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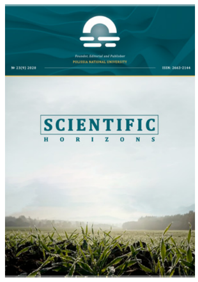

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Soil organic matter transformation under the influence of microbial agents and tillage in grain and oil crops in Southern Ukraine

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Abstract. This study aimed to evaluate the effectiveness of microbial agents in decomposing organic residues under different tillage practices in southern Ukraine from 2016 to 2020. Conducted at the Institute of Climate-Smart Agriculture, the research focused on dark-chestnut soil in a rainfed crop rotation involving winter wheat, grain

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sorghum, spring barley, sunflower, and a fallow field. Two factors were examined: microbial preparations and tillage (ploughing vs. ploughless). The Ecostern preparation, containing various bacterial strains and *Trichoderma* fungi, significantly accelerated winter wheat straw decomposition, achieving 45.9%-63.6% degradation within 90 days, a 31.4% increase over the control. The preparation Organic Balance, comprising *Bacillus subtilis* and other bacterial strains, maximised barley straw degradation at 80.1%. Sunflower residue mineralisation increased by 48.0%-55.5% with microbial treatments. These preparations also enhanced soil humus content by 0.06%-0.09%. The improved soil nutrient regime led to sorghum yield increases of 12.8%-45.3%, varying with tillage method. Spring barley yielded a maximum of 2.25 t/ha under ploughing with Organic Balance. Sunflower seed yields rose by 0.1-0.22 t/ha with ploughing. The accelerated organic matter transformation boosted soil biological activity, contributing to ecological sustainability. Ammonifying and nitrifying microorganism counts were highest with Ecostern and Organic Balance under shallow ploughless tillage, ranging from 19.82-25.87 and 7.31-12.76 CFU, respectively. Overall, the microbial preparations improved the soil's nutrient regime, resulting in significant increases in crop yields

Keywords: agroecosystem; cellulose decomposer; crop rotation; microorganisms; productivity; soil fertility; sustainability

INTRODUCTION

Ukraine faces the urgent task of increasing the efficiency of using both organic and mineral fertilisers. On irrigated land, environmental problems are largely associated with the use of large doses of mineral fertilisers. Reducing the chemical burden on the soil is possible by utilising atmospheric nitrogen and activating native soil resources. This goal can be achieved through the application of microbial preparations that stimulate nitrogen fixation from the atmosphere and mobilise phosphorus in the soil.

S. Stamenković *et al.* (2018) tell that the use of plant growth-promoting microorganisms (PGPMs) as a replacement for, or supplement to, conventional fertilisers can reduce their required dosage, improve ecological sustainability, and make agricultural practices more environmentally friendly. According to A. Panfilova (2021), one of the most significant roles in this regard is played by specific nitrogen-fixing bacteria, which, under certain crop and cultivation conditions, may replace the application of chemical nitrogen fertilisers. In addition, the soil biota facilitate the decomposition of plant residues into nutrients and stimulate the mineralisation of organic matter into mineral elements that are available for plant uptake and are subsequently accumulated in the soil. To promote the biological accumulation of nutrients in soils, specific microbial preparations are required. Some are applied by inoculating the soil, while others are used to treat seeds. Previous studies conducted in southern Ukraine by I. Bidnyna *et al.* (2021) confirm that microbial preparations can effectively compensate for the application of 40-60 kg/ha of mineral nitrogen and 15-30 kg/ha of phosphorus. Most microbial preparations contain strains of beneficial bacteria capable of fixing and accumulating atmospheric nitrogen in a form accessible to cultivated plants. These bacteria typically colonise and act in close proximity to plant roots, in the so-called rhizosphere. Inoculation of the rhizosphere with beneficial bacterial and fungal strains supports the ecological sustainability of the agroecosystem and enhances overall crop productivity. A. Aasfar *et al.* (2021) argue that the most widely used and effective soil-enhancing bacteria are nitrogen-fixing strains of Azotobacter, which significantly improve soil biological fertility and crop yields, contributing to sustainable agricultural development.

Soil microbiota and their activity determine the intensity, direction, and quality of organic matter transformation and nutrient cycling. J. Jansson and K. Hofmockel (2020) emphasise that this microbial activity plays a key role in influencing soil ecosystem stability and carbon sequestration, thus contributing to environmental sustainability and impacting greenhouse gas emissions and related climate concerns. The complex pool of soil organic matter, transformed by soil and rhizosphere microbiomes, is characterised by trophic diversity among microbial agents. It includes hundreds of heterotrophic bacterial strains with diverse traits and specific biological activities, including ecological transformation processes and patterns of soil organic matter immobilisation, as reported by M. Bohdan *et al.* (2021). P. Wu *et al.* (2021) also emphasise the importance of conducting robust and carefully designed studies on soil organic matter transformation under the influence of climate change and microbiome variation. Research into changes in chemical characteristics and metabolic rates provides essential insight into soil organic matter cycles, which, in turn, forms the basis for understanding the mechanisms underlying the transformation of complex organic compounds. A. Honchar *et al.* (2021) highlight the necessity of both theoretical and practical knowledge on this topic, as it determines the success of introducing external bacterial species into the soil microbiome and, consequently, affects the overall outcomes of crop symbiosis with new soil inhabitants.

Against the backdrop of ongoing climate change, agricultural science faces the challenge of transforming crop cultivation technologies based on the principles of climate-smart, environmentally friendly agriculture to ensure sustainable development and food security. It is particularly important to transition to climate-smart crop production in vulnerable arid and semi-arid regions, which are most severely affected by the intensification of global warming. For example, A. Teklu *et al.* (2024) report that climate-smart agricultural innovations, such as rational crop residue management, compost fertilisation, and efficient agroforestry practices, significantly improve food and nutrition security in Ethiopia, whereas soil and water conservation measures, among others, show inconclusive effects. In some cases, adaptation strategies prove insufficient to provide the necessary level of resilience, as found by P. Singh and H. Chudasama (2021) in their study conducted in the vulnerable semi-arid regions of India. Strategies for preserving and enhancing soil fertility form the foundation for effective adaptation of modern agriculture to current food security challenges and must ensure adequate resilience within agroecosystems, including the maintenance of soil fertility as a core parameter supporting crop production.

D. Pleissner (2020) notes that soil fertility is closely linked to the availability of essential nutrients for crops, a factor of both ecological and bioeconomic significance for the productivity and stability of agroecosystems. D. Ronga (2019) demonstrates the high efficiency and promising potential of microbial biofertilisers derived from specific algae, which can improve crop yields effectively without compromising environmental sustainability, biodiversity, or the economic viability of agrotechnologies. S. Rajan and M. Upsdell (2021) propose the introduction of *Acidithiobacillus* species into crop production to reduce the use of synthetic phosphorus fertilisers in modern agricultural practices, thereby enhancing the environmental safety of farming. Another promising form of microbial preparation is microbiological plant residue decomposers (e.g. stubble destructors and decomposers), which act by increasing the rate of stubble and straw decomposition and mineralisation, enhancing soil biological activity and, as a result, improving overall soil quality.

The main aim of this study was to evaluate the effectiveness and rationality of using microbial stubble destructors and cellulose decomposers to facilitate organic matter transformation in the soil under different tillage methods, including conventional ploughing and shallow surface tillage, within a typical rainfed crop rotation system in southern Ukraine.

MATERIALS AND METHODS

The study on the efficiency of microbial preparations for transforming soil organic matter was conducted under rainfed conditions in the south of Ukraine during the period 2016-2020, on the experimental fields of the Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences of Ukraine, located in the Bilozerka District of Kherson Region (coordinates: 46°44′33″ N, 32°42′28″ E). Observations and measurements were carried out within a typical crop rotation involving the following sequence of crops: winter wheat → grain sorghum → spring barley → sunflower → fallow field. The experiment was designed as a systematic trial with three replications. The measured area of each second-grade experimental plot per treatment was 44 m^2 (plot configuration: rectangular, 11×4 m). The soil of the experimental field was classified as darkchestnut, medium loamy, with a humus content of 2.2% in the arable layer, determined using Tiurin's method (DSTU 4289:2004, 2005). The field capacity of the one-metre soil layer, determined using the soil saturation method (Karkanis, 1983), was 22.4%, while the wilting point was 9.5%. Groundwater was found at depths exceeding 10 metres. The study examined two factors: Factor A – soil tillage system, Factor B – microbial preparation. The experimental design is summarised in Table 1.

***Table 1**. Experimental design: influence of tillage systems and microbial preparations on soil organic matter transformation*

Factor A	Factor B
Plough tillage (P) for: winter cereal precursors – 2325 cm; winter cereals – 12-14 cm; grain sorghum – 25-27 cm; spring barley – 18-20 cm; sunflower – 2830 cm	Control (no preparation applied)
	Preparation 1 (Ecostern; application rate: 0.3-2.0 L/ha)
	Preparation 2 (Organic Balance; application rate: 0.251.50 L/ha)
	Preparation 3 (Bionorm; application rate: 1.5 L/ha)
Deep ploughless tillage with chisel cultivator (CP) for: winter cereal precursors – 23-25 cm; winter cereals – 12-14 cm; grain sorghum – 25-27 cm; spring barley – 18-20 cm; sunflower – 28-30 cm.	Control (no preparation applied)
	Preparation 1 (Ecostern; application rate: 0.3-2.0 L/ha)
	Preparation 2 (Organic Balance; application rate: 0.251.50 L/ha)
	Preparation 3 (Bionorm; application rate: 1.5 L/ha)
Shallow ploughless tillage with disc implements (DT) at a depth of 12-14 cm for all crops in the crop rotation.	Control (no preparation applied)
	Preparation 1 (Ecostern; application rate: 0.3-2.0 L/ha)
	Preparation 2 (Organic Balance; application rate: 0.251.50 L/ha)
	Preparation 3 (Bionorm; application rate: 1.5 L/ha)

***Source:** compiled by the authors*

The key features and composition of the microbial preparations studied are as follows:

1) Ecostern is a biodecomposer of plant residues with specific activity aimed at enhancing soil biological activity, providing ameliorative and anti-degradation effects. The preparation was produced by BTU-CENTRE (Biotechnologies of Ukraine). Its composition includes bacteria from the genera *Bacillus*, *Paenibacillus*, *Azotobacter*, *Enterobacter*, *Enterococcus*, *Agrobacterium*, and fungi from the genus *Trichoderma*.

2) Organic Balance is a systemic biological preparation containing a beneficial consortium of microorganisms, including cellulose decomposers, nitrogen fixers, and phosphorus mobilisers. It accelerates the decomposition of organic matter and the accumulation of humus in the soil, thereby promoting increased soil fertility and the restoration of soil health. The preparation is also produced by BTU-CENTRE, and its microbial composition includes *Bacillus subtilis*, *Azotobacter*, *Paenibacillus polymyxa*, *Enterococcus*, and *Lactobacillus*.

3) Bionorm is a cellulose decomposer with a broad spectrum of activity. It is produced by the Institute of Agroecology and Environmental Management of NAAS. Its microbial composition comprises a complex of beneficial fungi (*Trichoderma harzianum*, *Trichoderma lignorum*) and bacteria (*Pseudomonas fluorescens*, *Pseudomonas aureofaciens*, *Paenibacillus polymyxa*).

Laboratory investigations were conducted in the certified analytical laboratory of the Institute of Irrigated Agriculture of NAAS (now the Institute of Climate-Smart Agriculture of NAAS). The content of macronutrients in the above-ground plant biomass was determined as follows: total nitrogen – by the Kjeldahl method (DSTU ISO 11261:2001, 2003); phosphorus – by the colorimetric method using ascorbic acid; potassium – by the flame photometric method (DSTU 4114:2002, 2003). The organic matter content in the soil was measured using Tiurin's method (DSTU 4289:2004, 2005). The number of major soil microbiota groups was assessed in the 0-30 cm soil layer by culturing a soil suspension in nutrient media: ammonifying bacteria – in meat-peptone agar; nitrifying bacteria – in aqueous agar with ammonium magnesium salt. Following inoculation, the cultures were incubated in a thermostat at 28°C for 14 days. Colony growth was quantified, assuming each viable cell could form a separate colony. Microbiota abundance was expressed in colonyforming units (CFU) per gram of absolutely dry soil. Soil moisture content was determined by the gravimetric method (DSTU ISO 11465:2001, 2003). Microbiological analyses were performed in triplicate.

Statistical processing of the data was conducted using a two-way ANOVA procedure adapted for agricultural research, with Fisher's least significant difference (LSD) test applied to identify statistically significant differences between treatments (Agbangba *et al.*, 2024). All analyses were conducted at $P < 0.05$. The study was conducted following the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

After harvesting, a substantial portion of organic matter in the form of shredded plant biomass and stubble remains on the field. The analysis of these residues revealed that the highest biomass levels were observed in the post-harvest period following winter wheat cultivation – 4.66-5.24 t/ha, while the lowest quantity of plant residues was recorded for spring barley – 2.35-2.50 t/ha (Fig. 1). The largest amount of plant residues was produced under ploughing tillage, totalling 15.88 t/ha. Chisel tillage reduced the quantity of plant residues by 7.6%, whereas shallow ploughless tillage led to a 13.4% reduction.

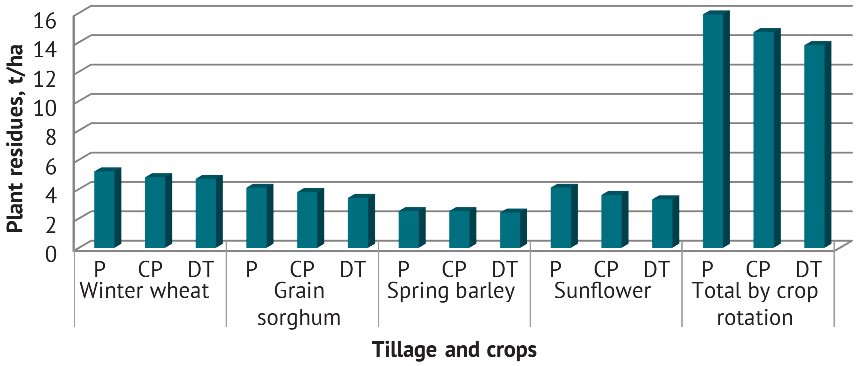

***Figure 1**. Effect of tillage on the yield of plant residues in the crop rotation*
***Source:** compiled by the authors*

The chemical composition and nutrient content of plant residues varied across crops. The highest levels of nitrogen (23.3-27.9 kg/ha) and phosphorus (12.3-147.8 kg/ha) were found in the organic biomass of grain sorghum, while the lowest were observed in the biomass of spring barley (12.2-13.0 kg/ha of nitrogen and 6.8-7.2 kg/ha of phosphorus, respectively). Over the entire crop rotation, the biomass contained

80.9-94.5 kg/ha of organic nitrogen, 39.0-45.5 kg/ha of phosphorus, and 226.1-269.1 kg/ha of organic potassium. The highest nutrient contents were observed under ploughing tillage, while the lowest were recorded under shallow tillage (Fig. 2). Varying tillage depths and methods led to differences in the rate of organic matter transformation. The most rapid transformation of plant organic matter was recorded under ploughing tillage, which is attributed to more effective shredding and incorporation into the soil (Table 2).

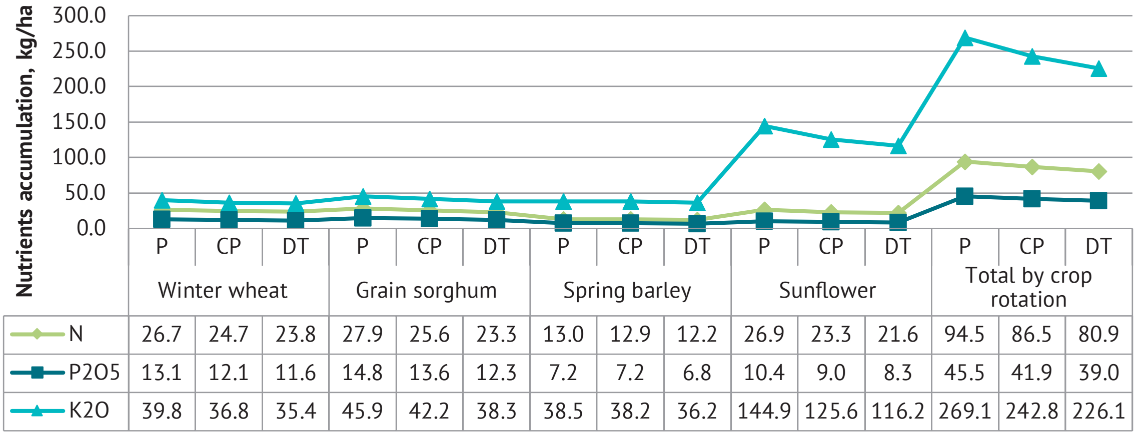

Figure 2. *Impact of soil tillage on the nutrient content in the biomass of cultivated crops*
Source: *compiled by the authors*

Table 2. *Influence of microbial preparations on the decomposition rate of plant residue in crop rotation over 90 days, depending on tillage systems, %*

Crop in the crop rotation	Microbial preparation (Factor B)	Soil tillage system (Factor A)		
		Plough	Ploughless	
			deep	shallow
Winter wheat	Control	23.0	21.9	18.7
	Preparation 1	63.6	53.9	45.9
	Preparation 2	59.7	49.4	41.6
	Preparation 3	56.1	47.6	40.0
Grain sorghum	Control	20.2	19.1	16.1
	Preparation 1	22.3	21.7	19.6
	Preparation 2	23.7	22.9	20.1
	Preparation 3	22.9	22.1	19.1
Spring barley	Control	31.5	29.0	24.7
	Preparation 1	55.0	50.1	47.3
	Preparation 2	55.3	51.9	47.6
	Preparation 3	53.9	49.7	46.7
Sunflower	Control	25.4	24.0	20.4
	Preparation 1	38.7	35.3	33.2
	Preparation 2	39.5	37.1	33.4
	Preparation 3	37.1	37.3	31.3
LSD_{05}, % for the studied factors: A – 1.9; B – 2.3				

Source: *compiled by the authors*

In the case of shallow disc tillage, the shredded plant biomass is incorporated only into the topsoil, where moisture is rapidly lost, negatively affecting the conditions for the survival and activity of the soil microbial community. This, in turn, results in slower transformation of organic matter. Therefore, in this tillage variant, the decomposition and transformation of plant residues proceed significantly more slowly than under deep tillage conditions. Optimising the transformation of plant residues into soil organic matter within the crop rotation enhances soil biological activity and leads to an increase in soil humus content (Fig. 3).

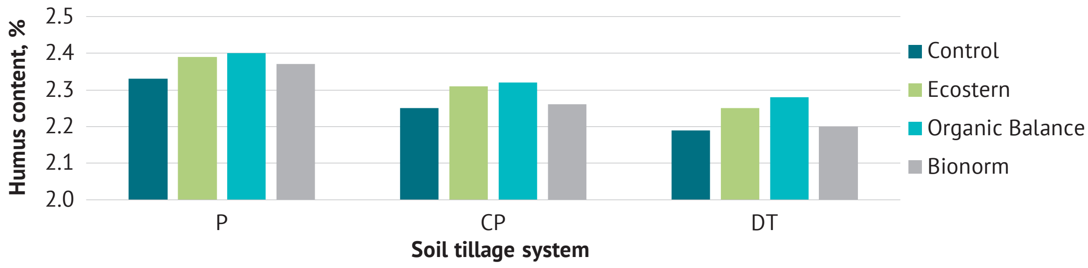

***Figure 3**. Soil humus content in the arable (0-30 cm) layer, depending on microbial preparations and tillage system, %*
***Source:** compiled by the authors*

It was found that deep incorporation of plant residues into the soil significantly increased organic matter content in the variants treated with the Ecostern microbial preparations (by 0.06%) and Organic Balance (by 0.07%-0.09%). However, the application of Bionorm did not lead to a significant increase in humus content. Under the shallow tillage system, the effect of Organic Balance on soil organic matter was greater (0.09% increase) compared with deep chisel and plough tillage (which showed only a 0.07% increase). The abundance of beneficial soil microbiota was influenced by the application of the studied microbial preparations. The number of ammonifying bacteria in the arable soil layer of the fallow field was slightly higher under the shallow tillage system (22.8125.87 million CFU), whereas under deep tillage systems, it ranged from 21.08 to 23.34 million CFU (Table 3).

***Table 3**. Number of ammonifying and nitrifying microbiota in the arable (0-30 cm) soil layer of the fallow field, depending on tillage systems and microbial preparations*

Soil tillage system (Factor A)	Microbial preparation (Factor B)	Number of microbiota in CFU per 1 g of absolutely dry soil					
		Ammonifying			Nitrifying		
		21 April	17 June	7 August	21 April	17 June	7 August
Plough	Control	21.08	17.34	16.69	10.78	8.07	7.63
	Preparation 1	22.60	21.71	21.51	11.98	10.16	9.03
	Preparation 2	23.34	22.17	22.47	12.53	11.17	9.34
	Preparation 3	22.03	22.01	22.14	9.94	9.44	7.63
Deep ploughless	Control	22.02	18.11	15.43	10.23	7.36	5.45
	Preparation 1	22.88	18.98	19.15	10.46	8.94	6.89
	Preparation 2	23.08	22.06	21.07	11.51	9.17	6.69
	Preparation 3	22.91	18.07	14.93	11.28	8.66	6.31
Shallow ploughless	Control	22.81	17.78	15.58	10.71	8.11	6.04
	Preparation 1	23.04	18.66	19.82	12.75	9.26	7.31
	Preparation 2	25.87	22.95	21.00	12.76	9.47	7.52
	Preparation 3	23.08	20.16	19.29	11.58	8.71	6.57
LSD_{05}	Partial differences:	A – 0.93; B – 0.90			A – 0.37; B – 0.32		
	Main effects:	A – 0.40; B – 0.34			A – 0.32; B – 0.27		

***Source:** compiled by the authors*

The application of Organic Balance had the strongest impact on the population of beneficial microbiota in the soil, exceeding the control by 3.08 million CFU per 1 g of absolutely dry soil under a deep tillage system. During the growing season, the number of ammonifying microorganisms decreased; however, the highest counts were recorded when Organic Balance was applied. During the growing season of grain sorghum, the population of nitrifying microorganisms in the soil was lower in all variants – by 15.6%-16.2% under deep ploughless tillage and by 19.6% under shallow ploughless tillage, respectively. The population of ammonifying microorganisms in the arable soil layer of spring barley crops increased by 4.8%-23.5% under ploughing with the application of microbial preparations, with the greatest increase observed when the Ecostern biopreparation was applied. Under deep ploughless tillage, the population of ammonifying microorganisms in the soil was 3.6%-44.2% higher than under ploughing. In the case of shallow ploughless tillage with Bionorm, the population of ammonifying microorganisms significantly exceeded that of the control variant (by 3.5%-7.7%). Changes in soil biological activity also affected the yields of the studied crops (Table 4).

Table 4. Crop yields, depending on tillage systems and microbial preparations

Microbial preparation (Factor B)	Tillage system (Factor A)			Average by Factor B
	Plough	Ploughless		
		deep	shallow	
Grain sorghum				
Control	3.32	3.01	2.90	3.08
Preparation 1	4.38	4.01	3.78	4.06
Preparation 2	4.76	4.36	3.81	4.31
Preparation 3	3.96	3.69	3.29	3.65
Average by Factor A	4.10	3.77	3.42	3.76
LSD_{05} t/ha: partial differences: Factor A – 0.23; Factor B – 0.20 main effects: Factor A – 0.09; Factor B – 0.11				
Spring barley				
Control	2.10	2.05	1.87	2.01
Preparation 1	2.16	2.13	2.10	2.13
Preparation 2	2.25	2.17	2.07	2.16
Preparation 3	2.21	2.10	1.99	2.10
Average by Factor A	2.23	2.12	1.96	2.10
LSD_{05} t/ha: partial differences: Factor A – 0.10; Factor B – 0.14 main effects: Factor A – 0.06; Factor B – 0.06				
Sunflower				
Control	3.31	2.95	2.66	2.97
Preparation 1	3.49	3.15	2.88	3.17
Preparation 2	3.51	3.17	2.90	3.19
Preparation 3	3.41	3.07	2.79	3.09
Average by Factor A	3.42	3.07	2.79	3.09
LSD_{05} t/ha: partial differences: Factor A – 0.10; Factor B – 0.14 main effects: Factor A – 0.06; Factor B – 0.06				

Source: *compiled by the authors*

Under ploughing, the highest yield of sorghum grain was obtained in the variants with Organic Balance application – 4.76 t/ha, and Ecostern application – 4.38 t/ha. Treatment with Bionorm resulted in lower sorghum yields, by 0.80, 0.73, and 0.63 t/ha, respectively. The switch to deep ploughless tillage reduced the effect of soil microbiota, with differences between the variants ranging from 0.35-0.67 t/ha. Under this tillage, Organic Balance produced a yield of 4.36 t/ha, and Ecostern – 4.01 t/ha. Under shallow ploughless tillage, sorghum yields were almost identical with Ecostern and Organic Balance treatments – 3.78-3.81 t/ha. Treatment with Bionorm led to a slightly lower yield, though it remained higher than that of the control. Under ploughing, all microbial preparations increased the yield of sunflower seeds by 0.06-0.20 t/ha, with the most significant increases recorded for Ecostern and Organic Balance. The application of Ecostern and Organic Balance under shallow disc tillage also resulted in an increase in sunflower yield by 0.22 and 0.24 t/ha, respectively.

Microbial preparations are essential for the successful transition towards biologisation in agriculture. M. Pylak *et al.* (2019) assert that current trends in the transformation of crop production based on sustainable, climate-smart organic agrotechnologies require microbial preparations to replace conventional chemical agents used for plant care and protection, as well as chemical fertilisers and soil ameliorants. P. Rowińska *et al.* (2024) confirm that among the various types of microbial agents used in agriculture, stubble biodestructors – in the form of plant residue decomposers and soil biological activity enhancers – are of great interest and importance in creating the conditions necessary for soil fertility preservation in conservation agriculture systems. The application of biological agents not only improves the overall fertility and ecological status of the soil but also contributes to increased yields and enhanced crop quality, thereby promoting the sustainability of agroecosystems and the environment.

The scientific and practical results of the present study are generally consistent with the findings of researchers from abroad. Studies by H. Chandra *et al.* (2020) have shown that soil fertility is directly related to the activity and vitality of beneficial soil microbiomes. Plant residues were found to transform into biochemical compounds available to plants over several years. This process depends on both abiotic and biotic factors, primarily soil moisture and temperature. E. Ampt *et al.* (2019) point out that the use of biological organic matter transformers accelerates the decomposition of plant residues and their incorporation into the soil, prevents unproductive losses through mineralisation and leaching, and contributes to enhanced soil fertility, increased crop yields, and improved quality of agricultural products.

In Ukraine, the majority of scientific studies have focused on the Ecostern microbial preparation. The study by O. Kovalenko (2023) reports that the use of this preparation within an integrated agrotechnology system resulted in a significant increase in the yield of spring barley varieties Hermes and Avatar. In addition, O. Kovalenko (2022) found that the treatment of plant residues with Ecosterm led to an increase in the population of cellulose-decomposing microbiota in the soil and promoted overall higher biological activity of beneficial soil microorganisms. Yields of winter wheat grain increased by 0.45-0.67 t/ha, depending on the preceding crop, as a result of Ecostern application as a stubble biodestructor. The study by O. Kuts *et al.* (2022) confirmed that a biological fertilisation system incorporating Ecostern as a stubble decomposer and Organic Balance as a source of beneficial bacteria resulted in the highest levels of nitrogen-fixing microbiota in the soil compared with conventional fertilisation systems. However, the yield increase under this system was not the highest when compared with organo-mineral fertilisation. The study by T. Khomenko *et al.* (2023) demonstrated that the application of Ecostern led to an increase in soil organic matter in the arable layer by 0.09%-0.11% compared to the control. V. Dudchenko *et al.* (2021) reported the beneficial effect of Ecostern on soil microbiota and soybean productivity within a rice-based crop rotation. A positive impact of biological preparation application was also noted in studies on legume crop productivity. Moreover, microbial agents were found to enhance the quality of pea and soybean seeds, as reported by I. Horodyska *et al.* (2021). A. Panfilova and Y. Byelov (2022) claimed that Ecostern application increased the availability of key nutrients in the soil, primarily due to improved mineralisation of precursor residues. It is important to note that the most favourable soil properties were observed under treatment with the microbial stubble decomposer in combination with plough tillage.

However, there are some inconsistencies in the current evidence regarding the application of stubble biodestructors. For example, V. Fomenko and A. Kaziuta (2023) found that the use of biological stubble destructors had negative effects on soil humus content and humification processes, in some cases even leading to dehumification. Therefore, the effectiveness of microbial biocomposers remains questionable, as their impact may vary significantly depending on soil type, tillage method, crop type, and other factors.

Concerning tillage systems, their impact is highly dependent on soil type and the general agroclimatic conditions of crop cultivation. There is some evidence in favour of no-till and minimal tillage practices for organic matter conservation, particularly in cropping systems where precursor residues are retained in the field. However, the difference, according to a study by B. Thapa *et al.* (2018), was statistically significant only for nitrogen (20.4%) and organic carbon (16.5%). The study provided strong support for the no-till system in terms of soil carbon sequestration compared to conventional deep tillage. M. Szostek *et al.* (2022) demonstrated that tillage systems significantly influence soil microbial activity, with the least favourable conditions observed under conventional ploughing, and the most favourable under simplified systems (e.g. shallow subsurface cultivation and disc harrowing). Similarly, the study by Y. Li *et al.* (2020) showed that reduced tillage and stubble retention led to higher microbial diversity and biological activity in soils. Soil biological activity was strongly influenced by both the depth and type of tillage, reaching its maximum under minimal and conservation tillage systems. This could be attributed to the increased microbial biomass observed under reduced tillage conditions. Different cropping patterns and tillage techniques influence nodulation, nitrogen fixation, and the composition of microbial communities. They also affect soil aeration, structure, and water-use efficiency. P. Angon *et al.* (2023) emphasise that conservation tillage systems are superior to conventional deep ploughing in maintaining optimal soil properties and fertility. Higher surface retention of crop residues, encouraged by conservation tillage, was directly associated with elevated levels of soil organic carbon, microbial biomass, potential nitrogen mineralisation, total nitrogen, and available phosphorus. No-tillage management promotes soil fertility, increases soil organic matter, and may even enhance the nutrient supply to crops through changes in microbial biomass mineralisation and nutrient immobilisation processes.

While these findings support reduced tillage, the study by B. Okorie and Y. Niraj (2022) offers contrasting evidence, highlighting improvements in overall soil fertility, as well as physical and chemical properties – including soil organic matter content – under conventional plough tillage. Nonetheless, in certain cases, ploughing may cause excessive soil loosening and loss of soil organic carbon. In such instances, no-till and minimal tillage practices prove more beneficial. Therefore, the influence of tillage systems on soil biological activity and fertility remains contentious, necessitating further robust investigation and meta-analysis.

CONCLUSIONS

The results of the study indicate that the most intensive transformation of wheat straw (45.9%63.6%) occurred following the application of the Ecostern microbial preparation, exceeding the control variant by 31.4%. The use of microbial organic matter-transforming agents increased the rate of grain sorghum residue decomposition by 5.9%-20.0%, with the Organic Balance biopreparation demonstrating the greatest efficiency. The intensity of barley straw transformation was 80.1% higher under the application of Organic Balance compared to the control. The treatment of sunflower plant residues with biodecomposer agents accelerated stubble transformation by 48.0%55.5%, with the degree of decomposition reaching 33.4%-39.5%. The application of microbial preparations promoted the immobilisation of organic polysaccharides in plant residues, increased microbial populations, and, consequently, facilitated the accumulation of organic nitrogen compounds within microbial biomass, thereby enhancing the return of organic matter to the biological cycle.

The establishment of a favourable soil nutrient regime through the use of biodecomposers resulted in increased sorghum grain yields by 12.8%-45.3%, depending on the tillage system. The greatest impact was observed with the Organic Balance preparation: yields ranged from 3.81 to 4.76 t/ha, whereas the control produced only 2.90-3.32 t/ha. Under plough tillage, the highest barley grain yield (2.25 t/ha) was also obtained with the application of Organic Balance. All biodecomposer agents led to increases in sunflower yield by 0.10-0.24 t/ha, with the highest yield (3.51 t/ha) observed under plough tillage combined with Organic Balance application. Overall, the use of microbial preparations under an optimal tillage regime offers a lever for efficient, environmentally sustainable regulation of soil fertility and biological activity, alongside notable improvements in crop productivity. Further research is needed to identify the most suitable microbial agents for specific agroecological conditions and agricultural practices.

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Трансформація органічної речовини ґрунту під впливом мікробіологічних препаратів і обробітку ґрунту на посівах зернових і олійних культур на півдні України

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Анотація. Дане дослідження мало на меті оцінити ефективність мікробних агентів у розкладанні органічних решток за різних способів обробітку ґрунту на півдні України в 2016-2020 роках. Дослідження проводилося на темно-каштановому ґрунті в богарній сівозміні з озимою пшеницею, зерновим сорго, ярим ячменем, соняшником та полем під паром, розташованими в Інституті кліматично орієнтованого сільського господарства Національної академії аграрних наук. Досліджували два фактори: мікробні препарати та обробіток ґрунту (полицевий чи беполицевий). Препарат «Екостерн», що містить різні штами бактерій та гриби *Trichoderma*, значно прискорив розкладання соломи озимої пшениці, досягнувши 45,9-63,6 % розкладання протягом 90 днів, що на 31,4 % більше, ніж у контролі. «Органік Баланс» з *Bacillus subtilis* та іншими бактеріальними штамами максимально прискорив розкладання соломи ячменю на 80,1 %. Мінералізація решток соняшнику збільшилася на 48,0-55,5 % після обробки біопрепаратами. Досліджувані препарати також підвищили вміст гумусу в ґрунті на 0,06-0,09 %. Покращення поживного режиму ґрунту призвело до збільшення врожайності сорго на 12,8-45,3 % залежно від обробітку ґрунту. Врожайність ярого ячменю становила 2,25 т/га за полицевої оранки та внесення препарату «Органік Баланс». Врожайність насіння соняшнику зросла на 0,1-0,22 т/га за полицевого обробітку ґрунту. Прискорена трансформація органічної речовини підвищила біологічну активність ґрунту, сприяючи його екологічній стійкості. Кількість амоніфікуючих та нітрифікуючих мікроорганізмів була найвищою за мілкого безполицевого обробітку ґрунту за внесення «Екостерн» та «Органік Баланс» і становила 19,82-25,87 та 7,31-12,76 КУО відповідно. Зрештою, мікробні препарати покращили поживний режим ґрунту, що призвело до значного підвищення врожайності сільськогосподарських культур

Ключові слова: агроекосистема; деструктор целюлози; сівозміна; мікроорганізми; продуктивність; родючість ґрунту; сталий розвиток

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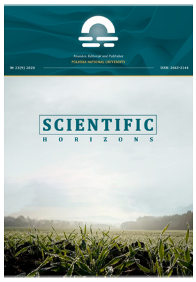

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Prospects for the cultivation of grain sorghum (*Sorghum bicolor* L. Moench) in the arid region of the Kazakh Aral Sea region: Literature review

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Abstract. The purpose of the present study was to substantiate effective breeding and agronomic solutions for improving the resistance of sorghum to climatic stresses in the conditions of the Aral Sea region. Based on an analysis of literature sources, the study showed that the agricultural sector of the Kyzylorda region of the Republic of Kazakhstan faces a persistent water shortage caused by both natural and anthropogenic factors. A considerable reduction in water inflows to the lower reaches of the Syr

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Darya, degradation of irrigation infrastructure, and deterioration of water quality create conditions under which conventional water-intensive crops such as rice become economically and environmentally unviable. A review of sources confirmed that, along with technical measures such as the introduction of water-saving technologies, the transition to more drought-resistant crops, including sorghum, is becoming increasingly significant. Sorghum was demonstrated to have unique physiological adaptations to water and heat stress due to its morphological and anatomical characteristics, growth phases, and ability to retain green mass. In the Aral Sea region, this crop is considered a key element in the strategy for adapting crop production to changing climatic conditions. Furthermore, sorghum has a wide range of applications, from food and feed to bioenergy, which highlights its agro-economic value. The literature review also noted growing interest in the genetic and breeding potential of sorghum: international gene banks hold more than 42,000 samples, including unique genotypes from Africa and Asia, which opens prospects for the creation of sustainable and high-yielding varieties. Thus, the findings of the literature review confirmed the pronounced adaptability of sorghum to the conditions of the Aral Sea region, its strategic significance in conditions of water stress, and the relevance of further breeding and agronomic developments aimed at its widespread introduction into the region's agriculture

Keywords: stress tolerance; genetic diversity; biopreparations; agrotechnical methods; water use efficiency

INTRODUCTION

The relevance of the present study is conditioned by the need to increase the resilience of agricultural crops, particularly sorghum, to extreme climatic conditions such as drought and hot temperatures. In the context of global climate change and increasing frequency of droughts in various regions of the world, the efficient use of water resources and ensuring food security are becoming priority tasks. Sorghum, due to its marked resistance to drought and hot conditions, is a promising crop that can play a key role in ensuring food security in arid regions. The problematic of the present study lies in the complexity of breeding drought- and heat-tolerant sorghum varieties, as high yield and tolerance to extreme conditions are often mutually exclusive traits. Furthermore, breeding for these traits requires consideration of many factors, such as genetic potential, interaction with the environment, and adaptive capabilities. Despite advancement in sorghum breeding, there is a need to develop more effective screening methods and genomic tools to accelerate the improvement of varieties with enhanced drought tolerance and heat tolerance.

L. Tokhetova *et al*. (2022) addressed the problem of creating source material for breeding for adaptability to stress factors. The researchers emphasised the value of developing sorghum varieties that can effectively adapt to extreme climatic conditions, including drought and hot temperatures. B.N. Nasiev and A.M. Zhilkybay (2022) focused on biological crop cultivation technologies in Western Kazakhstan. According to the researchers, the use of such methods can greatly increase plant resistance to drought, which is a vital aspect for the creation of sustainable sorghum varieties in arid regions. M. Masatbaev and N. Khozhanov (2021) investigated the influence of climatic factors on soil humus components. The researchers pointed out that the changing climatic conditions affect crop productivity and that, to maintain the sustainability of sorghum, it is necessary to create varieties capable of adapting to these changes.

S. Hossain *et al*. (2022) paid special attention to sorghum as a promising crop, considering it an essential element for food security in the context of climate change. These researchers noted that the creation of drought-resistant sorghum varieties is becoming a priority for countries facing water shortages. B.A. Pandian *et al*. (2022) considered not only the resistance of sorghum to herbicides but also emphasised the need to improve its resistance to climatic stresses. The researchers noted that selection for heat and drought tolerance is a crucial part of the breeding process, which contributes to the adaptability of sorghum under extreme climatic conditions. P.K. Subudhi *et al*. (2024) highlighted the key achievements in sorghum improvement, with the researchers emphasising that, for the successful cultivation of this crop under climate change, it is necessary to continue work on the development of varieties that are resistant to hot conditions and drought.

According to H. Hao *et al*. (2021), genomic technologies open new opportunities for sorghum breeding, providing valuable tools for the creation of varieties that are resistant to climate stress. The researchers emphasised that the use of such technologies can markedly accelerate the process of sorghum improvement in the context of global climate change. W. Yali and T. Begna (2022) highlighted the progress of sorghum breeding in Ethiopia, where the crop is crucial for food security. The researchers acknowledged the achievements in breeding but noted that further success required addressing issues of drought and heat tolerance. In their study of the state of cereal crops in Bangladesh, A.K.M.G. Sarwar and J.K. Biswas (2021) showed that sorghum is becoming a prominent feed crop despite challenges such as insufficient drought resistance. The researchers stressed the need to develop more drought-tolerant sorghum varieties to increase its productivity under extreme climatic conditions. T.W. Hermann *et al*. (2023) covered the genetic diversity of sorghum and its potential for improving varieties in Burkina Faso. These researchers emphasised the significance of developing sweet sorghum varieties that are resistant to drought and hot temperatures, which is particularly relevant for a region with unfavourable climatic conditions. According to H. Zheng *et al*. (2023), sorghum could become an essential element of global food security and bioenergy. The researchers noted that, due to its resistance to extreme climatic conditions, sorghum has immense potential for use as a food and energy crop. A. Ashesh *et al*. (2025) examined the current challenges and prospects for sorghum development, pointing out the need to use the latest technologies to create varieties that can adapt to climate change and ensure food security.

The purpose of the present study was to assess the resistance of sorghum genotypes to climatic stresses and the potential for breeding to improve their adaptability. The objectives of the study were to assess the resistance of various sorghum genotypes to drought and hot conditions, as well as to analyse the effectiveness of modern breeding methods to improve their adaptability. A literature review was conducted using data from scientific publications covering the climatic and agroecological conditions of the Aral Sea region, the biological characteristics of sorghum, its stress resistance, areas of application, genetic resources, and modern breeding approaches. The analysis was based on the findings of studies conducted both in Kazakhstan and in other countries with arid climates (including Ethiopia, Bangladesh, Burkina Faso, etc.).

