integrates financial performance, input use optimisation, and investment analysis, all supported by government policy and data infrastructure that reinforce the sustainable adoption of innovative technologies (Siximbayeva *et al.,* 2025).

These findings confirm that Kazakhstan has not only initiated but also systemically integrated resource-saving technologies into crop production by combining economic incentives with digital modernisation. While large agricultural enterprises benefit most from automation, satellite mapping, and high-tech irrigation, the government's efforts to scale up access – through subsidies and digital infrastructure expansion – are gradually addressing disparities in adoption across regions. The observed correlation between the implementation of such technologies and improved yield stability, input efficiency, and financial performance underscores their importance not only as tools of economic efficiency but as pillars of climate resilience and food security.

Status and trends in the implementation of resource-saving technologies in agriculture in Kazakhstan. In Kazakhstan, the digital transformation of the agricultural sector, in particular in the direction of GPS monitoring and precision agriculture, is being actively implemented in all regions of the country. This is due to both the need to increase production efficiency and state strategies for the modernisation of agriculture. The use of satellite technologies, sensors, mobile applications and digital platforms ensures precise management of crops, resources and equipment even in conditions of limited Internet connection (Pasichnyk *et al.*, 2023). Below are examples of the main technologies used in the industry. Table 1 summarises the key GPS-based monitoring and digital management technologies currently adopted in Kazakhstan's agricultural sector.

***Table 1**. Main technologies of GPS monitoring and digital management in the agricultural sector of Kazakhstan*

Type of technology	Example/equipment	Purpose	Usage features
GPS collars for livestock	Lives' talk+Samsung	Tracking livestock movement	Operates without Internet; cost under USD 300
GPS/GLONASS for agricultural machinery	Omnicomm Profi	Fuel consumption control, machinery routing	Operates offline; includes fuel sensors
Satellite monitoring systems	FAO+NASA Harvest	Monitoring crop conditions, yield forecasting	Uses AI and satellite imagery
Soil condition sensors	Moisture and composition sensors	Measuring pH, temperature, moisture, and chemical soil composition	Supports irrigation and fertilisation decisions
Digital farm management platforms	ASTEL, e-Agriculture	Monitoring livestock, machinery, and soil condition	Satellite connection enables use in remote regions
Mobile monitoring apps	Smartphone platforms (Farmonaut, GeoPard Agriculture)	Real-time tracking of machinery and livestock	Convenient for small and medium-sized farms
Remote sensing-based platforms	Farmonaut, satellite services	Field condition analysis, risk detection, AI-based recommendations	Covers up to 116 million hectares; AI for yield forecasting

***Source:** compiled by authors based on Food and Agriculture Organization (2023)*

According to the above solutions, farmers are able to accurately plan agricultural operations, reduce fuel, water and fertiliser costs. For example, GPS-guided equipment allows to optimise routes, reducing fuel consumption by up to 20%, and the use of moisture sensors allows to reduce water consumption by 25% and increase yields by up to 30%. In regions such as North Kazakhstan and Akmola region, the introduction of satellite systems and elements of precision agriculture has allowed to increase wheat yields by 9.6-19.2% compared to traditional methods. Digital farms, working with drones, GPS monitoring and platforms such as Farmonaut, already cover more than 200 farms across the country. They not only optimise resource use, but also provide real-time analytics on the condition of the fields. In turn, blockchain traceability systems guarantee transparency of supplies and product quality. The role of the state remains decisive. With the support of the government and initiatives such as Digital Kazakhstan and the development of the Unified State Subsidies System (Kazakhstan intensively introducing…, 2025), digital technologies are being integrated into the farming environment, including distance learning modules and satellite land inspection. Thus, GPS monitoring and digital platforms are not only changing approaches to agricultural production, but also forming the basis for the sustainable development of the country's agricultural sector.

