International Journal of Agriculture and Biosciences 2025 xx(x): xx-xx.
https://doi.org/10.47278/journal.ijab/2025.085
This is an open-access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
RESEARCH ARTICLE
eISSN: 2306-3599; pISSN: 2305-6622

Ensuring Sustainable Crop Production in the Steppe Zone of Kazakhstan through the Application of Precision Agriculture Methods: A Case Study of Spring Wheat Cultivation

Aliya Yskak [1,*], Almabek Nugmanov [1], Yuriy Tulayev [2], Saniya Tulkubayeva [2], Tatiana Paramonova [3], Gulnaz Yermoldina [1], Vadim Chashkov [1] and Karina Kazbekova [1]

[1]Akhmet Baitursynuly Kostanay Regional University, Kostanay, Republic of Kazakhstan
[2]Agricultural experimental station "Zarechnoye" LLP, Zarechnoye, Kostanay region, Republic of Kazakhstan
[3]Faculty of Soil Science, Lomonosov Moscow State University, Moscow, Russia
*Corresponding author: ayskak@mymail.academy

ABSTRACT

This study aimed to enhance agricultural productivity in Northern Kazakhstan by comparing conventional farming practices with modern precision agriculture technologies. The research was carried out during the 2023 growing season on the agricultural fields of the 'Altyn-Gul' enterprise. Precision agriculture tools such as NDVI for vegetation monitoring, remote sensing for soil fertility analysis, and nitrogen-phosphorus fertilizer trials were utilized. Observations included phenological stages, soil moisture levels, and nitrogen status in plants using devices such as GreenSeeker and N-tester. Statistical analysis was performed with a significant level of 5%. The results demonstrated that differentiated applications of nitrogen and phosphorus fertilizers significantly increased wheat yield, with productivity in certain zones rising by 127% compared to control plots. The integration of NDVI and soil fertility mapping optimized fertilizer application, leading to more uniform crop development and improved overall productivity.

Keywords: Precision agriculture; Northern Kazakhstan; NDVI; Wheat yield optimization; Sustainable farming practices

Article History
Article # 25-235
Received: 02-May-25
Revised: 06-Jun-25
Accepted: 19-Jun-25
Online First: 26-Jun-25

INTRODUCTION

Problem Statement

Agriculture is one of the key factors in diversifying the global economy, ensuring long-term sustainable development, food security, and improving living standards. Kazakhstan possesses enormous agricultural potential due to its vast agricultural lands (217 million hectares), favorable growth conditions, and low population density. Unfortunately, even with current governmental support, the agricultural sector contributes less than 10% to the country's GDP and remains unproductive and uncompetitive (Abuova et al., 2020). The main branches of Kazakhstan's agricultural sector are livestock breeding and crop production, with the latter forming the foundation of the country's agriculture and accounting for more than 54% (Danshin, 2024). According to Inform Buro (2022), in 2021, Kazakhstan's agricultural exports were dominated by spring crops such as wheat, barley, flaxseed, sunflower oil, and cotton fiber. Spring crops, particularly spring wheat, are among the primary crops cultivated in Kazakhstan. However, their efficiency and productivity remain generally low due to reliance on subsistence farming practices that employ traditional methods such as crop rotation, crop alternation, and shifting tillage. The low levels of productivity and investment are attributed to technological backwardness, insufficient knowledge and infrastructure, as well as soil degradation caused by erosion, overharvesting, and overgrazing (Zhengizkhan, 2023). The use of traditional farming methods, which include practices such as crop rotation, surface seeding, natural pest control, and the use of organic fertilizers, although accessible, does not align with the principles of sustainable development and should be replaced by modern sustainable agricultural practices such as pre-sowing soil preparation, rational farming and intermediate application of nitrogen fertilizers (Muhie, 2022).

Kazakhstan's agricultural practices are significantly influenced by its geographical variety. The nation sustains a wide variety of crops and cattle thanks to its enormous steppes, mountain regions, and extremely fruitful river

Cite this Article as: Yskak A, Nugmanov A, Tulayev Y, Tulkubayeva S, Paramonova T, Yermoldina G, Chashkov V and Kazbekova K, 2025. Ensuring sustainable crop production in the steppe zone of kazakhstan through the application of precision agriculture methods: A Case Study of Spring Wheat Cultivation. International Journal of Agriculture and Biosciences xx(x): xx-xx. https://doi.org/10.47278/journal.ijab/2025.085

A Publication of Unique Scientific Publishers

In-Press

basins. Due to their fertile soils and favorable climate, the southern regions – such as Almaty and Turkestan – are able to produce more agricultural output. Conversely, northern regions like North Kazakhstan and Pavlodar are typically hampered by harsher weather that results in low agricultural output and crop yields. Making adequate agricultural policies that are tailored to the demands of each and every location requires an understanding of these geographic and climatic variables (Kenzheali & Makhmetova, 2024). Northern Kazakhstan's agricultural productivity is still a major concern because traditional farming practices, which are still widely practiced there, frequently do not take these regional differences into account, resulting in inefficient resource use and uneven crop yields. The need for efficient and environmentally responsible farming systems is growing as the world's food demand rises and environmental sustainability becomes more and more important. Recent studies like Gouis et al. (2020) have shown that wheat yields globally were once stagnated due to factors that can be controlled efficiently by traditional agricultural practices, such as variable climates, heat stress, and less favorable preceding crops. Baimuratov et al. (2021) highlighted that conventional farming practices caused detrimental effects on the environment, including soil erosion, soil degradation, and groundwater pollution due to their heavy use of chemicals. They further suggested that in order to achieve both environmental preservation and economic and social prosperity, farming systems ought to be more sustainable, and precision farming is one potential remedy for this issue. Traditional/conventional approaches typically involve uniform application of chemical inputs (pesticides, herbicides, fertilizers) across entire fields, regardless of spatial heterogeneity in soil fertility, moisture availability, or crop health. This one-size-fits-all method often results in nutrient imbalances, overuse or underuse of fertilizers, and uneven crop development. These inefficiencies not only reduce yields but also contribute to environmental degradation through leaching, runoff, and greenhouse gas emissions (Zafar et al., 2025). The core research problem addressed in this study is the inefficiency of conventional agricultural practices in optimizing wheat production under the specific agronomic and environmental conditions of Northern Kazakhstan (Тогузова et al., 2023). In order to assess whether differentiated application of nitrogen and phosphorus fertilizers, guided by real-time data on crop and soil status, can significantly increase wheat yields in the region, the current study aims to close this gap by methodically comparing traditional farming methods with precision agriculture tools, such as remote sensing, NDVI (Normalized Difference Vegetation Index) monitoring, and soil fertility mapping. Determining the usefulness of precision technologies in field settings is a crucial component of the issue. Precision agriculture offers a means of optimizing input use, thereby potentially reducing environmental impacts while maintaining or increasing productivity. As a result, this study supports international initiatives for sustainable development goals and climate-smart agriculture (Spychak et al., 2025). The motivation for conducting this research lies in the urgent need to sustainably enhance the efficiency and productivity of Kazakhstan's agricultural sector through the application of advanced methods such as data analysis, GPS, unmanned aerial vehicles, and new technologies. Through these methods, farmers can significantly increase yields and efficiency, thereby reducing costs and environmental impact. We also aim to serve as an example for other developing countries by experimentally demonstrating the advantages of precision agriculture methods.