CLIMATIC AND SOIL CONDITIONS IN THE ARAL SEA REGION

Water scarcity in the Kyzylorda region of the Republic of Kazakhstan is a persistent problem that worsens year after year. The region is located in the lower reaches of the transboundary Syr Darya River and is completely dependent on water supplies from Uzbekistan and Kyrgyzstan. In a dry climate with high evaporation rates and degraded irrigation infrastructure, water supply is becoming a critical factor for the region's agricultural sector. According to the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan, in 2023, less than 6.9 bn m^3 of water flowed into the lower reaches of the Syr Darya, which is 2.1 bn m^3 less than in the same period in 2022. This represents a deficit of around 23%-25% compared to the normative values for the agricultural season. The water accumulation indicator in key regulatory structures was particularly alarming: at the end of summer 2023, there was 770 million m^3 less water in the Shardara Reservoir and the Koksarai Counter-Regulator than in the previous year (National report on…, 2023).

The water shortage directly affected the area under crops. In 2023, rice cultivation in the Kyzylorda region was reduced by more than 7,000 hectares compared to 2022. While in 2021-2022 the area under rice cultivation averaged 87-89 thsd ha, in 2023 it decreased to about 81.5 thousand hectares, according to data from the regional administration (Mass rice harvesting…, 2022). This is a necessary measure aimed at redistributing limited water resources in favour of less water-intensive crops and ensuring drinking water supplies for the population. The Syr Darya, as the main water artery of the region, also faces environmental challenges. Depletion of the riverbed, overgrowth with algae, and pollution from agricultural and industrial discharges all reduce water quality and increase losses during transport. According to environmental monitoring data, water losses in irrigation canals reach up to 40%, especially in old concrete and open channels that require modernisation. Drought and high soil salinity are other key limiting factors threatening agriculture in the region. Due to high mineralisation and water regime disturbances, over 35% of the region's agricultural land is subject to secondary salinisation, which critically affects crop yields and limits crop choice.

Against the backdrop of these problems, a set of measures aimed at adapting agriculture to water stress has been launched in the region. Firstly, cropland is being reallocated – instead of rice, sorghum, barley, millet, and maize, which are more drought-resistant, are increasingly being planted. Specifically, in 2023, about 4,000 ha were allocated for sorghum, which is almost twice as much as in 2021. Secondly, farmers are recommended to introduce drip and subsurface irrigation, which can save up to 30%-50% of water compared to conventional methods. Additionally, Kazakhstan is actively pursuing international cooperation with neighbouring countries on water distribution in the Syr Darya basin. However, the problem continues to be systemic: irregular discharges, lack of coordinated water supply schedules, and lack of uniform accounting and monitoring standards hinder the achievement of a sustainable water balance in the region.

BIOLOGICAL AND AGRONOMIC FEATURES

Grain sorghum, *Sorghum bicolor* L. Moench, is a staple food for millions of people living in approximately 30 countries in the subtropical and semi-arid regions of Africa and Asia (Rashwan *et al.,* 2021). Heat and water shortages during flowering are severe stress factors that considerably affect the yield of spring crops worldwide. These conditions are becoming particularly relevant in the context of global climate change, which is projected to cause global average temperatures to rise by 3.3°C-5.7°C by the end of the 21st century under the SSP5-8.5 scenario (Dhakar *et al.,* 2023). Such warming exacerbates extreme weather events such as droughts and abnormal heat, creating further challenges for agriculture. Although sorghum is considered a crop well-adapted to hot and dry climates due to its physiological resilience, it is not completely protected from the effects of terminal drought and heat stress. These factors are still among the most significant abiotic constraints to stable crop production, including sorghum.

The impact of heat stress on sorghum yield is determined by several key aspects: the timing of stress onset, its intensity and duration (Smith *et al.*, 2023). For example, if stress occurs during critical stages of plant development, such as flowering or grain formation, it can substantially reduce the final yield. The primary damage is manifested in a reduction in the number of grains per plant, which is a direct consequence of the disruption of pollination and fruit set (Yeraliyeva *et al.*, 2017). Therewith, an increase in the weight of individual grains is usually unable to fully compensate for the overall losses, which leads to a decrease in the overall productivity of the crop. Thus, despite sorghum's high adaptability to unfavourable conditions, its yield continues to be vulnerable to a combination of hot temperatures and moisture deficiency, which requires further research and the development of resistant varieties.

Sorghum development undergoes 12 distinct stages of organogenesis, each of which plays a significant role in the development of the plant and its yield (Dubery *et al.*, 2024). These stages are described in detail below: in the first stage – seed germination – the seed absorbs moisture from the soil, internal biochemical processes are activated, and embryo growth begins; this stage is critically dependent on soil temperature and moisture, as water deficiency or too low temperatures can slow down or even stop germination. This is followed by the second stage – emergence of seedlings and formation of the third leaf – when, after germination, the first shoots appear, followed by the formation of the first true leaves, including the third, which marks the beginning of active development of the aboveground part of the plant; at this stage, sorghum begins to photosynthesise and strengthen its root system. The third stage, tillering, is characterised by the active formation of lateral shoots, which increases the potential productivity of the plant; this process requires sufficient nutrients and water, while stressful conditions can limit the number of shoots. In the fourth stage, tillering continues, strengthening the plant's structure; sorghum becomes more resistant to external factors but is still sensitive to drought, which can reduce the number of productive shoots. The fifth stage, the booting phase, marks the beginning of vertical stem growth, when the leaves fold into a tube, preparing the plant for the reproductive stage; this is a transitional stage that requires a stable water supply for normal development. In the sixth stage – continued booting – stem growth continues, the plant elongates and strengthens; sorghum actively accumulates resources for the upcoming flowering, which makes it vulnerable to moisture or nutrient deficiencies. The seventh stage, stem growth, is associated with intensive elongation and thickening of the stem, as well as biomass accumulation; this stage is vital for the development of a powerful base that will support the future panicle and grains. The eighth stage – the heading stage – begins with the formation of the panicle, the reproductive organ of sorghum; this process is sensitive to temperature fluctuations and water deficiency, which can affect the quality and quantity of future grains. The ninth stage, the flowering phase, is crucial, as this is when pollination and grain setting occur; hot temperatures or drought at this time can lead to sterile flowers and a significant reduction in yield. In the tenth stage – grain formation and growth – after successful pollination, grain development begins; the plant directs resources to increase the size and number of grains, which depends on the availability of water and nutrients. The eleventh stage – grain filling – is characterised by the accumulation of nutrients such as starch and proteins in the grains, which determines their final weight and quality; lack of moisture at this stage can lead to immature or small grains. Finally, the twelfth stage – the wax and full ripeness phase – is the final stage, when the grains reach their optimum maturity; wax ripeness is characterised by partial drying, while full ripeness – by readiness for harvest, with environmental conditions at this stage affecting crop preservation (Fig. 1).

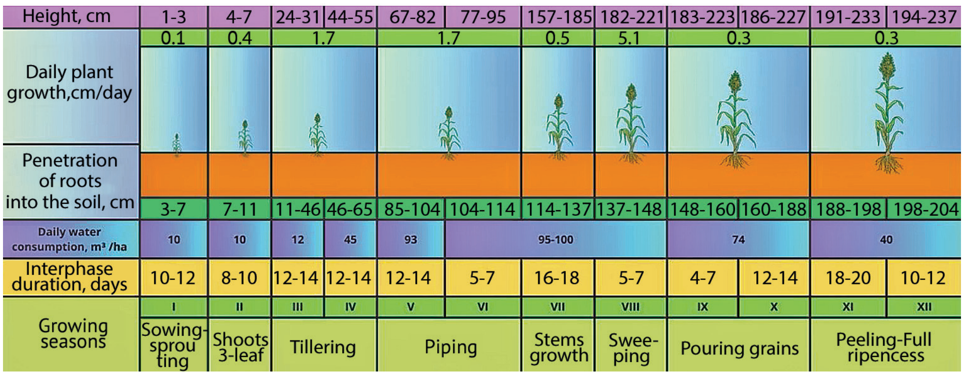

Figure 1*. Features of grain sorghum plant development*

Source: *compiled by the authors based on A.K. Rashwan et al. (2021), R. Dhakar et al. (2023), A. Smith et al. (2023), R. Kopecká et al. (2023), I. Dubery et al. (2024)*

Abiotic stresses: drought, hot temperatures, salinisation, and flooding continue to be the primary factors limiting crop growth and productivity under climate change (Kopecká *et al.,* 2023). Despite sorghum's high tolerance to extreme conditions such as heat, drought, saline soils, and excess moisture, in arid and semi-arid regions the plant often faces water shortages after flowering. The drought tolerance of sorghum is conditioned by both morphological and anatomical characteristics (the presence of a dense waxy coating on the leaves, their curling, and a well-developed root system) and physiological mechanisms, including osmotic regulation involving osmo-protectors and the 'stay green' ability.

FOOD USE OF SORGHUM IN FEED PRODUCTION AND BIOENERGY

Sorghum has been one of the key crops for centuries, providing food for millions of people in various parts of the world, especially in Africa, South Asia, and Latin America. In India, for instance, sorghum flour is traditionally used to make chapati, thin flatbreads that form the staple of the daily diet for a sizeable portion of the population, especially in rural areas (Meena *et al.*, 2022). In African countries, sorghum is widely used to prepare a variety of dishes, from thick porridges and flatbreads to bread, soft drinks, and even popcorn, highlighting its versatility and accessibility (Adebo, 2020). In Indonesia, this crop ranks third among cereals in terms of cultivation volume, behind only rice and maize, which indicates its significance in the local agro-economy. Although sorghum consumption is gradually declining in some regions due to competition from cheaper and more accessible products such as wheat or rice, it continues to play an indispensable role in food security, especially in arid and semi-arid areas (Pichura *et al.*, 2024). This is conditioned by its outstanding drought tolerance, ability to grow on poor soils and stable yields even under limited water supply.

Recently, sorghum has been gaining popularity in high-income countries such as the United States, Brazil, South Africa, and Kenya, where it is beginning to be perceived not just as a traditional crop for the poor, but as a valuable functional food product. Sorghum grain has a series of unique properties that make it particularly attractive to health-conscious consumers. It is gluten-free, making it an ideal choice for people with coeliac disease or gluten intolerance. Furthermore, sorghum is rich in antioxidants, micronutrients (such as iron, magnesium, and phosphorus), and polyphenols, which help reduce inflammation and strengthen the immune system. These qualities make sorghum a valuable component of a balanced diet, and its use in the food industry – from gluten-free baked goods to nutritious bars – is rapidly expanding in the global market.

Apart from its food uses, sorghum plays a prominent role in animal feed production, which is particularly significant for regions with limited natural resources (Sprynchuk *et al.*, 2023). Its green mass, haylage, silage, and grain are used to prepare high-quality compound feed, providing nutrition for livestock in semi-arid areas where other feed crops, such as maize, may be unable to withstand extreme conditions (Hadebe *et al.*, 2021). The advantages of sorghum in this area include its undemanding soil requirements, ability to use minimal amounts of water efficiently, and high biomass productivity. However, there are certain challenges associated with its use. These include the relatively short shelf life of green mass and grain due to high moisture content, vulnerability to pests such as birds and insects, and the need for technological solutions to increase nutritional value and improve yields. For instance, grain processing or the selection of resistant varieties can help overcome these limitations, making sorghum an even more competitive crop.

In recent years, scientists and agronomists have been paying particular attention to the bioenergy potential of sorghum, which opens new horizons for its use (Bakari *et al.,* 2023). Technical and sweet varieties of this crop can accumulate significant amounts of biomass rich in sugars and cellulose, making them a promising raw material for bioethanol and biogas production. Unlike many other bioenergy crops, such as maize or sugar cane, sorghum does not compete directly with food crops, as it can be successfully grown on marginal, low-fertility lands without requiring intensive irrigation or large investments in fertilisers (Bolokhovsky *et al.*, 2024). This makes it an economically viable and environmentally sustainable solution for resource-depleted regions. Furthermore, the use of sorghum in bioenergy contributes to reducing dependence on fossil fuels and greenhouse gas emissions, which is particularly relevant in the context of global climate change (Fig. 2).

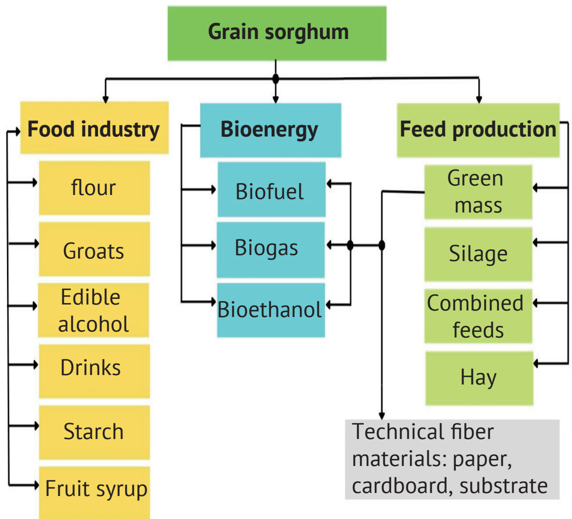

Figure 2. *Economic and industrial uses of grain sorghum*
Source: *compiled by the authors of this study based on O.A. Adebo (2020), Hadebe et al. (2021), K. Meena et al. (2022), S.T.H. Bakari et al. (2023)*

Thus, sorghum is a multifunctional crop that, thanks to its versatility and adaptability, can simultaneously address food, feed, and energy security challenges. In the context of a growing global population, declining arable land and increasing climate challenges, sorghum is poised to become a strategic crop, ensuring the stability and development of agricultural systems in the most challenging regions of the world.

GENETIC RESOURCES AND SELECTION

Genetic resources of sorghum preserved in global collections represent an extensive pool of more than 42,000 accessions (Mace *et al.*, 2020). One of the leaders in this field is the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, which holds approximately 38,000 germplasm samples covering approximately 80% of the genetic diversity of sorghum (Mangshin *et al.*, 2024). These samples have been carefully studied and preserved using both short-term and long-term storage methods, which allows them to stay viable for future research and breeding. Among the largest repositories, two key centres stand out: ICRISAT and the US Department of Agriculture's National Plant Germplasm System (USDA-NPGS), each with more than 41,000 samples, including historical lines, local ecotypes, wild species, and breeding results (Cuevas & Prom, 2020). In India, the National Bureau of Plant Genetic Resources has a collection of approximately 20,000 samples, while in China, the Institute of Germplasm Resources of Agricultural Crops has over 16,874 samples (Singh *et al.*, 2020). The Australian Centre for Tropical Crop and Forage Genetic Resources, on the other hand, focuses on a unique collection of local wild sorghum species, making it a valuable source for studying the wild genome of this crop and its potential for adaptation to extreme conditions. Furthermore, sorghum has gained attention in recent years due to its ability to grow on marginal lands where conventional crops such as wheat or maize are ineffective, making it a valuable asset for countries with limited agricultural resources.

Sorghum was first domesticated in North-East Africa, in a region stretching from Sudan to Ethiopia, which established this territory as the centre of its evolution (Barron *et al.*, 2020). It is here that the greatest diversity of ancient wild species is preserved, as well as a wealth of genetic lines formed over thousands of years of interaction between humans and nature. The USDA-NPGS collection, which includes nearly 41,000 samples, contains 7,217 specimens from Ethiopia and 2,552 from Sudan, highlighting their significance as primary sources. However, the genetic structure of these regions differs: in Sudan, the principal collection is represented by five ancestral populations, while in Ethiopia there are eleven, indicating a more complex genetic diversity of Ethiopian samples. Therewith, the genetic distance between samples (Ibrahim, 2021) from Sudan is greater than in Ethiopia, suggesting greater variability in the Sudanese collection. This contrast is explained not only by natural factors, but also by the historical migration routes of sorghum and the different approaches of local communities to its cultivation. Modern research shows that sorghum from these regions has unique characteristics, such as resistance to soil salinisation and the ability to maintain productivity with minimal irrigation, making them particularly valuable for breeding in the context of global warming.

Preservation of the genetic pool of sorghum requires comprehensive approaches and international cooperation to protect this resource (Reshetnikov *et al.*, 2023). Working with such collections involves their replenishment, maintenance, dissemination, study, and practical application. One of the challenges continues to be the standardisation of approaches to sample evaluation, as countries use different protocols and methods. Documentation has also been a long-standing problem, but major centres such as the USDA-NPGS and ICRISAT have taken steps to modernise their databases to provide access to detailed information on collections, including genome and phenotypic data. In 2007, sorghum experts developed a global strategy for the *ex situ* conservation of sorghum genetic diversity to standardise conservation efforts and facilitate the exchange of resources between countries (Enyew *et al.*, 2022). With growing populations and the increasing impact of climate change threatening food security, these collections are becoming increasingly significant for combating the biotic and abiotic stresses affecting humanity's ability to feed itself. Presently, the stewardship of these resources is more relevant than ever, providing a basis for the development of sustainable varieties in the face of global challenges. Moreover, sorghum is increasingly viewed as a dual-purpose crop: apart from food and feed, its biomass is used to produce biofuels, highlighting the need to preserve genetic diversity to support not only agriculture but also the energy sector (Havrysh *et al.*, 2022). This makes sorghum a strategic resource for sustainable development in an era of environmental and demographic change (Table 1).

***Table 1**. Major sorghum gene bank collections worldwide*

Region/Country	Institute/Organisation	Wild relatives	Cultivars	Total (% of total)
		Africa		
Ethiopia	Institute of Biodiversity Conservation (IBC)		9,772	9,772(4.1)
Kenya	National Gene Bank of Kenya, Crop Plant Genetic Resources Centre – Muguga KARI-NGBK	92	5,774	5,866(2.2)
Zambia	SADC Plant Genetic Resources Centre (SPRGB)	27	3,692	3,719(1.6)

Table 1. Continued

Region/Country	Institute/Organisation	Wild relatives	Cultivars	Total (% of total)
	Americas			
USA	Plant Genetic Resources Conservation Unit (PGRCU)	199	43,511	43,710(18.5)
Brazil	Centre for Genetic Resources Preservation Embara Milo et Sorgho		10,812	10,812(4.6)
Mexico	Biotechnologia (CENARGEN) Uguala		5,500	5,500(2.3)
	Asia			
India	International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	461	39,092	39,553(16,8)
India	ICAR National Bureau of Plant Genetic Resources	11	20,555	20,566
China	Institute of crop science, Chinese Academy of Agriculture Science	27	23,059	23,086
Japan	Department of Genetic Resources National Institute, ICS-CAAS	–	18,263	18,263(7.7)
Pakistan	Agrobiological Science (NIAS) Plant Genetic Resources Programme (PGRP)	–	–	–
	Europe			
France	Laboratoire de Génétique et Amélioration des Céréales, (LGAC)	27	7,278	7,305(3.0)
	Australia			
Australia	Australian Tropical Crops and Forages Genetic Recources Centre (ATCFA)	346	4,144	4,491(2.0)

Source: *compiled by the authors based on E. Mace et al. (2020), H. Cuevas and L. Prom (2020), K. Singh et al. (2020), A. Barron et al. (2020), M.E. Ibrahim (2021), M. Enyew et al. (2022), G.B. Mangshin et al. (2024)*

Thus, sorghum genetic resources accumulated in international collections represent a strategically significant basis for the sustainable development of the agricultural sector. Their diversity, encompassing both cultivated forms and wild relatives, offers enormous potential for the selection of varieties capable of adapting to adverse climatic conditions, drought, poor soils, and new diseases.

PROSPECTS FOR SELECTION AND AGRICULTURAL TECHNICAL SOLUTIONS. POTENTIAL FOR UTILISING FOREIGN GENETIC RESOURCES

The prospects for sorghum breeding in the Aral Sea region were based on the use of genetic resources collected in international collections and were aimed at creating varieties that are resistant to drought, heat, and other abiotic stresses (Sirany *et al.*, 2022). Foreign gene pools, specifically samples from the ICRISAT and USDA-NPGS collections, provided breeders with access to unique lines with high adaptability to extreme conditions (Pujiharti *et al.*, 2022). These collections contained both wild forms and breeding lines, providing broad potential for the development of hybrids capable of producing stable yields in arid climates (Liu, 2023). Breeding programmes introduced genomic technologies, including the use of molecular markers, which accelerated the selection process and increased the accuracy of developing stable varieties (Bvenura & Kambizi, 2022). Attention was also paid to the introduction of hybrid models involving foreign material, aimed at increasing productivity under conditions of limited water supply and high temperatures (Weldemichael *et al.,* 2024).

In parallel with breeding, agronomic approaches aimed at reducing climate risks were developed. Specifically, sowing dates were adjusted to prevent critical growth phases of sorghum from coinciding with periods of extreme heat (Dhar *et al.*, 2024). Measures were taken to improve soil water retention, deep loosening and mulching, which helped maintain productivity even with minimal irrigation (Soni *et al.*, 2023). Special attention was paid to the use of biopreparations and organic stimulants that improve plant resistance to stressful conditions (Somegowda *et al.,* 2021). At the farm level, adaptation measures were proposed, including the use of locally adapted varieties, agrochemical optimisation of nutrition, and minimum tillage technologies. These solutions helped to increase production efficiency and adapt it to the realities of climate change (Khalifa & Eltahir, 2023). The introduction of breeding and agronomic solutions together ensured the formation of a sustainable sorghum cultivation system in the Priaall, factoring in both global scientific developments and the specifics of local conditions (Yadav & Singh, 2024).

The use of such collections helped to expand the adaptive characteristics of the crop through the introduction of ecotypes that are resistant to hot temperatures, drought, and salt stress. First and foremost, attention was paid to genotypes that had been tested under arid farming conditions, which corresponded to the ecological conditions of the Aral Sea region. The potential of the foreign gene pool lay not only in its stability, but also in its high plasticity, ability to form yields under limited resources, and suitability for hybridisation with locally adapted forms (Biswas *et al.*, 2021). The introduction of breeding models was based on the integration of conventional and modern approaches, including molecular selection, marker-associated selection, and preliminary assessment of phenotypic stability. Considering the climatic characteristics of the region, there was a need to develop sorghum varieties that combine drought and heat tolerance, early maturity, and increased biomass (Dixit & Ravichandran, 2024). Such varieties had to meet the requirements of both food and technical uses. In the breeding model, special attention was paid to genotypes capable of demonstrating stable productivity under sharp temperature fluctuations and minimal water supply. The use of genomic resources obtained from international banks ensured a prominent degree of diversity of the source material, which was an essential condition for breeding success (Eduru *et al*., 2021).

Apart from breeding work, considerable attention was paid to agronomic practices aimed at optimising sorghum growing conditions (Liu *et al.*, 2022). One effective technique was to adjust sowing dates according to temperature forecasts and hydrothermal conditions, which helped to avoid the flowering and grain filling phases coinciding with extreme heat. This practice helped to stabilise yields in years with unfavourable climatic conditions. Deep loosening, minimal soil cultivation and mulching were also used to improve moisture retention and reduce evaporation (Choudhary *et al.*, 2025). At the farm level, it was recommended to introduce organic farming technologies and use biopreparations – microbiological growth stimulants, anti-stress complexes, and bioprotective agents. Their use ensured increased plant resistance to drought, improved nutrient uptake and increased the overall biological potential of crops. These measures not only reduced dependence on conventional agrochemicals but also formed sustainable agroecosystems capable of adapting to climate fluctuations. Thus, breeding and agronomic solutions aimed at adapting sorghum to the conditions of the Aral Sea region were based on a comprehensive approach: the use of foreign gene pools, the introduction of breeding models involving sustainable forms, the optimisation of sowing and plant nutrition technologies, and the active application of adaptive farming practices. All this formed a scientifically sound and practically applicable strategy for the sustainable cultivation of sorghum in arid regions.

The use of such collections helped to expand the adaptive characteristics of the crop through the introduction of ecotypes resistant to hot temperatures, drought, and salt stress. First and foremost, attention was paid to genotypes that had been tested under arid farming conditions, which corresponded to the ecological conditions of the Aral Sea region. The potential of the foreign gene pool lay not only in its stability, but also in its high plasticity, ability to form yields under limited resources, and suitability for hybridisation with locally adapted forms (Balakrishna *et al.*, 2020). Thus, against the backdrop of active development of genetic and biotechnological approaches in sorghum breeding, there is a continuing need for an integrated approach that combines the achievements of molecular biology with practical agronomic solutions. Gene editing methods such as CRISPR/Cas and transformation have admittedly opened new horizons in improving sorghum's resistance to stresses, including drought and hot temperatures. However, the introduction of these technologies at the field level continues to be limited, both from technical and economic perspectives. This highlights the need for the parallel development of applied solutions based on the adaptation of sowing dates, minimal soil cultivation, and the use of biopreparations and organic stimulants, which have already proven their effectiveness in agro-extreme regions.

The nutritional value of sorghum and its role in functional nutrition have also been the focus of recent research, where the crop is considered not only as a source of energy but also as a component of a healthy diet (Mwamahonje *et al.*, 2024). However, despite considerable attention to nutritional aspects, climate resilience is either not considered at all or only mentioned fragmentarily in these studies. This suggests the need to integrate biochemical, physiological and agronomic approaches into a single programme for sustainable crop cultivation. Active progress is also being made in the field of breeding, where marker-assisted selection methods are being used and genomic technologies are being introduced, which is helping to accelerate the creation of new varieties with target traits (Parikh *et al.*, 2021). However, without considering the conditions of their subsequent cultivation, such varieties may not reach their full potential. The use of biopreparations adapted to regional conditions has contributed to increasing plant resistance to abiotic stresses, reducing dependence on chemical fertilisers and pesticides, and forming more sustainable agroecosystems. Thus, the inclusion of agrotechnical solutions in the strategy for sustainable sorghum cultivation not only enhances the effect of breeding achievements but also ensures the practical applicability of the findings obtained in real agricultural production conditions.

Against this background, the development of localised sorghum cultivation models adapted to the conditions of regions such as the Aral Sea region is becoming particularly relevant. The introduction of genetically stable varieties must be accompanied by targeted agrotechnical measures – the selection of optimum sowing dates, soil cultivation depth, nutrition and water supply schedules, the use of bioprotective agents, and adapted microbiological complexes. This approach allows for the maximum use of the potential of both conventional and innovative agricultural technologies, creating a sustainable sorghum cultivation system in conditions of increased climatic risks.

CONCLUSIONS

The study identified key areas for sustainable development of the agricultural sector in the context of growing water scarcity in the Kyzylorda region of the Republic of Kazakhstan. It was found that water stress associated with reduced water volumes in the lower reaches of the Syr Darya, degradation of irrigation infrastructure and high evaporation rates directly affect crop selection, crop structure, and agronomic practices. These conditions have predetermined the need to search for alternatives to conventionally cultivated water-intensive crops, such as rice, and confirmed the potential of sorghum as a drought-resistant crop.

The study showed that sorghum has pronounced morphological and physiological adaptations, including a dense waxy coating on the leaves, a deep root system, and the ability to retain green mass, which ensures its survival and productivity under conditions of limited water supply. It was found that drought and heat stress are particularly critical during flowering, which requires the development of varieties that are resistant to terminal drought. Analysis of the phases of sorghum organogenesis confirmed the significance of each stage of crop development and its sensitivity to external conditions, especially during the reproductive phase. From a practical standpoint, the study provided an opportunity to substantiate the need to switch to sorghum cultivation in the Aral Sea region as part of a strategic adaptation to climate change. The study confirmed that the use of modern agronomic solutions – optimisation of sowing dates, introduction of drip and subsurface irrigation systems, use of biopreparations and adapted nutrition schedules – can substantially increase the sustainability and profitability of production. Furthermore, the study highlighted the potential of using the international sorghum gene pool, including materials from gene banks in India, the United States, and African countries, which expands the possibilities for local selection and adaptation of varieties. Thus, the findings obtained not only confirmed the effectiveness of sorghum under water stress conditions but also provided a basis for the development of adaptive agricultural strategies at the regional level.

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CONFLICT OF INTEREST

None.

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Перспективи вирощування зернового сорго (*Sorghum bicolor* L. Moench) у посушливому регіоні Казахстанського Приаралля: огляд літератури

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Анотація. Метою цього дослідження було обґрунтування ефективних селекційних та агрономічних рішень для підвищення стійкості сорго до кліматичних стресів в умовах Приаралья. На основі аналізу літературних джерел дослідження показало, що сільськогосподарський сектор Кизилординської області Республіки Казахстан стикається з постійним дефіцитом води, спричиненим як природними, так і антропогенними факторами. Значне скорочення надходження води в пониззя Сирдар'ї, деградація іригаційної інфраструктури та погіршення якості води створюють умови, за яких традиційні водоємні культури, такі як рис, стають економічно та екологічно нежиттєздатними. Огляд джерел підтвердив, що поряд з технічними заходами, такими як впровадження водозберігаючих технологій, перехід до більш посухостійких культур, включаючи сорго, набуває все більшого значення. Було продемонстровано, що сорго має унікальні фізіологічні адаптації до водного та теплового стресу завдяки своїм морфологічним та анатомічним характеристикам, фазам росту та здатності утримувати зелену масу. У Приаралі ця культура вважається ключовим елементом стратегії адаптації виробництва сільськогосподарських культур до змін кліматичних умов. Крім того, сорго має широкий спектр застосування, від продуктів харчування та кормів до біоенергетики, що підкреслює його агроекономічну цінність. В огляді літератури також відзначається зростаючий інтерес до генетичного та селекційного потенціалу сорго: міжнародні банки генів зберігають понад 42,000 зразків, включаючи унікальні генотипи з Африки та Азії, що відкриває перспективи для створення стійких та високоврожайних сортів. Таким чином, результати огляду літератури підтвердили виражену адаптивність сорго до умов регіону Аральського моря, його стратегічне значення в умовах водного стресу та актуальність подальших селекційних та агрономічних розробок, спрямованих на його широке впровадження в сільське господарство регіону

Ключові слова: стресостійкість; генетичне різноманіття; біопрепарати; агротехнічні методи; ефективність використання води

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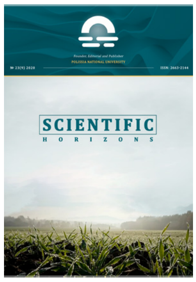

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Use of biologisation elements in the cultivation of grain and industrial crops to obtain high-quality products and preserve the environment

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Abstract. The study aimed to assess the effectiveness of introducing biologisation elements to increase crop yields and quality. An experiment was conducted to analyse the impact of biological and organic fertilisers, regulated irrigation and pesticide control on yields, product quality, soil nutrient content, CO_2 emissions and biodiversity. The results demonstrated that the use of biological fertilisers (biological products, composts, and humates) positively impacted the yield of all the crops studied. In

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variant 2, where varieties of wheat, corn, hemp and sunflower were used with biological fertilisers, an increase in yields of 12-20% was observed, depending on the crop. Organic fertilisers in variant 3 also showed an increase in yields, although to a lesser extent (8-15%). Regulated irrigation and pesticide control in variant 4 provided a stable yield increase of 10-12%, while combined fertilisation and irrigation in variant 5 gave the best results, albeit with smaller increases. The introduction of biological fertilisers also positively affected product quality. The oil content of soybean and sunflower in the plots with biological fertilisers was also higher compared to control variant 1. Analysis of the soil's nutrient content showed that the biological fertiliser increased the levels of nitrogen, phosphorus and potassium in the soil. CO_2 emissions decreased by 10-15% in areas with biological fertilisers, indicating a positive environmental effect of using such technologies. Biodiversity has also improved, with a 40% increase in the biodiversity index in the biological fertiliser plot. Thus, the results of the study confirm that the integration of biological and organic fertilisers, as well as effective water and pesticide management, can significantly increase crop yields and quality, reduce CO_2 emissions and contribute to biodiversity conservation

Keywords: crops; elements of technology; biological methods in crop production; ecology; plant yield and quality

INTRODUCTION

Grain and industrial crop production is a critical component of the agricultural sector, as it directly affects food security and economic development. However, traditional agronomic practices, such as the intensive use of chemical fertilisers and pesticides, are often accompanied by serious environmental problems. These include soil degradation, water pollution from runoff and pesticide residues, and loss of biodiversity due to the disturbance of natural ecosystems. To overcome these negative consequences and ensure sustainable development of the agricultural sector, the biologisation of agronomic processes is emerging as a promising approach. Biologisation involves the introduction of natural components and technologies, such as organic fertilisers, biostimulants, inoculants, and ecological soil cultivation methods. This approach aims to increase the efficiency of crop cultivation, improving soil quality and reducing the negative impact on the environment, thus contributing to the sustainable development of agriculture.

The analysis of scientific sources shows that the issue of biologisation in agronomy has been considered from various aspects. L.M. Potashova (2024) analysed innovative technologies in crop production, particularly biologisation methods, focusing on general aspects without specialising in specific crops, which provided a general overview of modern technologies but did not delve into specific aspects related to individual crops. The impact of deficit irrigation and iron fertilisation on soybeans in dry climates was studied by V. El Amine *et al.* (2024), which could be a part of agronomic biologisation practices. Z. Liu *et al.* (2024) studied the effect of no-till and organic fertilisation on kiwi productivity, which defined the effects of biological methods on different crops. E. Semenchenko (2024) analysed the dynamics of the main nutrients in the soil, which is important for assessing the effectiveness of biologisation. O. Ergasheva *et al.* (2024) assessed the impact of fertilisers on the yield and quality of barley and potatoes, which revealed the effects of different types of fertilisers. C. Pacheco *et al.* (2023) studied the impact of mineral and organic fertilisers on maize yield and soil carbon balance, which is also part of biologisation.

L. Wegner (2022) studied modern aspects of root energy that may affect the application of biological methods. In turn, M. Allam *et al.* (2022) conducted a meta-analysis of the impact of organic and mineral fertilisers on soil organic carbon and productivity. The biologisation of agriculture, as a way to increase economic efficiency was considered by S. Skok and V. Almashova (2023) and O. Costa *et al.* (2024), who studied the effect of biostimulants on plant growth and soil microbiome, which can be applied to biologisation technologies. Y. Li *et al.* (2024) analysed the dynamics of phosphorus fixation and mobilisation in agroecosystems, which is important for nutrition management in the context of biologisation. Notably, most studies focus on individual crops or types of fertilisers, leaving the integration of biological approaches in the integrated cultivation of different crops underdeveloped. Assessm ent of their environmental effects has also received insufficient attention. This creates a gap in understanding how biological methods can be effectively integrated into different agronomic systems and what their long-term effects are on ecosystems and economies.

Thus, the research problem is the need to assess the impact of the biologisation of agronomic practices on the cultivation of various crops in the Ukrainian agricultural climate. This includes an analysis of the effectiveness of the plant varieties under study in combination with biological and organic fertilisers and regulated irrigation. It is also necessary to analyse the impact of these elements of technology on environmental conditions. In this context, the study aimed to comprehensively assess the impact of biological and agronomic practices on the yield and quality of wheat, corn, soybeans and sunflower, as well as their impact on the environment. In particular, the effectiveness of the varieties and fertilisers under study was analysed, as well as their integration with modern elements of technology, such as controlled irrigation and pesticide control. The study hypothesises that the use of biological fertilisers and new agricultural-technological techniques can significantly increase yields and product quality while reducing the negative impact on the environment.

MATERIALS AND METHODS

The study was conducted from March 2022 to October 2024 at the Educational and Research Centre of Mykolaiv National Agrarian University. For the experiment, the crops presented in Table 1 were selected.

***Table 1**. Plant varieties used in the study*

Crop	Variety	Year	Country
Wheat	Odesa duma	2017	Ukraine
Corn	DM Victoria	2016	Ukraine
Hemp	Gliana	2007	France
Sunflower	Agent	2018	Ukraine

***Source:** compiled by the author based on the Ministry of Agrarian Policy and Food of Ukraine (2025)*

The equipment used for soil cultivation and fertilisation included John Deere tractors (USA), Horsch cultivators (Germany) and Amazone fertiliser spreaders (Germany). Measuring instruments included Fluke pyrometers (USA), Hanna Instruments pH meters (Italy) and Bosch moisture meters (Germany). The research methodology was based on a controlled experiment that included three experimental groups and a control group. The results of biological fertilisers were compared with traditional chemical fertilisers. Soil and crop samples were collected from each plot to analyse nutrient content, moisture levels and contamination. A formula was used to calculate the yield to assess the effectiveness:

$$Y = (W/A) \times 1000, \quad (1)$$

where Y – yield (t/ha); W – total yield weight (kg); A – plot area (ha).

Results were analysed using ANOVA to determine the statistical significance of differences between groups. Methods used included standard soil analysis techniques such as sampling, pH and organic matter determination (State Standard of Ukraine No. ISO 10390:2007, 2007). The environmental impacts were assessed using developed monitoring tools, including CO_2 emissions and biodiversity impacts.

The weather conditions during the experiment were characterised by the following trends: after sowing wheat in September and October, temperatures remained moderate, with average values ranging from 10°C to 18°C, which contributed to friendly germination. The autumn was rainy, which provided sufficient soil moisture for the development of the plant root system. However, in November, temperatures began to drop, marking the beginning of winter dormancy. The winter months were characterised by moderately cold weather. Average temperatures ranged from -2°C to 4°C, with periods of snow cover that protected the plants from frost. However, on some days the temperature dropped below -5°C, which could have affected plant survival. Overall, the wintering was satisfactory, and the plants remained viable until spring. In April, temperatures started to rise gradually, which helped winter wheat to emerge. The average temperature in this month ranged between 8°C and 15°C. Rains and temperature fluctuations affected the initial stage of crop growth. In May, temperatures continued to rise, with average values ranging from 14°C to 22°C. May had more stable weather conditions, which favoured active plant growth. The average temperature in June ranged from 18°C to 27°C. It was a period of active growth and development of crops, but there were also periods of extreme heat and insufficient moisture, which affected yields. In July, temperatures reached peak levels, with average temperatures ranging from 35°C to 38°C, and there was virtually no precipitation. Temperatures in August remained hot, with average temperatures ranging from 30°C to 35°C. August was marked by hot days and low humidity, which had a negative impact on the ripening phase of crops. In September, temperatures dropped, with average temperatures ranging from 15°C to 24°C. September was an important month for harvesting and was characterised by stable weather conditions.

Crop cultivation practices were generally accepted for the conditions in southern Ukraine, except for the factors under study. The study was conducted using several crops, including winter wheat, corn, hemp, and sunflower. Winter wheat is represented by the Odesa duma variety, corn by DM Victoria, sunflower by Agent, and hemp by Gliana. Several options were proposed to assess the impact of nutrition on yield and product quality. Variant 1 is a control, where no fertilisers or preparations are used. Option 2 used biological fertilisers: BioGrow compost (5 t/ha), Agrorhiz humates (10 litres/ha) and Soil Health bacteria (1 litre/ha). Option 3 involved the use of EcoTon organic fertiliser (8 t/ha). Option 4 included the use of pesticides: Fundazol fungicide (1.5 litres/ha), Actellik insecticide (0.5 litres/ha), Bactofit fungicide (2 litres/ha) and Intarsit biological pesticide (0.8 litres/ha). Option 5: combined application of organic and mineral fertilisers (State Standard of Ukraine No. 4884:2007, 2007).

The study also assessed the effectiveness of pesticides and biological plant protection products on Option 4. This demonstrated how these measures affect crop productivity. Two irrigation backgrounds were selected for the study: no irrigation and irrigation, which was used to analyse the impact of water resources on crop yields and quality. Each variant was analysed for yield and product quality. The number of fertilisers, preparations and water applied was determined separately to assess the impact of each factor on crop yields under different moisture conditions. The control plot was represented by the tested varieties without the use of additional agrotechnological techniques (Option 1). This ensured the principle of a single logical difference for comparing the results with other variants of the study. The results of the experimental variants were compared with the control variants to assess the effectiveness of the applied technology elements and determine their impact on productivity and quality. The study also involved regulatory documents governing the use of biological fertilisers, namely: Law of Ukraine No. 1264-XII (1991), Law of Ukraine No. 2775-IX (2022). The study complied with the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979). The study used an integrated approach, which demonstrated the use of biological elements in the cultivation of grain and industrial crops.

RESULTS

The use of biologisation elements is an important area for increasing crop yields. The introduction of biological fertilisers and new agronomic approaches in the study demonstrated different levels of impact on yields depending on the methods used. In variant 2, varieties of wheat, corn, hemp, and sunflower were applied together with biological fertilisers. The results demonstrated that for wheat, the introduction of biological fertilisers improved soil structure and contributed to better access to nutrients for plants. In the maize plot, biological fertilisers, especially bacteria for growth stimulation, had a positive impact on root development and increased water and nutrient uptake. In the case of hemp, the introduction of biological fertilisers increased yields by 16%, and in sunflowers, it had a positive impact on the formation of large and high-quality seeds. Varieties combined with organic fertilisers were used in variant 3. The use of organic fertilisers improved soil structure and provided additional nutrients, leading to a 9% increase in wheat yields compared to the control plots.

Organic fertilisers improved the water-holding capacity of the soil in the maize plot, which had a positive impact on plant development. It also improved the availability of nitrogen for soybeans, which helped to increase yields by 10%. Organic fertilisers contributed to better sunflower development and improved seed quality. The pesticide treatment was controlled in variant 4. Regulated irrigation provided an optimal level of soil moisture, which contributed to the stable growth of winter wheat. Pesticide control reduced corn yield losses due to diseases and pests. Hemp and sunflower increased yields due to optimal water management and pest control. In variant 5, winter wheat varieties "Odesa duma", maize "DM Victoria", hemp "Gliana", and sunflower "Agent" were grown with a combination of organic and mineral fertilisers, as well as irrigation control. Combined fertilisation and irrigation provided the best conditions for the growth and development of all the crops under study. The introduction of biologisation elements, such as biological and organic fertilisers, regulated irrigation and pesticide control, has had a positive impact on crop yields. Each of the approaches proved to be effective in increasing productivity, but the most significant effect was achieved in the variant with combined fertilisation and irrigation (Table 2). This confirms that the integration of different elements of technology is the key to increasing yields and product quality.