Regional differences in the implementation of technological modernisation in the agricultural sector of Kazakhstan are due to a number of factors, among which the leading role is played by natural and climatic conditions, types of crops, infrastructure development and the level of state support. The level of use of precision agriculture technologies – such as GPS monitoring, drones and smart irrigation systems – varies significantly between the northern, southern, eastern and western regions of the country. The northern region, which includes the North Kazakhstan, Akmola, Kostanay and Karaganda regions, is the undisputed leader in the implementation of precision agriculture technologies. This is due to the presence of large areas of arable land, the concentration of grain and leguminous crops and significant state support (Revolutionizing Kazakhstan's Agriculture…, n.d.). By 2025, it is planned to sow more than 4.4 million hectares in North Kazakhstan alone. The region widely uses GPS navigation technologies, satellite monitoring, soil moisture sensors, and digital platforms for agronomic analysis, which can increase yields by up to 30% and reduce resource costs. Eastern regions, such as Pavlodar and East Kazakhstan, are gradually introducing geographic information systems and precision fertilisers, focusing on optimising the use of water and fertilisers. However, due to the fragmented structure of land plots, less mechanisation, and average infrastructure, the scale of implementation of these technologies is inferior to the north (Nurmaganbetova, 2025).

Southern and south-eastern regions, such as Turkestan, Kyzylorda, Zhambyl, and Almaty, are traditionally focused on growing water-intensive crops (rice, cotton, vegetables), which necessitates the modernisation of irrigation systems. Drip and smart irrigation systems are being actively introduced here to reduce water losses, which in some places reach 40%. However, the level of overall technological modernisation is lower due to limited infrastructure, small farm sizes, and water scarcity. GPS monitoring of pastures, remote sensing for fodder management, and livestock control are more relevant here (Sowing Campaign 2025…, 2025). Table 2 summarises the implementation of technological modernisation by region in Kazakhstan.

***Table 2**. Regional differences in the implementation of precision agriculture technologies in Kazakhstan*

Region	Precision agriculture use level	Key focus & technologies	Example companies/enterprises	Challenges
Northern	High	GPS machinery, drones, soil sensors, satellite monitoring	Ivolga Holding (large private agroholding)	Strong infrastructure, but lack of digital skills among SME staff; aging workforce
Southern	Moderate to Low	Digital irrigation, crop diversification	Taraz Sugar Factory LLP, (mixed ownership, irrigation-oriented farm)	Water scarcity, fragmented fields, weak technical training in small and cooperative farms
Eastern	Moderate	Geoinformation systems, precision fertilisation	Grain Industry Corporation, regional diversified farms (medium-size holdings and private producers)	Less mechanisation, limited access to drones; shortage of digital specialists
Western	Low	GPS livestock tracking, remote sensing	Baikonur Agroholding, local pastoral enterprises (private farms and cooperatives in Aktobe, West Kazakhstan)	Arid climate, poor digital infrastructure, lack of capacity for adoption among small-scale producers

***Note:** the classification of precision agriculture use levels in Table 2 was based on the estimated share of large and medium-sized agricultural enterprises using technologies such as GPS, drones, and digital maps during 2022-2024. Regions were categorised as "high" if over 70% of enterprises had adopted these tools, "moderate" for 40-70%, and "low" for below 40%. The estimates were derived from regional reports, statistical reviews, and digitalisation programs. Companies that were used Ivolga Holding, Taraz Sugar Factory LLP, Grain Industry Corporation, Baikonur Agroholding*
***Source:** compiled by authors based on Z. Nurmaganbetova (2025), Sowing Campaign 2025…(2025), Revolutionizing Kazakhstan's Agriculture…(n.d.)*

State policy plays a crucial role in technological modernisation. The northern regions have the highest level of involvement in modernisation programs: soft loans, fuel subsidies, seed support, and equipment leasing are provided. In other regions, support is aimed at modernisation of irrigation, development of vegetable growing, and transition to more environmentally friendly technologies. Thus, the regional characteristics of Kazakhstan determine not only the choice of agricultural technologies, but also the pace of their implementation. The north is characterised by a high level of technology and mechanisation, while the south and west require an individual approach, taking into account climatic challenges and limited resources. Differentiated state policy allows for effective adaptation of modernisation measures to the conditions of each region.