Recent innovations in precision agriculture include big data, machine vision technologies, the Internet of Things (IoT), artificial intelligence, machine learning, deep learning, guidance systems, high-throughput phenotyping, robotics, and unmanned aerial vehicle technologies (Singh et al., 2020; Karunathilake et al., 2023).

Big data analytics tools are applied in precision agriculture to interpret large datasets on agricultural processes and to support effective decision-making. These analytical tools include data mining, statistics, artificial intelligence, predictive analytics, and neural language processing, and their forecasts assist farmers in solving complex challenges (Franzen & Mulla, 2015; Bhat & Huang, 2021). Big data are typically utilized through machine language, cloud computing, image processing, modeling, statistical analysis, normalized difference vegetation indices (NDVI), or geographic information systems to identify correlations, patterns, and trends within large datasets (Cravero & Sepúlveda, 2021).

Machine vision or agro-vision technology is used for image analysis and monitoring of crop growth processes. It also holds potential for detecting plant stress, nutrient deficiencies, weed presence, and diseases on leaves and fruits (Shin et al., 2023).

The Internet of Things is employed in agricultural sensors, cloud storage systems, smart devices such as drones, real-time remote control, and high-throughput phenotyping, providing better coverage, bandwidth, connection density, and end-to-end latency (Karunathilake et al., 2023). The existence of IoT architecture can address the issue of large data volumes by enabling high-speed data exchange (Saranya et al., 2023). Artificial intelligence is used to analyze large datasets to identify hidden patterns, thereby transforming agricultural data into meaningful information (Tanikawa, 2018). These patterns are utilized to detect diseases and pests and to predict yields. Machine learning and deep learning algorithms are employed to validate data and enhance the efficiency of smart farming. High-throughput phenotyping is a new method in precision agriculture that uses remote sensing, drones, artificial satellites, spectral imaging, and robotics to collect phenotypic data on plants, such as traits, growth rates, disease resistance, and moisture content (Haroon et al., 2022). This allows farmers to gain insights into plant behavior and aids in making informed decisions regarding sowing timing, irrigation methods and amounts, fertilizer application, and pest control (Chawade et al., 2019). A significant factor contributing to the reduced efficiency of spring crop cultivation is the soil load resulting from various

In Press

farming practices (e.g., traditional farming methods), leading to quality deterioration, nutrient loss, and overall yield decline. Precision agriculture methods, such as remote sensing, can be utilized to reduce soil load. Remote sensing technologies allow the analysis of soil composition (minerals, surface roughness, organic matter content, and moisture) and monitoring of soil degradation. This technology also enables tracking of soil degradation phenomena such as erosion, desertification, and salinization (Wang et al., 2023).

The Normalized Difference Vegetation Index (NDVI) is one of the most frequently used indicators in remote sensing. It uses the light reflectance ratio in the visible and near-infrared spectra to determine the quantity and condition of vegetation on a site. It can be used to monitor vegetation recovery and changes in plant cover (Team Cropin, 2021). Soil quality is crucial for improving the yield of spring crops. Nutrient-rich soil should contain sufficient levels of nitrogen, phosphorus, and potassium, as well as moderate amounts of sulfur, magnesium and calcium. These nutrients play an essential role in plant metabolic processes, and their deficiency can lead to yield reduction. Given the proven impact of nitrogen and phosphorus on plant growth and root morphology (Razaq et al., 2017), they are included in the majority of fertilizer compositions worldwide.

Typically, fertilizers offer advantages such as increasing crop yields, enriching soil through the supply or replenishment of micronutrients, and ensuring resistance to nutrient leaching (organic fertilizers). However, these benefits are accompanied by significant drawbacks, including nutrient overabundance, salt burn, runoff due to water solubility, excessive growth, environmental concerns, and reduced soil fertility caused by changes in local microorganisms, loss of beneficial bacteria, and so on (Hazra, 2016). Traditional agriculture assumes widespread application of fertilizers, pesticides, and herbicides, which have proven ineffective and harmful to the environment and human health due to overexposure or improper handling (Dhananjayan et al., 2019). In precision farming, farmers focus on reducing production costs and increasing profitability. In Brazil's Cerrado region, agrochemical usage was reduced through the application of precision spraying systems and real-time sensors (Zanin et al., 2022), which is only one of the many applications that precision farming offers (Noor et al., 2022; Anastasiou et al., 2023).

Precision agriculture promotes sustainable agricultural development and efficient resource management. Precision irrigation methods, such as soil moisture monitoring, drip and micro-irrigation, and water quality management, help to use water rationally and prevent shortages. The use of soil analysis methods and the timely application of nutrients ensures efficient nutrient use. Remote sensing and NDVI assist in pest and disease control, while drones and IoT systems help monitor crops and agricultural equipment (Khose et al., 2023). The purpose of this study is to address these agricultural challenges by comparing the efficiency of spring crop cultivation using traditional methods, such as crop rotation, with modern precision agriculture methods that take into account soil conditions, moisture levels, sowing times, and historical vegetation data to optimize resources and improve yields.

MATERIALS & METHODS

Study Design

During the spring fieldwork season of 2023, remote monitoring of changes in the vegetation index was conducted on the fields of "Altyn-Gul" LLP.

Research Methods Used

The experimental setup at the base farm of "Altyn-Gul" LLP included the following:

Development of an optimal basic mineral nutrition scheme for cereal crops. Use of remote monitoring to observe vegetation over an area of no less than 100 hectares. Creation of a biomass distribution map highlighting homogeneous zones based on the NDVI index.