***Table 2**. Crop yields (average for 2022-2024), t/ha*

Crop	Variety	Variant 1 (Control)	Variant 2 (Biological fertilisers)	Variant 3 (Organic fertilisers)	Variant 4 (Plant protection + watering)	Variant 5 (Combined application + watering)
Wheat	Odesa duma	3.2	4.5	4	4.8	5.2
Corn	Sweet Spirit	6	7.5	7	8.2	8.5
Hemp	Gliana	2.5	3.5	3	4	4.3
Sunflower	Agent	2.8	3.8	3.5	4.2	4.5

***Source:** compiled by the authors*

The use of biological fertilisers and processing technologies significantly affected the product quality of the studied crops. In the control variant, winter wheat demonstrated an average protein level and low grain strength, which led to satisfactory product quality. The use of biological fertilisers (BioGrow, Agrorhiz, Soil Health) had a positive impact on its quality. The protein content increased to 12.8%, which indicates an improvement in the nutritional value of the grain. Grain strength increased, and quality was rated as high due to improved structure and fewer defects. In the EcoTon organic fertiliser treatment, protein content increased, and although grain quality improved, it did not reach the level achieved in the biological fertiliser treatment. Regulated irrigation and pesticide control had a positive impact on wheat quality. Protein content reached

13.0%, although it did not exceed the results achieved with biological fertilisers. Combined fertilisation and irrigation resulted in a protein content of 12.9%, and wheat quality remained at a sufficient level, but also did not exceed the results with biological fertilisers.

In the control variant, corn had a low oil content and average grain quality, with a high level of defects. With biological fertilisers, an increase in oil content was observed, indicating an improvement in grain quality. Defects decreased, improving the overall quality of the product. In the variant with EcoTon organic fertiliser, oil content increased to 4.5% and grain quality improved compared to the control conditions. Regulated irrigation and pesticide control improved oil content and grain quality but did not reach the level of results with biological fertilisers. Combined fertilisation and irrigation provided the highest oil content, but grain quality remained average. Hemp showed a protein content of 10.0% with average seed quality and satisfactory nutritional value in the control variant. The varieties together with biological fertilisers provided a significant increase in protein content. This improved seed quality and nutritional value, which indicates the effectiveness of biological fertilisers. In the organic fertiliser variant, the protein content increased, which is an improvement, but did not reach the results of the biological fertiliser plot. Regulated irrigation and pesticide control had a positive effect on protein content, improving seed quality and nutritional value, but did not exceed the results of option 2. Combined fertilisation and irrigation improved protein content, but seed quality remained average.

The results of sunflower cultivation in the control variant showed an oil content of 43.5%, with average seed quality and high levels of damage. The use of biological fertilisers increased the oil content, indicating a significant improvement in seed quality and a damage reduction. Product quality was rated as high. Organic fertilisers also increase oil content. Seed quality improved but did not reach the level of option 2. Regulated irrigation and pesticide control resulted in higher oil content. Seed quality improved but did not exceed the results with biological fertilisers. Combined fertilisation and irrigation resulted in higher oil content. Seed quality was at a high level (Table 3). The impact of biologisation on the content of acceptable nutrients in the soil is significant and complex, as it involves several key processes and mechanisms that interact to improve soil fertility. Biological fertilisers, such as composts and humates, positively impact soil structure. Composts, which result from the decomposition of organic materials, add large amounts of organic matter to the soil. This increases the water-holding capacity of the soil, promotes the formation of a clodded soil structure and reduces the risk of erosion. Humates, which are derivatives of organic acids, improve soil aeration and increase its ability to retain moisture, which has a positive effect on overall fertility.

***Table 3**. Product quality (average for 2022-2024)*

Crop	Variant 1 (Control)	Variant 2 (Biological fertilisers)	Variant 3 (Organic fertilisers)	Variant 4 (Plant protection + watering)	Variant 5 (Combined application + watering)
Wheat	Protein content: 12.3% Grain strength: low Quality: satisfactory	Protein content: 13.5% Grain strength: high Quality: High	Protein content: 12.8% Grain strength: average Quality: good	Protein content: 13% Grain strength: average Quality: good	Protein content: 12.9 % Grain strength: average Quality: good
Corn	Oil content: 4.2% Grain quality: average Defects: increased	Oil content: 4.8% Grain quality: high Defects: decreased	Oil content: 4.5% Grain quality: average Defects: decreased	Oil content: 4.6% Grain quality: high Defects: decreased	Oil content: 4.7% Grain quality: average Defects: decreased
Hemp	Protein content: 10% Seed quality: average Nutritional value: satisfactory	Protein content: 12% Seed quality: high Nutritional value: better	Protein content: 11.5% Seed quality: average Nutritional value: good	Protein content: 11% Seed quality: average Nutritional value: good	Protein content: 11.8% Seed quality: average Nutritional value: good
Sunflower	Oil content: 43.5% Seed quality: average Damage: increased	Oil content: 47% Seed quality: high Damage: decreased	Oil content: 45.5% Seed quality: average Damage: decreased	Oil content: 46% Seed quality: high Damage: decreased	Oil content: 45.8% Seed quality: average Damage: decreased

***Source:** compiled by the authors*

Microbiological products, such as growth-stimulating bacteria, activate microbiological activity in the soil. The microorganisms contained in these products help to decompose organic residues and release nutrients in a form that is available to plants. For instance, some bacteria can convert inorganic nitrogen into a form that is easily absorbed by plants, improving the nitrogen supply to crops (Didur *et al.*, 2023). The application of biological fertilisers helps to increase the content of the main nutrients nitrogen (N), phosphorus (P) and potassium (K) in the soil. Composts and humates contain a significant amount of organic nitrogen, which gradually decomposes, providing a long-lasting effect. The phosphorus in composts and humates is gradually released and becomes available to plants, which is especially important for root development. Potassium contained in biological fertilisers improves the water balance in plants and their stress resistance (Table 4). Biological fertilisers improve the availability of nutrients in the soil. Composts and humates help to bind and retain nutrients, reducing leaching and ensuring their gradual release. Microbiological preparations help to break down complex organic compounds, converting them into forms that are easy for plants to absorb. In general, biologisation leads to an increase in the level of organic matter in the soil, which has a positive effect on overall fertility. Increasing the organic content improves not only the nutrient content but also the physical and chemical properties of the soil, such as its structure, water-holding capacity and aeration.

***Table 4**. Content of acceptable nutrients in the soil (average for 2022-2024)*

Crop	Variant 1 (Control)	Variant 2 (Biological fertilisers)	Variant 3 (Organic fertilisers)	Variant 4 (Plant protection + watering)	Variant 5 (Combined application + watering)
Wheat	Mobile nitrogen: 15 mg/kg P_2O_5: 10 mg/kg K_2O: 20 mg/kg	Mobile nitrogen: 25 mg/kg P_2O_5: 15 mg/kg K_2O: 30 mg/kg	Mobile nitrogen: 20 mg/kg P_2O_5: 12 mg/kg K_2O: 25 mg/kg	Mobile nitrogen: 22 mg/kg P_2O_5: 14 mg/kg K_2O: 28 mg/kg	Mobile nitrogen: 24 mg/kg P_2O_5: 16 mg/kg K_2O: 27 mg/kg
Corn	Mobile nitrogen: 18 mg/kg P_2O_5: 11 mg/kg K_2O: 22 mg/kg	Mobile nitrogen: 30 mg/kg P_2O_5: 18 mg/kg K_2O: 35 mg/kg	Mobile nitrogen: 23 mg/kg P_2O_5: 13 mg/kg K_2O: 28 mg/kg	Mobile nitrogen: 25 mg/kg P_2O_5: 17 mg/kg K_2O: 33 mg/kg	Mobile nitrogen: 28 mg/kg P_2O_5: 19 mg/kg K_2O: 30 mg/kg
Hemp	Mobile nitrogen: 12 mg/kg P_2O_5: 9 mg/kg K_2O: 18 mg/kg	Mobile nitrogen: 20 mg/kg P_2O_5: 14 mg/kg K_2O: 24 mg/kg	Mobile nitrogen: 15 mg/kg P_2O_5: 10 mg/kg K_2O: 20 mg/kg	Mobile nitrogen: 18 mg/kg P_2O_5: 13 mg/kg K_2O: 23 mg/kg	Mobile nitrogen: 19 mg/kg P_2O_5: 15 mg/kg K_2O: 22 mg/kg
Sunflower	Mobile nitrogen: 14 mg/kg P_2O_5: 10 mg/kg K_2O: 21 mg/kg	Mobile nitrogen: 26 mg/kg P_2O_5: 16 mg/kg K_2O: 32 mg/kg	Mobile nitrogen: 19 mg/kg P_2O_5: 12 mg/kg K_2O: 26 mg/kg	Mobile nitrogen: 21 mg/kg P_2O_5: 15 mg/kg K_2O: 29 mg/kg	Mobile nitrogen: 23 mg/kg P_2O_5: 17 mg/kg K_2O: 31 mg/kg

***Source:** compiled by the authors*

Thus, biologisation using organic and microbiological fertilisers significantly improves the nutrient content of the soil, increasing its fertility and productivity. This helps to provide plants with the necessary elements for growth and development, which in turn has a positive impact on the yield and quality of agricultural products. Biologisation, which includes the use of organic and microbiological fertilisers, can affect CO_2 emissions through various mechanisms (Trembitska & Bohdan, 2023). The application of organic fertilisers, such as composts and humates, improves soil structure and increases its organic content. This can reduce CO_2 emissions, as well-structured soils with higher organic matter content contribute to better soil carbon retention, reducing its release to the atmosphere. Composts and humates improve the water-holding capacity of the soil, which reduces erosion (Kyselov, 2024). Less erosion means less loss of organic material from the soil, which also helps to reduce CO_2 emissions. Microbiological products can affect the decomposition of organic matter, which also affects CO_2 emissions. Microorganisms accelerate the decomposition of organic materials, but this process can be more controlled, which can reduce CO_2 emissions.

Agronomic practices, such as managed irrigation and pesticide use, also impact CO_2 emissions. Managed irrigation can reduce CO_2 emissions by reducing the risk of soil drying out and improving soil moisture, which reduces the need for frequent tillage, which can be associated with CO_2 emissions. The impact of pesticides on CO2 emissions is less apparent, but their use can affect microbiological processes in the soil. Uncontrolled use of pesticides can disrupt the balance of microorganisms, which in turn can change CO_2 emissions (Table 5).

***Table 5**. CO_2 emissions at different experimental sites (average for 2022-2024)*

Variant	Type of fertiliser/agronomic practices	CO_2 emissions (kg/ha)	Reduction of CO_2 emissions (% from control plot)
Variant 1	Without additional measures	120	0%
Variant 2	Biological fertilisers (compost, humates, bacteria)	102	-15%
Variant 3	Organic fertilisers	106	-12%
Variant 4	Controlled irrigation and pesticide control + watering	116	-3%
Variant 5	Combined fertilisation + irrigation	108	-10%

***Source:** compiled by the authors*

Biologisation has a significant positive impact on biodiversity. Organic fertilisers promote the development of a variety of microorganisms in the soil, such as beneficial bacteria and fungi, which help to decompose organic matter and increase soil fertility. Biological fertilisers can support and increase the number of beneficial organisms, such as shrews and predatory insects, which help control pests and diseases (Shahini *et al.*, 2024). The use of biological fertilisers can increase plant diversity by improving the conditions for different types of crops to grow, which increases the overall biodiversity of the agricultural ecosystem.

Agronomic practices also have both positive and negative impacts on biodiversity (Fedoniuk *et al.*, 2024). Regulated irrigation can help maintain plant and microbial diversity by providing stable growth conditions. However, excessive irrigation can lead to problems with soil salinity, which can have a negative impact on biodiversity (Table 6). Pesticide applications can have a negative impact on biodiversity, as they can kill not only pests but also beneficial insects and other organisms, upsetting the ecological balance and reducing the diversity of organisms in the soil and on the surface.

Table 6. *Biodiversity in different variants (average for 2022-2024)*

Variant	Type of fertiliser/agronomic practices	Biodiversity index	Changes in biodiversity (% of the control site)
Variant 1	Without additional measures	1	0%
Variant 2	Biological fertilisers (compost, humates, bacteria)	1.4	+40%
Variant 3	Organic fertilisers	1.3	+30%
Variant 4	Controlled irrigation and pesticide control + watering	1.2	+20%
Variant 5	Combined fertilisation + irrigation	1.35	+35%

Source: *compiled by the authors*

Thus, biologisation and agronomic practices have different impacts on CO_2 emissions and biodiversity. The use of biological fertilisers generally reduces CO_2 emissions and increases biodiversity, while agronomic practices can have both positive and negative effects depending on their application and control.

DISCUSSION

The study demonstrated that the use of biological approaches in the cultivation of cereals and industrial crops can significantly improve their quality and resistance to environmental stress. The findings are important for developing strategies that will help preserve the environment and increase agricultural productivity. The introduction of biological methods can reduce the dependence on chemical fertilisers and pesticides, which correlates with modern environmental requirements and trends towards sustainable development. The results of the study on the impact of biological methods on plant productivity and soil quality are consistent with the findings of W. Huo *et al.* (2023). The authors determined that the optimal use of phosphate fertilisers in saline soils can significantly improve cotton yields by reducing excessive phosphorus in the soil, which is an important aspect for reducing negative environmental impacts. The study also demonstrates that optimising the use of biological fertilisers can help achieve similar results, reducing the risk of over-application of phosphate fertilisers and improving overall soil health. Q. Wang *et al.* (2024) investigated the effect of long-term straw management in wheat and cotton on root system performance and cotton yield. Their results indicate that phosphate fertilisers applied in combination with straw improve root carbohydrate metabolism and, as a result, increase productivity. Observations confirm these results, showing that biological methods, such as bio-phosphorus fertilisers and cover crops, can contribute to similar improvements in agricultural systems, increasing productivity and resource efficiency.

The use of magnetised water together with biodegradable films can significantly improve the distribution of water and salt in the soil, leading to increased tomato yields in arid conditions, as stated by Z. Zhou *et al.* (2024). The results confirm that innovative approaches can be integrated with biological methods to achieve similar effects, in the context of improving soil water retention and increasing crop productivity. In turn, N. Li *et al.* (2024) investigated the synergy between *Broussonetia papyrifera* and biofertilisation to stabilise bacterial communities and improve plant growth in copper dumps. These observations also indicate that biofertilisation can significantly improve the stability of the microbiological environment in agricultural systems, increasing the efficiency of plant systems under adverse conditions. M. Bashir *et al.* (2024) determined that polystyrene microplastics can affect the bioavailability and toxicity of copper compounds in maize. This study also highlights the importance of controlling pollutants and their impacts on agricultural systems, through biological methods that can help reduce the negative effects of pollution.

The results of the study by J. Bangre *et al.* (2024) on the impact of inorganic fertilisers and manure on soil quality and productivity in subtropical vertisols demonstrated that long-term use of these fertilisers can affect soil properties and crop productivity. The findings confirm that biological methods, such as biofertilisation, can provide sustainable improvements in soil quality and crop productivity through their long-term effects on soil structure and fertility. Differences in soil carbon content and crop growth in different agricultural conditions in China, emphasising the role of geochemistry and climate change, were studied by X. Yang *et al.* (2024). The results of this study also confirm the importance of considering geochemical and climatic factors when using biological methods to improve soil fertility and crop productivity. Biological approaches can help to adapt to climate change by improving soil organic matter content and structure. D. Wang *et al.* (2024) investigated the impact of different levels of fertiliser application on bacterial communities, enzyme activity and soil organic nitrogen fractions. This study confirms that biofertilisers can contribute to improving the microbiological environment and increasing nutrient use efficiency. The integration of biofertilisers into agronomic practices demonstrates a similar positive impact on soil structure and fertility (Shuvar *et al.*, 2022).

The responses of bacterial and fungal communities to three years of biofertiliser application to alkaline soybean soil were described by W. Gao *et al.* (2021). The results are consistent with this study, showing that biofertilisers can positively affect microbial activity and soil fertility, which is important for maintaining the long-term productivity of agricultural systems. The results of a study by J. Fachini *et al.* (2024) demonstrated that potassium-enriched fertilisers improved nutrient uptake in radish plants. This is consistent with the findings that fertilisers enriched with different nutrients can have a positive impact on crop productivity by improving nutrient availability and uptake. The impact of biofertilisers on nutrient cycling and crop productivity was studied by L. Melo and M. Sánchez-Monedero (2024). These results confirm that biofertilisers can be effective in improving nutrient cycling and ensuring sustainable crop productivity through their effect on the physical and chemical properties of the soil. C. Figueiredo *et al.* (2024) examined nutrient- and compost-enriched soil in terms of systemic productivity and environmental sustainability. The results are consistent with their findings that such biofertilisers can increase the productivity of agronomic systems and ensure environmental sustainability, due to their ability to improve soil structure and maintain soil fertility.

A study by I. Rashmi *et al.* (2024) on the effects of gypsum and organic amendments on soil stability, productivity and health under agricultural production in soda soils of India is noteworthy. The results of this study confirm that biological additives can be effective in maintaining soil health and increasing productivity, similar to the effects of organic additives in other agronomic systems. The study by X. Xie *et al.* (2024) confirmed that bacteria that stimulate plant growth and can withstand salt stress are effective in mitigating such stress in plants. These results support this claim, showing that bacteria can significantly increase crop resistance to salt, which is important for areas with high levels of salinity. Similar findings were reported by Z. Ning *et al.* (2024), who analysed the use of halophilic bacteria to reduce salt stress in rice. The results of the study are consistent with their findings, confirming the effectiveness of certain microorganisms in improving plant salt tolerance, which may be important for growing crops in saline environments. C. Cruz *et al.* (2023) also demonstrated that bacteria that stimulate plant growth can increase the resistance of maize to salinity. These results also confirm the positive impact of such bacteria, which highlights the potential of using these microorganisms to improve product quality under salt stress. L. Zhuang *et al.* (2024) highlighted the impact of reducing chemical fertilisers and applying organic fertilisers on soil fertility and productivity in apple orchards. The results also confirmed that the reduction of chemical fertilisers and the use of organic methods can have a positive impact on crop productivity and environmental sustainability, which is consistent with the findings of their study. A. Panfilova *et al.* (2021) determined that nutrition optimisation increases barley yields, which is consistent with the data obtained for wheat. These results confirm that nutrition is a critical factor in achieving high performance. The researchers also focused on optimising wheat-growing technologies, especially the Kolchuga variety, in the steppes of southern Ukraine. Their recommendations for optimisation can be supplemented with data on the impact of biological fertilisers on crop yields and quality.

The use of organic nitrogen fertilisers to improve soil health and increase yields was reviewed by S. Shahini *et al.* (2023). This study expands on these ideas by providing more detailed information on the impact of biological, organic and combined fertilisers on product quality. T. Kachanova *et al.* (2021) assessed the impact of weather conditions and sowing methods on chickpea productivity, highlighting the importance of environmental conditions for the success of agronomic practices. This complements the findings on the importance of agronomy for biodiversity conservation. V. Pichura *et al.* (2024) studied the influence of predecessors on the formation of water balance in winter wheat agrocenoses and soil moisture in the steppe zone. Their results emphasise the importance of agronomic management to optimise water resources, which can be applied to the present study, which also considers irrigation. The study demonstrated that elements of biologisation can significantly improve both product quality and environmental conditions. The differences found in comparison with previous studies highlight the need to adapt biologisation methods to specific growing conditions.

CONCLUSIONS

The study confirmed the effectiveness of introducing elements of biologisation in agronomic practice to increase crop yields and quality. In particular, the use of biological fertilisers (biological products, composts, and humates) improved the yield of all the crops studied. In variant 3 with organic fertilisers, yields increased by 8-15%, while regulated irrigation and pesticide control in variant 4 provided a stable yield increase of 10-12%. The best results were achieved in Plot 5 with combined fertilisation and irrigation. Biological fertilisers also improved product quality: soybean and sunflower oil content was higher. Soil nutrient analysis showed increased levels of nitrogen, phosphorus and potassium. CO_2 emissions decreased by 10-15% and biodiversity increased by 40%. Overall, the research results confirm that the integration of biologisation elements into agronomic practices is an effective strategy for improving yields, product quality and soil fertility. Biological fertilisers provided the most significant positive effect compared to other methods. The combined use of fertiliser and irrigation also demonstrated significant benefits, especially in terms of resource management and CO_2 emissions reduction. These results underline the importance of an integrated approach to agricultural ecosystem management to achieve high productivity and sustainability in agriculture.

It is recommended to introduce biological and organic fertilisers on a wide scale to increase yields and product quality. It is also necessary to continue to use regulated irrigation and control pesticide treatments for sustainable results. It is also important to explore the possibilities of combined fertilisation and irrigation to achieve the best results. The main areas for further research include studying the long-term effects of biological fertilisers on different soil types and climatic conditions, the optimal combinations of fertilisers and irrigation for different crops and an analysis the impact of biological fertilisers on plant resistance to diseases and pests. The study is limited by the specific types of fertilisers and irrigation used, as well as the geographical and climatic conditions of the sites. It is worth noting that the study was conducted in one geographical area (Mykolaiv region), which may limit the generalisability of the results to other regions. Moreover, the possible effects of other factors, such as genetic characteristics of crops and climate change, were omitted in this study.

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Використання елементів біологізації при вирощуванні зернових і технічних культур з метою отримання високоякісної продукції та збереження довкілля

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Анотація. Метою дослідження було оцінити ефективність впровадження елементів біологізації для підвищення врожайності та якості сільськогосподарських культур. Було проведено експеримент, у рамках якого проаналізовано вплив біологічних та органічних добрив, регульованого зрошення і контролю пестицидного оброблення на врожайність, якість продукції, вміст поживних речовин у ґрунті, викиди CO_2 та біорізноманіття. Результати показали, що використання біологічних добрив (біопрепарати, компости, гумати) позитивно вплинули на врожайність всіх досліджених культур. Зокрема, у варіанті 2, де були застосовані сорти пшениці, кукурудзи, конопель і соняшнику з біологічними добривами, спостерігалося збільшення врожайності на 12-20 % залежно від культури. Органічні добрива у варіанті 3 також показали підвищення врожайності, хоча й у меншому обсязі (8-15 %). Регульоване зрошення і контроль пестицидів у варіанті 4 забезпечили стабільний приріст врожайності на 10-12 %, а комбіноване внесення добрив і зрошення у варіанті 5 дало найкращі результати, хоча й з меншими збільшеннями. Впровадження біологічних добрив також позитивно вплинуло на якість продукції. Олійність сої та соняшнику на ділянках з біологічними добривами також була вищою порівняно з контрольним варіантом 1. Аналіз вмісту поживних речовин у ґрунті показав, що біологічні добрива підвищили рівні азоту, фосфору і калію в ґрунті. Викиди CO_2 зменшилися на 10-15 % на ділянках з біологічними добривами, що вказує на позитивний екологічний ефект застосування таких технологій. Біорізноманіття також покращилось, зокрема на ділянці з біологічними добривами спостерігалося зростання індексу біорізноманіття на 40 %. Таким чином, результати дослідження підтверджують, що інтеграція біологічних і органічних добрив, а також ефективне управління водними ресурсами і пестицидами може значно підвищити врожайність і якість сільськогосподарських культур, зменшити викиди CO_2 і сприяти збереженню біорізноманіття

Ключові слова: сільськогосподарські культури; елементи технології; біологічні методи в рослинництві; екологія; урожайність і якість рослин

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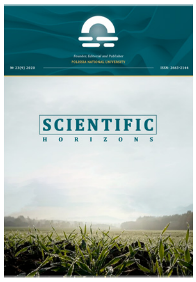

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The application of monoglycerides in swine husbandry: A review of current trends and prospects

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Abstract. The increasing prevalence of multi-resistant strains due to the widespread use of antibiotics in livestock farming represents a critical risk factor for both humans and animals. Therefore, the development of alternative strategies to replace antibiotics in animal production systems remains an urgent challenge. Various bioactive compounds have been proposed as alternatives; however, most fail to achieve efficacy comparable to that of antibiotics. The present review aimed to analyse recent studies regarding the effects and mechanisms of action of fatty acids and their glycerides on the digestive system of production animals. Mixtures of individual fatty acids and monoglycerides are considered promising substitutes due to their broad-spectrum antimicrobial, antiviral, anti inflammatory and metabolic effects. A key benefit of such mixtures is the maintenance of barrier integrity and immune function in the pig intestine under intensive farming conditions. Despite notable progress in the study of individual bioactive agents aimed at supporting pig productivity in the post antibiotic era, the molecular and cellular mechanisms underlying the effects of balanced blends of fatty acids and glycerides remain unclear. Recent evidence suggested that monoglycerides enhance resistance to infections, reduce mortality, and support consistent productivity in systems with limited antibiotic use. Reported findings indicated that individual monoglycerides improve intestinal morphology

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and enhance nutrient absorption efficiency. A significant aspect of their protective function is their ability to modulate the composition of the intestinal microbiota by selectively inhibiting the growth of pathogenic taxa. This review provided an overview of the key antimicrobial effects of monoglycerides. Collectively, these properties support the formulation of a scientifically grounded concept for entirely antibiotic-free livestock production. This concept may serve as an effective strategy for promoting sustainable pork production in line with modern standards. The review contributed to the understanding of both the limitations and potential of fatty acids and glycerides as alternatives to antibiotics

Keywords: monoglycerides; swine farming; immune system; intestinal morphology; microbiome; antibiotic resistance

INTRODUCTION

Global swine production is currently in a recovery phase following a crisis caused by the spread of African swine fever, which significantly reduced pig populations and pork production volumes in many countries, as well as the COVID-19 pandemic, which temporarily disrupted market activity. Global pork production is now exhibiting growth in both volume and price, operating within a context of intense competition, technological advancement and innovation. The intensification of pork production has facilitated the spread of disease, making it increasingly difficult to maintain productivity without the use of antimicrobial agents. Since the 1950s, growth promoters, including antimicrobial agents, have played a crucial role in enhancing animal productivity (Haulisah *et al.,* 2021). However, their use has led to a significant rise in antibiotic resistance. The European Union banned growth promoters in 2006 and introduced additional restrictions on the prophylactic use of antibiotics in 2018, which came into effect in 2022 (Jackman *et al.,* 2023). These restrictions have driven an active search for alternatives to antibiotics (Mykhalko, 2021; Szabó *et al.,* 2023). In the past decade, interest has compounded the alternative strategy concerning non-antibiotic growth promoters and antimicrobial substances to support animal health and enhance the profitability of swine farming.

In current livestock practices, there is increasing interest in the use of bioactive compounds as replacements for antibiotics in animal feed (Dahmer *et al.,* 2020). Among these compounds, monoglycerides and their derivatives are of particular interest. Monoglycerides offer several advantages in combating infectious diseases in animals compared to antibiotics. Firstly, they possess a broad spectrum of antimicrobial activity, inhibiting the proliferation of both viruses and bacteria, whereas antibiotics are only effective against bacteria. Secondly, pathogens face significant barriers in developing resistance to monoglycerides, making them effective not only for treatment but also for disease prevention (Tan *et al.,* 2021; López-Colom *et al.,* 2020). Third, monoglycerides are more effective than fatty acids and are safer than other organic agents, including formaldehyde, formic acid, and other acidifiers (Jackman *et al.,* 2022). Therefore, the application of monoglyceride blends as a replacement for antibiotics represents a promising approach in animal farming. The antimicrobial properties of monoglycerides depend on multiple mechanisms of pathogen suppression, while the selection for multi-resistant strains has not been observed among microbial populations. Taking into account that the emergence of multi-resistant strains represents one of the most critical global challenges, monoglycerides may offer a viable solution for developing alternative strategies to minimise both the presence of antibiotics in animal products and the risk of spreading multi-resistant strains.

This review was conducted using a systematic analysis of the available literature on organic acid and glyceride supplementation in swine farming. In addition, attention was given to the most important characteristics of these compounds to ensure their positive impact on both gut and overall animal health. The databases consulted included AGRICOLA, PubMed, Biological Abstracts, CAB Abstracts, the Index-Catalogue of Medical and Veterinary Zoology (ICMVZ), the International Veterinary Information Service (IVIS), and the Office International des Epizooties (OIE). Articles were included in the analysis if they contained at least two of the aforementioned keywords. This review provides a comprehensive overview of current data on the molecular mechanisms, potential, and effectiveness of monoglyceride application in swine production, and examines their impact on physiological state, productivity, and overall pig health. In addition, the authors discuss the effects of monoglycerides on the immune response, microbiome composition, and intestinal morphology. The is based on recent findings published in biomedical and veterinary medicine journals.

Thus, this review aimed to compile and clarify both foundational and recent data on the potential of monoglycerides as an alternative to antibiotics in swine farming.

GENERAL CHARACTERISTICS OF MONOGLYCERIDES

Monoglycerides are a class of glycerides consisting of a glycerol molecule covalently bonded to a fatty acid via ester linkage. Due to the presence of both primary and secondary hydroxyl groups in glycerol, there are two types of monoglycerides: 1-monoacylglycerols, where the fatty acid is attached to the first hydroxyl group, and 2-monoacylglycerols, where it is attached to the second hydroxyl group. Owing to their structure, monoglycerides possess both hydrophilic (water-attracting) and hydrophobic properties. Mono- and diglycerides are generally produced through the transesterification (glycerolysis) of triglycerides with glycerol (Panyod *et al.,* 2024). In industry, monoglycerides are primarily used as surfactants, typically in the form of emulsifiers. However, their most promising application appears to be as biologically active additives, providing a safe alternative to antibiotics and hormonal products.

Monoglycerides containing both short-chain and medium-chain fatty acids (SCFAs and MCFAs) exhibit direct antimicrobial effects *in vitro* and have the potential to enhance immune competence in animals, improve gut health, and reduce the risk of disease transmission in the postantibiotic era. SCFA α-monoglycerides, such as α-monopropionin and α-monobutyrin (derivatives of propionic and butyric acids), are primarily active against Gram-negative bacteria. In contrast, MCFA α-monoglycerides, such as α-monocaprylin, α-monocaprin, and α-monolaurin, are more effective against Gram-positive bacteria. Numerous studies have confirmed the antibacterial effects of α-monoglycerides *in vitro* and *in vivo*. Additionally, recent findings indicate that MCFA α-monoglycerides, particularly α-monolaurin, exhibit antiviral properties. P. Salvi and R. Cowles (2021) demonstrated that the biological activity of free butyric acid is associated with the regulation of cellular responses to maintain the viability and function of various cell types, including through histone deacetylase inhibition and G-protein-coupled receptor activation.

Medium-chain fatty acids (MCFAs) represent a class of saturated fatty acids containing from six to twelve carbon atoms. This class includes caproic, caprylic, capric, and lauric acids, which are present in natural products including cow's milk and vegetable oils extracted from coconut and the fruit of oil palms (López-Colom *et al.,* 2020). Mono-, di-, and triglycerides of MCFAs are typically formed via esterification with glycerol. Apart from serving as an energy source, MCFAs have demonstrated potential for improving gut morphology, stimulating growth, preventing infections, regulating immune responses, and functioning as alternatives to antibiotics (Dahmer *et al.,* 2020; Yu *et al.,* 2023). Several studies, including G. Chen *et al.* (2023), have shown that both mono- and triacylglycerols of DL-3-hydroxybutyrate are non-toxic, stimulate metabolic energy production upon intravenous administration, and can be used as nutrients in animal feed.

The primary structural feature responsible for the biological activity of monoglycerides (MGs) is the formation of micelles – self-assembled particles that form stable spheres once their concentration exceeds the critical micelle concentration (CMC). An increase in the length of hydrocarbon chains in the fatty acid residues of glycerides leads to stronger intramolecular hydrophobic interactions and alters the balance of micelle self-assembly (Yoon *et al.,* 2020). The nonionic nature of MGs allows them to form micelles at lower concentrations compared to MCFAs, which are anionic and subject to electrostatic repulsion (Feyaerts, 2022). Thus, the antimicrobial efficacy of MGs is related to the fatty acid composition and their ability to form micelles at lower concentrations. MGs exhibit inhibitory effects against a wide range of both bacteria and membraneenveloped viruses by disrupting their membranes. Recently, S. Tan *et al.* (2024) demonstrated that several fatty acids and monoglycerides exhibit significantly higher biological activity depending on the unique structure of their micelles, whereas the monomeric form of glycerides shows considerably lower or no activity. The antibacterial effects of MGs are associated with increased bacterial membrane permeability, local membrane damage, and the disruption of essential membrane functions, including electron transport, oxidative phosphorylation, and enzymatic activity (Casillas-Vargas *et al.,* 2021). MGs are also effective against membrane-enveloped viruses, where membrane disruption is a key component of their antiviral mechanism.

EFFECT OF MONOGLYCERIDES ON PERFORMANCE AND FEED CONVERSION IN PIGS

The supplementation of monoglycerides in pig diets has attracted particular attention due to their potential to improve productivity and feed conversion efficiency. This section examines the effects of MGs on growth, feed conversion, and overall pig health based on recent scientific research. A significant amount of conflicting data exists regarding the effects of SCFA- or MCFA-containing monoglycerides on the performance of weaned piglets (Cui *et al.,* 2020; Thomas *et al.,* 2020; Papadopoulos *et al.,* 2022). However, recent studies indicate that adding a monoglyceride blend to piglet diets reduces the growth-to-feed ratio in pigs infected with enterotoxigenic *Escherichia coli* (ETEC). C. Ren *et al.* (2019) reported that the addition of capric acid to piglet diets increased body weight gain and exhibited moderate antibacterial activity against *E. coli*. At the same time, studies have shown that a blend of monoglycerides composed of C4, C8, and C10 fatty acids did not affect broiler performance in birds infected with necrotic enteritis (Kumar *et al.*, 2021). Conversely, feed additives containing α-GML improved the growth performance of broilers, which was attributed to increased feed intake and enhanced gut health (Lan *et al.,* 2021). The application of α-GML also demonstrated a beneficial effect, enhancing antimicrobial efficacy in both sows and suckling piglets. Furthermore, α-GML supplementation stimulated weight gain in suckling piglets. The addition of α-GML to sow diets significantly increased ($P < 0.05$)

piglet body weight at weaning and improved overall crude fat digestibility in sows (Papadopoulos *et al.,* 2022).

Recent data have shown that a 0.1% dose of α-GML improves the performance and growth of weaned piglets and reduces post-weaning diarrhoea. The authors attribute these effects to improved nutrient digestion, suppression of systemic inflammation, maintenance of intestinal permeability, and promotion of a stable gut microbiota in piglets (Wei *et al.,* 2023). The addition of glycerol monolaurate to sow diets improves gut health in suckling piglets. Specifically, the results of GML supplementation demonstrated a significant increase in fat, lactose, and protein content in sow colostrum, while piglets exhibited a reduction in IL-12 concentration in the duodenum, and reductions in TNF-α, IL-1β, and IL-12 in the jejunum, as well as IL-1β in the ileum. These changes were accompanied by an increase in villus height, crypt depth, and the villus-to-crypt ratio in the small intestine of animals exposed to GML, compared with the control group (Zhao *et al.,* 2023). Together, these factors contribute to the growth and development of piglets.

The results obtained by J.T. Gebhardt *et al.* (2020) suggest that the addition of MCFAs to swine diets enhances growth performance, induces a prolonged immune response against PEDV infection, and has no effect on faecal microbial composition. The application of monoglycerides with lysolecithin in finishing pig diets reduces metabolic energy expenditure, improves weight uniformity within groups, and shortens the time required to reach the target slaughter weight, although feed conversion efficiency may decline (Gonzalez Sanchez *et al.,* 2022). Similar findings on feeding strategies aimed at minimising feed costs and improving pig performance have been reported by other researchers (Bassetto *et al.,* 2017). At the same time, the supplementation of a complex mixture containing lysolecithins, monoglycerides, and a synthetic emulsifier at a dose of 750 g/t in postweaning piglet diets significantly improves performance and enhances the digestibility of protein, fat, and fibre without increasing feed intake (Desbruslais *et al.,* 2023).

Thus, the use of monoglycerides and their derivatives in pig feeding has a stimulating effect on animal performance and health. Similar beneficial effects have been reported in animals challenged with infectious diseases. The inclusion of monoglycerides in pig diets demonstrates antimicrobial properties and enhances resistance to infectious diseases by reducing the incidence of diarrhoea and improving intestinal wall morphology.

EFFECTIVENESS OF MONOGLYCERIDES IN THE TREATMENT AND PREVENTION OF SWINE DISEASES

Nowadays, various MGs are widely proposed as feed additives in pig production to support intestinal health, improve feed conversion, and enhance the profitability of swine farming. MGs exhibit considerable potential to positively impact animal health due to their antimicrobial properties, which help reduce disease incidence and improve metabolic processes. Experimental data have demonstrated that MCFAs exhibit a high level of antimicrobial activity against various pathogens, including enveloped viruses, numerous bacterial taxa, pathogenic fungi, and protozoa (Coban, 2019). The study of fatty acids concerning their antimicrobial properties is well documented in the literature. The most common disease in piglets is post-weaning diarrhoea, which is often caused by the invasion and proliferation of enterotoxigenic *Escherichia coli* strain F18 or strain F4 in the small intestine. Clinical symptoms develop as profuse diarrhoea, stunted retardation in weight gain, rapid dehydration, and general weakness (He *et al.,* 2020). Recently, a study on glyceride blends containing butyric and valeric acids demonstrated the protective effects of these mixtures in reducing diarrhoea symptoms and supporting immunity in piglets co-infected with enterotoxigenic *E. coli* (López-Colom *et al.,* 2020). Specifically, pigs fed glycerides exhibited higher body weight, reduced diarrhoea severity, and lower levels of neutrophils and TNF-α in serum on day 4 post-inoculation. The use of an antimicrobial MCFA blend led to a significant reduction in the incidence of severe diarrhoea in weaned piglets challenged with enterotoxigenic *E. coli* F18. Furthermore, the supplementation of these fatty acids was accompanied by an increase in feed efficiency seven days post-inoculation. This blend also altered faecal microbiota diversity and the mucosal structure of the small intestine (Pluske *et al.,* 2021). Comparative analyses have shown that adding monoglyceride mixtures can enhance resistance to enteric pathogens in weaned piglets by lowering diarrhoea severity and mitigating both intestinal and systemic inflammation (Park *et al.,* 2024). However, the effectiveness of monoglycerides efficiency remains inferior to that of high doses of zinc oxide in treating diarrhoea symptoms.

The results of M. Tian *et al.* (2022) demonstrated that supplementation with a monoglyceride containing butyrate as a feed additive for pigs reduces the release of pro-inflammatory cytokines (TNF-α and interleukins) in the small intestine prior to enterotoxigenic *E. coli* infection via suppression of the NF-κB/MAPK-dependent pathway. Another study demonstrated that monoglycerides reduce the proliferative activity of porcine epidemic diarrhoea virus (PEDV), significantly inhibiting pathogen transmission among post-weaning piglets (Phillips *et al.,* 2022). Recent studies have shown that a blend of benzoic acid with probiotics, as well as with essential oils extracted from plants, exhibits a significantly greater protective effect against diarrhoea and enhances the performance of weaned piglets, compared with the application of benzoic acid alone (da Silva *et al.,* 2021; da Silva *et al.,* 2022).

Previous data have confirmed the ability of free MCFAs to inhibit viral proliferation. Various MCFAs, including capric (C10), lauric (C12), and myristic (C14) acids, have been described in several studies as antiviral agents (Jackman *et al.,* 2023). Similar to MCFAs, antiviral properties have also been reported for long-chain unsaturated fatty acids, such as oleic (C18), linoleic (C18:2), and linolenic (C18:3) acids, which are capable of suppressing the proliferation of herpes simplex virus (HSV), vesicular stomatitis virus (VSV), and Visna virus. Furthermore, other studies have demonstrated comparable antiproliferative efficacy of both MCFAs and glycerides derived from MCFAs against several retroviruses, including herpes simplex viruses types 1 and 2. Despite ongoing progress in the study of Seneca Valley virus (SVV) biology, there are currently no vaccines or effective chemical treatments for SVV-initiated infection. However, recent *in vitro* studies have shown that monolaurin can inhibit SVV replication with up to 80% high efficiency. Other *in vivo* studies have demonstrated that monolaurin can ameliorate clinical symptoms, reduce viral absorption and tissue damage, and preserve cell function in SVV-challenged piglets (Su *et al.,* 2023). Monolaurin significantly reduced inflammatory cytokine release and promoted interferon-γ production, thereby enhancing viral clearance. Researchers concluded that monolaurin could be a promising alternative or feed additive for the treatment of various viral infections in swine, including SVV.

The antiviral activity of caprylic, capric, and lauric acids, as well as GML, has been investigated in relation to African swine fever virus ASFV inhibition in liquids and feed. Effective compounds and dosages capable of inhibiting ASFV proliferation have been identified (Jackman *et al.,* 2023). The application of low GML doses exhibits limited effects on virus replication. However, relatively high doses of GML are highly effective, reducing virus replication by up to 99%. The onset of antiviral activity corresponded with the critical micelle concentration of GML, highlighting the crucial role of formulation in enhancing protective responses against ASFV (Jackman *et al.,* 2023). The use of modern nanotechnology enables the creation of more effective formulations without altering the chemical composition of bioactive substances. For example, natural GML has low water solubility and limited efficacy against gram-negative bacteria. It is noteworthy that nanoencapsulation not only enhances bioavailability but also reduces ecotoxicity (Lopes *et al.,* 2019).