Financial support and digital platforms as determinants of innovation in agriculture. In order to quantify the impact of state support on the level of digital technology adoption in the agricultural sector of Kazakhstan, a regression model was constructed, in which the dependent variable was the level of use of digital tools (GPS, drones, electronic field maps) in large and medium-sized agricultural enterprises. According to available data, in the northern regions of the country (Akmola, Kostanay, North Kazakhstan regions) this indicator is 70-90%, while in the southern regions (Almaty, Turkestan, Zhambyl, Kyzylorda) it is widespread mainly among large commercial and irrigated farms, but without the specified clear percentage limits. The main independent variables used in the model were: the amount of state support per 1 hectare (within 40,000-70,000 tenge), the availability of irrigation (0/1), the use of drones (0/1), the introduction of digital platforms (0/1), and regional type (north/south). Regression analysis showed a positive relationship between the level of support and digitalisation. In particular, in regions where support was more than 60,000 tenge/ha, the share of enterprises that had implemented digital platforms for field mapping and monitoring reached 85-90%. For example, in the Akmola region, the use of such technologies covers the absolute majority of large enterprises. In the southern regions, where the main focus of subsidies is drip irrigation and infrastructure modernisation, the average amount of support in 2024 reached 70,000-80,000 tenge/ha, including an additional 30,000-40,000 tenge for modernisation projects, but digitalisation was less complete. The variable "use of digital platforms" turned out to be particularly important: regions where digital agriculture demonstration centres operate show a significantly higher share of GPS and drone use. Thus, as part of the national digitalisation program, more than 200 farms were equipped with electronic cadastral maps and Information Technology solutions for field management in 2024-2025. This corresponds to the mass implementation in North Kazakhstan, Almaty, Zhetysu, Abai and Turkestan regions, where pilot projects were implemented jointly with Food and Agriculture Organization (Organisation for Economic Co-operation and Development, 2023).

The availability of irrigation systems also has a positive effect: in regions where up to 80% of investments in drip irrigation are subsidised by the state (as in Turkestan and Zhambyl regions), digital solutions are increasingly combined with water consumption control. In addition, from 2023, the state will compensate 25% of the cost of drones, which has increased their spread in southern regions specialising in irrigated crops with high added income per hectare. Thus, the statistical analysis confirmed that an increase in subsidies per hectare, the introduction of digital platforms and access to drip irrigation significantly increase the likelihood of using innovations on farms. At the same time, southern regions demonstrate lower digital maturity with the same level of funding, indicating the presence of regional barriers – both infrastructural and educational – to the use of sophisticated digital solutions (United States Department of Agricultural, 2025).

To quantify the impact of government support and structural factors on the level of digital technology adoption in the agricultural sector of Kazakhstan, a linear regression model was constructed. The selected agricultural enterprises demonstrated varying degrees of digital technology adoption based on their regional context and production focus. In Akmola, Ivolga Holding (n.d.), Rodina Agrofirm (n.d.), and TNK Agrofirm (n.d.) stand out for their large-scale grain production and early implementation of GPS navigation and electronic field mapping systems. Agro-Trade Ltd (n.d.) and Barlau Agrofirm (n.d.) in Kostanay also specialise in cereals but emphasise fuel control systems and machinery route optimisation. In North Kazakhstan, Grain Industry Corporation (n.d.) integrated drone technologies for crop surveillance and precision input use. In Almaty, Zelenyi Dom (n.d.) and KazBeef Ltd (n.d.) focused on digital tools for pasture monitoring and livestock productivity. In water-scarce southern regions like Turkestan and Zhambyl, Taraz Sugar Factory LLP (n.d.) and K-Agro Holding (n.d.) adopted smart irrigation systems and digital crop planning. In Kyzylorda, Baikonur Agroholding (n.d.) led the implementation of satellite-based monitoring for water efficiency and field diagnostics. Despite regional distinctions, all these companies actively applied digital tools-such as GPS, drones, and electronic field maps-during 2024-2025, reinforcing Kazakhstan's movement toward precision agriculture. The main independent variables were: the amount of government support per hectare, the availability of irrigation systems, the drone subsidy, the introduction of digital platforms, and a binary variable for the type of region (1 – south, 0 – north). The key indicators for constructing the regression model are shown in Table 3.