Records and Observations

The experiments were conducted (in two replicates) within the system of grain-fallow and crop rotation practices, with the following records and observations performed (Table 1): 1. Phenological observations were carried out remotely and using portable devices such as GreenSeeker, N-tester, and visual estimation methods, following established methodologies (Maisuryan, 1964; Gorin & Spencer, 1968). The recorded stages included sowing dates, full sprouting, tillering, budding, flowering, pod formation, maturation, and harvesting.

2. Agrometeorological observations were conducted independently using readings from the Caipos automatic weather station and data from the Kostanay agrometeorological station. Daily average air temperature and the sum of effective temperatures were measured, and precipitation amounts were recorded throughout the growing season.

3. Field germination and plant stand density were measured across four plots of 1m² each in all replicates of the experiment, supplemented by remote monitoring tools.

4. Determination of productive moisture reserves in the soil profile (up to 1 meter) was performed in 10cm layers before sowing and before harvesting (Vorobyev & Brandt, 1997).

5. Soil samples were collected before sowing to assess the content of key mineral nutrients, including nitrate nitrogen ($N\text{-}NO_3$), available phosphorus (P_2O_5), exchangeable potassium (K_2O), mobile sulfur (S), and organic matter content in the 0–20cm layer. Samples were prepared and submitted to the accredited laboratory of "Zarechnoye" LLP. Based on the data obtained, recommendations for nitrogen-phosphorus fertilizer application were developed to increase yield in the studied plots.

6. Weed infestation was assessed at the stage of full sprouting and before harvest using a quantitative-weight method, specifying the weed species composition over four plots of 0.25m² each.

7. Use of precision positioning systems during pre-sowing tillage and fallow field treatment.

8. Sampling of plant sheaves to determine yield size, plant productivity and organic matter structure, conducted in two replicates.

Table 1: Technological Process Scheme for Cultivating Field Crops (Spring Wheat) Using No-Till Technology

Technological Operations	Brand of Agricultural Machinery and Equipment	Timing	Agrotechnical Standards	Notes
1	2	3	4	5
Harrowing (moisture sealing)	MTZ-1221 + BCD-12	April		Lack of mulch on the soil surface, crust formation.
Pre-sowing herbicide treatment	MTZ-80 + OPSH-24 KAMAZ	May (depending on growth)	Active ingredient rate: Glyphosate 450–550g/ha, 900g/ha	Wind speed up to 4–5m/s. Volunteer crops and annual (grasses and broadleaves, if present) weeds. Perennial weeds.
Seed dressing	PTS-10	May.	LAMADOR (0.15 l/ton)	
Direct seeding	MTZ-1221 + 2 SZD-2.1	May	Spring wheat – 3.0 million viable seeds/ha Seeding depth 6–8 cm	Under no-till technology, sowing is done with SKP-2.1 equipped with anchor openers developed by LLP "Kostanay Agricultural Research Institute".
Direct seeding	K-744 + 5 SKP-2.1	May.	Spring wheat – 3.0 million viable seeds/ha Seeding depth 6–8 cm	Under no-till technology, sowing is done with SKP-2.1 equipped with anchor openers developed by LLP "Kostanay Agricultural Research Institute".
Herbicide application Water delivery	John Deere KAMAZ.	June.	Wheat Sekator Turbo (0.07 l/ha) + Bars Super (0.8 l/ha)	Wind speed up to 4–5 m/s. Doses selected based on actual weed infestation levels.
Fungicide application Insecticide application Water delivery	John Deere KAMAZ	July	Falcon (0.5 l/ha) KARATE (0.1–0.15 l/ha)	Wind speed up to 3 m/s. Optional treatment (selected fields) as needed.
Cutting and threshing with straw chopping	Vector	September.	Spring wheat	Preferably direct combining. Depending on the year's conditions, swath combining may be used.
Uniform distribution of plant residues	K-701 + BMZ-24	September.		For uniform distribution of plant residues (as needed).

9. Yield accounting and grain sampling were performed to determine grain moisture content, impurity levels, thousand kernel weight, and nutritional qualities.

Statistical data analysis was carried out according to B.A. Dospekhov's (1985) methodology. A significance level of 5% was adopted for all analyses. Guidance systems employed GPS (Global Positioning System) technology to provide real-time location information for equipment, optimizing field operations such as planting and harvesting. These systems were used in conjunction with sensor technologies for monitoring soil and crop variability and automating agricultural operations such as irrigation and seed sowing (Hedley, 2015). Robotics, autonomous systems, self-driving vehicles, and drones were utilized to perform various tasks such as spraying, harvesting, and weed control, thereby reducing costs and increasing efficiency. These robots are equipped with GPS, sensors, and machine learning algorithms to enhance autonomy and manage variability (Monteiro et al., 2021).

RESULTS

The research was structured around the practical application of site-specific fertilizer management technologies, enabling a more accurate assessment of intra-field variability in soil fertility. This approach facilitates the development of tailored mineral nutrition strategies that address specific production constraints limiting crop productivity. The study revealed considerable spatial heterogeneity within individual fields, particularly in the distribution of key soil fertility parameters such as humus content, available phosphorus, exchangeable potassium, and mobile sulfur compounds. Historical vegetation index analysis identified high-yielding zones (Fig. 1), which were found during ground surveys to be situated in landscape depressions characterized by elevated soil moisture levels. Soil sampling was conducted during spring field operations, and the analytical results for 2023 are presented in Table 2.

These results demonstrated a high nitrogen demand in zones where the projected yield exceeded 30–35 centners per hectare. Accordingly, ammonium nitrate was applied at a rate of up to 170kg of physical weight per hectare, 3–5 days prior to sowing. Application was performed using a Bourgault disc seeding complex, delivering fertilizer to a depth of up to 6cm. This rate represented the maximum allowable for single-pass mineral fertilizer application.