Fatty acids and monoglycerides have proven effective against *Neisseria gonorrhoeae*. Microemulsions containing α-linolenic acid have shown efficacy in treating neonatal gonococcal ophthalmia (Belagal, 2024). In the absence of vaccines, monocaprin may serve as a novel prophylactic agent to prevent *N. gonorrhoeae* growth and colonisation, against which the bacterium is unable to develop resistance (Churchward *et al.,* 2020). Stress associated with piglet weaning suppresses digestion, absorptive capacity, and intestinal energy provision. Supplementation with MCFAs has been shown to improve nutrient absorption and stimulate energy metabolism, which is an important component in maintaining development, daily growth, and viability in weaned piglets (Cui *et al.,* 2022). MCFAs, such as hexanoic and octanoic acids, have shown significant anticandidal activity, as have long-chain fatty acids, including lauric acid.

Thus, given intense competition and increasing food safety requirements, the supplementation of monoglyceride blends could represent a promising strategy to replace antibiotics in intensive animal farming. Furthermore, the combined antimicrobial and metabolic effects of monoglycerides may be important factors in reducing the risk of antibiotic resistance and enhancing the profitability of swine production. Monoglycerides, known for their antimicrobial and anti-inflammatory properties, are emerging as promising additives to enhance immune and antioxidant systems in pigs. The effects of monoglycerides are directed towards strengthening immunity, reducing oxidative stress, and increasing overall resilience to enteric infections. Administering α-GML to piglets at a dose of 1,000 mg/kg increases the cytokine release, particularly IL-10, and modulates the activity of antioxidant enzymes (GSH-Px) in the blood of weaned piglets. Under these conditions, serum MDA and TNF-α concentrations decrease. However, no differences were found in T-AOC and SOD activity, or IL-6 concentration in serum (Wang *et al.,* 2023). It is suggested that α-GML enhances antioxidant capacity by modulating intestinal barrier function.

In pigs, administering 0.6% α-GML reduced levels of free radicals, including hydrogen peroxide and malonic dialdehyde, in the small intestine. In addition, the aforementioned α-GML supplementation significantly increased the activity of both catalase and superoxide dismutase in both the small and large intestine parts (Papadopoulos *et al.,* 2022). J. Zhang *et al.* (2024) reported evidence suggesting that various mechanisms of antioxidant capacity transfer from maternal blood to the foetus via the transplacental barrier have also been explored through the use of α-GML supplement during pregnancy. Analysis of the observed data confirmed an inverse correlation between the concentration of lipopolysaccharides in sow plasma and both inflammatory and oxidative stress parameters.

EFFECTS OF MONOGLYCERIDES ON INTESTINAL MORPHOLOGY AND MICROBIOME IN PIGS

Gut health is a key factor in ensuring optimal productivity in pigs and resilience to infectious diseases. The application of monoglycerides has demonstrated stimulatory and protective effects on the normal morphology of intestinal structures, the balance of gut microbiota composition, and sustainable gut physiology, particularly in maintaining intestinal barrier function (Masiuk *et al.,* 2023). Recent data have shown that supplementation with α-GML at a dose of 1.0 g/kg in piglets increased the ratio of villus height to crypt depth in the duodenum. On the other hand, this study demonstrated that villus height in the small intestine, particularly in the jejunum and ileum, was increased compared to unexposed piglets; however, no effect was observed on crypt depth in the same tissue samples (Wang *et al.,* 2023). Additionally, GML promotes an increase in goblet cell numbers (Cui *et al.,* 2020). Supplementation with MCFA-containing glycerides has shown beneficial effects on various gut cell types, including epithelial, goblet, and immune cells, in post-weaning piglets. *E. coli* infection is associated with a reduction in both villus height and crypt depth, which are widely recognised indicators of intestinal health. However, in piglets exposed to LPS, MCFAderived glycerides restored villus morphology and increased IgA levels in the blood. A similar effect was observed in the ileum, albeit with a less pronounced impact (De Keyser *et al.,* 2019). The α-GML-supplemented feed additive, administered at a dose of 1.0 g/kg, increased the relative abundance of *Firmicutes* by 17.87% and decreased the *Bacteroidota/Campylobacterota* ratio. Moreover, α-GML application upregulated two specific taxa – *Blautia* and *Lactobacillus* – in the cecum, while species from the genera *Alloprevotella, Campylobacter*, and *Eubacterium* were significantly downregulated in the intestines of piglets compared to unexposed controls (Wang *et al.,* 2023).

Gene expression analysis indicated that linoleic acid significantly enhances the expression of genes regulating key signalling pathways linked to the antioxidant system (NRF1 and PPARγ), cellular responses (ap2 and C/EBPα), and metabolic energy synthesis. Cell culture experiments involving linoleic acid (LNA) revealed a reduced phosphorylation level of PPARγ at the Ser112 site, compared with cells exposed to either palmitic or oleic acid. The lack of a significant difference in triacylglycerol levels following inhibition of PPARγ Ser112 phosphorylation suggests divergent metabolic pathways for dietary fatty acids in adipose tissue cells. Exposure to LNA significantly promotes adipose tissue accumulation through modulation of PPARγ phosphorylation (Yu *et al.,* 2017).

Supplementation with GML upregulated the expression of several genes, particularly those encoding tight junction proteins, including claudins, occludins, and zonula occludens-1, in the middle section of the small intestine. However, in the ileum of piglets, only zonula occludens-1 expression was upregulated. These findings provide evidence that GML supplementation exerts a protective effect on intestinal barrier integrity (Cui *et al.,* 2020). Further data from a study involving the administration of 0.6% glycerol monolaurate showed a significant increase in occludin expression in the intestines of piglets (Papadopoulos *et al.,* 2022). Additionally, the application of GML to sows enhanced the levels of tight junction proteins – including zonula occludens-1, occludins, and claudins – in the small intestine. This was accompanied by upregulation of mucin subfamily mRNA expression and defensin protein family levels in the piglet gut (Zhao *et al.,* 2023).

Capric acid reduces total intestinal length, while probiotics do not affect intestinal mass or length but increase villus width and crypt depth in the epithelial cells of the small intestine. MCFAs do not influence these parameters. Recent data obtained by S. Park *et al.* (2024) provide evidence that both fatty acids and probiotics exhibit strong antibacterial effects, although each targets different pathogens: specifically, capric acid suppresses *E. coli* growth, while probiotics inhibit *C. perfringens* proliferation. Sequencing of 16S rDNA confirmed that supplementing sows with GML alters colonic microbiome composition and reduces the relative abundance of *Escherichia-Shigella* (Zhao *et al.,* 2023). Thus, monoglycerides can positively affect intestinal morphology, particularly by increasing villus height and improving the villus-to-crypt ratio, thereby promoting more efficient nutrient absorption. Additionally, monoglycerides can modulate gut microbiota composition by reducing pathogenic bacteria and supporting the balance of beneficial microbial taxa.

CONCLUSIONS

Monoglycerides exhibit significant potential in maintaining swine production due to their antimicrobial, antiviral, and anti-inflammatory properties. They not only contribute to improved animal productivity but also provide essential protection against infectious diseases. The use of monoglycerides in pig feed has demonstrated high effectiveness in reducing the incidence of diarrhoea caused by bacterial infections, particularly *Escherichia coli*, by stabilising gut microbiota and strengthening the immune system. Additionally, they can improve intestinal morphological parameters, such as villus height and the villus-to-crypt ratio, thereby enhancing nutrient absorption and overall pig health. Monoglycerides also play a crucial role in stimulating the immune and antioxidant systems, reducing oxidative stress, and helping to maintain animal health under stressful conditions, such as weaning or intensive rearing. Their antioxidant properties protect cells from damage and reduce inflammation, which is critical for supporting healthy metabolism and increasing animal disease resilience. Given the current imperative to reduce antibiotic supplementation in animal husbandry, monoglycerides serve as an effective alternative to traditional antimicrobial agents.

Thus, monoglycerides represent a promising and safe feed additive for enhancing the productivity, health, and overall resilience of pigs. Their application contributes to reducing dependence on antibiotics, supporting stable productivity and competitiveness in swine production amid global challenges such as combating antibiotic resistance and meeting the growing demand for environmentally sustainable products. Further study is required to identify monoglyceride blends with targeted antimicrobial and growth-promoting properties that can enhance the profitability of swine farming.

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CONFLICT OF INTEREST

The authors declare no financial conflicts of interest or personal relationships relevant to this article.

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Застосування моногліцеридів у свинарстві: огляд сучасних тенденцій і перспектив

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Анотація. Зростання числа мульти-резистентних штамів через тотальне використання антибіотиків у тваринництві є критичним фактором ризику як для людини, так і тварин. Тому, створення альтернативних стратегій відмови від антибіотиків в технологіях вирощування продуктивних тварин залишається надзвичайно питанням. Різні біоактивні сполуки пропонуються в якості альтернативи, однак, такі засоби не виявляють співмірної з антибіотиками ефективності. Метою представленого огляду було проведення аналізу досліджених за останній час ефектів та механізмів дії жирних кислот та їх гліцеридів на травну систему продуктивних тварин. Перспективними замінниками розглядаються суміші окремих жирних кислот і моногліцеридів завдяки їх багато спрямованим антимікробним, противірусним, протизапальним та метаболічним ефектам. Важливим ефектом таких сумішей є підтримка бар'єрної та імунної функцій кишечника свиней в умовах інтенсивного виробництва. Незважаючи на суттєвий прогрес у дослідженнях окремих біоактивних засобів для забезпечення продуктивності свинарства в пост-антибіотичну еру, молекулярні і клітинні механізми дії збалансованих сумішей жирних кислот і гліцеридів залишаються не розкритими. Сучасні дані свідчать про те, що моногліцериди підвищують резистентність тварин до інфекцій, знижують падіж та забезпечують стабільну продуктивність в умовах обмеженого використання антибіотиків. Недавні результати показали, що моногліцериди покращують морфологію кишечника і підвищують ефективність поглинання поживних речовин. Важливим аспектом протективних ефектів моногліцеридів вважається їх здатність модулювати склад мікробіоти кишечника шляхом селективного пригнічення патогенних таксонів. В огляді представлений аналіз принципово важливих антимікробних ефекти моногліцеридів. Все це разом, дозволяє розробити науково обгрунтовану концепцію відмови від антибіотиків у тваринництві, що може бути ефективним інструментом для побудови стратегії сталого виробництва свинини у відповідності до сучасних стандартів. Огляд сприятиме розумінню як перспектив, так і обмежень застосування жирних кислот та гліцеридів як альтернативи антибіотикам

Ключові слова: моногліцериди; свинарство; імунна система; морфологія кишечника; мікробіом; стійкість до антибіотиків

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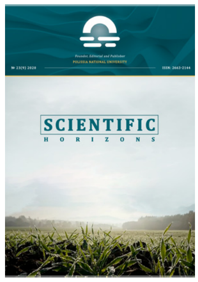

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Development of an HPLC-MS/MS method for the quantitative determination of chloramphenicol in honey from Kazakhstan

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Abstract. Addressing the issue of antibiotics, particularly chloramphenicol, in bee products is an urgent concern within the trade of these items due to potential risks to human health. Developing highly sensitive techniques for detecting trace amounts of antibiotic residues is crucial. This study aimed to establish an analytical method using HPLC-MS/MS (High-Performance Liquid Chromatography – Tandem Mass Spectrometry) for the identification and quantification of residual chloramphenicol

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in honey samples sourced from Kazakhstan. The developed method involved ultrasonic extraction followed by HPLC-MS/MS with electrospray ionisation in negative mode. Multiple reaction monitoring was utilised in configuring the parameters of the tandem mass spectrometric detector. The proposed procedure offered notable advantages, such as the simplicity and speed of the extraction process, as well as the sensitivity and accuracy of the detection method. The limit of detection achieved is 0.09 μg/kg, with a linear calibration curve spanning the concentration range of 0.1-1.0 μg/kg and a correlation coefficient of 0.9985. The extraction rate ranged between 97% and 101%. Importantly, this HPLC-MS/MS method for chloramphenicol determination in honey surpassed the maximum residue limit requirements (0.3 μg/kg) in terms of sensitivity, while maintaining methodological precision and a high extraction percentage. This compliance aligned with the standards outlined in Commission Decision 2002/657/EC. The method was applied to 14 honey samples from Kazakhstan, all of which were found to have chloramphenicol levels below the method's detection limit. However, when testing imported honey samples, two out of seven exceeded the detection limit for chloramphenicol. The developed HPLC-MS/MS method for detecting chloramphenicol residues in honey samples can serve as a valuable tool for routine laboratory analysis and for scrutinising potentially suspicious or questionable samples

Keywords: liquid chromatography; mass spectrometry; analysis; antibiotic; honey

INTRODUCTION

Honey is recognised as a natural product enriched with essential nutrients, including vitamins, minerals, calcium, and antioxidants, making it highly valued in both dietary and therapeutic contexts. The post-pandemic increase in consumer awareness regarding health and immunity has significantly heightened the market for natural and functional food products. The versatility of honey is seen in its extensive application within the culinary industry, including beverages, confectionary, and processed products, as well as in health, wellness, and cosmetic formulations. Its recognised therapeutic qualities, including blood pressure regulation, reduction of diabetes risk, and enhancement of wound healing, further support its commercial growth and interdisciplinary significance.

From a trade perspective, Kazakhstan exported honey valued at $490,000 in 2020, positioning the country 76th among global honey exporters (Honey in Kazakhstan, 2020). However, maintaining international competitiveness necessitates adherence to food safety regulations that prohibit the presence of specific antibiotic residues. Chloramphenicol, in particular, has been banned in food-producing animals due to its toxicological profile and association with aplastic anemia. Regulatory frameworks such as the Codex Alimentarius (CODEX STAN 12-1981), European Directives 2001/110/EC and 96/23/EC, and Commission Decision 2002/657/EC strictly regulate the permissible levels of antibiotic residues in honey (European Council, 2022).

Recent studies have drawn attention to the occurrence of veterinary drug residues in honey and the need for sensitive, reliable detection methodologies. H.O. Khalifa *et al.* (2024) emphasised the public health hazards linked to antimicrobial residues across the food chain and advocated for the adoption of enhanced detection methods, especially considering the increasing antimicrobial resistance. Y. Yang *et al.* (2022) introduced a refined QuEChERS approach integrated with UPLC-MS/MS for the detection of multi-antibiotic residues in honey, attaining elevated analytical sensitivity and confirming the system's suitability for regular monitoring of intricate matrices such as honey.

Liquid chromatography coupled with tandem mass spectrometry (HPLC-MS/MS) has been prominent among analytical techniques for monitoring antibiotic residues due to its exceptional selectivity, sensitivity, and compatibility with complicated matrices. Y. Zhang *et al.* (2019) evaluated LC-MS/MS techniques for the measurement of antibiotics in honey, highlighting the essential function in verifying regulatory adherence and identifying chemicals at sub-nanogram concentrations. The evaluation emphasised significant obstacles in technique standardisation and the necessity for matrix-matched calibration to guarantee accuracy in honey-based testing. The utilisation of analytical techniques to evaluate the quality and safety of honey relies on a precise comprehension of its compositional attributes (Kołacz *et al.*, 2023). A. Kobysh *et al.* (2025) illustrate the importance of investigating the botanical origin of honey, as floral and regional heterogeneity substantially affect the matrix composition and, in turn, the efficacy of residue detection methods. These findings underscore the necessity to customise analytical methods to the distinct physicochemical characteristics of honey sourced from particular ecological contexts.

E. Bonerba *et al.* (2021) examined the identification of chloramphenicol in honey samples from various production systems and emphasised the necessity for high-throughput and confirmatory procedures in standard food inspection. The research highlights the regulatory consequences of non-compliance, particularly when trace residues evade detection by less sensitive techniques. S. Saad *et al.* (2024) shown that honey contamination may arise from agricultural methods and environmental pollutants, underscoring the multifaceted nature of the issue, which includes indirect contamination via ambient exposure. S. Abera *et al.* (2025) presented a micro-extraction-based HPLC-DAD method for multi-residue antibiotic analysis, showcasing the versatility of innovative sample preparation processes and providing an alternative to more resource-demanding solid-phase extraction methods.

Notwithstanding these developments, a significant gap exists in the literature about the creation of verified, quick, and cost-effective confirmatory procedures specifically designed for the unique physicochemical properties of honey produced in Kazakhstan. The diversity of floral sources and beekeeping practices in the region requires a method that guarantees analytical sensitivity and methodological rigour while being suitable for routine laboratory use. The purpose of this study was to develop and validate a high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS) method for the quantitative determination of chloramphenicol residues in honey produced in Kazakhstan, ensuring compliance with international food safety standards.

MATERIALS AND METHODS

A certified chloramphenicol (CAP) standard of 98 % purity (Sigma-Aldrich, Milan, Italy) was used for the study. The structural formula of CAP is shown in Figure 1.

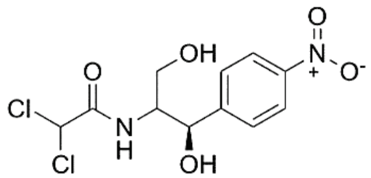

***Figure 1**. Structural formula of chloramphenicol*
***Source:** S. Akter Mou et al. (2021)*

Acetonitrile of HPLC grade with a purity of ≥99.9% obtained from Sigma-Aldrich in France, acetic acid (98-100% purity) sourced from Merck in Germany, and high-purity bidistilled water produced using the Milli-Q system by Millipore Corporation were utilised in the experimental procedures. Initial CAP standard solutions were prepared at a primary concentration of 1.0 mg/ml in acetonitrile. These solutions were stored in a meticulously sealed container within a refrigerator at 4°C in a dark environment for a maximum period of two months. To create working standard solutions, successive dilutions of the primary stock solution were made with acetonitrile until a concentration of 100 mg/ml was achieved. Chromatographic analysis was conducted using the UHPLC UltiMate 3000 system from Thermo Scientific in the USA. The separation process was executed using a C18 BDS Hypersil column with dimensions of 100×4 mm. The column temperature was maintained at 35°C, and a stabilisation time of 1 minute was observed. Chromatographic separation was achieved by employing a mobile phase composed of 0.5% acetonitrile dissolved in Milli-Q water (eluent A) and 0.1% acetic acid dissolved in acetonitrile (eluent B) at a flow rate of 0.5 ml/min. The elution process commenced with 0% B and was then incrementally increased to 45% B over a span of 9 minutes. Subsequently, the elution was further increased from 45% B to 100% B over 10.5 minutes, maintained at 100% B for 1 minute, and then returned to baseline conditions after an additional 1.5 minutes. The total running time, inclusive of column equilibration to its initial state, amounted to 16 minutes. Each injection volume was set at 20 µl.

The mass spectrometric analysis was conducted using a TSQ Quantum Access MAX tandem quadrupole mass spectrometer equipped with an Ion Max™ source, employing electrospray ionisation (ESI/APCI). Negative mode electrospray ionisation was employed with a cone voltage of 40V, a desolvation temperature of 500°C, and a desolvation gas (nitrogen) flow rate of 1000 l/h. The operational parameters of the mass spectrometer were set as follows: a capillary voltage of 3.00 kV, a source temperature of 300°C, collision gas consisting of argon, and atomisation gas using nitrogen with a flow rate of 50 l/h. Data processing was accomplished utilising the Xcalibur and Chromeleon Xpress software platforms.

Honey samples were collected from various sources, including retail outlets such as markets and trade centres in Almaty, as well as from different beekeepers across diverse geographic regions within Kazakhstan. These samples were stored in a dark environment at room temperature until they underwent analysis. To construct a calibration curve, one honey sample was specifically tested for the absence of target antibiotics. For the analysis, a test sample of honey weighing 1 g was combined with 10 ml of a 0.5% acetic acid solution in Milli-Q water, and the mixture was placed in a 15 ml volumetric flask. The flask was vigorously shaken for 2-3 minutes until complete dissolution was achieved. Subsequently, the sample underwent treatment in an Elmasonic S120H ultrasonic bath, operating at 37 kHz and with ultrasonic power set at 100 W, maintaining a temperature of 50 ± 3°C for 30 minutes. After achieving complete dissolution, the sample was then subjected to centrifugation for 4 minutes at 4000 rpm. The liquid phase obtained from this process was filtered through a 0.20 µm pore size polytetrafluoroethylene membrane filter (specifically, the Macherey-Nagel Chromafil Xtra PTFE-20/25). The filtered liquid was then transferred into a vial and injected into the system using a 20 µl volume.

RESULTS AND DISCUSSION

The HPLC-MS/MS method has gained considerable appeal as an analytical technique due to its distinct features, including specificity, sensitivity, and the capability to handle multiple analytes simultaneously. These attributes have contributed to its widespread utilisation in the precise detection of minute quantities of antibiotic residues, such as chloramphenicol, as highlighted in the work of Y. Zhang *et al.* (2019). This method is distinguished by its rapid analysis speed, superior resolution, increased peak capacity, and enhanced sensitivity.

To establish the methodology presented in this study, the precursor ion (321.1) was initially identified using the flow-through injection technique without applying collision energy. Subsequently, the optimisation of precursor ion products was carried out by introducing a standard CAP solution with a concentration of 150 mg/ml in both positive and negative polarity modes. In the analysis of the mass spectrum of chloramphenicol, it was evident that the positive ionisation mode primarily exhibited a protonated [M + H] + molecule as the principal peak, while the negative ionisation mode showed a deprotonated [M - H] - molecule. The negative ionisation mode, attributed to the deprotonation of CAP, delivered higher signal intensity and lower background noise. During the optimisation of parameters for the tandem mass spectrometric detector, particular emphasis was placed on achieving optimal conditions for generating precursor ions of CAP, including voltage at the cone and accurate m/z values based on the analyte's molecular mass. Multiple reaction monitoring (MRM) was employed to monitor the transitions from quantifier ions to qualifier ions (precursor-ion > product ion transitions, m/z). The mass spectra of standardised CAP samples prominently displayed deprotonated molecular signals at m/z 321.1. Additionally, three distinctive product ion fragmentations (151.9, 193.6, and 256.8) were obtained and monitored using appropriate collision energy settings (see Table 1 for details).

***Table 1**. Multiple reaction monitoring method (MRM method) for CAP determination*

Precursor ion, m/z	Product ion, m/z	Taper voltage, V	Collision energy, V	Holding time, min
	151.9		18	
321.1	193.6	40	12	7.09
	256.8		11	

***Source:** compiled by the authors based on H. Ye et al. (2022)*

The product ion mass spectra prominently featured ions with an m/z value of 151.9 (as depicted in Fig. 2), clearly corresponding to the loss of a C2H3OH-NHCOCHCl2 group. Additionally, other ion products observed in the MS/MS spectra included m/z 193.6 (indicative of the loss of NH2COCHCl2) and m/z 256.7 (associated with the loss of HCl and CO). In the quantification of CAP, it was considered three product ions, aligning with the requirements stipulated in Commission Decision 2002/657/EC, which implements Council Directive 96/23/EC regarding the performance of analytical methods and the interpretation of results (2002). The separation process was conducted by passing the sample through a chromatographic column, with the predominant product ion (m/z 151.9) exhibiting a retention time of 7.08 minutes (as illustrated in Fig. 3).

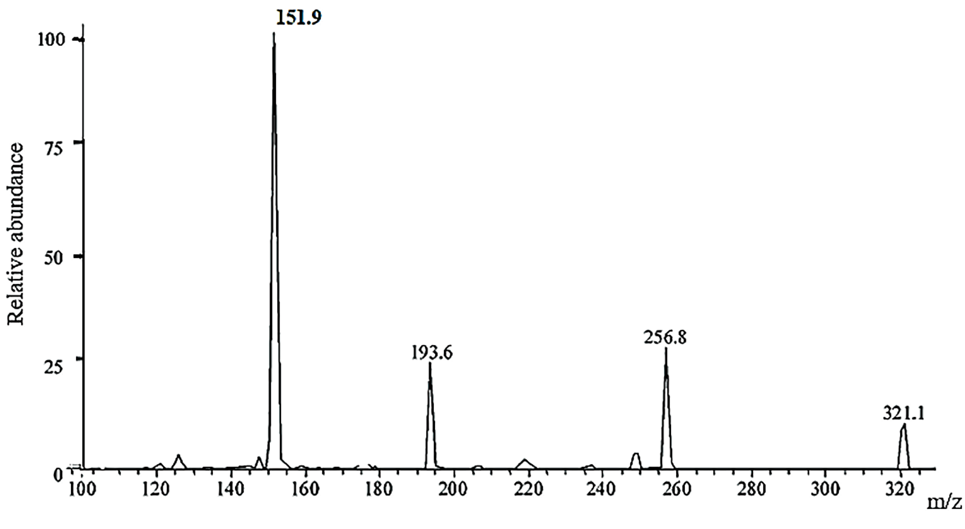

***Figure 2**. Mass spectra of chloramphenicol product ions*
***Source:** compiled by the authors based on B. Vuran et al. (2021)*

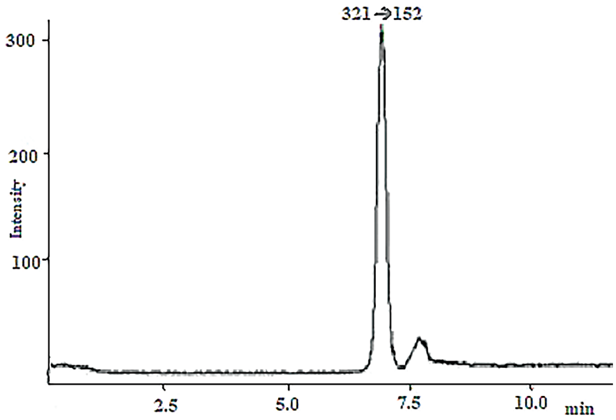

Figure 3. *MRM chromatogram of chloramphenicol*
Source: *compiled by the authors based on S. Rizzo et al. (2020)*

Effective sample preparation plays a crucial role in the overall analytical process. Given the intricate composition of honey samples and the stringent maximum residue limit (MRL) set for CAP in honey (MRL = 0.3 μg/kg), it is imperative to employ a robust sample processing technique that eliminates matrix interferences and concentrates CAP before its quantification, as emphasised by R. Pratiwi *et al.* (2023). The intricate composition of the honeycomb matrix itself, enriched with substantial quantities of sugars, enzymes, and proteins, demands a specialised approach to sample preparation. Notably, effective deposition of these components is essential because soluble proteins present in the sample extract can introduce significant matrix effects, disrupt phase separation during organic solvent extraction and sample purification, distort the analytical signal, and exert an adverse impact on the integrity of the chromatographic column. Consequently, this can lead to an overall increase in pressure within the chromatographic system, as highlighted by H.-N. Jung *et al.* (2022). To overcome these challenges, diverse methods are employed to optimise the sample preparation protocol, with the primary goal of achieving maximal extraction efficiency and recovery rates.

Among the widely adopted techniques, liquid-liquid extraction (LLE) and solid-phase extraction (SPE) stand out as the most prevalent (Yakubchak *et al.*, 2018). However, it's worth noting that LLE involves the use of solvents such as ethyl acetate, acetonitrile, chloroform, and hexane. In contemporary trends within analytical chemistry, there is a concerted effort not only to streamline sample preparation methods but also to minimise the reliance on organic solvents (Sniegocki *et al.*, 2019; Ilderbayeva *et al.*, 2024). The composition of the adsorbent can be considered as the basis of the SPE method, as it influences the selectivity and the absorption capacity. The most commonly used Oasis HLB and Strata-X cartridges offer low matrix effect and high extraction rates. However, a common disadvantage of the SPE method is that such a procedure requires additional resources and time, which appreciably increases the cost of analysis. The fast, simple, cheap, efficient, reliable, and safe (QuEChERS) method also finds application as compared to the time-consuming and expensive SPE, QuEChERS can be very flexibly modified into several forms by changing the type and amount of sorbents (Vuran *et al.*, 2021). However, the QuEChERS procedure for honey typically involves extraction, protein precipitation and purification (Veiga-del-Baño *et al.*, 2024). After extracting the solid sample using acetonitrile in an aqueous medium, a subsequent step involves a liquid-solid extraction, often referred to as dispersion solid-phase extraction (SPE). This phase aims to eliminate the majority of residual matrix interferences, albeit introducing some complexity to the analysis process.

To establish a confirmatory method for detecting chloramphenicol residues in honey sourced from Kazakhstan, authors adopted the approach described in section 2, which involves ultrasonic extraction using an aqueous acetic acid solution followed by input into an HPLC system without additional purification steps. While literature reports on the application of ultrasonic extraction have primarily focused on extracting phenols from olive oil (Kivrak & Kivrak, 2021), polyphenols (Rivera-Mondragón *et al.*, 2019), phenolic acids from plants used in traditional medicine (Sukor *et al.*, 2018; Garibli *et al.*, 2021), and mycotoxins from cereal products (Streit *et al.*, 2022), there is a notable scarcity of studies regarding the development of an ultrasonic method for chloramphenicol determination in honey using high-performance liquid chromatography and tandem mass spectrometry. In the formulation of the method employed in this study, the selection of acetic acid as the extraction solvent and the parameters for ultrasonic treatment were determined through preliminary experiments and a thorough analysis of limited literature data (Manimekalai *et al.*, 2019). Since cost-effectiveness is one of the critical characteristics of a technique designed for routine analysis of food of animal origin for quality and safety parameters, the advantage of optimised sample preparation is that in this system a purification stage, solid-phase extraction is not necessary. The uniform distribution of ultrasound in the liquid allows the mixture to be mixed and homogenised for ultrasonic extraction.

The CAP content of the tested honey samples was carried out according to a calibration curve using Xcalibur and Chromeleon Xpress software. The calibration curve was plotted against a matrix of pure (control) honey in the concentration range of 0 to 1.0 μg/kg, and was linear in the interval studied (Fig. 4). The correlation coefficient was 0.9985. The validation of the developed method for the analysis of honey samples was carried out by testing a control (pure) honey sample and one loaded with a standard solution at four different concentration levels with concentration calculations from the calibration graph on the honey matrix. Samples were analysed for three consecutive days to determine precision and validity. The extraction rate was 97-101%, which meets the requirement of 50 to 120% (Commission decision..., 2002).

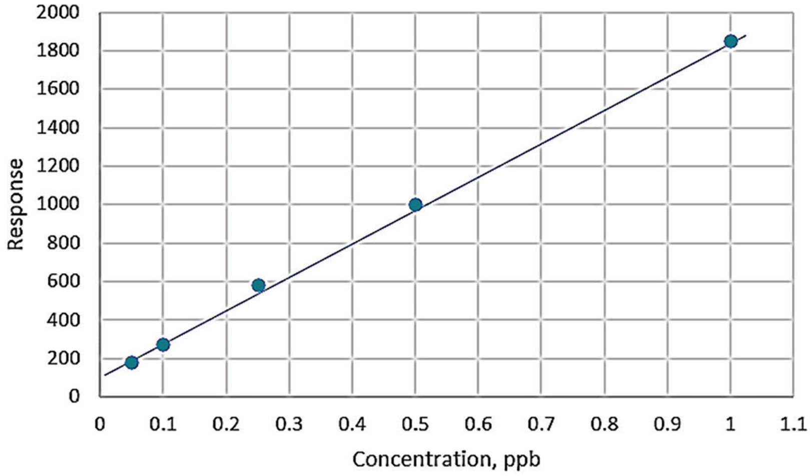

Figure 4. *Calibration chart for the determination of chloramphenicol in honey*
Source: *compiled by the authors based on M. Rydchuk et al. (2019)*

The limit of detection (LOD) and limit of quantification (LOQ) values were assessed and found to be 0.09 µg/kg and 0.18 µg/kg, respectively. In the context of honey quality control, various countries have established maximum residue limits (MRL) for chloramphenicol in honey, such as 0.3 µg/kg in European Union nations, 0.1 µg/kg in Belgium, and a complete absence of chloramphenicol allowed in the USA. From the data presented, it's evident that the developed HPLC-MS/MS method for chloramphenicol determination in honey surpasses the sensitivity requirements set by the established MRL of 0.3 µg/kg. This achievement is coupled with a commendable level of methodological precision and a high percentage of extraction, thus aligning with the stipulations outlined in Commission Decision 2002/657/EC, which implements Council Directive 96/23/EC concerning the performance of analytical methods and result interpretation (2002), particularly with regard to confirmatory methods.

The developed HPLC-MS/MS methodology for determination of chloramphenicol in honey was tested in the analysis of 7 samples of honey produced in Kazakhstan, taken in different retail outlets (markets, trade centre) in Almaty and 7 samples taken from several beekeepers from different geographical regions of Kazakhstan. None of the samples tested contained the target analyte at a level above the detection limit of the developed method. Honey contamination can be linked to intensive farming and industrial activities. In addition, beekeepers are not always registered as defined by legislation, can purchase veterinary medicines themselves (without prescriptions) and do not keep records on the treatment of bees (indicating the date of application, name of the medicine and period of excretion). The presence of chloramphenicol residues in honey can also be attributed to the use of products containing a combination of chloramphenicol and its SS-pair stereoisomer, dextramycin. It's important to note that dextramycin lacks therapeutic efficacy; nevertheless, it has been frequently detected in unreported quantities within counterfeit bee preparations, leading to its inadvertent presence in honey (Yanovych *et al.*, 2018). The enzyme immunoassay method, most commonly used for incoming inspection of raw materials in honey processing plants, does not provide adequate control for dextramycin residues (Dvykaliuk *et al.*, 2023).

In addition to the "human factor" that directly causes contamination of bee products, there are also indirect factors. For example, the use of Styrofoam or technical foils with foil to insulate the top of the nest can give false positives for the presence of chloramphenicol. Furthermore, it's important to acknowledge that the dataset under analysis may not be considered highly representative due to its reliance on a limited number of honey samples acquired through random sampling. Nevertheless, the results obtained unmistakably demonstrate the efficacy of this method for detecting CAP residues in routine analysis, making it suitable for adoption by production and quality control laboratories.

The established HPLC-MS/MS technique for quantifying CAP in honey samples from Kazakhstan has exceptional sensitivity, methodological accuracy, and economical sample preparation. An analysis alongside comparable academic studies highlights both similarities and differences that emphasise the originality and practical importance of the current study. G. Cilia *et al.* (2020) examined the antibacterial properties of Ukrainian honey, uncovering considerable regional heterogeneity in bioactivity, which they ascribed to floral origin. While the work did not explicitly evaluate synthetic antibiotic residues, the focus on compositional variability corresponds with the methodological approach to matrix calibration and underscores the necessity of customising detection methodologies to the physicochemical characteristics of locally produced honey. S.A. Dar *et al.* (2024) provided a comprehensive analysis of honey classification, composition, and contamination hazards, specifically concerning veterinary drug residues. The observations concerning the frequency of such residues in emerging markets underscore the significance of the study, which addresses this issue with a validated HPLC-MS/MS method capable of measuring chloramphenicol at levels well below internationally approved MRLs.

M. Hutchings *et al.* (2019) offered a historical perspective on antibiotic development and expressed apprehensions regarding the enduring residues in the food chain that contribute to antimicrobial resistance. The following research directly tackles this issue by introducing a swift and sensitive confirmatory approach to avert low-level residues of prohibited antibiotics, such as chloramphenicol, from contaminating the food supply, thereby providing a preventive framework against the hazards identified by M. Hutchings *et al.* A more detailed methodological comparison is apparent with Y. Li *et al.* (2021), who created a quantum dot-based immunochromatographic strip for the swift detection of antibiotics in honey. While the methodology enabled on-site testing and offered multiplex functionality, it was deficient in confirmatory robustness and precision compared to tandem mass spectrometry. Conversely, HPLC-MS/MS technology, although more labour-intensive, provides superior analytical precision and adheres to regulatory criteria, including Commission Decision 2002/657/EC (2002).

C.M.G. Lima *et al.* (2020) performed a comprehensive assessment of antibiotic residues in honey and emphasised the related public health issues. The research promoted ongoing surveillance and enhanced testing techniques, underscoring the significance of the method's relevance to national residue monitoring initiatives in Kazakhstan. Consistent with the findings, this study indicated the possible presence of CAP in imported honey samples, emphasising the need for rigorous import regulations. R. Phipps (2025), in his assessment on the international honey market, highlighted the growing regulatory oversight in global honey trading, particularly inside the EU. The findings of the following study affirm that sophisticated analytical techniques are essential for maintaining the export competitiveness of Kazakh honey, especially in areas where regulatory adherence is strongly linked to trade access.

G.G. Rimkus *et al.* (2020) underscored the constraints of immunoassays, such as ELISA, in identifying stereoisomeric variants of chloramphenicol, including dextramycin, potentially resulting in false-negative outcomes. The mass spectrometric technique surmounts this constraint by precise ion fragmentation and MRM-based detection, facilitating accurate separation and quantification of chloramphenicol, thus enhancing reliability. S. Rizzo *et al.* (2020) devised a salting-out aided liquid-liquid extraction (SALLE) method integrated with LC-MS/MS for the detection of CAP. The salting-out method, however effective, necessitates more complex sample preparation. Conversely, the present study's ultrasonic extraction utilising aqueous acetic acid provides a more efficient, environmentally sustainable, and expedited alternative, without sacrificing extraction efficacy or method validation.

M. Rydchuk *et al.* (2019) developed a UPLC-MS/MS multimethod for the detection of diverse antimicrobial substances in honey, emphasising the capability for concurrent analysis. Although the approach exhibited remarkable sensitivity, this study is unique in its specific targeting of chloramphenicol and in refining a more straightforward ultrasonic extraction protocol devoid of supplementary purification steps, thereby enhancing its practicality for routine domestic testing laboratories with constrained resources. These comparisons confirm that although previous studies have greatly enhanced antibiotic residue detection in honey, the current study progresses the field by providing a validated, resource-efficient, and regulation-compliant analytical method specifically designed for the unique physicochemical properties of Kazakh honey. The results not only address current methodological deficiencies but also offer a reproducible framework for national quality control systems.

CONCLUSIONS

A precise, dependable, rapid, and highly sensitive technique has been established for the detection of chloramphenicol in honey sourced from Kazakhstan. This method leverages a high-performance liquid chromatograph coupled with a tandem quadrupole mass spectrometric detector employing negative mode electrospray ionisation. In setting the parameters of the tandem mass spectrometric detector special attention was paid to establishing the optimum conditions for obtaining chloramphenicol precursor ions – cone voltage and accurate m/z value. Multiple reaction monitoring was used to track precursor-ion > product-ion transitions (m/z). As a result of optimised HPLC-MS/MS parameters, high sensitivity, and selectivity of target component extraction were observed. The analytical performance of the developed methodology was improved with almost no additional time and resource consumption during the sample preparation step. The analyte was extracted using ultrasound and introduced into the HPLC system without the use of additional purification methods such as solid-phase extraction. The method adhered to the confirmatory standards outlined in Commission

Decision 2002/657/EC, which implements Council Directive 96/23/EC governing the execution of analytical techniques and the interpretation of the outcomes.

14 samples of honey from Kazakhstan were analysed using the developed method. It was found, that none of the samples contained the target analyte at a level above the detection limit of the method. When analysing samples of imported honey, in two samples out of 7 the amount of CAP exceeded the permissible norms. The application of the indicated method in laboratories would limit the uncontrolled use of antibiotics in beekeeping, ensure high quality of honey and hence increase its competitiveness. This method holds valuable potential for monitoring and controlling the illicit utilisation of CAP in food production. It represents a crucial step in assessing the ramifications of unauthorised CAP use, whether by beekeepers employing prohibited preparations or medicines readily accessible in retail pharmacies intended for human use. Furthermore, this methodology could serve as a foundational framework for the creation of an HPLC-MS/MS technique capable of detecting and quantifying CAP, and potentially other antibiotic residues sharing structural similarities, across various food matrices. New research questions and perspectives emerged in the course of the study. The study of other analytes used in beekeeping whose residues in honey can be determined by the developed HPLC-MS/MS methodology, without significant modification of the sample preparation procedure and chromatographic system parameters. Exploring additional bee-derived products like beeswax, bee venom, pollen, and royal jelly is a promising avenue. These substances find application both as dietary supplements and in medicinal contexts, making them worthy subjects of investigation.

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CONFLICT OF INTEREST

None.