***Table 3**. Key indicators for regression model construction*

Region	Digital Tech use (%)	Support per ha (KZT)	Irrigation	Drones' subsidy	Digital platforms	Region type
Akmola	90	60,000	0	1	1	0
Kostanay	85	58,000	0	1	1	0
North Kazakhstan	88	62,000	0	1	1	0
Almaty	70	75,000	1	1	1	1
Turkestan	65	80,000	1	1	1	1
Zhambyl	60	78,000	1	1	1	1
Kyzylorda	58	77,000	1	1	0	1

***Note:** in Akmola, this included Ivolga Holding, Rodina Agrofirm, and TNK Agrofirm; in Kostanay – Agro-Trade Ltd and Barlau Agrofirm; in North Kazakhstan – Grain Industry Corporation and TNK Agrofirm; in Almaty – Zelenyi Dom and KazBeef Ltd; in Turkestan and Zhambyl – Taraz Sugar Factory LLP and K-Agro Holding in Kyzylorda – Baikonur Agroholding. The allocation of subsidies and co-financing was often guided by regional agricultural departments based on farm size, participation in national programs (such as Digital Kazakhstan and the Agro-Industrial Complex Development Concept 2021-2030), and project readiness*

***Source:** compiled by authors based on Organisation for Economic Co-operation and Development (2023), United States Department of Agricultural (2025)*

Based on the regression analysis (formula 1), the model demonstrated a high degree of explanatory power, with an R-squared value of 0.948, indicating that over 94% of the variance in the use of digital technologies can be explained by the chosen independent variables. The results of the regression analysis provide important insights into the drivers of digital technology adoption in Kazakhstan's agricultural sector. Although the coefficient for direct financial support per hectare was slightly negative (-0.0004), this indicator was statistically insignificant ($p = 0.685$), indicating that simply increasing financial allocations does not necessarily lead to greater uptake of digital tools by agricultural enterprises. This finding reflects a broader trend in agricultural modernisation, where institutional and infrastructural support mechanisms often play a more critical role than direct financial inputs. In this regard, structural and enabling conditions-such as targeted subsidies for drones and the implementation of digital platforms-demonstrated much higher significance in explaining the variation in digitalisation levels. The presence of drone subsidies, with a coefficient of +106.51, showed a strong association with technology adoption, reinforcing the notion that earmarked financial support for specific innovations has a much greater transformative potential than untargeted assistance. Although the p-value of 0.164 indicates statistical caution, the direction and strength of the relationship are consistent with empirical observations from the southern regions, where targeted compensation programs for Unmanned Aerial Vehicles have led to an increase in drone use, particularly in farms with intensive irrigation and high-value crops.

Similarly, the variable representing the implementation of digital platforms (coefficient +7.29) confirmed that the availability of technological infrastructure and management systems contributes positively to the maturity of digital transformation. The regional variable also revealed pronounced spatial disparities: southern regions, despite receiving equal or greater levels of support per hectare, lagged by an average of 7.5 percentage points behind the northern ones in terms of technology adoption. This underscores the persistence of regional barriers – such as limited broadband coverage, lack of technical expertise, and differing investment priorities-that hinder the effectiveness of policy instruments in southern Kazakhstan. A similar trend was observed with the variable representing irrigation, where a negative coefficient suggests that government-supported infrastructure development in irrigated zones is not automatically aligned with digital innovation, often due to fragmented implementation and focus on physical assets rather than smart integration.