Table 2: Content of Main Nutrients in the 0–20 cm Soil Layer, LLP "Altyn-Gul", 2023

Sampling Point №	$N\text{-}NO_3$	Availability	P_2O_5	Availability	Mobile Sulfur Forms	Availability
1	9.3	Low	63	Very High	4.3	Low
2	11.2	Medium	114	Very High	5.5	Low

During spring wheat sowing, it was recommended to apply a general rate of 65kg of physical weight of ammonium phosphate per hectare, as for the entire field. As a result of the work carried out according to the 2023 scheme with the application of nitrogen and phosphorus mineral fertilizers, operations were based on the practical use of the outcomes of differentiated fertilizer application at the farm's fields, which allowed achieving the maximum yield increase. In 2022, during research conducted on the experimental field, the following was identified (Fig. 2). As shown in Fig. 2, during the vegetation period, spring wheat exhibited optimal biomass; however, the best plant conditions were observed in variants with fertilizer application in zones of increased productivity, which contributed to better subsequent plant development (Fig. 3). Additionally, it should be emphasized that under production conditions, heterogeneity often manifests not only in agrochemical indicators, as clearly reflected by the plant development indices during growth. Nevertheless, ground-based assessment enables the most accurate visual evaluation of these differences. The nitrogen status of the plants was determined using portable devices N-tester and GreenSeeker (Table 3, Fig. 4 & 5).

In-Press

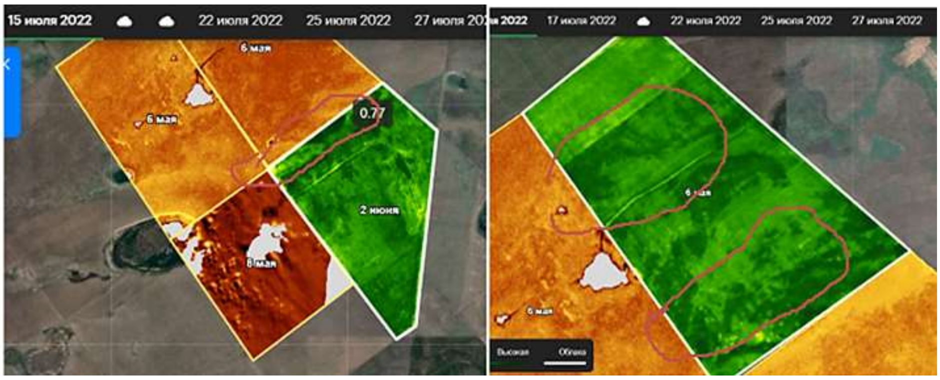

Fig. 1: Comparative assessment of the NDVI index using remote sensing (RS).

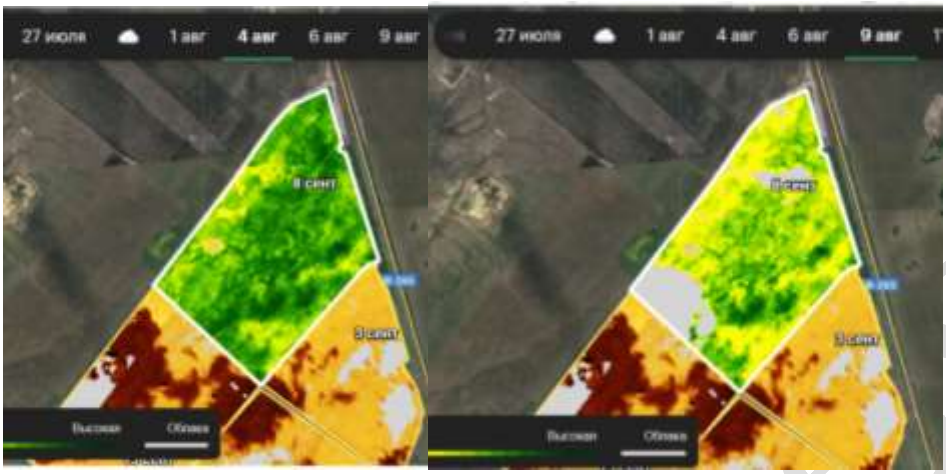

Fig. 2: Comparative assessment of the NDVI index using remote sensing (RS), August 4 and 9, 2022.

Table 3: Nitrogen Content in Wheat Leaves Using Portable Devices N-Tester and GreenSeeker, 2022

Sample Number	Nitrogen, %	N-Tester Reading	GreenSeeker Reading
Control (two years)	4.05	543	0.62
P28 (first year application)	3.47	595	0.71
N20	4.33	592	0.68
P28 (two consecutive years)	4.57	580	0.66
Control (P28 residual effect)	4.13	537	0.65

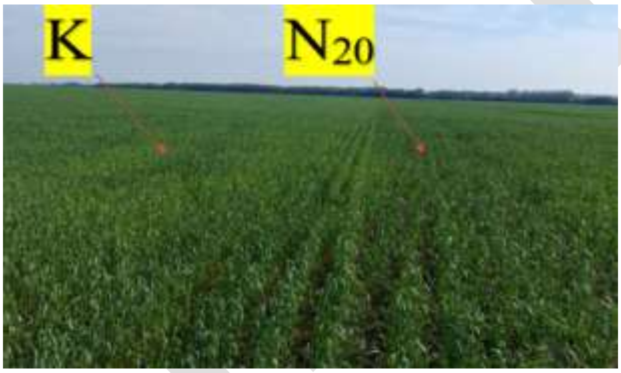

Fig. 3: Intermediate evaluation of morphometric indicators during the study of the effectiveness of differentiated mineral fertilizer application at LLP "Altyn-Gul", 2022.

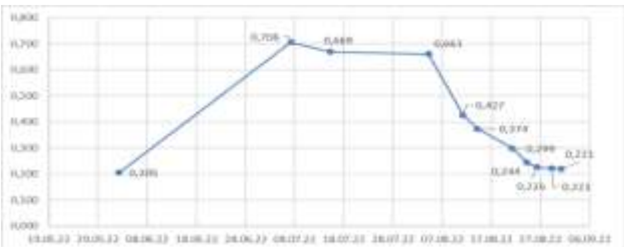

Fig. 4: Graph of vegetation index dynamics in spring wheat, LLP "Altyn-Gul".