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Розробка методу ВЕРХ-МС/МС для кількісного визначення хлорамфеніколу в меді з Казахстану

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Анотація. Проблема наявності антибіотиків, зокрема хлорамфеніколу, у продуктах бджільництва є актуальною у зв'язку з ризиками для здоров'я людини та впливом на торгівлю цими продуктами. Важливим завданням є розробка високочутливих методів для виявлення залишкових кількостей антибіотиків. Метою цього дослідження було створення аналітичного методу із застосуванням ВЕРХ-МС/МС (високоефективна рідинна хроматографія – тандемна мас-спектрометрія) для ідентифікації та кількісного визначення залишків хлорамфеніколу в зразках меду з Казахстану. Запропонований метод передбачав ультразвукову екстракцію з подальшим аналізом за допомогою ВЕРХ-МС/МС з електроспрейною іонізацією в негативному режимі. Параметри тандемного мас-спектрометричного детектора налаштовано з використанням режиму множинного моніторингу реакцій. Запропонована методика мала значні переваги, зокрема простоту та швидкість екстракції, а також високу чутливість і точність виявлення. Межа виявлення становила 0.09 мкг/кг, а калібрувальна крива була лінійною в діапазоні концентрацій 0.1-1.0 мкг/кг з коефіцієнтом кореляції 0.9985. Вихід екстракції становив від 97 % до 101 %. Важливо зазначити, що цей метод визначення хлорамфеніколу за допомогою ВЕРХ-МС/МС перевищував вимоги до граничного рівня залишків (0.3 мкг/кг) за чутливістю, водночас зберігаючи високу точність та ефективність екстракції. Метод відповідав вимогам, викладеним у Рішенні Комісії 2002/657/ЕС. Метод було апробовано на 14 зразках меду з Казахстану, в жодному з яких не було виявлено хлорамфеніколу вище межі виявлення. Водночас у двох із семи зразків імпортного меду концентрація хлорамфеніколу перевищувала межу виявлення. Розроблений метод ВЕРХ-МС/МС може бути ефективним інструментом для рутинного лабораторного аналізу та перевірки підозрілих або сумнівних зразків меду

Ключові слова: рідинна хроматографія; мас-спектрометрія; аналіз; антибіотик; мед

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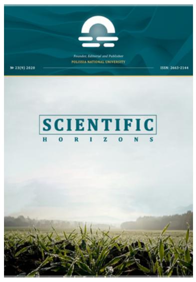

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Practical aspects of environmental assessment of water bodies transformation

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Abstract. One of the components of the environmental assessment of the state of transformation of surface water bodies is hydromorphological assessment, which has recently been applied in Ukraine as a necessary component of the implementation of the implemented international environmental legislation. The aim of the article was to provide a practical application of hydromorphological assessment methods on the example of two objects with artificially constructed structures. The hydromorphological assessment was carried out according to a certified methodology developed by the

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Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine. A number of hydromorphological indicators were monitored according to the methodology. The hydromorphological assessment included field surveys of each water body, database development, including mapping, digitisation of the results and preparation of reports. From 09 to 24 September 2024, experts surveyed two unnamed streams of the IV and V orders of the Danube River basin within the settlements of Karapachiv and Nova Slobidka in the Vyzhnytsia and Dniester districts of Chernivtsi Oblast. Based on the results of the survey and analysis of the studied indicators using environmental assessment methods that comply with the European Union Water Framework Directive, such criteria as river continuity and runoff correspond to the lowest assessment for both sites. Taking into account the principle of European water legislation, according to which a criterion indicating that there is a risk of a surface water body not achieving good ecological status automatically places it in the "at risk" category. Therefore, hydromorphological assessment is critical for integrated river basin management, implementation of action programmes, in particular, to restore the free flow of watercourses and ensure conditions for maintaining their good ecological status and potential. The study further developed the practice of environmental assessment of water body transformation

Keywords: European Union Water Framework Directive; Danube River Basin; surface water body; risk criteria; hydromorphological assessment

INTRODUCTION

Environmental assessment of the transformation of water bodies, as noted by V. Khilchevskyi *et al.* (2022), does not have a long tradition in the field of water management. In fact, only a few European Union member states had relevant survey and assessment schemes in place before the EU Water Framework Directive (EU WFD) came into force. According to the authors M. Hirschnitz-Garbers *et al.* (2022), most EU Member States have environmental assessment systems that are available for the entire national river network. For the first river basin management plans in 2009 and within the framework of river basin analyses in Ukraine and the EU at the beginning of the 21st century, an analysis of anthropogenic pressures and impacts was conducted, which led to the conclusion that transformational changes put most river basins in Europe at risk, as noted by M. Korchemlyuk and L. Arkhypova (2016) in their previous works and confirmed by official sources (European Environment Agency, 2025). According to O. Shumilova *et al.* (2023), the types of transformational changes differ between EU Member States, but hydromorphological changes such as interruption of river continuity and fish migration by artificial barriers are a common problem, as noted in the EU Guidance Documents. In Ukraine, according to the conclusions of the updated river basin management plans, in accordance with the water strategy (Order of the Cabinet of Ministers of Ukraine dated December No. 1134-p, 2022), significant financial efforts are required in the future to restore the changed hydromorphological conditions of river water bodies to achieve good status no later than 2027.

Given the active phase of implementation of the EU Water Framework Directive in Ukraine, the need to develop a full-fledged national hydromorphological monitoring system is becoming particularly relevant, which will allow for the identification of "highly modified" water bodies, timely implementation of environmental restoration measures, and promotion of sustainable water management at the local and transboundary levels. As shown in P. Arulbalaji *et al.* (2019), anthropogenic changes in the hydrology and morphometry of aquatic ecosystems affect the functioning of lakes and rivers in various ways. Initially, they have a profound impact on coastal communities, and eventually, as Prykhodko *et al.* (2020) point out, they lead to changes in the ecosystems of the entire water body.

This is especially important in the context of climate change adaptation, increasing anthropogenic pressure on small rivers, and the need to provide ecosystem services to local communities, as proven by M. Prykhodko *et al.* (2023). The development and application of adapted methodologies in combination with geoinformation technologies, digital mapping and databases will help improve the quality of decision-making and fulfil Ukraine's international obligations in the field of water protection. As stated in the Order of the Ministry of Environment of Ukraine No. 313 (2020), in this context, it is important not only to analyse the hydromorphological state, but also to take into account the relationship with physicochemical and biological parameters, which will allow for an integrated assessment of the state of water bodies in accordance with European standards.

Testing of methods for improving the practical application of environmental assessment of water body transformation was the objective of this research, with the aim of disseminating the results obtained for widespread use in the practice of environmental protection institutions and environmental education. The practice of hydromorphological assessment is a component of risk analysis and classification of the ecological state, analysis of anthropogenic pressures and impacts, as well as planning and design of environmental improvement measures, as can be seen in research funded by the World Wildlife Fund (WWF Report, 2024). Much effort has been put into developing environmental assessment methods and management measures that focus primarily on eutrophication, while hydromorphological pressures have not been adequately addressed. Therefore, the aim of the study was to analyse the application of hydromorphological assessment methods on the example of two water bodies with artificial hydraulic structures.

MATERIALS AND METHODS

The methodological recommendations for hydromorphological monitoring of surface water bodies used in this study were developed by scientists of the Hydromorphological Monitoring Laboratory at the Department of Systemic Hydrometeorological Research of the Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine within the framework of Research work 6/18 "Development of a scientific and methodological basis for hydromorphological monitoring of surface water bodies of Ukraine" (Hydromorphological assessment, 2019). The recommendations were developed based on the work of Slovak and Croatian scientists S. Poikane *et al.* (2019) and M. Kijowska-Strugala *et al.* (2021) to determine the degree of change in river hydromorphology According to Appendix V, the EU WFD (Directive 2000/60/EC of the European Parliament…, 2000) requires the assessment of the following hydromorphological elements to assess high, good and moderate status (Table 1).

Table 1*. Determination of high, good and satisfactory ecological status in rivers based on hydromorphological parameters*

Item	High status	Good status	Satisfactory status
Hydrological regime	The amount and dynamics of runoff and the corresponding connection to groundwater fully or almost fully reflect undisturbed conditions.	The biological quality elements achieve their respective values in accordance with the EU WFD.	The biological quality elements achieve their respective values in accordance with the EU WFD.
River continuity	The continuity of the river is not disturbed by anthropogenic activities and ensures free migration of aquatic life and transport of sediments.	The biological quality elements achieve their respective values in accordance with the EU WFD.	The biological quality elements achieve their respective values in accordance with the EU WFD.
Morphological condition	Channel structures, changes in width, depth, flow velocity, substrate conditions, and riparian zone structure and condition are completely or almost completely undisturbed.	The biological quality elements achieve their respective values in accordance with the EU WFD.	The biological quality elements achieve their respective values in accordance with the EU WFD.

Source: *Directive 2000/60/EC of the European Parliament… (2000)*

Table 1 shows that hydromorphological pressure is only indirectly estimated for good and moderate condition. This becomes particularly important for pressure and impact analysis and risk assessment, and thus requires a representative analysis approach, which is proposed in this study. In this study, the assessment was carried out using the following approach: analysis of the risk of water bodies failing to meet their objectives due to hydromorphological changes by implementing the proposed risk criteria using: the results of the survey of selected sites and hydromorphology assessment; existing national information on hydromorphological and related loads presented in O. Ostapenko *et al.* (2020), V. Khilchevskyi and V. Karamushka (2022).

Both sources of information for the analysis were carefully collected to ensure success. The approach is based on the application of expert judgement used in M. Perschke *et al.* (2023), C. Kupferschmidt *et al.* (2024) and assumes that experts working on hydromorphological assessments are largely familiar with the datasets, natural conditions and loads in the basin, and their appropriate combination during risk assessment. Any gaps in knowledge about the loads and impacts in the pilot basins need to be highlighted and sought to be filled. The on-site surveys serve to collect the missing information, fill in the gaps and complete the pressure and impact analysis and risk assessment further. As for the other parameters, when it comes to hydromorphology, anthropogenic pressure has different effects depending on the size of the river or its catchment area. In risk assessment, this fact should be taken into account, in particular, when establishing and applying risk criteria, according to S. Avdullahi and A. Hajra (2023) and L. Arkhypova *et al.* (2022). Different methodologies are used to address this issue (UNENGO "MAMA-86", 2014; Resolution of the Cabinet of Ministers of Ukraine No. 758, 2018). To facilitate implementation, this approach used river size categories based on the typology shown in Table 2.

Table 2. *River types for hydromorphological assessment depending on their size*

Size of the river	Description of the river type	Size of the catchment area
Small	Mountain "gravel" river type	10 km^2 – 100 km^2
Medium	Semi-mountainous "gravel" river type	100 km^2 – 1000 km^2
Large	Lowland river type	> 1000 km^2

Source: *Guidance document addressing hydromorphology and physico-chemistry... (2014)*

Based on experience with EU WFD risk assessments, the approach is to use the most relevant types of hydromorphological pressure rather than using every element that is part of a hydromorphological study. For each of the five identified pressure types, risk criteria are proposed to be implemented using available data and expert opinion to determine whether water bodies are at risk from hydromorphology according to the three risk categories. The five pressure types for which criteria are proposed are listed in Table 3.

The criteria for assessing the risks of failure to achieve environmental goals are presented in Table 4.

Table 3. *Anthropogenic factors leading to hydromorphological risks*

Pressure group	Type of pressure, including display of factors
Disruption of the continuity of aquatic habitat along the river	Disruption of habitat continuity along the river and fish migration routes
Artificial structures in the channel, disruption of connection with groundwater	Water retaining structures for hydropower; drinking water reservoirs; irrigation intake structures; other barriers;
Factors leading to the depletion of water bodies	Water abstraction may result in the formation of river sections affected by depletion in certain periods of the year (danger to hydrobionts sensitive to environmental flows)
Hydrological changes in channel width, depth, flow velocity and sediment transport	Factors: bank protection, dredging, gravel-sand extraction, irrigation; hydropower; water intake and discharge; aquaculture, etc.
Morphological changes in channel structure, substrate condition, and riparian zone structure and condition	Storage/impact of reservoirs/backwater: river sections affected by altered flow conditions upstream of artificial barriers (change of river character to lake character) and due to dredging of the channel.

Source: *compiled by the authors*

Table 4. *Criteria for assessing the failure to achieve environmental goals*

Risk category	Category justification
1	A water body "at risk" is at risk of failing to fulfil the environmental objective of the EU WFD. There is one or more significant hydromorphological change (barriers, reservoirs, water abstraction). The morphology of the river is "significantly altered or heavily modified". Water bodies in this group should be classified as highly modified.
2	A water body "possibly at risk" is at risk of not meeting an EU WFD environmental objective. Data sets are insufficient to apply the criteria, so gaps need to be filled. Or no significant hydromorphological changes (barriers, reservoirs, water abstraction, hydropics) have been assessed. However, the river morphology (if available) is "moderately modified". This group is temporary because a decision on whether these water bodies should be classified as "temporary SSSIs" cannot be made and requires additional data and research. There is no reliable information on the functioning of the fish passage There is no reliable information on water intake. There is no reliable information on the length of the backwater zone or the total length of several backwater zones is 10-30% of the total length of the surface water body.
3	The "no risk" water body is not at risk of failing to meet the EU WFD environmental objective. No significant hydromorphological changes (barriers, reservoirs, water abstraction, hydropics) have been assessed. The river morphology is "almost natural" or "slightly modified". The water bodies in this group should be considered as natural river bodies in terms of hydromorphology. However, other types of pressure can be assessed.

Source: *Guidance document addressing hydromorphology and physico-chemistry... (2014)*

An important part of the hydromorphological monitoring was the pre-field work (data collection and preparation of the field survey). From 09 to 24 September 2024, specialists from the Prut and Siret River Basin Water Resources Management Authority surveyed two unnamed streams of the IV and V orders of the Danube River basin within the settlements of Karapachiv and Nova Slobidka in the Vyzhnytsia and Dniester districts of Chernivtsi Oblast. Many of the functions and parameters were assessed prior to the field survey, which improved the quality of the field data collection. The following materials were used to prepare the field surveys:

- terrain plans, used by the authors also in R. Kravchynskyi *et al.* (2021);
- historical maps of the 19th century and topographic maps of 1970-1980 (1:100,000) to determine modern hydromorphological forms;
- satellite imagery to analyse land use in the floodplain, riparian zone and within the catchment, as shown in J. Feher *et al.* (2012);
- online maps from various online resources (e.g. OpenStreet maps, Google maps);
- other materials on water abstraction, water management, etc. as shown in T. Garbowski *et al.* (2023).

During the field surveys, the following hydromorphological elements were considered in accordance with (Methodology for assigning a surface water body..., 2019) and the requirements of Directive 2000/60/EC of the European Parliament (2000): disruption of river continuity and habitat; hydrological changes; change in river morphology. In addition, the information (photographs, field diaries) obtained during the fieldwork was useful for the hydromorphological assessment of the survey units. More specific parameters were also investigated, including channel geometry, substrate composition, channel vegetation and organic debris, bank structure and associated changes, flow conditions, interruption of longitudinal continuity by artificial structures, vegetation type, adjacent land use and channel-floodplain interactions. Changes in river morphology were taken into account for the preliminary pressure analysis. A five-point scale was used to assess each hydromorphological feature. According to this scale, the assessed surface water bodies (SWBs) were assigned to one of the classes. The classes were indicated by the following colours: blue – 'almost natural', green – 'slightly modified', yellow – 'moderately modified', orange – 'significantly modified' and red – 'highly modified' (Table 5).

***Table 5**. Classification periods for the five classes (Score Group A)*

Score Range	Class	Description	Colour
From 1 to < 1.5	1	Almost natural	Light Blue
From 1.5 to < 2.5	2	Slightly modified	Green
From 2.5 to < 3.5	3	Moderately modified	Yellow
From 3.5 to < 4.5	4	Significantly modified	Orange
From 4.5 to 5.0	5	Heavily modified	Red

***Source:** Hydromorphological assessment (2019)*

In cases where three classes are used to describe the hydromorphological status of surface water bodies in the "Rivers" category, the definitions provided in Table 6 shall be applied, and the indicated classes must be represented on maps (if required) using the corresponding colour scheme for presenting results.

***Table 6**. Classification definitions for the three classes (Score Group B)*

Score Range	Class	Description	Colour
From 1 to < 2.5	1	Close to natural to slightly modified	Light Blue
From 2.5 to < 3.5	3	Slightly to moderately modified	Yellow
From 3.5 to 5.0	5	Heavily modified to very heavily modified	Red

***Source:** Hydromorphological assessment (2019)*

Hydromorphological assessment is an important component of environmental assessment, as it allows to determine the ecological state of surface water bodies and serves as a basis for making appropriate management decisions to ensure the principles of integrated river basin management. This is especially important when applied to transboundary water bodies, which include all water bodies in the area of the Danube River Basin, Europe's largest, and whose preservation in good condition is a key to sustainable development not only for Ukraine but also for all nineteen countries that share the Danube River Basin.

RESULTS AND DISCUSSION

This study assessed the hydromorphological modification of two surface water bodies in the Danube River basin. To put the above guidelines into practice, a hydromorphological analysis of an unnamed stream, which is a left tributary of the Hlybochok River and belongs to the Prut sub-basin (Danube River Basin), was carried out. The water body is located in the village of Karapchiv, Vyzhnytsia district, Chernivtsi region (Fig. 1).

***Figure 1**. Geographical reference of the 3 survey points of the detected artificial structures outside Karapchiv village*
***Source:** Google map with mapped survey points*

The channel of the studied water body is a low-flowing channel with a catchment area of 0.3 km^2. Its width ranges from 0.5 m to 1.5 m, depth from 0.02 m to 0.05 m, and average width is 0.8 m. The channel of the water body is composed of silt and clay with the remains of trees. Artificial ponds have been constructed here, which contributed to the change of the stream channel. Its floodplain is weakly defined with natural vegetation (Fig. 2). The constructed hydraulic structures on the ponds, which are more than 1 m high, are silted up, and therefore have a negative impact on the continuity of the stream flow, impeding the migration of aquatic life and the transport of suspended sediments.

***Figure 2**. Unnamed stream (Karapchiv village)*
***Source:** photo materials from field research*

The graphical results of the hydromorphological assessment of the unnamed stream (Karapchiv village) by three-digit code and in accordance with the zone are presented in Fig. 3 and Fig. 4.

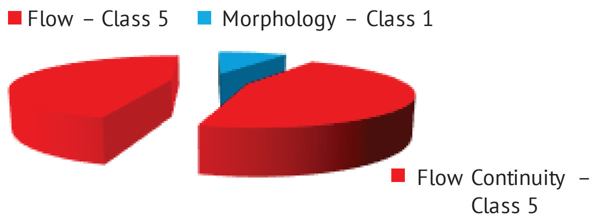

***Figure 3**. Quality classes according to hydromorphological assessment of an unnamed stream in Karapchiv village by three-digit code*
***Note:** 1 - slightly changed, 5 - heavily changed*
***Source:** compiled by the authors*

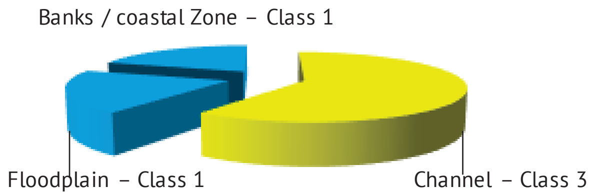

***Figure 4**. Quality classes by hydromorphological assessment of an unnamed stream in Karapchiv village in accordance with the zone*
***Note:** 1 - slightly changed, 5 - heavily changed*
***Source:** compiled by the authors*

According to the European classification, this indicates a risk of not achieving good ecological status and automatically places the site (an unnamed stream in the village of Karapchiv) in the "at risk" category.

A generalised hydromorphological assessment of the unnamed river in the Karapchiv village settlement is presented in Table 7.

***Table 7**. Generalised results of hydromorphological assessment of the unnamed river in Karapchiv settlement*

Scorecard	Score value	Score Range
Single point	2,34	2
3-digit code	Morphology – 1.83	2
	Flow – 5.00	5

Table 7. Continued

Scorecard	Score value	Score Range
3-digit code	River continuity – 5.00	5
	Unique code based on the assessment results – 255	
In accordance with the zone	River channel – 3.3	3
	Banks/coastal zone – 1.15	1
	Floodplain – 1.27	1
	Unique code based on the assessment results – 2_1_1	

Note: *IPV code: UA_R_16_S_1_Si. Coordinates of the beginning of the DO: latitude: 48°19´15.92´´; longitude: 25°25´58.02´´. River name: no name. Name of the area: Karapchiv*
Source: *compiled by the authors*

The results obtained indicate the need to implement measures to restore the free flow of the watercourse and improve the ecological condition and potential of the unnamed stream. By analogy, a hydromorphological analysis of another water body, an unnamed stream in the village of Nova Sloboda, Dniester District, Chernivtsi Region, which is a tributary of the Dratiste River (Prut sub-basin, Danube basin), was carried out (Fig. 5). The channel of the unnamed stream in the village of Nova Sloboda was winding and overgrown. Its width ranged from 2.0 m to 4.0 m. It is composed of silt and clay. The channel dries up in the low water period. The floodplain of the stream is low, overgrown with bushes and grass (Fig. 6).

***Figure 5**. Geographical reference of 9 survey points for detection of artificial structures outside Nova Sloboda village*
Source: *Google map with mapped survey points*

***Figure 6**. Unnamed stream (overgrown), (Nova Sloboda village)*
Source: *photo materials from field research*

The water body under study has undergone significant anthropogenic impact due to the construction of artificial ponds in the channel. Hydraulic structures on the ponds are silted up, and therefore they are an obstacle that affects the continuity of the stream, the nature of erosion and sedimentation, and impede the migration of all types of biota and sediment transport. The hydromorphological assessment of the unnamed stream (Nova Sloboda village) by three-digit code and according to the zone is presented in Fig. 7 and Fig. 8 and in Table 8.

According to the European classification, this indicates a risk of not achieving good ecological status and automatically places the object – an unnamed stream in the village of Nova Sloboda – in the "at risk" category.

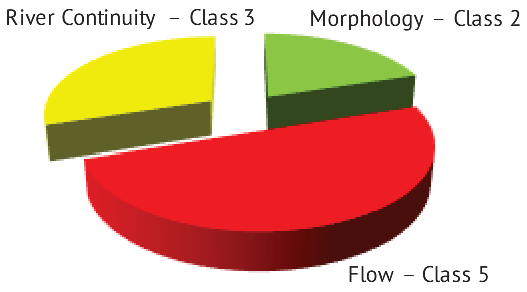

***Figure 7**. Quality classes according to hydromorphological assessment of an unnamed stream in the village of Nova Sloboda by three-digit code*
***Note:** 2 – slightly modified, 3 – moderately modified, 5 – heavily modified*
***Source:** compiled by the authors*

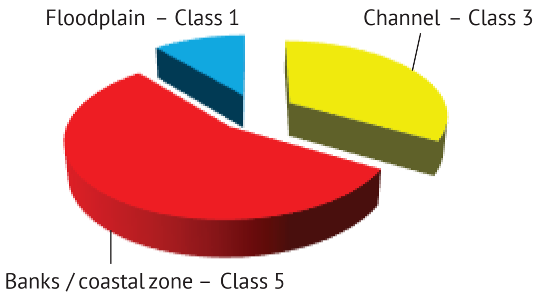

***Figure 8**. Quality classes according to hydromorphological assessment of the unnamed stream in Nova Sloboda village in accordance with the zone*
***Note:** 1 - slightly modified, 3 - moderately modified, 5 - heavily modified*
***Source:** compiled by the authors*

The results obtained indicate the need to implement measures to restore the free flow of the watercourse and improve the ecological condition and potential of the unnamed stream in the village of Nova Sloboda.

***Table 8**. Summary of hydromorphological assessment results of an unnamed stream in Nova Sloboda village*

Scorecard	Score value	Score Range
Single point	2.33	2
3-digit code	Morphology – 2.02	2
	Flow – 5.00	5
	River continuity – 3.00	3
	Unique code based on the assessment results – 253	
In accordance with the zone	River channel – 3.03	3
	Banks/coastal zone – 2.00	2
	Floodplain – 1.33	1
	Unique code based on the assessment results – 3_2_1	

***Note:** IPV code: UA_R_16_S_1_Si. Coordinates of the beginning of the DO: latitude: 48°24´50.20´´, longitude: 27°11´17.24´´. River name: no name. Name of the place: Nova Sloboda*
***Source:** compiled by the authors*

Both streams have critical flow and continuity problems: a score of 5 for flow indicates depletion of the watercourse during dry periods. The sites automatically fall into the 'at risk' category according to Directive 2000/60/EC of the European Parliament... (2000). Despite similar overall assessments, Nova Sloboda shows a worse condition of the riparian zone, and Karapchiv shows a more critical disruption of the river's continuity. Comparative results of the hydromorphological assessment of the two unnamed streams are presented in Table 9.

***Table 9**. Comparative results of hydromorphological assessment*

Option	Stream (Karapchiv)	Stream (Nova Sloboda)
Single point	2.34 (class 2)	2.33 (class 2)
Morphology	1.83	2.02
Flow	5.00	5.00
River continuity	5.00	3.00
Channel	3.3	3.03
Banks / coastal zone	1.15	2.00
Floodplain	1.27	1.33
General category	255 (at risk)	253 (at risk)

***Source:** compiled by the authors*

Thus, the following differences in the hydromorphological elements of the studied unnamed streams were found.

1. River continuity:

- Karapchiv: severe impairment (grade 5, the worst).
- Nova Sloboda: moderate impairment (grade 3).

In Karapchiv, the waterworks (ponds) have a higher height and degree of siltation, which completely prevents the flow and migration of aquatic life.

2. Banks / coastal zone:

- Karapchiv: better condition (1.15).
- Nova Sloboda: worse condition (2.00).

In Karapchiv, the natural vegetation of the coastal zone has been preserved, while in Nova Sloboda, overgrowth and development are changing the natural landscape.

3. Morphology and channel: in both cases the channel is altered, but in Karapchiv the morphology is slightly better. In both cases, the channel dries up in the low water period, is silted and clayey, with artificial structures.

Both water bodies have a high level of anthropogenic impact, mainly due to hydraulic structures that change the natural regime of the watercourse.

It is recommended to implement restoration measures, such as clearing, dismantling or reconstructing barriers and restoring floodplains. These are critical for achieving good ecological status. Streams are an example of highly modified surface water bodies and should be taken into account in the management plans for the Prut sub-basin and the Danube basin as a whole.

The surveyed water bodies are small rivers. UA_R_16_S_1_Si (small river in lowland silicas) of the IV and V orders of the Danube River basin (Prut sub-basin) within the settlements of Karapachiv and Nova Slobidka. In the study by T. Garbowski *et al.* (2023) assessed the hydromorphological state of 10 watercourses (30 measurement sites) in Poland on the basis of a multimetric hydromorphological index for rivers based on a proposed new approach to the definition of river valleys (small watercourses). This study is distinguished by an adapted practical component of hydromorphological assessment. In many studies in recent years, such as J. Wang *et al.* (2023), D. Shanafelt *et al.* (2023), hydromorphological changes are considered as important water management issues, in addition to organic pollution, nutrient pollution, and pollution caused by hazardous substances. The authors S. Zaborowski *et al.* (2023), based on their research, managed to determine the size, dynamics and scale of changes occurring in the river under different conditions of its transformation, including as a result of anthropogenic pressure. In this study, and in Ukraine in general, hydromorphological changes are considered to be part of river basin management plans (Order of the Cabinet of Ministers of Ukraine dated December No. 1134-p, 2022).

Although the list of hydromorphological assessment elements presented is extensive and in line with the EU WFD, a gap in the assessment that prevents a full analysis of anthropogenic pressures and impacts is that field studies were conducted exclusively for a selected sample of water bodies and did not cover the entire length of the river network. The focus was rather on identifying a reference location as a basis for condition assessment, but not necessarily on pressure and impact checks. However, the information gathered from the field surveys, which has so far been carefully prepared by experienced experts and staff of the Prut and Siret River Basin Water Resources Management (Prut and Siret River Basin Water Resources Management, n.d.), is considered a very valuable basis for complementing and completing the pressure and impact analysis using this approach for integration into the Danube River Basin (Prut sub-basin) management plan.

Guided by the provisions of the EU WFD, Z. Odnorih *et al.* (2020) elements used to determine the high ecological status of water are biological quality elements, chemical quality elements, general physico-chemical quality elements, and hydromorphological quality elements. According to N. Gomelia *et al.* (2018), this means that a water body can have a high status only if its hydromorphology and physical and chemical indicators demonstrate a high status. According to O. Mandryk *et al.* (2021), I. Klymchuk *et al.* (2022), the elements used to determine the good status of water are biological quality elements, chemical quality elements and general physico-chemical quality elements. This means, according to V. Strokal (2021), K. Stefanidis *et al.* (2024), that good status can be achieved in a water body even if hydromorphological indicators indicate a lower status. Also N. Glibovytska *et al.* (2024) emphasise that any assessment of a status lower than good, which is satisfactory, bad or very bad, is based solely on the assessment of biological quality elements and chemical quality elements. Kolesnik *et al.* (2017) and S. Vikhryst *et al.* (2018). However, according to C. Skoulikaris and A. Zafirakou (2019) and L. Simkiv *et al.* (2021), both hydromorphology and general physicochemistry of water bodies play a crucial role in assessing pressures and impacts, as their change can affect the state of the aquatic ecosystem This means that pressures on both hydromorphological and general physicochemical elements can consistently affect biological quality elements and, therefore, according to V. Kopei *et al.* (2020), change the respective status of a water body.

In the above context, according to E. Soule *et al.* (2023), altered hydromorphological, general physical and chemical parameters and the impact of significant anthropogenic pressure on them serve as indicators to assess whether a water body is at risk of losing its designated water status and reducing the level of ecosystem services. H. Zelinska *et al.* (2021), V. Kopei *et al.* (2023) state that the introduction and implementation of risk criteria and/or thresholds for hydromorphological and general physicochemical elements can be used to assess significant pressures and impacts on the state of water as a component of sustainable development. A well-known study by M. Kijowska-Strugala *et al*. (2021) compares the quality of mountain stream habitats in areas without visible anthropogenic integration and those permanently altered by human activities between mountainous areas in different climatic zones. The fieldwork was conducted using the British River Habitat Survey (RHS) method. In contrast, this study involved a set of field works with a full-scale survey of water bodies, photography, the formation of a digital database, mapping and preparation of reports presenting the results of hydromorphological assessment.

According to S. Poikane *et al*. (2019), hydromorphological pressure is the second most common type of pressure on aquatic ecosystems in European countries (after eutrophication). Ukrainian researchers V. Khilchevskyi *et al*. (2022) also argued that anthropogenic changes in the hydrology and morphometry of aquatic ecosystems affect the functioning of lakes and rivers in various ways. Initially, they have a profound impact on coastal communities such as macrophytes, benthic invertebrates and fish fauna. Finally, as Z. Odnorih *et al*. (2020), they lead to changes in the ecosystems of the entire water body. The importance of hydromorphological assessment is related to the need to establish the ecological status of surface water bodies and make appropriate management decisions based on it, in particular, to prepare an appropriate programme of measures as part of river basin management plans. This is especially important in the case of transboundary water bodies, which include all water bodies in the area of the largest European Danube River Basin, whose preservation in good condition is a key to sustainable development not only for Ukraine but also for all nineteen countries whose territory lies within the Danube River Basin.

CONCLUSIONS

As a result of the research, the practice of environmental assessment of the transformation of small water bodies was improved. According to the results of the hydromorphological assessment in accordance with the requirements of the EU Water Framework Directive of two unnamed small watercourses of the IV and V orders of the Danube basin (Karapchiv and Nova Sloboda villages in Chernivtsi Oblast), both water bodies under study fall into the lowest category according to such criteria as river continuity and runoff. In accordance with the EU WFD principle, when determining the category of a surface water body, the rule is applied that if at least one of the criteria is assessed as "at risk", the entire body is classified as such. In view of the above, both streams are significantly modified water bodies and belong to Class V – highly modified.

Both streams have critical problems with flow and continuity: a score of 5 for flow indicates depletion of the watercourse during dry periods. In Karapchiv village, the waterworks (ponds) have a higher height and degree of siltation, which completely impedes the flow and migration of aquatic life. Despite similar general assessments, the stream in Nova Sloboda village shows a worse condition of the riparian zone, and in Karapchiv village - a more critical violation of the river continuity. Both water bodies have a high level of anthropogenic impact, mainly due to hydraulic structures that change the natural regime of the watercourse. It is recommended to implement restoration measures, such as clearing, dismantling or reconstructing barriers and restoring floodplains. These are critical for achieving good ecological status. Streams are an example of highly modified surface water bodies and should be taken into account in the management plans for the Prut sub-basin and the Danube basin as a whole.

The prospect of further research is to expand the application of the methodology to a wider network of small watercourses of different geomorphological types in Ukraine, its digitalisation, integration of hydromorphological parameters with bioindicative methods for assessing the state of aquatic ecosystems, and the creation of a full-fledged national database of hydromorphological monitoring as a tool to support management decisions in the field of water resources protection.

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CONFLICT OF INTEREST

None.

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Практичні аспекти екологічної оцінки трансформації водних об'єктів

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Анотація. Однією з складових екологічної оцінки стану трансформації поверхневих водних об'єктів є гідроморфологічна оцінка, яка нещодавно почала застосовуватись в Україні як необхідна складова виконання імплементованих міжнародних документів екологічного законодавства. Метою статті було практичне застосування методик гідроморфологічного оцінювання на прикладі двох об'єктів, які мають штучно збудовані споруди. Гідроморфологічне оцінювання проводилося згідно атестованої методики, розробленої Українським гідрометеорологічним інститутом Державної служби України з надзвичайних ситуацій та Національної академії наук України. Моніторингу підлягали визначений методикою ряд гідроморфологічних показників. Гідроморфологічне оцінювання включало польові обстеження кожної ділянки водних масивів, формування бази даних, включно з картуванням, оцифрування результатів та підготовку звітів. Фахівцями з 09 по 24 вересня 2024 року було обстежено два безіменних струмка IV і V порядків басейну р. Дунай в межах населених пунктів Карапачів та Нова Слобідка Вижницького та Дністровського районів Чернівецької області. За результатами обстеження та аналізу досліджуваних показників із застосуванням методик екологічної оцінки, що відповідають Водній Рамковій Директиві Європейського Союзу, такі критерії, як неперервність течії річки та стік, відповідають найнижчій оцінці для обидвох об'єктів. Беручи до уваги принцип Європейського водного законодавства, згідно з яким критерій, що вказує на наявність ризику недосягнення доброго екологічного стану ділянки поверхневого водного масиву, автоматично відносять її до категорії «під ризиком». Тому гідро морфологічне оцінювання є критично важливими для інтегрованого управління річковим басейном, впровадження програм заходів, зокрема, з відновлення вільної течії водотоків та забезпечення умов підтримки їх доброго екологічного стану та потенціалу. В роботі дістала подальшого розвитку практика екологічної оцінки трансформації водних об'єктів

Ключові слова: Водна Рамкова Директива Європейського Союзу; річковий басейн Дунаю; масив поверхневих вод; критерії ризику; гідроморфологічна оцінка

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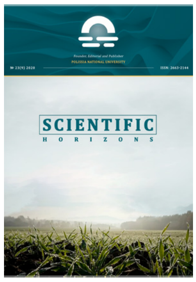

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Innovative technologies in the production of agricultural machinery to improve the efficiency of agribusinesses

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Abstract. The purpose of the study was to analyse innovative technologies in the production of agricultural machinery and their impact on improving the efficiency of agricultural enterprises. The study applied various scientific methods to comprehensively analyse the impact of innovative technologies on the efficiency of enterprises in the field of agricultural engineering. The study found that the use of innovative technologies in agricultural engineering significantly increases the efficiency of agricultural enterprises. The analysis showed that the use of precision farming systems equipped with sensors and GPS technologies allows optimising the allocation of resources such as water and fertilisers, which leads to increased yields and lower costs. Automation of operations using autopilots on tractors and combines, as in the John Deere and Fendt models, has demonstrated a reduction in labour costs and a reduction in the

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influence of the human factor, which also contributes to increased productivity. Electrification and hybridisation of agricultural machinery, which has been actively implemented in countries such as Denmark and Germany, has proved economically beneficial, contributing to a reduction in carbon dioxide emissions and a reduction in operating costs. The introduction of artificial intelligence for monitoring and diagnostics of equipment has allowed minimising downtime and increasing the service life of equipment due to timely detection of malfunctions. In general, it has been established that the use of these technologies contributes to the sustainable development of agricultural enterprises, optimisation of production processes, and reduction of operating costs. The transition to more environmentally friendly production of agricultural machinery contributes to improving the environmental situation in regions with a high degree of agricultural mechanisation. The introduction of sustainable technologies in mechanical engineering has shown its effectiveness in reducing resource consumption, which makes agricultural enterprises more competitive in the global market

Keywords: precision agriculture; automation; GPS technology; electrification; artificial intelligence

INTRODUCTION

Modern agriculture is undergoing an active technological transformation aimed at increasing the productivity and efficiency of agricultural enterprises. Innovations in mechanical engineering open up new opportunities for automation, optimisation, and sustainable development, providing the agricultural sector with machinery capable of coping with the growing challenges of the industry, such as climate change and lack of resources. The introduction of advanced solutions such as precision farming systems, automated tractors with autopilot and electric installations allows farmers to use resources efficiently and reduce costs. These changes contribute to the improvement of production processes and make agricultural enterprises more environmentally friendly and competitive. The importance of such technologies increases in the context of the need for environmental sustainability and increased efficiency of agricultural activities, especially in the light of global trends towards sustainable development and concern for the environment. Thus, the introduction of innovative technologies becomes a key factor in ensuring sustainable growth and prosperity of the agricultural sector.

The problem of introducing innovative technologies into agricultural engineering remains relevant. This is conditioned by the need to increase the productivity and sustainability of agricultural enterprises in the face of modern challenges. A. Monteiro *et al.* (2021) emphasised the importance of precision farming for optimising resource use and increasing yields, noting that the introduction of such technologies has significantly reduced the cost of fertilisers and irrigation. U. Ahmad and L. Sharma (2023) focused on the impact of GPS technologies and sensors on real-time process management, arguing that these tools have contributed to improving the efficiency of agricultural enterprises by more precisely monitoring the condition of crops. F. Mocera *et al.* (2023) investigated the possibilities of electrification of tractors, contributing to the reduction of carbon dioxide emissions, and demonstrated that electric machines can not only reduce the environmental burden, but also reduce operating costs. M. Merz *et al.* (2022) highlighted the advantages of automated autopilot systems for reducing labour costs and improving field accuracy, pointing out that such systems have allowed farmers to focus on more complex aspects of farm management. J. Jung *et al.* (2020) examined the role of artificial intelligence in monitoring and diagnosing agricultural machinery to prevent downtime, showing that the use of AI can significantly improve equipment reliability and service life.

Y. Guo *et al.* (2020) investigated methods for optimising production processes using new technologies, believing that modern approaches can significantly improve the efficiency of agricultural enterprises. K.S. Uralovich *et al.* (2023) focused on sustainable development, linking it with the introduction of environmentally friendly solutions in mechanical engineering, and showed that environmental innovation has become an important factor in competitiveness. A. Subeesh and C. Mehta (2021) examined the impact of automation on cost reduction in the agricultural sector, arguing that process automation has helped not only to reduce costs, but also to improve product quality. P. Rambe and P. Khaola (2021) reviewed the competitiveness of agricultural enterprises through the introduction of innovative technologies, emphasising that modern developments have allowed farmers to successfully compete in the global market. Y. Zhu *et al.* (2022) emphasised that the transition to more sustainable technologies has significantly improved the environmental situation in highly mechanised regions, showing that such changes can lead to improved quality of life in rural areas. However, despite significant achievements in this field, gaps remain that require further study. In particular, insufficient integration of various technologies in agricultural enterprises may limit their effectiveness and sustainability. In addition, it is necessary to investigate the impact of innovations on small and medium-sized agricultural enterprises, and develop strategies for adapting existing equipment to modern requirements.

Thus, the purpose of the study was to systematically investigate and evaluate innovative technologies used in agricultural engineering, with a focus on their impact on the productivity of agro-industrial complexes.

MATERIALS AND METHODS

In the course of the research, the method of complex analysis was used, which allowed comprehensively assessing the impact of various innovative technologies on the efficiency of enterprises in the field of agricultural engineering. This method covered many aspects, including technical, economic and environmental factors, which helped to create a complete picture of how new technologies affect the agricultural sector. The comprehensive analysis examined key elements such as the introduction of digital technologies, including GPS, sensors, and data analysis systems. These components played an important role in the modernisation of agricultural machinery and process optimisation, which contributed to increased overall productivity and efficiency.

A comparative analysis method was used to analyse automation using autopilot in agricultural machinery. This approach allowed comparing the performance of tractors and combines equipped with autopilots, such as models from John Deere (2025) and Fendt (2025), with conventional means. The comparative analysis identified the advantages and disadvantages of each technology, assessed their impact on production processes, and determined how automation can reduce labour costs and improve the accuracy of operations. This method also helped to identify the factors contributing to the successful implementation of new technologies in the agricultural sector. In addition, the study used a systematic approach to analyse the introduction of electric and hybrid tractors. This method provided a deeper understanding of how these technologies can help to reduce carbon dioxide emissions and reduce operating costs. The systematic approach ensured the integration of various aspects such as economic feasibility, technical characteristics, and environmental benefits. This enabled a comprehensive analysis, which was necessary to make informed decisions about the introduction of electric and hybrid tractors into the practice of agricultural enterprises.

Precision farming systems were studied using the method of applied analysis, which helped to examine in detail their effectiveness in managing irrigation, fertilisation, and tillage. The applied analysis allowed assessing how specific technologies and techniques can be applied in the real working conditions of agricultural enterprises. This approach also helped to identify practical recommendations for farmers and agronomists to optimise production processes.

The data analysis method has also been used to study the application of artificial intelligence technologies in the diagnosis and monitoring of agricultural machinery. This method analysed how artificial intelligence can help to identify malfunctions at an early stage and adjust the operation of equipment. Data analysis helped to understand how the introduction of artificial intelligence technologies can improve the reliability and efficiency of machinery, which was important to reduce the risk of breakdowns and increase the service life of equipment. In addition, the sustainability assessment method was used to analyse new models of agricultural machinery, which were developed considering environmentally friendly materials and reduced fuel consumption. This method allowed evaluating how such practices can be implemented for effective resource management and compliance with the principles of sustainable development. The assessment of sustainable development included an analysis of social, economic, and environmental aspects, which contributed to the development of a comprehensive view of the future of agricultural engineering and its interaction with the environment.

RESULTS

Modern agricultural machinery is undergoing significant changes due to the integration of digital technologies. The introduction of technologies such as GPS, sensors, and data analysis systems allows automating many processes, significantly increasing the efficiency of agricultural enterprises. With the help of GPS systems, farmers can accurately determine the location of equipment and effectively manage field operations. This helps to avoid unnecessary expenditure of time and resources (Gabriel & Gandorfer, 2023).