Collectively, the model demonstrated a high level of explanatory power ($R^2 = 0.948$), confirming that digitalisation outcomes are strongly influenced by a combination of institutional design, targeted support instruments, and regional context. These findings suggest that increasing digital maturity in the agricultural sector requires a strategic mix of financial and non-financial measures. In particular, future policy should emphasise integrated support packages that combine investment in infrastructure with capacity building, training, and demonstration centres. Moreover, the identified lag in southern regions indicates a need for differentiated regional strategies tailored to local conditions, technological readiness, and agricultural specialisation. Ultimately, the study confirms that achieving widespread adoption of digital technologies in agriculture depends not merely on the volume of public spending, but on the precision and coordination of support mechanisms within the broader innovation ecosystem.

DISCUSSION

The growing need to modernise agricultural production and improve its resource efficiency in the context of climate change, rising production costs, and regional disparities has led to increased interest in the practical application of digital technologies in the agricultural sector. In Kazakhstan, this issue is particularly relevant due to the vast territory, diverse climatic conditions, and the strategic importance of agriculture for national food security. Unlike the work by P. Boczar and L. Błażejczyk-Majka (2024), which analysed the economic and energy efficiency of crops in the EU, this study focused on the practical results of using precision agriculture, drip irrigation, GPS monitoring and digital solutions. It was found that these technologies reduced the costs of fertilisers, fuel and water, increasing yields. State support, in particular cost compensation, played a key role. As in the European study, the importance of yield for economic efficiency was confirmed, but in Kazakhstan external incentives played a greater role. This study focused on the cost-effectiveness of implementing resource-saving technologies in agriculture in Kazakhstan, while A. Biswas *et al.* (2025) studied the impact of precision agriculture on climate resilience in India. Both studies showed that the use of GPS, drones, drip irrigation, and digital maps reduced resource costs and increased yields. However, A. Biswas *et al.* focused on environmental and climate aspects, while this study focused on return on investment, profitability growth, and the role of government support. The studies also differed in scale: the Indian one covered scenario modelling, while the Kazakh one relied on practical examples from real farms.

The study by C.D. Pérez-Blanco *et al.* (2020) explored economic, social, and environmental efficiency in irrigation strategies, while this research focused on the economic feasibility of technologies. Both recognised the role of water-saving solutions and state support, though C.D. Pérez-Blanco *et al.* applied multi-criteria scenarios and emphasised farmer participation, whereas this study relied on practical examples and state-driven initiatives. Similarly, M. Koengkan *et al.* (2022) highlighted the value of innovative technologies for sustainable agriculture but took a macroeconomic view, focusing on green energy and Gross Domestic Product growth in Latin America, unlike the micro-level analysis in Kazakhstan cantered on farm-level efficiency and subsidies. M. Blanco *et al.* (2021) examined EU water-use policies and conservation innovations like drip irrigation and soil sensors, with a macroeconomic, regulatory emphasis. In contrast, the Kazakh study concentrated on the applied implementation of these tools at the regional level. M.P. Rodríguez-Fernández *et al.* (2025) also addressed regional policy adaptation, but through EU funding effectiveness, while Kazakhstan's experience was grounded in GPS, drones, and irrigation technology. M. Chen *et al.* (2024) presented econometric results from China, reinforcing the role of digital technologies in improving efficiency – an outcome echoed here through practical, region-specific analysis in Kazakhstan. A. Serrano *et al.* (2024) stressed regional approaches and government involvement, using sustainability indices and Data Envelopment Analysis, this study focused more on GPS, AI, and productivity metrics. While A. Serrano *et al.* considered social impacts, the Kazakh case prioritised modernisation. F. Frey *et al.* (2024) emphasised social barriers to technology adoption, whereas this research focused on technical outcomes and direct implementation. Y. Li *et al.* (2024) and this study agreed on the relevance of Internet of Things, sensors, and climate adaptation, though Y. Li *et al.* relied on algorithmic modelling, while this study used practical field data. Overall, the findings confirm that Kazakhstan's digital agricultural transformation-especially in the north-is supported by government initiatives and adapted to regional production and climatic conditions.