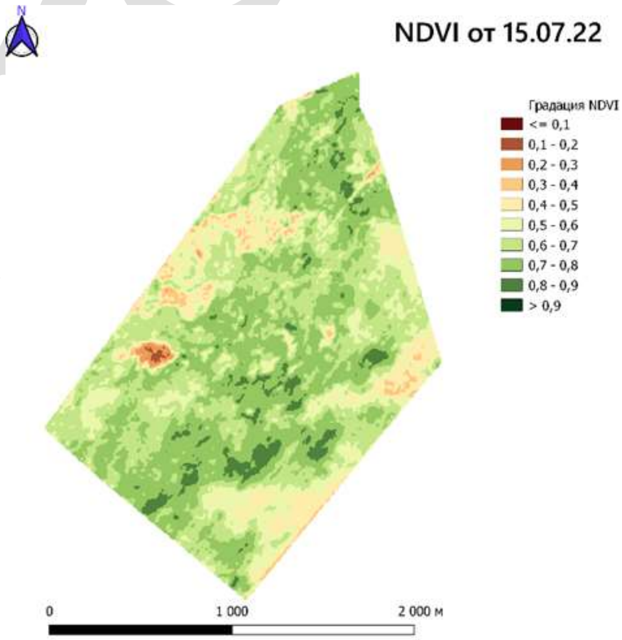

Fig. 5: NDVI image, July 15, 2022.

Fig. 5 presents the maximum vegetation index values, which were recorded on July 15, 2022. At that time, the crop was in the early heading stage. After the onset of full heading, the index value decreased by 6% and remained at that level until August 4, corresponding to the grain-filling stage, after which the vegetation index declined steadily until August 29, 2022, reaching the full maturity stage. During the 2023 research conducted at the experimental field, the following was revealed (Fig. 6 and Table 4). Based on the obtained data when assessing NDVI on June 10, 2023, statistically significant differences were identified depending on the experimental variant ($P<0.001$) (applied method: Kruskal–Walli's test) (Fig. 7). We also conducted an NDVI analysis on July 5, 2023, depending on the experimental variant (Table 5). According to Table 5, statistically significant differences ($P<0.001$) were identified during the NDVI evaluation on July 5, 2023, depending on the experimental variant (applied method: Kruskal– Walli's test). Accordingly, changes in the index indicated the most favorable growth and development conditions for the crops (Fig. 8 and 9). Based on the results of the 2023 fieldwork, it was revealed that the intermediate application of nitrogen fertilizers followed by sowing-time application of phosphorus mineral fertilizers on plots with maximum productive moisture reserves and historically high vegetation indices ensured a yield increase of 127% compared to the average yield on typical leveled control plots.

Fig. 6: Comparative assessment of the NDVI index using remote sensing (RS), June 10, 2023.

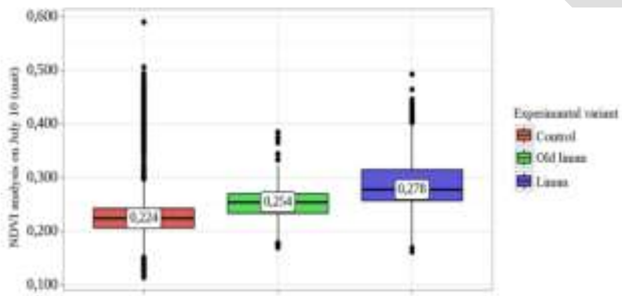

Fig. 7: NDVI analysis on June 10, 2023, depending on the experimental variant.

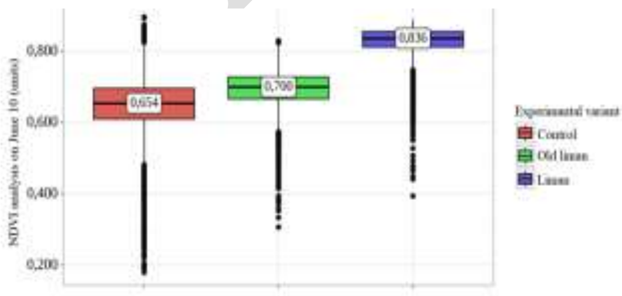

Fig. 8: NDVI analysis on July 5, 2023, depending on the experimental variant.

Fig. 9: Field condition based on remote sensing (RS) data, July 22, 2023.

Table 4: NDVI Analysis on June 10, 2023, Depending on the Experimental Variant

Indicator	Categories	NDVI on June 10 (units)			p-value
		Me	$Q_1 – Q_3$	n	
Experimental variant	Control	0.224	0.206–0.242	25802	< 0.001*
	Old Liman	0.254	0.233–0.270	7481	$p_{\text{Old Liman vs. Control}} < 0.001$
	Liman	0.278	0.257–0.314	7172	$p_{\text{Liman vs. Control}} < 0.001$
					$p_{\text{Liman vs. Old Liman}} < 0.001$

* – differences between indicators are statistically significant ($P<0.05$)

Table 5: NDVI Analysis on July 5, 2023, Depending on the Experimental Variant

Indicator	Categories	NDVI on July 5 (units)			p
		Me	$Q_1 – Q_3$	N	
Experimental variant	Control	0.654	0.610 – 0.696	25802	< 0.001*
	Old Liman	0.700	0.667 – 0.728	7481	$p_{\text{Old Liman vs. Control}} < 0.001$
	Liman	0.836	0.812 – 0.856	7172	$p_{\text{Liman vs. Control}} < 0.001$
					$p_{\text{Liman vs. Old Liman}} < 0.001$

* – differences between indicators are statistically significant ($P<0.05$)

DISCUSSION

The effectiveness of differentiated fertilizer application and other agrochemical inputs is largely dependent on intra-field variability in soil fertility and crop conditions. In fields with uniform fertility levels, the differentiation of fertilizer doses, logically, is not required. Numerous studies on the effectiveness of differentiated fertilizer application, both domestically and internationally, have shown that it is often not economically justified, primarily because the degree of intra-field fertility variability is not adequately considered. This result is justified by the studies of Zhuravleva (2024), who achieved an 82% increase in yield after applying differential fertilizer application. The study also agrees with Zheng et al. (2022) who highlighted the economic factor surrounding differential fertilizer application. From their study, they concluded that farmers characteristics such as gender and age, technology cognition, and social capital all positively impact farmers' differential fertilizer application and to further promote this practice, the government should focus on strengthening policy support, technical support, education guidance, and classification. On the contrary, Snapp et al. (2023) proposes that differential fertilizer application may be cost effective, economically viable and critical to counteracting high prices. Specifically, the results of long-term research on the differentiated application of nitrogen fertilizers for seed potato production in the state of Idaho (USA) demonstrated that the yield gain compared to conventional fertilizer application was generally minor, and the profit from nitrogen dose differentiation did not cover the costs associated with the adoption of the new technology. This is not an isolated case. Consequently, over the past decade, there has been a noticeable decline in practitioners' interest in differentiated agrochemical application, theoretically explained by the cyclical development of new agro-technologies. This result does not align with recent studies carried out by Trawczyński and Trawczyński (2021), Blecharczyk et al. (2023) and Khakbazan et al. (2024) who concluded that long-term research on the differentiated application of nitrogen fertilizers for plant cultivation demonstrated impressive yield gain and had the potential for reducing environmental effects. Blecharczyk et al. (2023) highlighted that favorable results were obtained when combining nitrogen fertilizers with organic manure. The disparity in results can be explained by Trawczyński and Trawczyński (2021) who concluded that the response to differential fertilizer application depends on the specific plant breeds and climatic conditions. This research gap can be further explored to comprehensively understand how different spring crop varieties respond to differential fertilizer application. This will create opportunities for the creation optimal hybrids that perform well with low-cost fertilizers and can thrive in varying climatic conditions. The decline in interest in differential agrochemical application though general can be alleviated by financial support, long term ecological compensation mechanism, proper agricultural extension programs and implementing tailored policies that cater to the different types of farmers in the country (Liu et al., 2023). The results of the study show that the intermediate application of nitrogen fertilizers followed by sowing-time application of phosphorus mineral fertilizers demonstrated a yield increase and this aligns with the study of Li et al. (2022) who concluded that delayed application time of slow-release fertilizer can serve as a nutrient-management measure aimed at improving nutrient use and yield and saving labor cost. The results of this study demonstrated the yield but this data is insufficient in market-based decisions. Further research is recommended to thoroughly evaluate factors such as nutritional contents that play important roles in market quality assessment.