The use of sensors installed on agricultural machines plays an important role in monitoring the condition of crops and soil. These devices can collect information about humidity, temperature, and other important indicators, which allows farmers to make more informed decisions about irrigation and fertilisation. As a result, optimising resource allocation becomes not only more accurate, but also less costly, which helps to reduce financial costs. Data analysis systems based on modern algorithms and machine learning methods help to process and interpret huge amounts of information received from sensors and GPS. This allows agricultural enterprises to identify patterns, predict yields, and minimise risks associated with changing weather conditions or other factors. Thus, the integration of digital technologies into agriculture not only improves production processes, but also ensures a more sustainable development of the agricultural sector in the face of the growing challenges of our time.

The integration of digital technologies into the agricultural sector opens up new horizons for improving the productivity and sustainability of agricultural enterprises (Wrzecińska *et al.*, 2023). Farmers can use resources efficiently, reduce losses, and increase work efficiency, which is the key to the successful development of agriculture in the future. Automation of agricultural processes is becoming an important aspect of modern agricultural production. The introduction of tractors and combines with autopilot, such as models from John Deere and Fendt, is fundamentally changing the approach to field operations (Table 1). These machines are capable of performing tasks with high accuracy, which significantly reduces the likelihood of errors and increases overall work efficiency.

***Table 1**. Comparison of John Deere and Fendt tractors by key characteristics*

Characteristics	John Deere	Fendt
Main purpose	Universal and specialised operations	Universal and high-precision operations
Available models	6M, 7R, 8RX, 9RX	500 Vario, 900 Vario, 1000 Vario
Autopilot technologies	StarFire, AutoTrac	VarioGuide, FendtONE
Autopilot accuracy	±2.5 cm with RTK	±2 cm with RTK
Resource management	AutoPowr system (up to 15% fuel economy)	Fendt Efficient Technology (up to 17% fuel economy)
Electrification options	Limited models with electric motor up to 30 kW	Hybrid models with electric motor up to 50 kW
Environmental friendliness	Compliance with Tier 4 and Tier 5 standards	Compliance with Tier 4 and Tier 5 standards
Noise level in the cabin	70 dB	68 dB
Technical maintenance	Oil change interval is every 500 hours.	Oil change interval is every 600 hours.
Price	USD 100,000-550,000	USD 120,000-600,000

***Source:** created by the authors based on John Deere (2025) and Fendt (2025)*

Tractors with autopilot are equipped with advanced navigation and control systems, which allows them to accurately follow set routes, minimising the risk of crossing rows and losing crops. This not only improves the quality of work, but also reduces fuel costs, as the machines work more efficiently. Automation also optimises time costs, allowing farmers to focus on more complex aspects of farm management, such as data analysis and planning. Using combine harvesters with autopilot during the harvesting process also brings significant benefits. Such machines can operate in low visibility conditions, which makes them indispensable in difficult weather conditions. Automation of the cleaning process helps to avoid excessive wear and tear of equipment and extend its service life. This, in turn, helps to reduce operating costs and increase the profitability of the agricultural enterprise. However, the introduction of autopilot in agriculture requires certain personnel training and maintenance costs. Despite this, the benefits of automation, such as reduced human resource costs and increased productivity, far exceed the possible costs.

Automation using autopilot in agriculture has brought significant benefits to agricultural enterprises (Table 2). The introduction of autopilots in tractors and combines has significantly reduced labour costs and made the distribution of labour more rational. Autopilots also help to improve seeding accuracy by minimising skips and repeat passes, which improves yields and reduces losses. Reducing field processing time and reducing the number of mechanical errors highlights the importance of these technologies for reducing the impact of the human factor, and for more efficient fuel consumption, which reduces operating costs.

***Table 2**. Automation using autopilot in agriculture*

Indicator	Before the introduction of autopilot	After the introduction of autopilot	Change
Labor costs (thousand USD/year)	130	90	-31%
Seeding accuracy (%)	85	98	15%
Processing time of one field (hours/ha)	3.5	2.3	-34%
Fuel consumption (litres/ha)	12	9	-25%
Mechanical error rate (%)	10	3	-70%

***Source:** created by the authors based on I. Beloev et al. (2021)*

Thus, automation using autopilot is becoming not only a trend, but also a necessity for agricultural enterprises seeking to increase their competitiveness and stability in the market. Investments in modern technologies open up new horizons for agriculture, ensuring its effective development in the face of modern challenges. Electrification of agricultural machinery is becoming a key focus for countries seeking to reduce carbon dioxide emissions, such as Denmark and Germany (Johnstone *et al.*, 2021). In the context of global warming and environmental crises, the introduction of electric and hybrid tractors is becoming particularly relevant. These innovative solutions not only help to minimise the negative impact on the environment, but also prove to be economically beneficial for agricultural enterprises.

High-efficiency electric tractors are characterised by low noise and vibration levels, which makes their operation more comfortable for both operators and farm animals. Such machines are capable of operating on the basis of renewable energy sources, which significantly reduces dependence on fossil fuels and reduces the carbon footprint of the agricultural sector. In addition, many agricultural machinery manufacturers are actively developing technologies that allow the use of solar panels to charge electric machines, which further increases their environmental friendliness (Wen *et al.*, 2022). Hybrid tractors that combine both electric and diesel systems provide the necessary power and productivity, allowing farmers to work in difficult conditions and over large areas. These machines can reduce operating costs, as electric energy is often cheaper than conventional fuels, and also requires less maintenance. This makes them attractive to many agricultural enterprises seeking to optimise their costs and increase profitability (Pascuzzi *et al.*, 2024). Nevertheless, the transition to electrical technology is fraught with certain challenges. The need to develop charging infrastructure and support the maintenance of electric machines can represent significant costs at the initial stage. However, long-term benefits such as fuel savings and lower carbon emissions make these investments worthwhile.

Electrification of machinery contributes not only to cost savings, but also to improving the environmental situation in agricultural areas (Table 3). The transition to electric and hybrid models has allowed agricultural enterprises to reduce carbon dioxide emissions and reduce operating costs for equipment maintenance. Electric models provide a lower noise level, which increases the comfort and safety of working in the fields. In addition, the energy efficiency of these machines is higher compared to conventional models, which makes their use an economically and environmentally sound step towards the sustainable development of the agricultural sector.

***Table 3**. Electrification of machinery in agriculture*

Indicator	Conventional diesel models	Electrified models	Reduction, %
Fuel costs (thousand USD/year)	180	120	-33%
CO_2 emissions (tonnes/year)	45	10	-78%
Maintenance cost (thousand USD/year)	70	50	-29%
Noise level (dB)	85	65	-24%

***Source:** created by the authors based on E. Scolaro et al. (2021)*

Electrification of agricultural machinery is an important step towards more sustainable and efficient agricultural production. In countries seeking to reduce CO_2 emissions, such technologies open up new opportunities to enhance the competitiveness and environmental sustainability of agricultural enterprises. Investments in electric and hybrid tractors not only contribute to improving the environment, but also provide long-term economic benefits for farmers. Precision farming systems are an important tool for improving the efficiency and sustainability of agricultural enterprises. With global climate change and increasing demand for food resources, precise management of irrigation, fertilisation, and tillage is becoming a necessity. These systems allow farmers to use available resources more efficiently, minimising losses and significantly increasing yields.

One of the key aspects of precision farming systems is the ability to accurately monitor soil and plant conditions. With the help of sensors and GPS technologies, farmers can obtain data on humidity, nutrient levels, and other important characteristics (Raj *et al.*, 2022). This allows farmers to adapt their actions to specific conditions, ensuring optimal conditions for the growth and development of crops. For example, automated irrigation systems can adjust the water supply in real time depending on the current needs of plants, which reduces the risk of both waterlogging and drying out of the soil (Askaraliev *et al.*, 2024). In addition, precision farming systems help to optimise fertiliser application, which contributes not only to higher yields, but also to reducing the negative impact on the environment. The use of differentiated fertilisation technologies allows accurately calculating the required doses for each specific area of the field, which reduces the risk of overuse and leaching of nutrients into reservoirs. This not only improves product quality, but also reduces resource costs, which makes agricultural enterprises more competitive.

However, the introduction of precision farming systems requires initial investments and some knowledge on the part of farmers. Farmers must be prepared to learn and adapt to new technologies in order to take full advantage of all the benefits they offer. Nevertheless, despite the possible difficulties, the long-term benefits associated with increased productivity and reduced costs make these technologies attractive to agricultural enterprises. Precision farming systems are therefore an important step towards more efficient and sustainable agriculture. They open up new horizons for farmers, allowing them not only to increase yields, but also to take care of the environment. The introduction of these technologies contributes to the creation of more sustainable agricultural enterprises capable of successfully coping with modern challenges and ensuring food security. The introduction of artificial intelligence (AI) technologies in agriculture has become a real breakthrough, allowing agricultural enterprises to improve equipment diagnostics and monitoring (Shaikh *et al.*, 2022). These technologies help to identify malfunctions at an early stage and adjust the operation of machines, which significantly reduces the risk of breakdowns and increases the service life of equipment. Artificial intelligence is capable of processing large amounts of data and analysing them in real time, which makes it an indispensable tool in managing modern agricultural production.

One of the main applications of AI is predictive analytics, which allows predicting possible malfunctions based on the analysis of equipment condition data. Sensors installed on the machines collect information about vibration, temperature, and other parameters that may signal problems. Using machine learning algorithms, AI-based systems can quickly and accurately determine when maintenance needs to be performed, preventing more serious breakdowns and, as a result, downtime. In addition, AI can also optimise the operation of agricultural equipment by controlling its settings depending on specific operating conditions. For example, automatic systems can adjust the operating modes of tractors and combines depending on the soil condition or yield, which increases overall productivity and work efficiency. This allows farmers not only to reduce maintenance costs, but also to achieve better production results. Nevertheless, the introduction of AI technologies in agriculture requires certain investments and changes in the organisational structure of enterprises. Farmers should be ready to learn and adapt to new technologies, which can be a challenge for many of them. However, the long-term benefits associated with longer service life and lower repair costs make these technologies very attractive.

Artificial intelligence for diagnostics and monitoring is becoming an important tool in modern agriculture (Zelisko *et al.*, 2024). It not only increases the efficiency of the equipment, but also contributes to the sustainable development of agricultural enterprises. Based on AI, farmers can focus on more complex aspects of managing their business, confident in the reliability and performance of the equipment they use. Sustainable production is becoming one of the key principles of modern agriculture, and new models of agricultural machinery are playing an important role in this. The development of machines based on the use of environmentally friendly materials and reduced fuel consumption contributes to the implementation of the principles of sustainable development in agricultural enterprises. Such technologies not only help to reduce the negative impact on the environment, but also contribute to saving resources, which is beneficial for farmers in the long run.

Modern agricultural machinery manufacturers are actively researching and implementing eco-friendly materials such as recycled plastics and composites that reduce the overall carbon footprint of machine manufacturing (Cenci *et al.*, 2021). These innovations not only reduce the amount of waste, but also improve the operational characteristics of machinery. For example, lightweight materials reduce the weight of machines, which reduces fuel consumption and increases manoeuvrability, especially in difficult field conditions. In addition, new models of equipment are being developed with an emphasis on energy efficiency. Technologies aimed at reducing fuel consumption provide significant savings both at the level of individual farms and across the entire agricultural sector. This is especially true in the context of rising fuel prices and global efforts to reduce greenhouse gas emissions. The use of alternative energy sources such as solar panels and biofuels also contributes to more sustainable production and reduces dependence on traditional fossil resources.

Nevertheless, the transition to sustainable production and the introduction of new technologies requires farmers to make certain investments and changes in their usual approaches to farming (Melchior & Newig, 2021). Many farmers may face difficulties in mastering new technologies and integrating them into production processes. However, the long-term benefits associated with saving resources and improving environmental sustainability make these changes necessary and justified. Thus, sustainable production and resource conservation are becoming important aspects of modern agriculture. The development of new machinery using environmentally friendly materials and energy-efficient technologies opens up new opportunities for agricultural enterprises. These changes not only help to reduce the negative impact on the environment, but also ensure that farmers are more competitive in the face of growing demand for environmentally friendly products. Investments in sustainable production are becoming an important step towards creating a more responsible and efficient agricultural sector capable of meeting modern challenges.

DISCUSSION

The study found that the introduction of innovative technologies in the production of agricultural machinery has significantly increased the efficiency of agricultural enterprises. An analysis of the results showed that the use of precision farming systems and automated machines allowed farmers to significantly reduce the cost of resources such as water and fertilisers, while increasing yields. The introduction of new models of tractors and combines with autopilot function also helped to reduce labour costs and minimise the influence of the human factor on production processes. This problem was also investigated by Y. Liu *et al.* (2021), where the results confirmed that innovative technologies play a key role in increasing the productivity of agricultural enterprises, allowing them to optimise processes and reduce costs. The use of modern information systems, such as geoinformation technologies and the Internet of Things, allows farmers to obtain up-to-date information about the state of fields and plants, which contributes to more efficient resource management. In addition, automation of the processing and distribution of agricultural products reduces labour costs and minimises the risks associated with the human factor.

D.M.K.S. Hemathilake and D.M.C.C. Gunathilake (2022) also showed that modern agricultural technologies, including precision farming and the use of genetically modified organisms, significantly contribute to increasing crop yields. These technologies ensure more efficient use of resources such as water and fertilisers, which reduces costs and improves product quality. The introduction of new methods of tillage and pest management also contributes to crop resistance to diseases and adverse weather conditions, which ultimately leads to an increase in the total yield. The integration of innovative technologies into the agricultural sector requires not only significant investments, but also the willingness of agricultural enterprises to make changes in the production process (Bulgakov *et al.*, 2017). It is important that employees are trained in new working methods, which will allow them to effectively use new tools and systems. In addition, it is necessary to consider the possible risks associated with the introduction of technologies, such as dependence on high technologies and potential failures in the system, which underlines the importance of an integrated approach to the modernisation of agricultural enterprises. In addition, the results of the study demonstrated that electric and hybrid tractors, which are actively being introduced in countries such as Denmark and Germany, not only contributed to reducing carbon dioxide emissions, but also proved economically beneficial for farmers. Farmers using such technologies noted a reduction in operating costs and an improvement in the environmental situation in regions with a high degree of agricultural mechanisation. This indicates that eco-friendly technologies can become an important tool for achieving sustainable development of agricultural enterprises.

M. Beligoj *et al.* (2022) concluded that electric and hybrid tractors represent a significant step towards reducing the carbon footprint in the agricultural sector, as they significantly reduce greenhouse gas emissions compared to conventional diesel models. The use of such tractors helps to reduce air and soil pollution, which contributes to improving the quality of the environment and preserving ecosystems. In addition, the low noise level generated by electric and hybrid machines contributes to a more comfortable working environment for operators and minimises the negative impact on wildlife. The study by H. Dzwigo *et al.* (2021) revealed that the introduction of environmentally friendly technology, such as electric and hybrid tractors, can lead to significant cost savings in the long term due to lower fuel and maintenance costs. Although the initial investment may be high, the operating costs become significantly lower, which makes such technologies economically attractive for agricultural enterprises. In addition, the use of environmentally friendly technology can open access to subsidies and tax benefits, which further increases the economic efficiency of its implementation.

These results confirm the above study, as they demonstrate a clear correlation between the introduction of environmentally friendly technology and the improvement of both economic and environmental performance of agricultural enterprises. This shows that switching to electric and hybrid tractors not only helps to reduce their carbon footprint, but also allows farmers to optimise their costs, making them more competitive in the market. Thus, investments in sustainable technologies not only contribute to environmental protection, but also represent a reasonable step towards economic stability and growth of the agricultural sector. Diagnostic and monitoring systems based on artificial intelligence have also shown their effectiveness in increasing the service life of equipment and reducing the risk of breakdowns. Due to the timely detection of malfunctions and adjustment of equipment, farmers were able to minimise downtime and reduce maintenance costs. The use of AI in the agricultural sector has become an integral part of successful management, allowing farmers to focus on the more important aspects of doing business. Noteworthy is the study by N. Gupta *et al.* (2020), who also found that artificial intelligence plays a key role in the diagnosis of agricultural equipment, allowing for more accurate and rapid identification of possible malfunctions and their causes. Machine learning-based systems can analyse data on the operation of machinery in real time, identifying deviations from normal operation and predicting potential failures before they occur. This significantly reduces equipment downtime and increases its efficiency, which is especially important in conditions of seasonal agricultural production.

In turn, A. Abid *et al.* (2020) concluded that early detection of malfunctions in agricultural equipment brings significant benefits, including reduced repair and maintenance costs. By knowing about potential problems in advance, farmers can plan maintenance and replacement of parts, which minimises unexpected breakdowns and increases the reliability of machinery during critical periods such as harvest. In addition, stable operation of the equipment helps to increase the overall productivity of agricultural enterprises, allowing them to use resources more efficiently and efficiently (Bulgakov *et al.*, 2019). These data are consistent with the theses given in the previous section, as they emphasise the importance of using artificial intelligence to improve the reliability and efficiency of agricultural equipment. As already noted, the introduction of AI technologies not only optimises diagnostic processes, but also significantly reduces equipment downtime, which is critical for successful farming. Thus, the results confirm that early detection of malfunctions, provided by modern technologies, is a key factor in improving the overall productivity of agricultural enterprises and the sustainability of their operations.

However, despite significant achievements, there are still gaps in this area that require additional study. One of the key problems was the lack of integration of various technologies, which limited the ability of agricultural enterprises to maximise the use of all available resources. The impact of innovations on small and medium-sized agricultural enterprises also requires a more detailed analysis, as they often face difficulties in adapting new technologies due to limited financial resources. N. Khan *et al.* (2021) also conducted a study, the results of which confirmed that the integration of new technologies into the agricultural sector faces many challenges, including lack of funding and limited access to educational resources for farmers. Many agricultural enterprises, especially in developing countries, are experiencing difficulties in implementing modern technologies due to high initial costs and a lack of qualified personnel capable of effectively using new tools. These barriers can lead to an uneven distribution of innovations, which affects the overall competitiveness of the sector. D. Radicic and S. Petkovich (2023) also found that innovations can significantly change the work of small and medium-sized agricultural enterprises, providing them with access to modern technologies that were previously available only to large agricultural companies. However, small businesses may face difficulties in implementing innovative solutions due to limited financial resources and lack of experience in managing new technologies. Nevertheless, successful integration of innovations can increase their competitiveness, improve production efficiency, and ultimately lead to higher incomes, which makes supporting such initiatives an important task for the state and agricultural policy.

Comparing the data obtained during the research, it is possible to identify a clear trend that the successful integration of new technologies into the agricultural sector directly depends on the level of training and support of small and medium-sized agricultural enterprises. This confirms that without proper training and access to finance, many agricultural enterprises may not take advantage of the benefits offered by modern innovations. Therefore, to achieve sustainable development of the sector, it is necessary to create conditions conducive to the introduction of technology and professional development of employees, which will ultimately have a positive impact on the entire industry. In addition, there were many questions regarding the adaptation of old equipment to new requirements and technologies. This became a serious obstacle for many farmers who were unable to upgrade their machines and use advanced solutions. The need to introduce new approaches to maintenance and modernisation of machinery also highlights the importance of supporting and training farmers so that they can adapt to changing conditions and effectively use innovative technologies (Karaiev *et al.*, 2021).

M.A. Ibrahim and M. Johansson (2021) concluded that adapting outdated equipment to modern requirements is becoming a necessary step for agricultural enterprises seeking to remain competitive in a rapidly changing market. This practice includes upgrading existing machines and technologies, which reduces the cost of new equipment and extends the life of old assets. However, for successful adaptation, it is necessary to consider the technical characteristics and capabilities of the equipment, and meet new safety standards and environmental requirements. A. Fleming *et al.* (2021) revealed that in the context of technological change, improving the skills of farmers is becoming a key factor for the effective use of new technologies and equipment. Modern agricultural enterprises require knowledge in the fields of information technology, agronomy, and resource management from employees, which makes training and retraining vital. By investing in the education of their employees, farmers not only increase productivity, but also contribute to the sustainable development of the agricultural sector, which ultimately affects the economic stability of the entire industry.

When analysing the results of the study, it becomes clear that the successful adaptation of outdated equipment and advanced training of farmers are interrelated processes that contribute to the overall efficiency of agricultural enterprises. Modernisation of machinery requires not only financial investments, but also awareness of new technologies on the part of employees, which underlines the need for an integrated approach to the development of the agricultural sector. To achieve sustainable results, it is important to simultaneously invest in equipment upgrades and staff training, which will effectively respond to the challenges of modern agriculture and improve its competitiveness. Thus, the results of the study confirmed the importance of introducing innovative technologies in the production of agricultural machinery to improve the efficiency of agricultural enterprises. These technologies open up new opportunities for automation, optimisation and sustainable development of the agricultural sector. Nevertheless, to achieve maximum effect, it is necessary to continue studying emerging issues to ensure the harmonious and sustainable development of agriculture in the modern world.

CONCLUSIONS

The results of the study confirmed that innovative technologies in the production of agricultural machinery play a key role in improving the efficiency of agricultural enterprises. The introduction of precision farming systems, process automation, and the use of electrified machinery has led to significant reductions in resource costs such as water and fertilisers, and increased yields. This indicates that farmers can use their resources more efficiently, which is especially important in the context of global climate change and the growing need for food. The analysis showed that tractors and combines with autopilot function not only reduced labour costs, but also minimised the influence of the human factor, which increased the accuracy of operations. Automation of processes allowed optimising the allocation of resources and improving production performance. The use of modern technologies, such as artificial intelligence for diagnostics and monitoring, has provided farmers with the opportunity to detect malfunctions in a timely manner, which has helped to increase the service life of machinery and reduce maintenance costs. This, in turn, has improved overall productivity and reduced the risks associated with unforeseen breakdowns. However, despite the results achieved, the study also revealed gaps that require further investigation. For example, insufficient integration of various technologies limited their full use, especially in small and medium-sized agricultural enterprises facing financial difficulties. These enterprises often do not have the opportunity to invest in new technologies, which makes it difficult for them to compete in the market. Adapting old equipment to new requirements also remained an urgent problem, as many farmers use outdated machines, which hinders their development.

In general, the results obtained emphasise the need for further implementation and development of innovative technologies in agriculture. These changes not only contribute to increased productivity, but also create a sustainable and competitive agricultural sector that can effectively respond to modern challenges and market demands. To achieve these goals, it is important to continue studying emerging issues and support farmers in the process of implementing new solutions, which, in turn, will contribute to the creation of a more efficient and environmentally sustainable agricultural system. The limitation of the study is the lack of data on the long-term effects of the introduction of innovative technologies on the production processes and economic performance of agricultural enterprises. It is necessary to study the impact of innovative technologies on small and medium-sized agricultural enterprises to better understand how they can adapt to new conditions and effectively use available resources.

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Інноваційні технології у виробництві сільськогосподарської техніки для підвищення ефективності роботи агропідприємств

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Анотація. Дане дослідження спрямоване на аналіз інноваційних технологій у виробництві сільськогосподарської техніки та їх впливу на підвищення ефективності роботи агропідприємств. У дослідженні було застосовано різні наукові методи для всебічного аналізу впливу інноваційних технологій на ефективність агропідприємств у сфері сільськогосподарського машинобудування. Під час дослідження встановлено, що застосування інноваційних технологій у сільськогосподарському машинобудуванні значно підвищує ефективність роботи агропідприємств. Аналіз засвідчив, що використання систем точного землеробства, оснащених датчиками і GPS-технологіями, дає змогу оптимізувати розподіл ресурсів, таких як вода і добрива, що призводить до збільшення врожайності та зниження витрат. Автоматизація операцій за допомогою автопілотів на тракторах і комбайнах, як у моделях John Deere і Fendt, продемонструвала зниження трудовитрат і зменшення впливу людського фактора, що також сприяє підвищенню продуктивності. Електрифікація та гібридизація сільськогосподарської техніки, активно впроваджувана в таких країнах, як Данія та Німеччина, виявилися економічно вигідними, сприяючи зменшенню викидів вуглекислого газу та скороченню експлуатаційних витрат. Впровадження штучного інтелекту для моніторингу та діагностики обладнання дало змогу мінімізувати простій і збільшити термін служби техніки завдяки своєчасному виявленню несправностей. Загалом встановлено, що використання цих технологій сприяє сталому розвитку агропідприємств, оптимізації виробничих процесів і скороченню експлуатаційних витрат. Перехід на більш екологічне виробництво сільськогосподарської техніки сприяє поліпшенню екологічної обстановки в регіонах із високим ступенем механізації сільського господарства. Впровадження стійких технологій у машинобудуванні показало свою ефективність у скороченні ресурсоспоживання, що робить агропідприємства більш конкурентоспроможними на світовому ринку

Ключові слова: точне землеробство; автоматизація; GPS-технології; електрифікація; штучний інтелект

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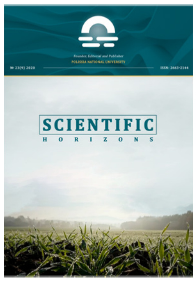

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Kazakhstan's meat market: Analysis of production, consumption, and export

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Abstract. This article aimed to analyse Kazakhstan's meat market's current state and development trends, focusing on production, consumption, and export, as well as identifying key issues and prospects for the industry. The study was based on an analysis of statistical data for 2014-2025 obtained from official sources, a comparative assessment of the efficiency of different farming structures (agroholdings, farms, and private subsidiary farms), and a regional analysis of production specialisation in the Almaty, Turkestan, and Karaganda regions of Kazakhstan. It was found that

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poultry production increased by 135% (to 340,000 tonnes in 2023), beef production by 18% (to 567,000 tonnes), whereas pork production declined by 45% due to epizootics. Kazakhstan was identified as the leading beef producer in Central Asia (2.5 times more than Uzbekistan) but lagged behind Kyrgyzstan in lamb production. The study revealed that agroholdings accounted for 55% of national production with a 18-22% profitability, whereas small farms demonstrated only 5-8% profitability due to manual labour and high production costs. Key issues identified included dependence on imported feed (70% of premixes), a deficit of modern processing infrastructure (only 35% of enterprises met international standards), and high interest rates on farm loans (14-18% per annum). The practical significance of this study lies in substantiating recommendations for reducing import dependence, developing vertically integrated clusters (e.g., KazMeatCluster), expanding state support for small farms, and investing in digital technologies. The findings may be used to develop strategies for the advancement of Kazakhstan's agricultural sector, enhance its competitiveness in international markets, and attract foreign investment

Keywords: agriculture; livestock farming; agricultural clusters; regional specialisation; economic efficiency

INTRODUCTION

The meat market is a strategic sector of Kazakhstan's economy, playing a key role in ensuring food security and shaping the country's export potential. Since 2010, there has been dynamic growth in the production of certain types of meat, particularly poultry and beef, yet the sector faces significant challenges. The main issues include low productivity levels in traditional livestock farming, dependence on imported feed, and limited modern processing infrastructure. As Kazakhstan integrates into global agri-food chains, there is a growing need to improve farming models, increase economic efficiency, and expand sales markets. Particular attention should be given to the competitiveness of Kazakh meat products in the global market. Considering global trends in changing dietary preferences and increasing quality and sustainability requirements, it is crucial to assess the country's position relative to other regional and international producers. An analysis of global trends suggests that competitive advantages can be achieved through the adoption of a cluster approach, the modernisation of agri-industrial enterprises, and enhanced state support (Pavliuk *et al.*, 2025).

Scientific literature highlights various aspects of Kazakhstan's meat sector development. Research by G.K. Dambaulova *et al.* (2022) includes a meta-analysis of the potential of Kazakh pork in the international market and identifies key issues limiting the industry's development, such as epizootic risks and insufficient state support. The economic assessment of the livestock sector and the prerequisites for establishing a meat hub to strengthen the country's export position have been examined by researchers such as G. Abdikerimova *et al.* (2024). M. Jia and L. Zhen (2021) analysed food production and consumption using the emergy method, identifying key patterns of Kazakhstan's food security and factors affecting the resource efficiency of livestock farming. A. Ibyzhanova *et al.* (2022) explored Kazakhstan's food export potential, identifying opportunities for expanding meat product exports to international markets while emphasising the need to improve logistics and comply with international standards. Similar conclusions have been drawn regarding the potential for meat exports to China, where Kazakhstan could occupy a significant niche if production quality and efficiency were enhanced (Ibyzhanova *et al.*, 2024).

A global analysis of meat consumption was conducted by C. Whitton *et al.* (2021), with findings indicating that growth rates in developed countries are slowing, highlighting the importance of expanding Kazakhstan's exports to emerging markets. A. Zielińska-Chmielewska *et al.* (2021) investigated the impact of the COVID-19 pandemic, which caused disruptions in maintaining continuity in food supply chains in the meat market, emphasising the need for producers to adapt to new logistical challenges. The correlation between the use of digital technologies and the volume of agricultural exports was identified by A.K. Wardhana and R.T. Ratnasari (2022), confirming the advisability of investing in the digitalisation of the agricultural sector. The analysed studies indicate the need for a comprehensive approach to the development of Kazakhstan's meat sector. The key areas for improvement include modernising production facilities, reducing dependence on imported feed, developing export channels, and implementing innovative production technologies (Melnyk *et al.*, 2024). State support plays a crucial role in shaping the industry's competitiveness; however, its accessibility to small and medium-sized producers remains limited (Mamenko *et al.*, 2024).

The aim of this study was to assess the key trends in the development of Kazakhstan's meat market, particularly in terms of production, consumption, and exports, as well as to identify the main factors limiting the sector's efficiency and potential opportunities for its further development.

MATERIALS AND METHODS

The study was based on a comprehensive analysis of meat production, consumption, and exports in Kazakhstan from 2014 to 2025, focusing on the Almaty, Turkestan, and Karaganda regions. The selection of this period was driven by significant structural changes in the agricultural sector that began after 2014, particularly due to the implementation of state programs for modernisation and the development of agro-industrial clusters. To assess the dynamics of changes in the meat sector, statistical, economic, regional, and comparative analyses were applied. The data sources included official reports from the Ministry of Agriculture of the Republic of Kazakhstan (2025), the Bureau of National Statistics (2025), and international organisations such as Food and Agriculture Organization (FAO) (2023), the Organisation for Economic Co-operation and Development (OECD) (2021), and the World Bank (2021).

Special attention was given to a comparative analysis with Central Asian countries: Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan. The comparison aspects included the dynamics of meat production and consumption, the level of infrastructure and logistics development, the efficiency of state support for the agricultural sector, and the specifics of meat product exports, particularly to neighboring and global markets. The selection of these countries was determined by their geographical proximity, similar natural and climatic conditions, and the structure of the agricultural sector. This approach made it possible to assess Kazakhstan's competitiveness in the regional meat market and to identify the strengths and weaknesses of the industry.

The business models of successful enterprises in Kazakhstan's meat sector were also studied separately. The analysis covered three main types of production structures: agroholdings, farms, and private producers. The selection of these models was justified by their significance in the national meat production structure. Agroholdings were chosen due to their dominant role in meat production and export, enabled by their scale and vertical integration. Farms were included to assess the average level of efficiency and the impact of cooperative models on profitability. Private producers were examined to understand the role of small-scale production in supplying the domestic market and their ability to adapt under limited resources and a lack of large-scale state support. The first group consisted of large vertically integrated agroholdings that carried out the full production cycle – from feed cultivation to processing and export of the finished product. Enterprises such as Aitas KZ (poultry production) and KazMeatCluster (beef) were considered, as they demonstrated high efficiency due to automation, quality control, and state support. The second group included medium-sized farms specialising in beef and lamb production for the domestic market. The experience of cooperative farms, such as the Almaty Meat Union and Turkestan Agro, was analysed, as they employed cooperative models to enhance profitability and facilitate market access. The third group comprised private producers with local specialisation operating in the traditional sheep and pig farming sectors. The study examined small farms in the Zhambyl region, focusing on lamb production, which ensured their competitiveness even in the absence of significant state support. Additionally, the effectiveness of state support programs for farmers and agro-enterprises in the meat industry was assessed, including subsidies for feed procurement, preferential loans, tax benefits, and investment grants.

The dynamics of meat production were analysed using the compound annual growth rate (CAGR) (1):

$$\mathrm{CAGR} = \frac{V_t}{V_0} - 1, \tag{1}$$

where V_t – is the production volume in the final year of the study period, V_0 – volume is the volume of production in the initial year, t – is the duration of the period in years.

This method made it possible to evaluate the growth rate of the meat sector and identify the most promising production areas. The economic analysis included an assessment of the profitability level of different types of meat using the formula (2):

$$\mathrm{R} = \frac{\mathrm{P}-\mathrm{C}}{\mathrm{C}} \times 100\%, \tag{2}$$

where P – is the average market price of the product, C – is the production cost.

The economic efficiency of three main forms of management – agroholdings, farms, and private households – was examined to evaluate their resilience to market fluctuations. The regional analysis included an assessment of the impact of climatic factors, feed availability, state support levels, and demographic characteristics on meat production specialisation in different regions of Kazakhstan. This was achieved by calculating the average production costs of meat in various regions and their impact on competitiveness. A comparative analysis between Kazakhstan and Central Asian countries was conducted based on the evaluation of beef, lamb, and poultry production volumes and export potential. The revealed comparative advantage (RCA) coefficient was used, calculated as follows (3):

$$\mathrm{RCA} = \frac{X_i}{M_i} / \frac{X_t}{M_t}, \tag{3}$$

where X_i – is the export volume of a specific type of meat from Kazakhstan, X_t – is the total meat export volume from the country, M_i – is the import volume of the respective type of meat, M_t – is the total meat import volume.

An RCA > 1 indicated Kazakhstan's competitive advantage in the production of a particular type of meat. For beef, this meant that the country had a greater export capacity relative to imports, signifying a strong position in the international market. For poultry, an RCA > 1 indicated high export competitiveness, particularly due to the development of modern poultry farms and state support programs. Conversely, for pork and lamb, an RCA > 1 showed that while Kazakhstan could meet domestic demand, the export of these types of meat remained limited due to epizootic risks and lower production levels compared to other regional countries. The analysis of state support examined the impact of subsidies, tax benefits, and infrastructure projects on industry development. The subsidy efficiency coefficient was calculated as follows (4):

$$\mathrm{ES} = \frac{\Delta \mathrm{Y}}{\mathrm{S}}, \tag{4}$$

where ΔY – represents the increase in production volumes, S – is the amount of state support received.

This calculation determined how effectively budgetary funds were used to stimulate meat farming development. Programs such as "Agrobusiness-2025" (subsidies, loans) (World Bank, 2021), "Digital AIC" (IoT solutions) (Ministry of Agriculture of the Republic of Kazakhstan, 2025), and clusters (KazMeatCluster) were analysed. Data processing included assessing the impact of budgetary funds on production growth, regional dynamics, and the challenges faced by small farms in accessing support. The level of dependence on imported feed and its impact on meat production costs was also studied. The share of imported feed in total feed expenses was calculated using the formula (5):

$$\mathrm{CI} = \frac{\mathrm{I_c}}{\mathrm{C_t}}, \tag{5}$$

where I_c – is the volume of imported feed, C_t – is the total feed expenditure.

The applied methods, including the use of software tools such as SPSS (for descriptive statistics and correlation analysis), Stata (for econometric modeling of production dynamics), and Python (with Pandas and NumPy libraries for automating RCA, ES, and CAGR index calculations), enabled an objective assessment of Kazakhstan's meat sector development. Initial data processing was performed in Excel, ensuring structured information management. These tools allowed for a comprehensive consideration of economic efficiency, regional characteristics, and state support mechanisms.

RESULTS

Meat production dynamics in Kazakhstan. Between 2014 and 2025, meat production in Kazakhstan underwent significant changes due to structural reforms in the agricultural sector, investments, and external risks. According to the Ministry of Agriculture of the Republic of Kazakhstan (2025), beef production increased by 18% (from 480,000 tonnes in 2013 to 567,000 tonnes in 2023), driven by expanded export agreements with China and the development of clusters in the Turkistan region. Mutton production remained stable, with an average annual output of 210,000-230,000 tonnes. However, its share in the overall balance declined from 25% to 20% due to growing competition from poultry farming (Bureau of National Statistics, 2025). The most dynamic segment is poultry production, which increased by 135% (from 145,000 tonnes in 2013 to 340,000 tonnes in 2023). This growth is linked to the establishment of large-scale poultry farms with closed production cycles, such as "Astana Poultry" and "Food-Master", which received funding under the "Agrobusiness-2025" programme (World Bank, 2021). In contrast, pork production declined by 45% (from 95,000 tonnes to 52,000 tonnes) due to recurrent outbreaks of African swine fever between 2019 and 2021, leading to the closure of 60% of small pig farms (Committee for Veterinary Control and Supervision of the Ministry of Agriculture of the Republic of Kazakhstan, 2023).

Compared to other Central Asian countries, Kazakhstan leads in beef production, surpassing Uzbekistan by 2.5 times (227,000 tonnes) and Kyrgyzstan by 4 times (140,000 tonnes) (Food and Agriculture Organization, 2023). In the poultry sector, Kazakhstan also outperforms neighbouring states: Uzbekistan produces 290,000 tonnes of chicken, while Turkmenistan produces 80,000 tonnes (Organisation for Economic Co-operation and Development, 2021). However, Kazakhstan lags behind Kyrgyzstan in mutton production, where this type of meat accounts for 35% of the agro-balance (Central Asia Regional Economic Cooperation, n.d.). Figure 1 illustrates the dynamics of changes in the production of key meat types in Kazakhstan from 2014 to 2025.

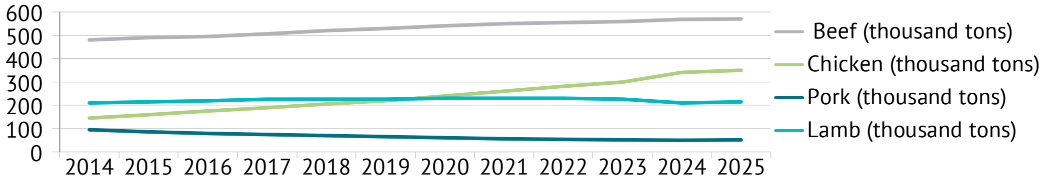

***Figure 1**. Meat production dynamics (2014-2025)*

***Source:** compiled by the authors based on Ministry of Agriculture of the Republic of Kazakhstan (2025) and Bureau of National Statistics (2025)*

A key trend in recent years is the increasing export orientation of the industry. Following an agreement with China on beef supplies (2022), exports of this type of meat increased by 40% (to 90,000 tonnes in 2023), while domestic consumption remained stable (Ministry of Economy of the Republic of Kazakhstan, 2025). An analysis of Revealed Comparative Advantage (RCA) confirms Kazakhstan's competitiveness in beef production (Table 1).

Table 1. RCA comparison for meat in Central Asian countries (2023)

Country	Beef (RCA)	Mutton (RCA)
Kazakhstan	2.1	0.7
Uzbekistan	0.9	0.5
Kyrgyzstan	1.2	1.8
Tajikistan	0.4	1.1
Turkmenistan	0.6	0.9

Source: *compiled by the authors*

RCA calculations show that Kazakhstan has a comparative advantage in beef production, while its competitiveness in mutton production is lower than in other Central Asian countries. At the same time, a shortage of domestic feed (70% of premixes are imported) and droughts in 2022 limit profitability, increasing dependence on external markets. Thus, the dynamics of meat production in Kazakhstan between 2014 and 2025 reflect structural shifts, including an increase in beef and poultry production, a decline in pork production, stable mutton production, and a shift towards export orientation. However, the industry remains dependent on imported feed and climatic risks.

Geographical structure and regional specialisation of meat production in Kazakhstan. Meat production in Kazakhstan is characterised by significant regional differentiation due to climatic conditions, feed resources, and historical specialisation. According to Bureau of National Statistics (2025), Almaty, Turkistan, and Karaganda regions account for over 60% of the national meat output. Almaty region contributes the most, producing 28% of the country's beef and 35% of its mutton, mainly due to developed pasture-based livestock farming. Turkistan region specialises in cattle breeding, supported by state programmes for integrated clusters, which account for 22% of the country's beef production. Regions with the highest productivity include Karaganda, which accounts for 25% of poultry production due to modern poultry farms such as the "Karaganda Poultry Complex". Northern regions (e.g., Akmola) show increasing beef production (+12% in 2022-2023) due to investments in artificial insemination and feeding technologies (Organisation for Economic Co-operation and Development, 2021). Meanwhile, southern regions (Zhambyl, Turkistan) maintain traditional sheep farming, where manual labour accounts for 60%, limiting production scale (Food and Agriculture Organization, 2023).

Meat production in Kazakhstan is shaped by natural, economic, and social factors that vary significantly by region. Climatic conditions, infrastructure development, state support, and demographic factors determine the specialisation and efficiency of the sector. For instance, droughts in the south limit feed resources, while northern regions benefit from logistical advantages for exports (Table 2).

Table 2. Factors of regional meat production dynamics

Factor	Impact on Production
Climatic conditions	Droughts in Turkistan and Zhambyl (2022-2023) reduced forage crop yields by 25%, increasing beef production costs.
Infrastructure	Northern regions have better logistics for exports via border checkpoints with Russia; the south lacks cold storage facilities
Economic support	Turkistan and Karaganda receive 40% of feed subsidies, stimulating productivity growth
Demographics	A high rural population in Almaty region (45%) provides a cheap labour force for small farms

Source: *compiled by the authors based on World Bank (2021), Central Asia Regional Economic Cooperation (n.d.) and Ministry of Economy of the Republic of Kazakhstan (2025)*

The regional distribution of meat production in Kazakhstan reflects the interaction of natural, economic, and institutional factors. Future growth will require investments in irrigation systems in the south, expanding processing facilities in northern regions, and integrating small-scale producers into value chains.