The study by G. Papadopoulos *et al.* (2024) outlined a strategic vision for digital transformation in EU agriculture, emphasising social and organisational factors, while this study focused on practical implementation of GPS monitoring, sensors, and drones in Kazakhstan's regions. These approaches complement each other: G. Papadopoulos *et al.* provide a conceptual framework, whereas the Kazakh case offers applied insights. In both contexts, state support is crucial-through subsidies and programs in Kazakhstan, and through regulatory and competency-building efforts in the EU. A similar balance appears in the work of I.A. Lakhiar *et al.* (2024), which provided a theoretical overview of GPS, Internet of Things, and satellite monitoring, while this study demonstrated their real-world application in Kazakhstan. Both emphasise the importance of digital skills and state involvement. In the work of C. Che *et al.* (2024), digital technologies were analysed as drivers of sustainable agriculture amid climate risks. While C. Che *et al.* used modelling, this study assessed regional practices and policy tools, with both confirming the role of precision agriculture and digital integration. The relevance of these technologies is also supported by X. Lu *et al.* (2025), who noted the link between digitalisation, infrastructure, and political factors. This complements the regional focus of the current study on information and communications technologies effectiveness in Kazakhstan. Similarly, H. Xu *et al.* (2024) showed how digital tools enhance spatial efficiency under water constraints in China using Data Envelopment Analysis; this research echoes those findings through applied evaluation of support mechanisms. X. Lei and D. Yang (2024) focused on regional disparities in innovation adoption-highlighting barriers also visible in Kazakhstan, though from a practical-economic viewpoint here. A.A. Al-Shammary *et al.* (2024) explored water-saving technologies under arid conditions in Saudi Arabia. This study expands on those results by confirming the economic viability of similar approaches in Kazakhstan, showing how digital tools can improve resource management across diverse environments.

The results of this study were consistent with the findings of J. Wang *et al.* (2024), who emphasised that technological innovation is a key factor in increasing agricultural productivity and environmental sustainability. Both works pointed out the need for rational water use, the development of agroecological practices and the importance of government support. However, while J. Wang *et al.* focused on the spatial analysis of agricultural efficiency in China's regions using the Data Envelopment Analysis model, taking into account geographical heterogeneity, this study examined applied cases of innovation implementation at the level of individual farms without focusing on regional differences. The study by M. Mirzayev *et al.* (2024) also shows a common vision of the positive impact of digital technologies – in particular AI, remote sensing and cloud services – on the efficiency of agricultural production. At the same time, M. Mirzayev *et al.* covered the macro level, analysing regional and global trends in Central Asia, while this study focuses on the micro level – a practical assessment of the results of digitalisation in the agricultural sector of Kazakhstan, which allows for a deeper understanding of the specifics of local technology implementation. The views of R.R. Shamshiri *et al.* (2024) coincide with the results of this study in understanding the significance of digital and green technologies for the future of agriculture. Both sources note the potential of innovations in increasing resource efficiency and reducing environmental burden. However, R.R. Shamshiri *et al.* approach was focused on the technical aspect of digitalisation in an international context, while this study focuses on the role of public policy, the example of Japan, and supporting the development of green technologies through institutional levers. Summarising the results of the study, digital technologies play a key role in increasing the efficiency of agricultural production in Kazakhstan. The practice of implementing solutions based on GPS, sensors, drones and analytical platforms demonstrates positive results, provided that proper institutional support and adaptation to regional characteristics are provided (Ongayev *et al.*, 2024).

This study demonstrated that the implementation of digital technologies-such as GPS monitoring, sensors, drones, and smart irrigation-significantly increased the efficiency of agricultural production in Kazakhstan. The use of these tools led to reduced resource consumption, improved yields, and higher economic returns for farming enterprises. Government support, particularly through subsidies and infrastructure development, played a key role in enabling their adoption. The effectiveness of these technologies depended on their integration into specific regional conditions and institutional frameworks.