Despite the positive advantages of precision agriculture, its implementation although at early stages in regions such as Northern Kazakhstan (Abdullaev et al., 2020; Abuova et al., 2020) and Eastern Kazakhstan (Toguzova et al., 2023) remains limited due to insufficient training, literacy, digital competence, financial resources, and infrastructure (Saliu & Deari, 2023). To significantly increase the yield of spring crops in Kazakhstan, or agricultural crops in general, it is necessary to organize proper training for farmers on the potential benefits of precision agriculture adoption. These educational initiatives would help bridge the literacy and digital technology gap between farmers in developed and developing countries. Public acceptance of precision agriculture remains one of the barriers, as most traditional farmers find it difficult to embrace change. To address this issue, a gradual transition to precision agriculture is recommended, allowing farmers to familiarize themselves with innovations and fully adopt them over time. By addressing these gaps, we are taking important steps toward preserving human health and biodiversity and achieving sustainable development goals through precision agriculture. Adequate support from government authorities and agricultural unions, such as the Farmers' Union of Kazakhstan, is also crucial for improving the state of agriculture in Kazakhstan. At the same time, an optimistic forecast for the foreseeable future of precision agriculture is based on the hope for deeper theoretical developments and more systematic information and technical support for its implementation.

A limitation to this study lies on the single location study (base farm of "Altyn-Gul" LLP) which limits the applicability of the obtained results. Future research concerning precision agriculture in Northern Kazakhstan should implement comparative studies across different farms and regions so as to obtain reference datasets that can be easily applied. The narrow evaluation of precision agriculture tools is one of its main limitations. The N-tester, GreenSeeker, and NDVI indices used in the study to track nitrogen and vegetation levels although useful, they only represent a microcosm of precision agriculture. Precision agriculture includes a wider range of technologies, such as variable-rate irrigation systems, soil electrical conductivity sensors, drone-based multispectral imaging, and machine learning models for yield prediction. To completely evaluate the possible advantages and drawbacks of precision agriculture future research should focus on evaluating a wider range of precision agriculture technologies. The lack of an environmental impact assessment is another limitations. Although the study emphasizes how precision agriculture can increase crop yields and resource efficiency, it offers no empirical evidence of the environmental effects of these methods. Because precision agriculture can cut down on water waste, pesticide runoff, and excessive fertilizer use, it is frequently marketed as a sustainable substitute for conventional farming. However, without direct measurement or modeling of these environmental factors such as changes in soil health, greenhouse gas emissions, nutrient leaching, or biodiversity impacts the

In Press

claims of environmental sustainability remain speculative.

Conclusion

The conducted research is of significant scientific interest, and the results will contribute to the development of modern methods for increasing the yield and quality of crop production. We must also develop pre-sowing treatment methods that correspond to the cultivated crops and the terrain, such as soil testing, variable rate technology, GPS mapping, seed selection and treatment, automated soil preparation and bed formation, moisture management, and predictive modeling based on historical data. Agrochemicals should be applied using precise methods, with real-time application and controlled-release fertilizers, while the government should implement data storage systems to promote the processing of large volumes of data.

DECLARATIONS

Funding: This study did not get any financial support from any organization/agency.

Acknowledgement: This work was carried out within the framework of project BR24992785 "Organization and implementation of comprehensive research to ensure the sustainable development of the agro-industrial complex of the Kostanay region with the establishment of a scientific and research technology center".

Conflict of Interest: None.

Data Availability: All the data is available in the article.

Ethics Statement: This study did not involve human participants or animal subjects and therefore did not require formal ethical approval. All experimental procedures involving crop cultivation, soil sampling, and the use of precision agriculture technologies were conducted following relevant institutional, national, and international guidelines and legislation. The research was carried out on agricultural land with the permission and cooperation of the management of "Altyn-Gul" LLP, and no personal data or sensitive information was collected.

Author's Contribution: The contribution of each author is as follows: Aliya Yskak gathered and curated data and contributed to drafting the manuscript. Almabek Nugmanov conceptualized the study. Yuriy Tulayev developed the methodology. Saniya Tulkubayeva conducted an investigation. Tatiana Paramonova performed the formal analysis. Gulnaz Yermoldina contributed to writing and editing the manuscript. Vadim Chashkov provided resources and technical support. Karina Kazbekova assisted with data validation. All authors revised and approved the final version of the manuscript.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Abdullaev, K., Irmulatov, B., Komarov, A., & Nugis, E. (2020). Precision agriculture in the North of Kazakhstan. *Agraarteadus: Journal of Agricultural Science, 31*(2), 115-121. https://dx.doi.org/10.15159/jas.20.25

Abuova, A.B., Tulkubayeva, S.A., Tulayev, Y.V., Somova, S.V., & Kizatova, M.Z. (2020). Sustainable development of crop production with elements of precision agriculture in Northern Kazakhstan. *Entrepreneurship and Sustainability Issues, 7*(4), 3200–3214. https://doi.org/10.9770/jesi.2020.7.4(41)