Structure of production enterprises and efficiency of farming models in Kazakhstan's meat sector. Meat production in Kazakhstan is shaped by three main types of farms: agroholdings, private farms, and household farms. According to the Ministry of Agriculture of Kazakhstan (2025), agroholdings account for 55% of national meat production, private farms for 30%, and household farms for 15%. This trend is driven by increased investment in large integrated clusters combining livestock breeding, processing, and logistics. Agroholdings (e.g., "Astana-Foods", "KazAgro") demonstrate the highest efficiency due to production scale, modern feeding technologies, and automation. Their average profitability is 18-22%, with beef production costs of 800-900 tenge per kg. In contrast, private farms have limited productivity due to financial constraints: only 20% receive loans at 10% annual interest, while household farms face rates of up to 15% (Bureau of National Statistics, 2025). Household farms dominate mutton production (40% of national output) and serve local markets. Their efficiency is limited by manual labour, high costs (1,100-1,300 tenge/kg), and lack of processing facilities (Food and Agriculture Organization, 2023). According to Organisation for Economic Co-operation and Development (2021), labour productivity in household farms is three times lower than in agroholdings (Table 3).

Table 3*. Efficiency of different farming models (2024)*

Indicator	Agroholdings	Private Farms	Household Farms
Profitability (%)	18-22	10–14	5–8
Feed costs (%)	45	60	70
Export share (%)	65	20	0

Source: *compiled by the authors based on Bureau of National Statistics (2025)*

The dominance of agroholdings highlights their role in Kazakhstan's export potential. However, sustainable industry growth requires support for small-scale producers through cooperatives and lower credit rates. Innovative approaches to production organisation, such as vertical integration, energy efficiency, and small farm cooperation, play a key role in Kazakhstan's meat industry. These models help reduce production costs, increase profitability, and integrate into global supply chains. The most notable examples include large clusters, high-tech poultry farms, and farmer cooperatives that demonstrate adaptability to market challenges (Table 4).

Table 4*. Successful business models in Kazakhstan's meat industry*

Company/Project	Region	Business model	Key advantages
KazMeatCluster	Turkistan Region	Vertically integrated cluster	25% cost reduction due to in-house feed bases and automated feeding.
Aitas KZ	Karaganda Region	Full-cycle poultry farm	80% of poultry meat exported to China; 24% profitability.
Cooperative "Almaty Meat Union"	Almaty Region	Small farmer cooperative	30% income growth through collective use of infrastructure.

Source: *compiled by the authors based on Ministry of Economy of the Republic of Kazakhstan (2025)*

The structure of production enterprises in Kazakhstan's meat sector exhibits significant differentiation in efficiency and scale. Agroholdings, controlling over half of national production, dominate due to technological modernisation, vertical integration, and access to financing. Despite limited resources, smallholder and private farms remain critical for supplying local markets and maintaining social stability in rural regions. Successful business models, such as full-cycle production clusters or farmer cooperatives, highlight the potential of innovation and collective solutions in overcoming structural challenges. However, ensuring sustainable development requires systematic support for small producers through subsidies, affordable loans, and infrastructure projects. These measures will help balance economic efficiency with social and environmental goals.

Economic efficiency of meat production: Costs, profitability, and influencing factors. Meat production in Kazakhstan is characterised by significant fluctuations in cost and profitability due to the diversity of products, farm sizes, and external economic factors. The highest costs are observed in pork production due to epizootic risks, while poultry is the most economically efficient thanks to intensive technologies and scalability. Feed costs remain the primary expenditure component, particularly for livestock with long growing cycles, highlighting dependence on imported resources and vulnerability to climate change. Large agroholdings dominate the sector due to high profitability achieved through automation, export operations, and government subsidies. In contrast, medium-sized farms face restrictions due to limited access to affordable credit and a lack of infrastructure for deep processing. Small producers focusing on local markets demonstrate the lowest efficiency due to outdated methods and a high share of manual labour (Table 5).

Table 5*. Effectiveness of government support for different types of farms*

Type of farm	Production increase (ΔY, thousand tonnes)	Subsidies (S, billion tenge)	Efficiency score (ES = ΔY/S)
Large agroholdings	8	10	0.8
Medium-sized farms	2	1.5	1.3
Small producers	0.5	0	-

Source: *compiled by the authors*

The economic stability of the sector is largely dependent on external factors. Veterinary costs have risen due to outbreaks of infectious diseases, particularly impacting pig farming. Rising energy prices and a lack of cold storage infrastructure in southern regions have further increased the burden on producers. While government support programmes help reduce costs for large enterprises, their inaccessibility to small farms exacerbates competitive imbalances (Table 6).

***Table 6**. Economic indicators of meat production (2023-2024)*

Indicator	Beef	Mutton	Poultry	Pork
Cost (tenge/kg)	900-1,100	800-1,000	400-500	1,300-1,500
Profitability (%)	8-12	10-15	18-22	3-5
Feed Cost Share (%)	60-70	55-65	45-50	50-60

***Source:** compiled by the authors based on Ministry of Agriculture of the Republic of Kazakhstan (2025)*

Thus, the main drivers for improving economic performance are reducing dependence on imported feed, investing in processing and logistics infrastructure, and expanding support mechanisms for small and medium-sized farms. The integration of innovative solutions and the development of export channels can ensure sustainable sector growth amid global challenges.

Key challenges and constraints in industry development. Kazakhstan's meat industry faces several systemic challenges limiting its competitiveness in domestic and international markets. One of the main obstacles is the lack of modern processing infrastructure and logistics capacities. According to World Bank (2021), only 35% of meat processing enterprises in the country meet international quality standards, while 60% of equipment is outdated. The absence of cold storage facilities in southern regions forces producers to lower raw material prices to avoid spoilage, reducing profit margins. Feed shortages remain a critical issue affecting livestock productivity. According to the Ministry of Agriculture of the Republic of Kazakhstan (2025), 70% of premixes and vitamin supplements are imported, while droughts in 2022-2023 reduced forage crop yields by 25%. This has increased beef production costs by 18-20% and slowed average daily weight gains in livestock to 600 g compared to 1,200 g in the EU.

Limited financing complicates industry modernisation. Small and medium-sized farms face high loan interest rates (14-18% annually) and difficulties in securing collateral. According to the Ministry of Economy of the Republic of Kazakhstan (2025), only 22% of agricultural producers receive development loans, whereas in the EU, this figure reaches 65%. The lack of long-term investment programmes restricts technology purchases for productivity improvements. Low productivity in traditional livestock farming significantly impacts competitiveness. For instance, average milk yields are 3,200 litres per year compared to 8,500 litres per year in the EU, while meat yield per animal is 15-20% lower than global standards (Food and Agriculture Organization, 2023). This is due to the prevalence of extensive feeding methods, a lack of breeding programmes, and limited veterinary services in remote areas.

Government support for Kazakhstan's meat industry. State support for the meat industry in Kazakhstan is implemented through funding programmes, including "Agrobusiness-2025" and "Digital Agro-Industrial Complex". According to the Ministry of Agriculture of the Republic of Kazakhstan (2025), over 120 billion tenge was allocated for sector subsidies in 2023, with 65% directed towards feed supply and farm modernisation. The effectiveness of these programmes is reflected in the 12% increase in beef production and 18% increase in poultry production in 2022-2023 (World Bank, 2021). However, only 30% of farmers received direct funding, highlighting unequal access to resources between large agroholdings and small farms (Organisation for Economic Co-operation and Development, 2021).

Subsidies and grants significantly influence industry development, particularly in regions with high production concentrations. For example, in Turkistan Region, feed subsidies reduced beef production costs by 15-20%, while in Karaganda Region, equipment purchase grants increased poultry farm productivity by 25% (Ministry of Economy of the Republic of Kazakhstan, 2025). However, small farms remain overlooked: only 10% receive state support due to documentation complexities and a lack of collateral. Government policy perspectives focus on diversifying support mechanisms. In 2024, pilot projects were introduced for livestock insurance and interest rate compensation on farmer loans. The expansion of the "Digital Agro-Industrial Complex" programme, which includes IoT systems for monitoring feeding and animal health, is planned. Forecasts suggest that this could increase the profitability of small farms by 8-10% by 2025. A key challenge remains integrating remote regions into state programmes, as only 20% of farms have internet access to use digital tools. Government support for Kazakhstan's meat industry contributes to production growth and modernisation. However, its effectiveness depends on financing accessibility for small farms, diversifying support mechanisms, and integrating digital technologies, which remain critical challenges for further development.

DISCUSSION

The results of the study on Kazakhstan's meat market aligned with global trends in livestock development and meat product exports. The experience of meat product exports in Ethiopia demonstrated that the effectiveness of foreign trade depended on infrastructure development, quality control, and access to international markets (Melkamworkassefa, 2024). Similar challenges were observed in Kazakhstan, where infrastructure constraints and insufficient international certification of products created barriers to expanding exports. The prospects for the development of cultivated meat raised concerns in countries with advanced livestock industries. Research by B.D. da Silva and C.A. Conte-Junior (2024) indicated that states economically dependent on traditional livestock farming might face risks of declining demand for natural meat. This confirmed the necessity for Kazakhstan's meat sector to diversify and adapt to new consumer trends. Pork production in the European Union transformed due to regulatory changes and the introduction of environmental standards (Mateos *et al*., 2024). A similar approach could be relevant for Kazakhstan, as the country also aimed to implement more sustainable agricultural models.

Green financing was becoming a key tool for improving product quality and its export potential. China's experience showed that financial mechanisms stimulating eco-friendly production contributed to better meat product quality and international competitiveness (Ma *et al*., 2024). This confirmed the feasibility of introducing similar approaches in Kazakhstan. Trade models used in China's seafood sector highlighted the importance of a strategic export approach, which involved optimising production processes and actively utilising government support (N'Souvi *et al*., 2024). Considering these factors could enhance Kazakhstan's export strategy in the meat sector. Protectionist policies and the introduction of new trade barriers had a negative impact on global trade. K. Handley *et al.* (2024) analysed the consequences of increased import tariffs in the United States. For Kazakhstan, this underscored the need to expand trade partnerships and seek new export opportunities to reduce dependence on a limited number of markets. Macroeconomic factors also significantly influenced the dynamics of the meat market. A study of the U.S. red meat market showed that changes in production, demand, and pricing policies shaped long-term economic trends that could also affect other countries (Melo *et al*., 2021). Kazakhstan needed to consider these aspects when formulating its meat sector development strategy.

One crucial factor affecting the efficiency of meat production was greenhouse gas emissions and measures to reduce them. Implementing technologies aimed at reducing the carbon footprint was one of the key directions for global agricultural development (Skribbe *et al*., 2024). Such mechanisms could be beneficial for Kazakhstan, given its high import dependence on feed and significant energy consumption in cattle farming, which made the industry vulnerable to global climate policy regulations. Kazakhstan's export activities faced challenges similar to those in Ethiopia, where key obstacles included logistical constraints, high transportation costs, and inadequate infrastructure for international trade (Wakaso *et al*., 2025). Similar challenges in Kazakhstan required the implementation of specialised programs to improve logistics and expand international product certification. Turkey's experience in exporting water resources, particularly crustaceans, demonstrated that expanding production required an effective marketing strategy and adaptation to international market standards (Mazlum *et al*., 2025). This approach could be applied in Kazakhstan to stimulate meat product exports to new regional markets.

An analysis of export trade dynamics in China's aquaculture sector highlighted the importance of diversifying sales markets (Kong *et al*., 2025). This insight could be useful for Kazakhstan, as dependence on a limited number of trade partners posed risks to the stability of meat exports. Environmental aspects of meat production remained one of the industry's key challenges, as high resource consumption and significant CO_2 emissions required technological process improvements (Iakubchak *et al*., 2024). An analysis of the production chain in Italy's meat industry demonstrated the effectiveness of measures aimed at waste reduction and resource optimisation (Ferronato *et al*., 2021). Applying this experience could help reduce the environmental impact of Kazakhstan's meat sector. Changes in demand structure and the influence of alternative protein sources also affected the meat market (Dossybayev *et al*., 2024). An analysis of educational and labor changes in Vietnam showed that workforce adaptation to new economic conditions was critical for maintaining the efficiency of the agricultural sector (Hang, 2021). A similar approach could be implemented in Kazakhstan to prepare specialists for the introduction of innovative livestock technologies.

Research on the impact of plant-based alternatives on the meat market indicated the potential decline in demand for traditional meat products due to the growing interest in eco-friendly substitutes (Lusk *et al*., 2022) This trend could affect Kazakhstan's meat market, requiring strategic planning to mitigate the risks of decreasing domestic consumption. Changing consumer attitudes toward meat products influenced market dynamics. A study conducted in Brazil demonstrated that public perceptions of meat production's environmental impact had significantly transformed, creating challenges for traditional producers (Hötzel & Vandresen, 2022). Similar trends could emerge in Kazakhstan, as the global shift toward sustainable production models required adaptation and the implementation of environmentally oriented technologies.

Meat product safety remained a critical factor for export potential (Uazhanova *et al.*, 2024). An analysis of food incidents related to red meat confirmed that the effectiveness of food safety control systems directly influenced consumer demand and trust in meat products (Warmate & Onarinde, 2023). For Kazakhstan, this emphasised the need to strengthen safety standards and improve quality control systems to expand access to international markets.

Export diversification remained an essential factor for the stability of the agri-food sector. A study of Côte d'Ivoire's agri-food industry confirmed that flexibility in foreign trade policy and adaptation to demand changes contributed to increased industry competitiveness (Coulibaly *et al.*, 2021). Kazakhstan also needed to consider these aspects and expand meat product sales markets. The experience of Gulf countries showed that diversifying export products could reduce economic vulnerability to fluctuations in global markets (Fatima *et al.*, 2021). This reinforced the importance of seeking new export opportunities for Kazakhstan's meat products, particularly through the development of niche segments such as halal products. The production of halal meat in Kazakhstan had significant export potential, especially considering Pakistan's experience, where proper certification and adaptation to Islamic market requirements contributed to expanded export opportunities (Magsi *et al.*, 2020). Considering these aspects could strengthen Kazakhstan's position in international halal markets. An analysis of Indonesia's policy on nickel ore exports and battery industry development showed that strategic export regulation and domestic infrastructure development could significantly enhance sector competitiveness (Pandyaswargo *et al.*, 2021). This confirmed the feasibility of applying a similar approach in Kazakhstan's meat sector, particularly through supporting domestic processing and expanding opportunities for producers.

Overall, the study results confirmed the necessity of a comprehensive approach to Kazakhstan's meat sector development, which included strengthening safety standards, expanding export opportunities, adapting to changes in consumer preferences, and integrating environmentally sustainable practices.

CONCLUSIONS

The study of Kazakhstan's meat market over the period 2013-2023 revealed significant structural changes. Poultry production increased by 135% (from 145,000 tons to 340,000 tons) due to investments in large poultry farms (e.g., "Astana Poultry") and government modernisation programs ("Agrobusiness-2025"). Beef production grew by 18% (from 480,000 tons to 567,000 tons) thanks to export agreements with China signed in 2022. In contrast, pork production declined by 45% (from 95,000 tons to 52,000 tons) due to African swine fever outbreaks in 2019-2021. Kazakhstan became the leading beef producer in Central Asia, surpassing Uzbekistan's output by 2.5 times (227,000 tons) and Kyrgyzstan's by four times (140,000 tons). However, it lagged behind Kyrgyzstan in lamb production, where lamb accounted for 35% of the meat market. The economic efficiency of the sector varied by business model. Large agro-holdings like "KazMeatCluster" demonstrated profitability of 18-22% due to economies of scale, automation, and exports. In contrast, small farms had profitability of only 5-8% due to manual labor, high production costs, and limited infrastructure access. A major issue remained dependence on imported feed: 70% of premixes were imported, making the industry vulnerable to global price fluctuations. A lack of modern infrastructure, particularly refrigerated warehouses in the southern regions (Turkistan, Zhambyl), restricted export potential, forcing producers to lower raw material prices.

Government support, such as feed subsidies under "Agrobusiness-2025", improved the situation but covered only 30% of farmers. For instance, in the Karaganda region, subsidies boosted poultry farm productivity by 25%, but small farms remained underserved due to complex documentation requirements. Future development required reducing import dependence by expanding domestic feed production, easing small farms' access to subsidies and loans (5-7% annually), modernising infrastructure (cold storage, IoT systems), and expanding exports to the EU after obtaining quality certifications. The study's limitations are related to the lack of data on small farms due to the lack of centralised accounting, as well as the impact of external factors such as the droughts of 2022-2023 and energy price fluctuations. In the future, it is worth analysing the effectiveness of vertically integrated clusters (e.g., "KazMeatCluster"), investigating the impact of digitalisation on small farms, and assessing the environmental impact of livestock intensification. The findings emphasise that Kazakhstan has the potential to become a key meat exporter in Central Asia, but this requires overcoming structural imbalances, strengthening public-private partnerships, and investing in innovation. Success will depend on integrating small-scale producers into value chains, developing their own feed bases, and adapting to global challenges such as climate change and competition.

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None.

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Ринок м'яса в Казахстані: Аналіз виробництва, споживання та експорту

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Анотація. Метою статті є аналіз поточного стану та тенденцій розвитку ринку м'яса в Казахстані, з акцентом на виробництві, споживанні та експорті, а також визначення ключових проблем і перспектив галузі. Дослідження ґрунтується на аналізі статистичних даних за 2014-2025 роки, отриманих з офіційних джерел, порівняльній оцінці ефективності різних сільськогосподарських структур (агрохолдингів, фермерських та особистих селянських господарств), а також регіональному аналізі спеціалізації виробництва в Алматинській, Туркестанській та Карагандинській областях Казахстану. Було виявлено, що виробництво м'яса птиці зросло на 135 % (до 340,000 тонн у 2023 році), виробництво яловичини – на 18 % (до 567,000 тонн), тоді як виробництво свинини скоротилося на 45 % через епізоотії. Казахстан був визнаний провідним виробником яловичини в Центральній Азії (в 2,5 рази більше, ніж Узбекистан), але відстає від Киргизстану у виробництві баранини. Дослідження показало, що на агрохолдинги припадає 55 % національного виробництва з рентабельністю 18-22 %, тоді як малі фермерські господарства демонструють лише 5-8 % рентабельності через ручну працю та високі виробничі витрати. Серед ключових проблем – залежність від імпортних кормів (70 % преміксів), дефіцит сучасної переробної інфраструктури (лише 35 % підприємств відповідають міжнародним стандартам) та високі відсоткові ставки за кредитами для фермерських господарств (14-18 % річних). Практичне значення дослідження полягає в обґрунтуванні рекомендацій щодо зниження імпортозалежності, розвитку вертикально-інтегрованих кластерів (наприклад, KazMeatCluster), розширення державної підтримки малих фермерських господарств та інвестування в цифрові технології. Результати дослідження можуть бути використані для розробки стратегій розвитку аграрного сектору Казахстану, підвищення його конкурентоспроможності на міжнародних ринках та залучення іноземних інвестицій

Ключові слова: сільське господарство; тваринництво; аграрні кластери; регіональна спеціалізація; економічна ефективність

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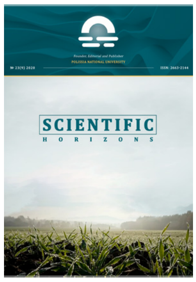

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Assessing the efficiency of management information systems in agrarian companies

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Abstract. The purpose of this study was to determine the effectiveness of implementing information systems in agricultural enterprises and their impact on optimising management processes and productivity. The main objectives were to analyse how digital technologies affect decision-making, reduce costs, increase productivity, and identify barriers to their integration. The methodology included an analysis of scientific publications, a political, economic, social, technological analysis, a comparative assessment of key performance indicators before and after the implementation of the

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systems, as well as a case study based on the experience of the Kazakh company "Atameken-Agro". In particular, the analysis of publications allowed to identify trends and problems of digitalisation in the agricultural sector. The political, economic, social, technological analysis helped to assess the political, economic, social, and technological factors that influence the implementation of information systems. The results of the study confirmed that the implementation of information systems has a significant positive impact on the productivity and management of enterprises. In particular, at Atameken-Agro, digitalisation has reduced grain losses by 63%, reduced administrative costs by 15%, and increased the transparency and accuracy of management decisions. The AgroStream system has provided centralised access to real-time data, which has increased the efficiency of monitoring and planning. In addition, the introduction of automated processes has contributed to the optimisation of resource use and increased environmental responsibility. The study's findings indicated that successful integration of information systems in agriculture requires a comprehensive approach, including adaptation to local conditions, government support, infrastructure expansion, and staff training

Keywords: digital transformation; technological infrastructure; agricultural enterprises; process optimisation; resource utilisation

INTRODUCTION

Numerous issues confronting the modern agriculture sector include resource scarcity, market volatility, climate change, and heightened competitiveness. In these circumstances, process optimisation, productivity gains, cost reduction, and the sustainable growth of businesses all depend heavily on the deployment and efficient use of management information systems. Even though these systems have a lot of potential, not enough research has been done on how beneficial they are in many agricultural businesses. Adapting these technologies to business objectives, assessing the effect on financial outcomes, and determining obstacles to their adoption are all crucial concerns. Because it seeks to evaluate the efficacy of management information systems, pinpoint the variables influencing their operation, and formulate suggestions for enhancing their utilisation, this study is pertinent. The results obtained will help to increase the competitiveness of the agricultural sector and its resilience to modern challenges.

Insufficient use of management information systems in agricultural enterprises limits the efficiency of processes and decision-making (Zelisko *et al.*, 2024). M. Melzer *et al.* (2023) studied this topic, determining that the most popular functions of the systems are quality assurance, inventory and financial management. The results of the study showed that functions that automate processes and ensure compliance with legal requirements are most in demand. At the same time, there are gaps in the study of the impact of these systems on the long-term economic efficiency of enterprises, which requires further research. Among the key challenges of the agricultural sector are improving management efficiency and implementing innovative technologies (García-Juárez *et al.*, 2024). Z.Y. Abdullahi *et al.* (2022) studied the use of IoT in precision agriculture, demonstrating its positive impact on monitoring, production optimisation, and environmental sustainability. At the same time, gaps have been identified, including high implementation costs and insufficient technical training of farmers, which requires the development of affordable solutions for small farms.

Agricultural management faces challenges in adopting information systems (AIS) to boost productivity. A.B. Santoso *et al.* (2023) studied AIS in Indonesia's rice production, highlighting its role in optimising farming and ensuring sustainability. Barriers include poor rural infrastructure, limited farmer knowledge, and low adoption rates, requiring strategies to improve accessibility, education, and infrastructure. The analysis of digitalisation in agriculture has revealed that the adoption of farm management information systems (FMIS) plays a vital role in improving operational efficiency and decision-making processes. C. Giua *et al.* (2021) focused on farm-level MIS adoption and highlighted the drivers and barriers within this context. Their findings emphasised that factors such as the size of farms, farmers' education levels, and the usability of the systems significantly impact the adoption process. However, challenges such as poor interoperability, insufficient technical skills, and limited technological infrastructure remain unresolved. These gaps indicate the need for further studies to enhance system compatibility and foster better user engagement.

Insufficient integration of land management information systems limits the efficiency of agriculture. N. Potapova and D. Lavrynchuk (2019) emphasised the importance of geoinformation technologies and automation for making informed decisions in land management. The main gaps remain low informatisation of enterprises and poor integration of these systems into practical activities, which requires further research. The use of information management systems in the agricultural sector faces challenges of effective data management and energy conservation. C. Li (2024) investigated the use of 5G technology in building agricultural product and information management models, in particular in terms of load balancing and energy efficiency. The results emphasise that the use of 5G improves data access and processing and reduces energy consumption. However, the study identified gaps, including insufficient consideration of system scalability and integration of multi-level management, which requires further development to ensure full implementation.

Integration of information systems in agriculture is a relevant area of research. V. Vakulenko and L. Xiaowei (2021) analysed the experience of implementing integrated systems in agricultural enterprises, which provides a reduction in costs by 7-30% and an increase in labor productivity by up to 50%. At the same time, insufficient attention has been paid to the adaptation of such systems for small farms. The problem of insufficient integration of digital technologies in agriculture remains relevant. R. Gabdualiyeva *et al.* (2024) examined the digitalisation of the agricultural sector in Kazakhstan, emphasising its benefits, including the use of global positioning system (GPS), drones, and artificial intelligence to improve productivity and quality. They identified gaps, such as low digital literacy, lack of infrastructure and funding, that need to be addressed for effective technology adoption.

The purpose of this study was to determine the effectiveness of information systems implementation in agricultural enterprises and their impact on optimisation of management processes and productivity.

MATERIALS AND METHODS

The study used a comprehensive approach, which included an analysis of scientific publications, conducting a political, economic, social, technological (PEST) analysis, compiling a comparative table of efficiency before and after the implementation of information systems, as well as a case study based on the experience of the Kazakh company "Atameken-Agro" (Agricultural holding JSC "Atameken-Agro"..., 2023). The analysis of publications became the basis for identifying the main trends, advantages and problems of implementing information systems in agriculture. Particular attention was paid to the analysis of literature, with a focus on sources addressing the optimisation of processes, increasing productivity, reducing costs and introducing innovative technologies in the industry (Beese *et al.,* 2023; Sharma, 2023; Chesang', 2024). Based on the information collected, a PEST analysis was conducted, which allowed assessing the political, economic, social and technological factors influencing the implementation of information systems in agricultural enterprises. For comparative analysis, a table was created that reflects the key performance indicators of enterprises before and after the implementation of information systems. In particular, aspects related to the accuracy of decision-making, costs of management and operational processes, labor productivity, data transparency and scalability of operations were considered (Mokhtar *et al.,* 2022; Ordoñez *et al.,* 2024).

Particular attention was paid to the case study of the company "Atameken-Agro", which is one of the leading agricultural enterprises in Kazakhstan. Within the, interviews with management, framework of this case, official company reports, as well as data on the implementation of the AgroStream system adapted to the specifics of the Kazakhstani market were analysed (Features of digitalization..., 2018; Lysenko, 2019; Digitalization of the..., 2023). Based on the data obtained, recommendations were developed for further improvement of the company's information systems, including the integration of modules based on artificial intelligence, the use of drones and satellite images for field monitoring, as well as the implementation of blockchain-based systems to increase the transparency of operations. This approach allowed not only to assess the effectiveness of already implemented solutions, but also to identify strategic directions for further development of the company and adaptation of the industry to modern challenges.

RESULTS

Assessment of the impact of information systems on the efficiency of enterprise management. Businesses' internal information environments are greatly enhanced by information systems, which promote improved forecasting and decision-making. By ensuring that precise and up-to-date data is easily accessible, these technologies empower management to make risk-averse decisions. According to research, the use of enterprise systems improves management profits projections' frequency and accuracy, demonstrating better access to data that is important for making decisions. Additionally, by centralising and streamlining data operations, these systems eliminate redundancies and facilitate a smooth information flow across departments. Enhancing the internal information environment gives management the resources they need to make wise strategic and operational choices, which promotes organisational coherence and overall efficiency. Modern information systems' predictive capabilities can help businesses anticipate market developments and proactively address possible obstacles. Before making important decisions, businesses can, for example, simulate many scenarios and assess the results thanks to enhanced analytics included into these platforms. In addition to improving operational agility, this skill puts businesses in a position to take advantage of new opportunities in a cutthroat industry. Better data reporting and visualisation enable leaders to convey insights more successfully, guaranteeing departmental and team alignment (Kasianiuk & Kasianiuk, 2024).

In medium-sized and large businesses, modern information systems are essential tools for cutting operating expenses and increasing profitability. Through the provision of a centralised platform for information gathering, retrieval, processing, and transmission, these systems facilitate data-driven management decisions and streamline company procedures. This simplified method guarantees that resources are distributed effectively, avoids human mistake, and eliminates duplication of work. For example, real-time stock level monitoring using automated inventory management systems can cut waste and guarantee prompt restocking. Higher profitability and reduced operating expenses are the results of such efficiency. Information systems' cost-effectiveness is further improved by their modular design. Businesses can scale operations gradually by breaking the system up into subsystems that are suited to particular tasks, such supply chain management, finance, and human resources. Because of this flexibility, businesses can increase their technology capabilities without having to pay hefty upfront fees. Additionally, by doing away with the requirement for substantial on-premise infrastructure, cloud-based information systems save money by guaranteeing scalability and lowering maintenance costs. Businesses can concentrate their financial resources on strategic initiatives that generate greater returns by using such cost-effective strategies (Fatieieva, 2020).

By supplying timely, pertinent, and reliable information, management information systems (MIS) are essential in giving businesses a competitive advantage. The ability to effectively use resources while accomplishing organisational goals is crucial in today's dynamic and competitive global market. By coordinating technology capabilities with corporate strategy, MIS maximises resource use and boosts productivity. Advanced decision-support systems, for instance, examine enormous datasets to find patterns and insights that help businesses develop strategies that meet consumer needs (Chernetska & Chernetskyi, 2023). By encouraging cooperation and knowledge exchange across organisational boundaries, the strategic application of MIS also stimulates innovation. Businesses that successfully use MIS can enhance performance indicators like market response, operational effectiveness, and customer happiness. These technologies also give businesses the ability to track key performance indicators (KPIs) and make real-time strategy adjustments to stay ahead of the competition. By incorporating MIS into essential business operations, a robust framework that facilitates long-term expansion and market adaption is produced (Yamoah *et al.*, 2024).

An organisation's efficiency and creativity are increased when its Knowledge Management (KM) and Enterprise Resource Planning (ERP) systems are integrated. Together, these platforms facilitate the smooth flow of information across departments, remove organisational silos, and optimise workflows. While KM systems make sure that decision-makers have access to important insights and knowledge, ERP systems consolidate vital operational data. When combined, they create an atmosphere where adaptability and effectiveness coexist, allowing businesses to react quickly to changes in the market (Chesang', 2024). Through the reduction of redundancies and the rationalisation of information flows, this integration also enhances strategic performance. For instance, a company can optimise inventory levels, cut lead times, and enhance customer service by integrating its ERP and supply chain management system. Additionally, businesses can leverage collaborative knowledge by combining ERP and KM systems, which promotes innovation and continual improvement. Organisations can improve their flexibility and competitiveness in quickly changing industries by coordinating technology tools with strategic objectives.

Notwithstanding the many advantages, enterprises must overcome the difficulties posed by the complexity of contemporary information systems architecture in order to optimise productivity. Operational flexibility, transparency, and decision-making predictability can all be adversely affected by high system complexity. Inadequate system integration, for instance, might result in inconsistent data, delays in operations, and higher expenses. These difficulties highlight the value of strong enterprise architecture management (EAM), which guarantees that technology solutions complement corporate goals. By controlling the interactions between organisational and technical elements, an effective EAM reduces the risks related to complexity. EAM improves system performance and reliability through standardisation, system integration, and process optimisation. Furthermore, frequent system architecture changes and audits guarantee that new issues are dealt with as soon as they arise. Businesses can attain strategic and operational excellence by utilising the full potential of their information systems through proactive complexity management (Beese *et al.*, 2023).

The implementation of modern information systems in enterprises leads to significant improvements across various aspects of management, including decision-making, forecasting accuracy, cost reduction, and operational efficiency. These systems provide centralised access to real-time data, streamline workflows, and enhance integration between departments. To better understand the impact of information systems, the Table 1 compares key metrics before and after their implementation, illustrating the improvements achieved through digital transformation.

Table 1. *Impact of information systems on key enterprise metrics*

Aspect	Before implementation	After implementation	Key improvements
Decision-making	Relies on fragmented, outdated information	Access to real-time, centralised data	Enhanced accuracy and faster decision-making

Table 1. Continued

Aspect	Before implementation	After implementation	Key improvements
Forecasting accuracy	Limited due to inconsistent data	Improved with automated analytics	Higher precision in forecasting
Operational costs	High due to inefficiencies and manual processes	Reduced through process automation	Decrease in duplication and waste
Productivity	Lower due to manual processes and delays	Increased with workflow automation	Time saved, allowing focus on value-added activities
Scalability	Difficult due to rigid, isolated systems	Enabled by modular and cloud-based solutions	Easier adaptation to growing organisational needs
Integration and flexibility	Siloed systems with limited information sharing	Integrated ERP and KM systems	Improved collaboration and innovation
Complexity management	High due to unstandardised systems	Enterprise architecture management implemented	Increased transparency and efficiency

Source: *compiled by the authors based on J. Beese et al. (2023); L.E. Yamoah et al. (2024); A. Chesang' (2024)*

Information systems have a significant impact on enterprise performance, as demonstrated by the data in the Table 1. These technologies help firms increase forecasting accuracy, save operating expenses, and boost production by resolving inefficiencies and improving decision-making skills. Additionally, improved cooperation and creativity are encouraged by the integration of ERP and KM systems, and long-term sustainability is guaranteed by efficient complexity management. These enhancements show how important digital transformation is to attaining organisational success and preserving competitive advantage in ever-changing marketplaces.

Analysis of the main advantages and disadvantages of using information systems in agriculture. The integration of information systems (IS) is causing a revolutionary change in the agricultural industry. By improving resource management, encouraging sustainability, and increasing output, these technologies have the potential to completely transform agricultural methods. Adoption and application of IS in agriculture are not without difficulties, though. Regulatory barriers, poor infrastructure, and low levels of digital literacy are some of the problems that frequently prevent their full potential. This review looks at the benefits and drawbacks of IS in agriculture, giving a thorough picture of how they affect the industry and pointing out areas that need more focus to reach their full potential. By increasing operational effectiveness and productivity, information technology has completely changed agricultural practices. Farmers can apply resources like water, fertiliser, and pesticides with remarkable accuracy thanks to precision agriculture, which mostly depends on IS. With studies demonstrating productivity benefits of up to 30%, this focused approach not only reduces waste but also dramatically boosts crop yields. Farmers can concentrate on more strategic facets of farming by automating repetitive operations like inventory management and soil moisture monitoring, which increases overall farming efficiency (Sharma, 2023).

Sustainability is also another important benefit that IS offers. In order to lessen the influence on the environment and encourage eco-friendly behaviors, technologies like blockchain and machine learning are essential (Pushak *et al.*, 2021). Blockchain promotes confidence among stakeholders and supports fair trade initiatives by guaranteeing supply chain transparency and traceability. To maximise resource utilisation, encourage climate-resilient farming, and lower greenhouse gas emissions, machine learning algorithms examine climate, soil, and crop data. With the use of these technologies, farmers may ensure long-term environmental stability by coordinating their operations with the objectives of sustainable development (Ordoñez *et al.,* 2024).

IS's capacity to promote the use of contemporary agricultural technologies, especially among smallholder farmers, is another important benefit. Farmers are empowered to make prompt and well-informed decisions when they have access to real-time information on weather patterns, soil conditions, and pest outbreaks (Zuo *et al.*, 2024). By bridging the information gap, IS promotes technology adoption and boosts productivity in emerging nations. Additionally, IS makes it possible to manage land resources more effectively by using tools like remote sensing and Geographic Information Systems (GIS), which offer in-depth knowledge about the state of the land. In order to maximise production and resource efficiency, this data aids in the optimisation of land usage, irrigation systems, and crop rotations. Information systems in agriculture encounter many obstacles that restrict their use and efficacy, despite their many benefits. The high cost of implementation and upkeep is one of the main obstacles. Smallholder farmers frequently lack the financial resources to invest in advanced technology like GIS, blockchain, and precision agriculture instruments. Larger businesses profit from IS, while smaller farmers find it difficult to access these technologies, resulting in a digital gap.

Another significant issue is low levels of digital literacy. Many farmers, especially those in rural areas, lack the abilities and know-how required to successfully manage complicated IS. This problem is made worse by inadequate training programs and a dearth of technical assistance, which keeps farmers from taking full advantage of IS. The efficient application of IS in agriculture is further hampered by inadequate infrastructure. For IS to be implemented successfully, access to contemporary hardware, dependable electricity, and stable internet connectivity are necessary. But in rural and isolated places, these resources are frequently scarce, which lessens the possible impact of IS (Mokhtar *et al.,* 2022). The integration of IS in agriculture is further complicated by issues with data management. To extract useful insights, the massive volumes of data produced by IS must be saved, examined, and interpreted. The practical use of IS is restricted by problems like inadequate data quality, a lack of standardisation, and challenges with model interpretation. Farmers and agribusinesses face additional challenges due to regulatory and legal ambiguities around digital technologies like blockchain and unmanned aerial vehicles (UAVs). These difficulties slow down the adoption of IS and deter investment in it. To better understand the external factors influencing the adoption and effectiveness of IS in agriculture, a detailed PEST analysis is presented in Table 2.

Table 2*. PEST Analysis of information systems in agriculture*

Factor	Positive Impacts	Negative Impacts
Political	Supportive government policies promoting digital transformation	Regulatory uncertainties, especially regarding UAVs and blockchain
Economic	Increased profitability through resource optimisation	High implementation and maintenance costs
Social	Improved access to agricultural information for smallholder farmers	Limited digital literacy and lack of technical training
Technological	Advancements in machine learning, blockchain, and GIS tools	Dependence on robust infrastructure, often unavailable in rural areas

Source: *compiled by the authors*

With major advantages including increased production, sustainability, and resource management, the analysis emphasises the revolutionary potential of information systems in agriculture. To fully utilise IS's promise, however, obstacles including exorbitant prices, low levels of digital literacy, inadequate infrastructure, and regulatory concerns must be resolved. The adoption of IS is driven by external factors including technical improvements and supportive government legislation, as seen in Table 1, although there are still infrastructure and economic constraints. Coordination between the agricultural community, technological developers, and legislators is crucial to overcoming these obstacles. IS can be successfully incorporated into agricultural processes by making infrastructural investments, encouraging digital literacy, and creating transparent regulatory frameworks. This will support the industry's innovation and sustainable growth.

Analysis of information systems implementation in the company. Atameken-Agro is one of the leading agricultural companies in Kazakhstan, which is actively engaged in the cultivation of grain and oilseeds. Since its foundation in 2003, the company has been focused on achieving high results through the use of modern technologies, effective management and sustainable development. "Atameken-Agro" operates on large agricultural areas and is one of the flagships in the implementation of innovative approaches in the agricultural sector of Kazakhstan (Agricultural holding JSC "Atameken-Agro"v..., 2023). One of the most important steps in the company's development was the introduction of IS, which allowed to automate a significant part of operational and management processes. Since 2014, the company's management has been actively looking for digitalisation solutions to reduce costs, increase productivity and optimise resource utilisation. In 2016, the company entered into a partnership with AgroStream, an IT company that offered to develop a module for planning flow charts (Features of digitalization..., 2018). This module was subsequently transformed into a full-fledged information system adapted to the needs of the Kazakhstani agricultural market.

The installation of specialised equipment, including barriers, electronic scales, and cameras in the fields, was necessary for the AgroStream system's execution. Nonetheless, the system's efficacy is demonstrated by the decrease in a number of production losses and costs. For example, in the first season of adopting AgroStream, one of Atameken-Agro's farms was able to reduce grain refraction, a major expense issue, by 63%. Overall, the digitised control over production processes enables the management of the agroholding to access real-time data from anywhere in the world about the quantity, location, and quality of stored grain. This data is updated every five minutes, ensuring continuous monitoring. Since the movement of grain operates 24/7, controlling this complex technological process would be nearly impossible without such a program. The system's capabilities highlight its essential role in streamlining operations and enhancing transparency in agricultural production, setting a new standard for efficiency in the sector (Digitalization of the.., 2023).

In addition to economic efficiency, the implementation of IS has helped to improve sowing planning, monitoring of crop cultivation technologies, and resource optimisation. The collected data allowed the company to analyse the effectiveness of different technologies, varieties, and crops. For example, it became possible to identify the most profitable crops that provide high yields in the climate and soil conditions of Kazakhstan. This, in turn, made it possible to implement the principles of precision farming, which is one of the key areas of development of the modern agricultural sector. An important achievement was the automation of accounting processes, which reduced administrative costs by 15%. In addition, the system provided integration with government agencies, simplifying the process of obtaining subsidies, certification and reporting. This has significantly increased the transparency of the company's operations and ensured the trust of partners and government agencies (Lysenko, 2019).

Despite the successes achieved, the implementation of information systems was accompanied by a number of challenges. One of the biggest barriers was staff training. At the initial stages, many employees did not understand the importance of digitalisation and resisted change. Implementing IS required not only technical training, but also a change in the mindset of employees. To overcome this challenge, the company's management organised a series of training programs, regular consulting, and technical support. Thanks to a corporate culture that fosters collective decision-making, they managed to engage employees in the change process, increase their motivation, and ensure the effectiveness of the strategy (Features of digitalization..., 2018). Another significant challenge was the limited infrastructure. The lack of stable Internet access in many rural areas of Kazakhstan made it difficult to fully utilise IS. This required additional investments in the development of technological infrastructure. In addition, the high costs of purchasing equipment, developing software, and maintaining the system posed financial challenges to the company. However, the company was able to partially compensate for these costs by improving its efficiency. The results of the information systems implementation at Atameken-Agro have shown that digitalisation is not just a trend, but a necessity for modern agriculture. Thanks to this, the company was able to achieve a significant increase in productivity and profitability, optimise resource use and ensure sustainable development (Lysenko, 2019).