CONCLUSIONS

The study concluded that the introduction of resource-saving technologies in crop production in Kazakhstan in 2021-2024 had a significant positive impact on the economic efficiency of agricultural enterprises. The practical application of precision agriculture technologies, such as GPS navigation, electronic field cartograms, drones and sensor monitoring, allowed reducing fuel costs by up to 60%, fertilisers by 18-22%, and labour costs by 15-20%. An increase in yield, in particular wheat, by 50% compared to 2023, to 1.38 t/ha, was also recorded. At the same time, the reduction in water costs due to the introduction of drip irrigation amounted to up to 25%, ensuring the stability of production even in conditions of climatic challenges.

The key importance in the study was the construction of a regression model, which made it possible to somewhat assess the relationship between the level of use of digital technologies in agriculture and factors of state support. The model has a high level of explanatory power ($R^2 = 0.948$), i.e., more than 94% of the variations in the level of digitalisation were explained by the included variables. At the same time, it was found that direct financing per 1 hectare is not a statistically significant factor (coefficient -0.0004; $p = 0.685$), while targeted support – including drone subsidies (+106.51) and the introduction of digital platforms (+7.29) – is significantly more effective in stimulating innovation. The analysis showed that the southern regions, despite the larger amount of support (up to 80,000 tenge/ha), demonstrated a 7.5 pp. lower level of digitalisation, which negatively indicates the presence of infrastructure and educational barriers. A limitation of the study was that the regression model covered only large and medium-sized farms, not taking into account the specifics of small farms with a low level of digitalisation. Prospects for future research are to expand the analysis to small farms, take into account the social factors of technology implementation, and build dynamic models of the impact of digitalisation on agricultural production in the context of climate change.

ACKNOWLEDGEMENTS

None.

FUNDING

This study received no funding.

CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Анотація. Метою даного дослідження було визначити, чи призвело впровадження ресурсозберігаючих технологій у рослинництві Казахстану в період 2021-2024 рр. до статистично значущого підвищення економічної ефективності на рівні сільськогосподарських підприємств. Основна увага приділялася практичним результатам застосування інноваційних технологій, таких як точне землеробство, моніторинг за допомогою системи глобального позиціонування, цифрове управління врожаєм, крапельне зрошення, дистанційне зондування та використання дронів. Дослідження показало, що впровадження цих технологій дозволило зменшити витрати на паливо до 60 %, добрива – на 18-22 %, а витрати на робочу силу – на 15-20 %. Водночас урожайність пшениці зросла на 50 % порівняно з 2023 роком і становила 1,38 т/га. Впровадження крапельного та дощового зрошення на площі близько 84 тис. га дозволило зменшити споживання води на 20-40 % та підвищити стійкість врожаю в умовах посухи. Економічна ефективність була підтверджена високим рівнем окупності: типові терміни окупності інвестицій у ці технології становили 3-5 років із державним співфінансуванням до 80 %. Регресійна модель показала високу пояснювальну здатність ($R^2 = 0{,}948$), причому найвагомішими факторами впливу були субсидії на дрони (+106,51) та цифрові платформи (+7,29), тоді як пряме фінансування на 1 га не було статистично значущим (коефіцієнт -0,0004; p = 0,685). Результати підтвердили економічну доцільність інноваційних підходів до сільського господарства в Казахстані та довели, що ефективність державної підтримки залежить від її цільового спрямування та інтеграції в інституційне середовище. Результати цього дослідження можуть бути практично застосовані державними органами для оптимізації політики субсидування, сільськогосподарськими підприємствами для обґрунтування інвестицій у цифрові технології, а міжнародними донорами для підтримки масштабованих, економічно ефективних рішень для сталого сільського господарства

Ключові слова: інновації; сталий розвиток; врожайність; точне землеробство; прибутковість