Abuova, A.B., Tulkubayeva, S.A., Tulayev, Y.V., Somova, S.V., & Kizatova, M. (2020). Sustainable development of crop production with elements of precision agriculture in Northern Kazakhstan. *Journal of Entrepreneurship and Sustainability Issues, 7*(4), 3200–3214. https://doi.org/10.9770/jesi.2020.7.4(41)

Anastasiou, E., Fountas, S., Voulgaraki, M., Psiroukis, V., Koutsiaras, M., Kriezi, O., Lazarou, E., Vatsanidou, A., Fu, L., Bartolo, D.F., Barreiro-Hurle, J., & Gómez-Barbero, M. (2023). Precision farming technologies for crop protection: A meta-analysis. *Smart Agricultural Technology, 5*, 100323. https://doi.org/10.1016/j.atech.2023.100323

Baimuratov, A., Bastaubayeva, S., Arslan, M., & Yeraliyeva, Z. (2021). Effect of fertilizer application on winter wheat productivity under precision agriculture in Kazakhstan. *Biodiversitas Journal of Biological Diversity, 22*(3), 123.

Bhat, S.A., & Huang, N.F. (2021). Big data and AI revolution in precision agriculture: Survey and challenges. *IEEE Access, 9*, 209–222. https://doi.org/10.1109/ACCESS.2021.3102227

Blecharczyk, A., Kowalczewski, P.Ł., Sawinska, Z., Rybacki, P., & Radzikowska-Kujawska, D. (2023). Impact of crop sequence and fertilization on potato yield in a long-term study. *Plants, 12*(3), 495. https://doi.org/10.3390/plants12030495

Chawade, A., van Ham, J., Blomquist, H., Bagge, O., Alexandersson, E., & Ortiz, R. (2019). High-throughput field-phenotyping tools for plant breeding and precision agriculture. *Agronomy, 9*(5), 258. https://doi.org/10.3390/agronomy9050258

Cravero, A., & Sepúlveda, S. (2021). Use and adaptations of machine learning in big data: Applications in real cases in agriculture. *Electronics, 10*, 552. https://doi.org/10.3390/electronics10050552

Danshin, A.I. (2024). Kazakhstan. Khozyaystvo. Sel'skoye khozyaystvo [Kazakhstan. Economy. Agriculture]. *Big Russian Encyclopedia*. https://bigenc.ru/c/kazakhstan-khoziaistvo-sel-skoe-khoziaistvo-45ffc8

Dhananjayan, V., Jayakumar, S., & Ravichandran, B. (2019). Conventional methods of pesticide application in agricultural field and fate of the pesticides in the environment and human health. In *Controlled release of pesticides for sustainable agriculture* (pp. 1–39). Cham: Springer. https://doi.org/10.1007/978-3-030-23396-9_1

Dospekhov, B.A. (1985). Methodology of field experience. *M.: Agropromizdat, 351*, 6.

Franzen, D., & Mulla, D. (2015). A history of precision agriculture. In Q. Zhang (Ed.), *Precision agriculture technology for crop farming* (pp. 1–19). Boca Raton: CRC Press. https://doi.org/10.1201/b19336-1

Gorin, P. A. J., & Spencer, J. F. T. (1968). Galactomannans of Trichosporon fermentans and other yeasts; proton magnetic resonance and chemical studies. *Canadian Journal of Chemistry*, 46(13), 2299–2304. https://doi.org/10.1139/v68-373

Gouis, J.L., Oury, F., & Charmet, G. (2020). How changes in climate and agricultural practices influenced wheat production in Western Europe. *Journal of Cereal Science, 93*, 102960.

Haroon, M., Wang, X., Afzal, R., Zafar, M. M., Idrees, F., Batool, M., Khan, A.S., & Imran, M. (2022). Novel Plant Breeding Techniques Shake Hands with Cereals to Increase Production. *Plants, 11*(8), 1052. https://doi.org/10.3390/plants11081052

Hazra, G. (2016). Different types of eco-friendly fertilizers: An overview. *Sustainability in Environment, 1*(1), 54–70. https://doi.org/10.22158/se.v1n1p54

Hedley, C. (2015). The role of precision agriculture for improved nutrient management on farms. *Journal of the Science of Food and Agriculture, 95*(1), 12–19. https://doi.org/10.1002/jsfa.6734

Inform Buro (2022). Agroproduktsiya na eksport: Chto, kuda i v kakikh ob'yomakh postavlyayet Kazakhstan [Agro-products for export: What, where and in what volumes Kazakhstan supplies]. *Inform Buro*. https://informburo.kz/stati/agroprodukciya-na-eksport-cto-kuda-i-v-kakix-obyomax-postavlyaet-kazaxstan

Karunathilake, E.M.B.M., Le, A.T., Heo, S., Chung, Y.S., & Mansoor, S. (2023). The path to smart farming: Innovations and opportunities in precision agriculture. *Agriculture, 13*(8), 1593. https://doi.org/10.3390/agriculture13081593

Kenzheali, Y., & Makhmetova, A. (2024). Analysis of sustainable agricultural development in Kazakhstan: Key economic and climatic indicators. *Eurasian Journal of Economic and Business Studies, 68*(4), 47–60.

Khakbazan, M., Mohr, R., Tomasiewicz, D.J., Nelson, A., & Bizimungu, B. (2024). Economic response of potato to nitrogen rate, timing of nitrogen application, cultivar, and irrigation. *Canadian Journal of Plant Science, 104*(6), 652–669. https://doi.org/10.1139/cjps-2023-0159

Khose, S.B., Dhokale, K.B., & Shekhar, S. (2023). The role of precision farming in sustainable agriculture: Advancements and impacts. *Agriculture & Food: E-Newsletter, 5*(9), 115–119.

Li, G., Fu, P., Cheng, G., Lu, W., & Lu, D. (2022). Delaying application time of slow-release fertilizer increases soil rhizosphere nitrogen content, root activity, and grain yield of spring maize. *The Crop Journal, 10*(6), 1798–1806. https://doi.org/10.1016/j.cj.2022.04.014

Liu, T., Li, Q., & Wang, H. (2023). Study on farmers' willingness to accept for chemical fertilizer reduction based on the choice experiment method: A case study of communities surrounding Poyang Lake, China. *Water, 15*(21), 3863. https://doi.org/10.3390/w15213863

Maisuryan, N.A., 1964. Rastenievodstvo (Crop Husbandry), Moscow: Kolos. https://scholar.google.com/scholar_lookup?&title=Rastenievodstvo&publication_year=1964&author=Maisuryan%2CN.A

Monteiro, A., Santos, S., & Gonçalves, P. (2021). Precision agriculture for crop and livestock farming – Brief review. *Animals, 11*(8), 2345. https://doi.org/10.3390/ani11082345

Muhie, S.H. (2022). Novel approaches and practices to sustainable agriculture. *Journal of Agriculture and Food Research, 10*, 100446. https://doi.org/10.1016/j.jafr.2022.100446

Noor, S., Baharom, A., Hamzah, A., Hisham, B., Bakar, A., & Zawawi, N.Z. (2022). Precision agriculture for efficient use of agrochemicals and improved soil health promoting food security through combating soil degradation in the Asia-Pacific. Paper presented at the *Asia Pacific Forum on Sustainable Development*, March 28–31, 2022, Bangkok, Thailand.

Razaq, M., Zhang, P., Shen, H.-L., & Salahuddin (2017). Influence of nitrogen and phosphorous on the growth and root morphology of *Acer mono*. *PLOS ONE, 12*(2), e0171321. https://doi.org/10.1371/journal.pone.0171321

Saliu, F., & Deari, H. (2023). Precision agriculture: A transformative approach in improving crop production. *International Journal of Research and Advances in Agricultural Science, 2*(3), 14–33.

Saranya, T., Deisy, C., Sridevi, S., & Anbananthen, K.S.M. (2023). A comparative study of deep learning and Internet of Things for precision agriculture. *Engineering Applications of Artificial Intelligence, 122*, 106034. https://doi.org/10.1016/j.engappai.2023.106034

Shin, J., Mahmud, S., Rehman, T. U., Ravichandran, P., Heung, B., & Chang, Y.K. (2023). Trends and prospect of machine vision technology for stresses and diseases detection in precision agriculture. *AgriEngineering, 5*(1), 20–39. https://doi.org/10.3390/agriengineering5010003

Singh, P., Pandey, P.C., Petropoulos, G.P., Pavlides, A., Srivastava, P.K., Koutsias, N., Deng, K.A.K., & Bao, Y. (2020). Hyperspectral remote sensing in precision agriculture: Present status, challenges, and future trends. In P. C. Pandey, P. K. Srivastava, H. Balzter, B. Bhattacharya, & G. P. Petropoulos (Eds.), *Hyperspectral remote sensing: Theory and applications* (pp. 121–146). Elsevier. https://doi.org/10.1016/B978-0-08-102894-0.00009-7

Snapp, S., Sapkota, T.B., Chamberlin, J., Cox, C.M., Gameda, S., Jat, M.L., Marenya, P., Mottaleb, K.A., Negra, C., Senthilkumar, K., Sida, T.S., Singh, U., Stewart, Z.P., Tesfaye, K., & Govaerts, B. (2023). Spatially differentiated nitrogen supply is key in a global food–fertilizer price crisis. *Nature Sustainability, 6*(10), 1268–1278. https://doi.org/10.1038/s41893-023-01166-w

Spychak, Y., Rozhkova, T., Tytova, L., Biliavska, L., Bakumenko, O., Tatarynova, V., & Burdulaniuk, A. (2025). Changes in the seed and soil micobiota caused by seed treatment with chemical and biological agents. *Ecological Engineering & Environmental Technology (EEET), 26*(1). 103–110. https://doi.org/10.12912/27197050/195636

Tanikawa, T. (2018). Mechanization of agriculture considering its business model. In T. Kozai (Ed.), *Smart plant factory* (pp. 241–244). Springer. https://doi.org/10.1007/978-981-13-1065-2_16

Team Cropin (2021). NDVI and its practical applications in agriculture. *Cropin Blog*. https://www.cropin.com/blogs/ndvi-normalized-difference-vegetation-index.html

Toguzova, M., Shaimardanova, B., Shaimardanov, Z., Assylkhanova, Z.A., & Rakhymberdina, M. (2023). Analysis of the introduction of precision farming elements in East Kazakhstan: Problems and prospects of development. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 48*, 125–130. https://doi.org/10.5194/isprs-archives-XLVIII-5-W2-2023-125-2023

Trawczyński, C., & Trawczyński, C. (2021). Assessment of mineral nitrogen fertilization of early potato varieties in integrated production. *Journal of Elementology, 26*(1). https://doi.org/10.5601/jelem.2020.25.4.2066

Vorobyev, M., & Brandt, R. (1997). How do insect pollinators discriminate colors? *Israel Journal of Plant Sciences*, *45*(2–3), 103–113. https://doi.org/10.1080/07929978.1997.10676677

Wang, J., Zhen, J., Hu, W., Chen, S., Lizaga, I., Zeraatpisheh, M., & Yang, X. (2023). Remote sensing of soil degradation: Progress and perspective. *International Soil and Water Conservation Research, 11*(3), 429–454. https://doi.org/10.1016/j.iswcr.2023.03.002

Zafar, M.M., Razzaq, A., Anwar, Z., IJAZ, A., Zahid, M., Iqbal, M.M., Farid, G., Seleiman, M.F., Zaman, R., Rauf, A., & Xuefei, J. (2025). Enhancing salt tolerance and yield potential in cotton: insights from physiological responses, genetic variability, and heterosis. *Turkish Journal of Agriculture and Forestry*, *49*(1), 110–124. https://doi.org/10.55730/1300-011x.3252

Zanin, A.R.A., Neves, D.C., Teodoro, L.P.R., da Silva Júnior, C.A., da Silva, S.P., Teodoro, P.E., & Baio, F.H.R. (2022). Reduction of pesticide application via real-time precision spraying. *Scientific Reports, 12*, 5638. https://doi.org/10.1038/s41598-022-09607-w

Zheng, S., Yin, K., & Yu, L. (2022). Factors influencing the farmer's chemical fertilizer reduction behavior from the perspective of farmer differentiation. *Heliyon, 8*(12), e11918. https://doi.org/10.1016/j.heliyon.2022.e11918

Zhengizkhan, Z. (2023). Agricultural development of Kazakhstan. *Eurasian Research Journal, 5*, 45–58.

Zhuravleva, L. (2024). Evaluation of the effectiveness of the use of differentiated technologies in crop production. *BIO Web of Conferences, 93*, 02003. https://doi.org/10.1051/bioconf/20249302003

IJAB Press