The company's economic performance demonstrates the effectiveness of the implemented solutions. According to the reports, the company's profitability increased by 30%, which was made possible by reducing costs and optimising processes. In particular, the company has reduced losses of grain, fertilisers and fuel, which has not only reduced costs but also increased the company's environmental responsibility (Lysenko, 2019). The experience of "Atameken-Agro" demonstrates that a major element in raising the agriculture sector's level of competitiveness is digitisation. When putting their own digital strategy into practice, other businesses might utilise this example as a guide. But it's crucial to remember that a number of variables, such as government support, infrastructure, and employee training, affect how well digitisation goes. The business is still working to improve its information systems in spite of the outcomes.The business intends to launch artificial intelligence-powered modules soon that will forecast yields, track illnesses, and maximise resource utilisation. By providing its digital solutions to other nations, the corporation also hopes to increase its market share abroad. The digitalisation of Atameken-Agro is an illustration of Kazakhstan's agricultural industry's effective transition. The main advantages of this system are its simplicity, intuitive interface and the ability to generate comprehensive reports.

Atameken-Agro can take a variety of actions to enhance company operations, including enhancing information systems and streamlining procedures. Increasing the functionality of information systems is one of the main goals. A more precise evaluation of future performance will be possible with the integration of new modules, such as AI-based yield forecasting, which takes previous data, soil characteristics, and weather variables into account. Better resource planning and increased overall efficiency will result from this. It is also worthwhile to implement drones and satellite imagery for plant health monitoring, as this will enable prompt reaction to possible threats and early disease or pest detection. Another important aspect is the creation of modules for analysing the costs and profitability of individual crops, which will allow the company to assess the economic feasibility of growing certain crops and choose the most profitable options.

Precision farming could advance significantly with additional advancements. More economical and environmentally friendly crop, irrigation, and fertilisation planning will be possible with the application of geo-analytics. These procedures can be automated to help save money and guarantee more consistent outcomes. Furthermore, the implementation of water management systems will improve water utilisation and prevent over-irrigation. The business can think about funding the creation of blockchain-based solutions in order to raise the degree of digitisation. This will guarantee the accuracy and transparency of data pertaining to supply, logistics, and the value chain. Additionally, blockchain will contribute to a rise in consumer and partner trust, which is a critical component of growing markets. Enhancing staff training is another crucial area. To help staff members better comprehend and use the newest technologies, the organisation should routinely host training sessions and educational initiatives. It is crucial to foster a digital culture among staff members in addition to teaching them how to utilise the tools, as this will speed up the acceptance of new ideas.

Increasing the extent of Internet coverage in remote areas is also something worth considering. The business can accomplish this by working with suppliers and government organisations to guarantee reliable access to information systems, even on the most isolated farms. The business should also enhance its internal technical support procedures to guarantee the seamless operation of information systems and quickly address technical problems. Therefore, putting these suggestions into practice will enable Atameken-Agro to boost managerial effectiveness and productivity while also enhancing its competitiveness in both local and foreign markets. Utilising contemporary information technologies will support the company's long-term growth by fostering environmental responsibility and financial gains.

DISCUSSION

Information systems play a key role in the transformation of the agricultural sector, contributing to increased productivity, optimisation of operational processes and ensuring transparency of management decisions. Modern research emphasises the importance of implementing digital technologies in agriculture both at the level of individual enterprises and within the framework of national strategies. The use of innovative solutions, such as resource planning systems, information flow management and big data analysis, allows not only to reduce costs, but also to expand opportunities for sustainable development and adaptation to global challenges (Potryvaieva *et al.*, 2024). The study by V. Zhuk *et al.* (2023) focuses on the importance of information support for the agricultural sector through the introduction of modern accounting and reporting standards that meet international requirements. The main focus is on the problems of asymmetry of information, imperfections of existing accounting systems and lack of integration with global standards such as the Farm Accountancy Data Network (FADN). The authors emphasise that for the sustainable development of the agricultural sector, it is necessary to create a unified national accounting system that will ensure transparency, efficiency and validity of management decisions. Both studies emphasise the importance of improving information systems, but V. Zhuk *et al.* focus more on integration with international standards and improving government policy, while this study demonstrates the effectiveness of implementing digital solutions at the level of a particular enterprise. The key difference is that V. Zhuk *et al.* study emphasises the need for institutional frameworks and national strategies, while this study looks at the implementation of information systems as a means of solving specific production problems, such as reducing resource waste, increasing yields, and optimising processes.

A. Tarasiyk *et al.* (2023) explored the potential of intelligent management systems for agricultural enterprises, focusing on cutting-edge technologies such as artificial intelligence, neural networks, and digital twins for forecasting and optimising activities. Their research highlights technical advancements, including big data analysis, process automation, and cloud solutions for resource management. Unlike this study, which emphasises practical applications of existing systems in real-world scenarios, A. Tarasiuk *et al.* prioritise conceptual development and the integration of innovative global technologies. Despite these differences, both studies underscore the transformative role of digitalisation in agriculture, aiming to enhance efficiency and optimise processes.

This study and A. Hutorov (2024) study have different emphases in their approaches, although both focus on the importance of information systems in the agricultural sector. A. Hutorov study develops a comprehensive methodology for macroeconomic assessment of the effectiveness of agricultural science development based on the analysis of inter-sectoral balances, integration of scientific data into the national economy, and inter-sectoral linkages. Important aspects of this approach are the assessment of the social, economic, and geo-economic impact of research, which allow for the assessment of the overall effectiveness of agricultural science at the macro level. A. Hutorov research is aimed at strategic macroeconomic planning, emphasising the need to take into account national and international indicators, and illustrates the practical effectiveness of implementing information systems in real-world conditions. For example, A. Hutorov emphasises the importance of science's impact on overall economic development, while this study focuses on the application of innovations to achieve short-term goals and optimise the activities of a particular agricultural holding.

S.O. Koberniuk (2023). highlights the role of digital platforms – social media, e-commerce, and mobile applications – in enhancing marketing strategies in agriculture. The study emphasises modern marketing concepts like Marketing 4.0 and 5.0, which support effective communication, improve customer engagement, and broaden market reach. Additionally, S.O. Koberniuk analyses global trends, including AI, robotics, sensors, and drones, demonstrating their potential to transform the agricultural sector. While both studies address digitalisation's capacity to enhance efficiency and optimise costs, S.O. Koberniuk work adopts a strategic perspective, focusing on marketing and competitiveness. In contrast, this study prioritises practical applications at the enterprise level, such as resource management and productivity improvement.

The study of S. Bashlai *et al.* (2023) focuses on the introduction of digital tools into the strategic management systems of agricultural companies, emphasising the importance of digitalisation for improving management efficiency. The main focus is on such aspects as automation of financial and investment planning, use of big data processing technologies, and introduction of artificial intelligence for analysing and forecasting business processes. The authors emphasise that digital technologies are the key to ensuring the competitiveness of agricultural business, helping to increase productivity, reduce costs and improve decision-making. Both studies emphasise the importance of digital technologies in improving the efficiency of agricultural business, but differ in their approaches. S. Bashlai *et al*. study focuses on the strategic aspects of digitalisation and its integration into the overall management system, including the use of artificial intelligence, blockchain, and cloud technologies. Atameken-Agro's study is more applied and demonstrates specific results achieved through the implementation of digital solutions within one company. The difference also lies in the scope of the research: S. Bashlai *et al*. focus on global trends and the development of digitalisation strategies for the Ukrainian agricultural sector as a whole, while this study focuses on the practical application of digital technologies in a specific organisation.

L. Berezina and N. Bahan (2023) analyse the efficiency of resource use in agricultural enterprises, focusing on the evaluation of information and time resources. Their research introduces universal indicators for assessing resource efficiency and highlights the importance of creating effective databases to support the adoption of innovative technologies. Both studies share a common emphasis on digitalisation and the role of information systems in enhancing management efficiency. However, L. Berezina and N. Bahan work adopts a broader perspective, focusing on general measures for improving agricultural enterprise management. Using cutting-edge information technologies to optimise transportation, warehousing, and customer service, L.B. Hnatyshyn and N.V. Trushkina (2021) investigate the digital transformation of logistics management in agricultural firms. While addressing obstacles including organisational and financial limitations, the authors emphasise the possibility for attaining economic, social, and environmental benefits using digital platforms. L.B. Hnatyshyn and N.V. Trushkina offer a more comprehensive theoretical framework and suggest methods for the agricultural industry as a whole, in contrast to this study, which concentrates on the actual application of digital technologies inside a particular firm.

L. Tereshchenko (2021) research on assessing the economic effect of implementing MIS. Both studies point to the key role of introducing modern technologies to achieve economic benefits and increase transparency and quality of governance. L. Tereshchenko emphasises the need to develop a balanced scorecard that includes goals, critical success factors, and key performance indicators. This allows to evaluate not only financial but also non-financial results of the Operations Integrity Management System (OIMS) implementation. It uses the Balanced Scorecard methodology as a strategic management tool covering various aspects of the company's activities, including customer relations, finance, internal business processes, and innovation. The focus is on a comprehensive approach to assessing the effectiveness of the PIM, taking into account both financial and non-financial aspects. The differences between the studies lie in the methodological approach and scope. L. Tereshchenko's study focuses on a general methodology for assessing the effectiveness of the IMS, while this study presents specific cases of successful implementation. L. Tereshchenko also emphasises the strategic importance of implementing OIMS for achieving long-term goals, while this study shows short-term results.

V. Pestsov (2024) study focuses on ERP systems as a tool for optimising resource management. The author highlights ERP functions such as inventory management, finance, personnel and quality control, and also emphasises the importance of SaaS solutions for enterprises with limited financial resources. V. Pestsov focuses on the technological capabilities of ERP, transparency of business processes and sound management decisions supported by real-time data analysis. In terms of convergence, both studies recognise the need for digitalisation in the agricultural sector and emphasise the economic benefits of automation, such as cost reduction, increased efficiency and transparency. They also share the conclusion that it is important to adapt technologies to the needs of small and medium-sized enterprises to ensure their competitiveness. An important difference is that V. Pestsov's study pays more attention to the integration of ERP systems with cloud technologies and the scalability of functionality, which is especially useful for enterprises that need flexible solutions. This study focuses on adapting information systems to the specifics of the local agricultural market, emphasising individual solutions for individual enterprises.

O. Zelinska and V. Hovorukha (2019) focus on the effectiveness of implementing ERP systems in small and medium-sized agricultural enterprises. Their research highlights the integration of business processes, automation of routine tasks, and improved access to analytical data as key benefits of such systems. While both studies emphasise the role of digital technologies in enhancing resource management and productivity, O. Zelinska and V. Hovorukha concentrate on tailoring ERP systems to meet specific enterprise needs. In contrast, this study examines a large agricultural holding, showcasing a comprehensive digitalisation initiative that includes monitoring, data management, and planning systems. The study by S. Ihnatenko and I. Tomashuk (2024) focuse on the automation of management accounting in agricultural enterprises through the use of modern digital tools. They emphasise the importance of implementing technologies such as ERP systems, Internet of Things (IoT), Big Data, blockchain and cloud computing, which allow optimising management processes, increasing accounting accuracy, reducing costs and improving the competitiveness of enterprises. The researchers note that accounting automation, big data analytics and the use of robotic systems are key factors in the development of the agricultural sector. Both studies emphasise the importance of digitalisation in the agricultural sector as a means of increasing the efficiency and competitiveness of enterprises. As in Ignatenko's study, this study recognises that the implementation of digital solutions requires significant investments and staff training. Both approaches also emphasise the importance of integrating digital systems into operational processes. The main difference between the studies is the level of focus. Ignatenko and his co-authors analyse a wide range of digital technologies, including their strategic integration and potential benefits at the industry level. At the same time, this study focuses on the practical impact of implementing a specific information system at the level of an individual enterprise.

O. Sumets *et al.* (2023) emphasise the development of integrated information systems for agricultural enterprises, utilising methods like clustering and forecasting to optimise resource use and automate management processes. Both studies highlight the critical role of digitalisation in enabling data-driven decision-making. However, while O. Sumets *et al.* focus on the theoretical foundations and industry-wide prospects of information systems, this study examines their practical implementation at the enterprise level, specifically in "Atameken-Agro". This dual perspective provides insights into both local applications and broader strategic opportunities for the agricultural sector's digital transformation.

AIS and their potential to boost efficiency and productivity, especially in developing nations, are examined by N.R. Vajjhala (2021). Precision farming, e-agriculture technology, and FMIS are important subjects. While addressing issues including technical complexity, insufficient infrastructure, and the requirement for farmer training, the study emphasises AIS's potential to reduce poverty, optimise agricultural processes, and enhance information availability. In addition to stressing the value of training and removing technological obstacles, both studies highlight how AIS may increase management efficiency and transparency. But whereas this study takes an applied method, examining particular implementation outcomes in a single firm, N.R. Vajjhala research uses a global and theoretical perspective, concentrating on AIS's wider implications. A. Látečková *et al.* (2018) examine the role of ERP systems in Slovak agricultural enterprises, emphasising their potential to integrate business processes, provide real-time data access, and optimise operations. Their work highlights challenges like insufficient computerisation, employee training, and information security, as well as the need to modernise existing systems for medium-sized and small enterprises. In contrast, this study focuses on practical digitalisation efforts in Kazakhstan, showcasing examples such as machinery control systems, resource monitoring, and reducing grain and fuel losses. While both studies underline the importance of information systems for competitiveness, A. Látečková *et al.* prioritise general strategies for ERP implementation, whereas this research highlights the adaptation of digital solutions to local conditions for cost-effective results.

The analysis of scientific works indicates a common understanding of the importance of information systems in the modernisation of the agricultural sector. Despite differences in approaches – from global strategies and the development of conceptual models to the practical implementation of digital solutions at the level of individual enterprises, all studies confirm the effectiveness of digitalisation as a means of increasing competitiveness, optimising resources and ensuring sustainable development. The difference in the scale of analysis, methodology and emphasis allows for a comprehensive assessment of the potential of information systems and the identification of priority areas for their implementation.

CONCLUSIONS

According to the research, the implementation of information systems in agricultural enterprises has significant potential for optimising management processes, increasing productivity and ensuring sustainable development of the industry. The results of the analysis indicate that the effective use of such systems can contribute to reducing operating costs, increasing the accuracy of decision-making and improving the transparency of operational processes. At the same time, there are a number of challenges, such as insufficient technical training of employees, high implementation costs and limited infrastructure, which slow down the pace of digitalisation. In particular, the experience of the company "Atameken-Agro" demonstrates that digital technologies can radically change the approach to managing resources and processes in agribusiness. Thanks to the integration of specialised systems, the company was able to reduce grain losses by 63% during the first season of implementation, as well as reduce administrative costs by 15%. These achievements emphasise the importance of individualising systems to the needs of the local market and adapting them to the specifics of enterprises. At the same time, it is important to note that the implementation required significant investments in staff training, infrastructure modernisation and corporate culture changes, which are critical factors for the success of digitalisation.

A key advantage of information systems is their ability to ensure integration between different divisions of the enterprise, increase forecasting accuracy and facilitate the implementation of advanced approaches, such as precision agriculture. For example, the analysis of data on climate, soils and crop condition allows enterprises to respond to possible risks in a timely manner, optimise the use of fertilisers and water resources, which contributes to increasing the environmental sustainability of production. The overall analysis confirms that the successful integration of information systems into agriculture requires a comprehensive approach, including staff training, infrastructure development, adaptation to local conditions and support from the state. Cooperation between technology manufacturers, agricultural enterprises and government organisations also plays an important role. Such an approach allows not only to increase management efficiency, but also to strengthen the competitiveness of enterprises in international markets. In summary, the implementation of information systems is a key factor in the modernisation of the agricultural sector, contributing to sustainable development, efficient use of resources and increased environmental responsibility. However, there are also significant limitations. Among them are the high initial cost of implementing technologies, the lack of a sufficient number of qualified personnel and insufficient Internet coverage in rural areas.

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Анотація. Метою даного дослідження було визначення ефективності впровадження інформаційних систем в сільськогосподарських підприємствах та їх впливу на оптимізацію управлінських процесів і продуктивність. Основними завданнями було проаналізувати, як цифрові технології впливають на прийняття рішень, зниження витрат, підвищення продуктивності, а також виявити бар'єри на шляху їх інтеграції. Методологія включала аналіз наукових публікацій, політичний, економічний, соціальний, технологічний аналіз, порівняльну оцінку ключових показників ефективності до і після впровадження систем, а також тематичне дослідження на основі досвіду казахстанської компанії «Атамекен-Агро». Зокрема, аналіз публікацій дозволив виявити тенденції та проблеми цифровізації в аграрному секторі. Політичний, економічний, соціальний, технологічний аналіз допоміг оцінити політичні, економічні, соціальні та технологічні фактори, які впливають на впровадження інформаційних систем. Результати дослідження підтвердили, що впровадження інформаційних систем має значний позитивний вплив на продуктивність та управління підприємствами. Зокрема, в компанії «Атамекен-Агро» діджиталізація дозволила зменшити втрати зерна на 63 %, скоротити адміністративні витрати на 15 %, підвищити прозорість і точність управлінських рішень. Система AgroStream забезпечила централізований доступ до даних у режимі реального часу, що підвищило ефективність моніторингу та планування. Крім того, впровадження автоматизованих процесів сприяло оптимізації використання ресурсів та підвищенню екологічної відповідальності. Результати дослідження свідчать, що успішна інтеграція інформаційних систем у сільському господарстві вимагає комплексного підходу, що включає адаптацію до місцевих умов, державну підтримку, розширення інфраструктури та навчання персоналу

Ключові слова: цифрова трансформація; технологічна інфраструктура; сільськогосподарські підприємства; оптимізація процесів; використання ресурсів

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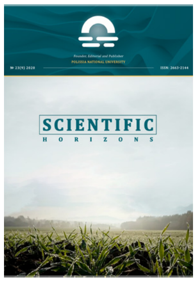

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Export potential of agricultural products: Financial aspects

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Abstract. This study analysed the financial mechanisms that stimulate the development of the export potential of agricultural products in order to strengthen Kazakhstan's position in global markets. It examined the role of the agricultural sector in the country's economic development and the factors influencing its competitiveness in international trade. To assess the sector's export potential, key financial instruments were evaluated, including government subsidy programmes, tax incentives, and export risk insurance mechanisms. The analysis highlighted the role of specialised financial institutions – such as Agrocredit Corporation and KazAgroFinance – which provide

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farmers with access to credit and leasing for production modernisation and export development. The influence of infrastructure, particularly transport and logistics corridors, on the cost and timeliness of agricultural deliveries was also considered. Technological advancement in the agro-industrial sector was identified as a critical factor in export growth. In addition, the importance of government policies aimed at improving macroeconomic stability, managing currency risks, and developing financial institutions is emphasised. The study presented data on the dynamics of Kazakhstan's agricultural exports, which grew from USD 2.1 billion in 2015 to USD 5.1 billion in 2024. Despite positive trends, challenges remain, including yield instability, limited processing capacity, and high transportation costs. Particular attention is given to exports to China, which rose from USD 351 million in 2019 to USD 954 million in 2023. The key findings underlined the necessity of expanding financial support tools, such as concessional loans, export risk insurance, and subsidies for transportation costs. Strategic investments in agricultural processing, new export corridors, and the digitalisation of certification procedures will further enhance Kazakhstan's competitiveness in global markets and support continued export growth in the agricultural sector

Keywords: international trade; food security; trade barriers; subsidies and grants; currency risks

INTRODUCTION

In the context of globalisation and the expansion of international trade, agricultural exports play a pivotal role in the development of national economies. For many countries with well-developed agricultural sectors, such exports serve as a vital source of foreign exchange earnings, contribute to economic diversification, and stimulate investment activity. However, the effectiveness of this process is largely contingent on financial factors, including access to credit resources, subsidy schemes, taxation policies, risk insurance, and international settlement mechanisms. The relevance of this study lies in the pressing need to enhance the competitiveness of domestic agricultural products in global markets. Contemporary challenges – such as price volatility in commodity markets, sanctions-related restrictions, shifts in global trade policies, and macroeconomic instability – necessitate the development of robust financial strategies to support the export potential of the agricultural sector. Furthermore, the integration of new technologies, the digitalisation of financial transactions, and the use of risk hedging instruments are increasingly essential for the successful performance of agricultural exporters.

Despite the sector's high export orientation, several issues hinder its sustainable development. Chief among these is insufficient financial support for producers, limited access to long-term and preferential credit, and barriers to securing export subsidies. In addition, exchange rate volatility and elevated logistics costs introduce further financial risks for exporters (Kryvovyazyuk *et al.*, 2024). Customs barriers and the need to comply with international standards for product quality and safety also exert a considerable influence on the sector's performance. The export potential of agricultural products can be examined through the lens of key economic categories such as competitiveness, financial stability, and international trade relations. Within the framework of financial analysis of export activities, financing instruments play a crucial role. These include bank loans, leasing, factoring, government subsidies, and export risk insurance. Contemporary models of international trade highlight the significance of financial mechanisms in ensuring the sustainable growth of agricultural exports, as well as the necessity of active government involvement in creating a favourable environment for agribusiness development (Bekmuratov *et al.*, 2024).

Numerous studies focused on the financial dimensions of agricultural exports underscore the importance of various financial support tools in enhancing the competitiveness of domestic producers. For instance, E.J. Kane (2021) found that the availability of concessional lending and subsidies has a direct impact on the volume of agricultural exports, as it lowers production costs and promotes the modernisation of the agricultural sector. Similarly, A. Baubekova *et al.* (2020), in their analysis of government financing programmes in Kazakhstan, concluded that the presence of a well-developed financial support system for agricultural exports enables the country to achieve more stable growth in foreign trade performance. A. Ibyzhanova *et al.* (2024) examined the impact of currency fluctuations on the export revenues of agricultural enterprises and concluded that effective currency risk hedging strategies can mitigate the adverse effects of exchange rate instability. Their findings align with those of I.A. Raifu and A. Aminu (2020), who investigated the application of derivative financial instruments in agricultural exports and demonstrated that hedging through futures and options contributes to stabilising the incomes of export-oriented farms.

The issue of high logistics costs was explored by M. Rahman *et al.* (2022), who, through a comparative analysis of national logistics financing models, showed that optimising transport costs and investing in infrastructure significantly enhance export potential. J. Salimova-Tekay (2022) focused on export risk insurance and demonstrated that the availability of effective supply insurance mechanisms reduces the financial losses incurred by enterprises in force majeure situations. D.D.D. Fiankor *et al.* (2021) investigated the impact of international quality standards on the financial sustainability of agricultural exporters and found that the costs associated with product certification are offset by increased trust from foreign buyers. Concurrently, research by K.M. Mang'ana *et al.* (2023) revealed that targeted support for small and medium-sized agricultural enterprises by specialised financial institutions contributes to expanding their share in total agricultural exports.

In analysing government support measures, E. Ohrn (2023) concluded that tax incentives for agricultural exporters can serve as an effective instrument for stimulating foreign trade, though their efficacy depends significantly on the transparency of preference distribution mechanisms. A.W. Al-Khatib (2024) examined the impact of the digitalisation of financial transactions in export activities and demonstrated that the adoption of electronic payment systems and blockchain technologies can accelerate and secure settlements between exporters and importers. Collectively, these studies highlight the wide range of financial factors influencing the export potential of agricultural products. Nevertheless, despite the substantial body of research, several aspects of financial support for agricultural exports remain underexplored. In particular, the effectiveness of integrated financial strategies that combine government support, private investment, and international financial instruments requires further investigation. Moreover, the impact of digital technologies on access to credit for agricultural exporters remains insufficiently assessed, as do the mechanisms for insuring export risks in an increasingly unstable global market.

The aim of this study was to examine effective financial mechanisms that foster the sustainable development of the export potential of agricultural products, with due regard for current challenges and global market trends. The objectives of the research were: to analyse existing financial instruments for supporting the export of agricultural products and identify their advantages and limitations; to assess the impact of digitalisation on the accessibility and efficiency of financing agricultural exports; and to develop recommendations for improving public and private financial support mechanisms for agricultural exporters.

MATERIALS AND METHODS

The study employed a set of methods aimed at assessing the export potential of Kazakhstan's agricultural sector. The research involved an analysis of regulatory documents, strategic programmes, and government initiatives governing the development of the agro-industrial complex and its export capacity. Key factors influencing the competitiveness of agricultural products in the global market were examined, including financial mechanisms, infrastructure development, government support measures, and international trade relations. Statistical data were sourced from official institutions such as the Bureau of National Statistics (n.d.), the International Trade Centre (n.d.), and the Ministry of Agriculture of the Republic of Kazakhstan (n.d.). To evaluate export dynamics, data on the value and volume of agricultural exports during the period 2015-2024 were analysed. Statistical methods used included the calculation of growth rates, dynamic indices, and comparative analysis of key indicators across major product categories, including crop production, livestock, and processed agricultural goods.

The study further assessed the role of financial instruments in stimulating agricultural exports. It examined mechanisms such as lending, subsidies, tax incentives, export risk insurance, and digital financial solutions currently applied in Kazakhstan to support exporters. Particular emphasis was placed on the activities and programmes of Agrarian Credit Corporation JSC (n.d.), KazAgroFinance JSC (n.d.), and the Export Credit Agency of Kazakhstan JSC (n.d.). To evaluate the effectiveness of financial mechanisms, the analysis incorporated data on the volume of loans issued, subsidies allocated, insurance pay-outs made, and the dynamics of export financing uptake. These indicators provided insight into how various financial tools contribute to enhancing the export performance of Kazakhstan's agricultural sector Additionally, the study examined the influence of infrastructure-related factors on the export potential of Kazakhstan's agricultural sector. The condition of logistics systems, transport corridors, warehouse capacities, and export terminals was assessed. Public and private investments in the modernisation of transport infrastructure were analysed, including initiatives implemented under the One Belt, One Road programme (World Bank, 2020). The logistics costs borne by Kazakhstan's agricultural exporters and their effect on the final cost of products were also considered.

One of the key components of the study was the analysis of Kazakhstan's international trade relations. Export flows and the country's main trading partners were examined, including China, Central Asian countries, the European Union, and the Middle East. Data on export structure, supply volumes, and changes in trade policy were utilised. Particular attention was given to the dynamics of exports to China, based on data from the International Trade Centre (n.d.). The study also explored digital tools and financial mechanisms that influence the development of the agricultural sector. The Agricultural Animal Identification System (AIIS) was analysed as a means of tracking livestock and monitoring product movement. Additionally, the Information System for the Traceability of Crop Production was studied for its role in controlling supply chains and ensuring compliance with international standards (Modern digital solutions..., 2025). The financial aspects of agricultural exports were further analysed using the example of the Baiterek Venture Fund (n.d.), which supports enterprises in the sector through credit and investment instruments. Based on these analyses, the study identified areas for improving the export strategy, financial mechanisms, and logistics infrastructure, all of which are critical to enhancing the efficiency and international competitiveness of Kazakhstan's agricultural products.

RESULTS

The export potential of the agricultural sector plays a vital role in the economic development of countries with well-established agricultural industries. It not only ensures the inflow of foreign currency revenues but also enhances the competitiveness of national products in global markets. In the context of globalisation, population growth, and increasing global demand for food, agricultural exports are becoming a key driver of sustainable economic growth. However, the development of this potential depends on numerous factors, including financial mechanisms, infrastructure, government support, and international trade relations. For many nations, the agricultural sector is of strategic importance, contributing significantly not only to food security but also to gross domestic product (GDP). Agricultural exports provide states with foreign exchange earnings, improve the trade balance, and stimulate the development of related industries such as transport, logistics, and raw material processing. Moreover, successful agricultural exports contribute to the technological advancement of the sector (Friedmann, 2021). Competing in global markets necessitates the modernisation of production, the adoption of advanced agricultural technologies, the enhancement of quality control systems, and the implementation of standards that comply with international requirements. These improvements, in turn, drive productivity and support the sustainable development of agriculture.

Despite the critical role of agricultural exports, their development is confronted by a number of challenges and factors affecting the competitiveness of products in international markets. Chief among these is access to financial resources. It is essential for agricultural enterprises to secure financing for production development, equipment modernisation, and the expansion of export operations. Countries with well-developed financial support systems for farmers tend to experience higher growth in export potential (Al-Ababneh *et al.*, 2022). In Kazakhstan, for instance, government programmes such as loan subsidies and tax incentives for the agricultural sector support export expansion, although further improvements to these mechanisms remain necessary. Secondly, infrastructure exerts a significant influence on export potential. Access to modern logistics systems, efficient transport corridors, adequate warehouse facilities, and well-functioning export terminals all determine the cost and speed of product delivery. Although Kazakhstan benefits from a unique geographical position between Europe and Asia, underdeveloped infrastructure and high transport costs continue to constrain the export potential of its agricultural sector.

Thirdly, international trade relations and national economic policy play a critical role. Trade barriers, tariff restrictions, sanctions, and product quality requirements can either facilitate or hinder export development. Kazakhstan is actively engaged in integration processes within the Eurasian Economic Union (EAEU) and is expanding cooperation with China, the Middle East, and the European Union, thereby opening new opportunities for market diversification (Manatovna *et al.*, 2023). Another key factor is technological development and innovation in the agro-industrial complex. The adoption of precision farming techniques, advanced irrigation systems, genetic research, and biotechnology can significantly improve yields and product quality, thereby enhancing competitiveness in global markets (Goel *et al.*, 2021). Environmental and climatic conditions also influence export potential. In Kazakhstan, agricultural output is highly dependent on weather variability, necessitating the adoption of adaptive technologies and risk management strategies. The implementation of agricultural risk insurance schemes and the development of irrigation infrastructure can greatly enhance production resilience and, in turn, boost export potential (Balogh & Jámbor, 2020).

The development of the export potential of the agricultural sector is unattainable without an effective system of financial support that enables enterprises to minimise risks, enhance productivity, and compete successfully in international markets. Financial instruments utilised in export activities include various lending mechanisms, government subsidies, tax incentives, risk insurance, and innovative digital solutions. When used competently, these instruments strengthen the resilience of the agricultural sector and encourage export expansion. One of the most critical tools for supporting agricultural exports is access to financial resources through lending and leasing. For enterprises targeting foreign markets, long-term loans with low interest rates are particularly important, as they enable investment in production modernisation, equipment procurement, and the development of logistics infrastructure (Ehlers *et al.*, 2021). In Kazakhstan, this role is performed by specialised financial institutions such as the Agrarian Credit Corporation and KazAgroFinance, which offer affordable credit to farmers aiming to enhance their export capacity. Leasing programmes also play a significant role in supporting agricultural exports by allowing enterprises to upgrade their fleet of agricultural machinery without requiring substantial upfront investment. This is particularly beneficial for small and medium-sized farms, which often face difficulties in securing large-scale loans.

To further stimulate agricultural exports, the government employs a range of financial support mechanisms, including subsidies for production and transportation costs, as well as risk insurance (Erten & Leight, 2021). In Kazakhstan, programmes that reimburse a portion of transport costs help exporters reduce the final price of their products, thereby improving their competitiveness in foreign markets. Additionally, tax incentives for agricultural exporters serve as a strong motivator for expanding foreign trade activities. For instance, reducing the tax burden on export transactions or exempting agricultural exports from value-added tax (VAT) enables enterprises to retain more capital for reinvestment in production and operational development. Agricultural exports are subject to a wide range of financial risks, including exchange rate volatility, fluctuations in global commodity prices, demand instability, and political restrictions. In this context, export risk insurance plays a crucial role. In Kazakhstan, agricultural enterprises can utilise the services of insurance providers such as KazakhExport, which offer guarantees for export contracts and protect producers against financial losses. Hedging against price and currency risks is another effective mechanism for safeguarding export revenues. The use of futures contracts and options allows agricultural exporters to lock in favourable prices for their products, thereby mitigating the impact of abrupt market fluctuations (Oglend & Straume, 2020). However, this tool remains underdeveloped in Kazakhstan and requires further integration into the agricultural sector's financial practices.

Modern technologies have a profound influence on the financial infrastructure supporting exports. The adoption of digital platforms for processing export contracts, the implementation of blockchain technologies for international settlements, and the use of automated financial management systems can streamline trade operations and enhance transaction transparency (Edeh *et al.*, 2020). Kazakhstan has already begun digitalising financial transactions through initiatives such as electronic agricultural receipts, which enable producers to secure financing against future harvests. The state plays a central role in creating the conditions necessary for the sustainable development of agricultural exports. Government intervention is essential not only to correct market imbalances but also to mitigate the financial risks faced by agricultural producers operating in foreign markets. The establishment of a favourable financial environment requires comprehensive measures encompassing export policy regulation, the development of financial institutions, infrastructure improvement, and the promotion of innovation within the agribusiness sector (Lin & Zhang, 2020).

One of the most important areas of state support for agricultural exports is the establishment of a predictable and sustainable macroeconomic policy. Fluctuations in exchange rates, inflation risks, and changes in tax legislation directly impact the financial stability of agricultural exporters. By regulating tax and customs policies, government agencies can create favourable conditions for agricultural enterprises, reducing administrative barriers and offering preferential tax regimes for export-oriented businesses. A key instrument of state policy is the control of inflation and currency risks, as rising domestic prices or sharp exchange rate fluctuations can render agricultural exports less profitable (Andrei *et al.*, 2020). In Kazakhstan, state financial institutions such as the National Bank and the Ministry of Finance are capable of taking measures to stabilise the national currency, thereby facilitating long-term export planning.

The state also plays an active role in the development of institutions that offer targeted financing for agricultural exports. In Kazakhstan, organisations such as KazAgroFinance, the Agrarian Credit Corporation, and the Export Credit Agency of Kazakhstan provide preferential loans, export risk insurance, and guarantees for international contracts. Additionally, public funds dedicated to export support are used to attract private investment into the agricultural sector and to subsidise interest rates on export-related loans. These mechanisms enable agricultural enterprises to expand their export geography, modernise production facilities, and minimise financial losses. The success of agricultural exports is also closely linked to the development of logistics and transport infrastructure (Chukurna *et al.*, 2022). The state has a critical role in the modernisation of warehouse facilities, transport corridors, ports, and terminals that support the uninterrupted export of agricultural goods. In Kazakhstan, the government is actively investing in transport infrastructure under the One Belt, One Road initiative, which broadens the export potential of the agricultural sector. Programmes aimed at constructing logistics centres, such as dry ports and multimodal transport hubs, help to reduce transportation costs and increase the volume of exported goods.

Moreover, the digitalisation of financial processes, the automation of export contract management, and the development of electronic trading systems contribute to reducing the bureaucratic burden on agricultural exporters. Kazakhstan is implementing blockchain-based technologies in the agricultural export system to enhance the transparency of transactions between exporters and foreign buyers. State digitalisation programmes in the agricultural sector also facilitate access to financial resources, accelerate product certification procedures, and increase the efficiency of export operations. With its vast agricultural land and favourable climatic conditions for cultivating a variety of crops, Kazakhstan possesses significant potential in agricultural exports. Table 1 presents the volume of agricultural exports, illustrating the growth trajectory of the sector.

***Table 1**. Volume of agricultural exports of Kazakhstan for 2015-2024, million USD*

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Plant growing	1,102.7	1,106.8	1,290.3	1,850.0	1,994.5	1,950.0	2,236.8	3,070.2	2,910.7	2,222.9
Cattle breeding	39.9	39.0	52.4	108.1	180.2	81.8	154.0	176.0	175.4	226.5
Processed agricultural products	945.1	978.2	1,087.2	1,133.5	1,115.0	1,348.7	1,428.4	2,346.3	2,311.5	2,655.0
Total for agricultural products	2,087.7	2,123.9	2,429.8	3,091.6	3,289.6	3,380.6	3,819.2	5,592.6	5,397.6	5,104.4

Source: *created by the authors Bureau of National Statistics (n.d.)*

The analysis of the Table 1 indicates a generally positive trajectory in Kazakhstan's agricultural exports, despite certain periods of decline. The most notable growth has occurred in the crop production category, where export volumes nearly tripled – from USD 1,102.7 million in 2015 to a peak of USD 3,070.2 million in 2022 – before declining in 2023-2024. The livestock sector also demonstrates export growth, though with more pronounced fluctuations, including a dip in 2020 and a subsequent recovery to USD 226.5 million in 2024. The most consistent growth has been observed in the export of processed agricultural products, which reached USD 2,655.0 million in 2024, reflecting increased global demand for value-added agricultural goods. Overall, the total volume of Kazakhstan's agricultural exports increased by more than 2.4 times over the review period, peaking at USD 5,592.6 million in 2022, followed by a modest decline in the subsequent years. This decrease may be attributed to shifting external market conditions, logistical challenges, or fluctuations in international demand.

Kazakhstan's agricultural exports are primarily composed of grain crops, oilseeds, flour products, meat, and dairy. Wheat and flour continue to account for the largest share of exports, reflecting Kazakhstan's longstanding strength in grain production. The primary importers of Kazakhstani wheat and flour include neighbouring Central Asian countries – Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan – as well as Afghanistan, Iran, and China. In addition to grains, the export of oilseeds such as rapeseed, sunflower, and flax is expanding, with Kazakhstani producers increasingly accessing new markets in Europe and Southeast Asia, where demand for high-quality vegetable oils and oilseeds is high. Meat exports, particularly of beef and lamb, are also on the rise. Kazakhstan is strengthening its position in markets such as China, Russia, and the Middle East, including Iran, Saudi Arabia, and the United Arab Emirates (Ministry of Agriculture..., n.d.). However, despite these positive developments, the export potential of the meat sector remains partially underutilised. This is largely due to challenges related to product certification, veterinary and sanitary standards, and limited domestic processing capacity.

Trends in the development of agricultural exports in Kazakhstan reveal a positive trajectory, characterised by product diversification, the expansion of export destinations, the adoption of digital technologies, and active government support. Nonetheless, despite these advancements, the sector continues to face a number of challenges that require comprehensive and coordinated solutions. A key trend is the diversification of export products. While Kazakhstan has traditionally maintained a strong position in grain and flour exports, recent years have witnessed a growing focus on higher value-added products. The country is actively developing exports of processed agricultural goods such as vegetable oils, dairy products, meat, and honey. One particularly promising area is the export of organic products, for which demand is increasing in international markets. The growth of this segment not only enhances the competitiveness of Kazakhstan's exports but also reduces reliance on volatile global commodity prices.

Kazakhstan has also significantly broadened the geographic scope of its agricultural exports, moving beyond traditional markets such as Central Asia, Russia, and Afghanistan. Particular emphasis is now placed on strengthening trade relations with China, the Gulf countries, the European Union, and Southeast Asia. China has emerged as a key strategic partner for Kazakhstan's agricultural sector. In 2023, agricultural exports to China reached USD 1 billion – almost double the value recorded in the same period of the previous year. Currently, 1,718 Kazakhstani enterprises export to China, including 1,629 engaged in crop production and 86 in livestock farming. The principal exported goods include grain crops, meat products, and oilseeds. To further increase export volumes, Kazakhstan plans to align its agricultural products with Chinese standards and regulatory requirements, thereby responding to the growing demand for high-quality agricultural goods (EastFruit, 2024). Table 2 presents the volume of agricultural exports to China, illustrating the country's growing role as a strategic export destination for Kazakhstan.

Table 2. Volume of exports of main agricultural products from Kazakhstan to China in 2019-2023, thousand USD

	2019	2020	2021	2022	2023
Livestock	44	0	0	0	43
Meat and edible meat by-products	13,581	3,910	977	28	0
Fish and crustaceans, molluscs, aquatic invertebrates	4,085	502	115	475	2,910
Dairy products; bird eggs; natural honey; food products of animal origin	94	4,726	2,215	2,259	2,337
Other products of animal origin	3,307	942	2,037	2,476	4,521
Vegetables and edible roots and tubers	10	16	0	27	6
Cocoa and cocoa products	846	1,571	1,700	5,562	10,633
Tobacco and manufactured tobacco substitutes	4,377	11,915	14,237	5,987	13,971
Grains	98,210	95,558	42,736	7,1218	335,208
Oil seeds and fruits; various grains, seeds, and fruits; industrial or medicinal	95,583	130,923	76,893	214,130	283,035
Fats and oils of animal, vegetable, or microbial origin, and their cleavage products; finished edible fats	99,684	92,765	40,374	165,700	172,283
Residues and waste from the food industry; prepared animal feed	30,905	45,436	12,793	73,614	128,899
Total	350,726	388,264	194,077	541,476	953,846

***Source:** created by the authors International Trade Centre (n.d.)*

The growth in exports of grain – from USD 98.2 million in 2019 to USD 335.2 million in 2023 – and oilseeds – from USD 95.6 million to USD 283 million – is particularly noteworthy, reflecting China's strong demand for these product categories. In contrast, exports of meat and edible meat by-products have declined to nearly zero, which may be attributed to sanitary restrictions or shifts in market demand. At the same time, exports of processed products, such as cocoa derivatives and residues from the food industry, have increased significantly, reinforcing the trend towards diversification in Kazakhstan's agricultural export structure. Overall, the data reflect positive dynamics and signal considerable potential for further growth in Kazakhstan's agricultural exports to China, particularly in segments such as vegetable oils, grains, and value-added processed products. Modern agriculture in Kazakhstan is increasingly integrating digital technologies to enhance the efficiency and transparency of export operations. The Ministry of Agriculture has introduced the Unified State Information System of Subsidies (GISS), which encompasses all areas of subsidies within the agro-industrial complex. This system ensures transparency in the subsidy allocation process, reduces corruption risks, and allows farmers to track the status of their applications in real time. Since its launch in 2023, GISS has processed over 240,000 applications, with more than 177,500 approved (Modern digital solutions..., 2025).

In the livestock sector, an automated Integrated Livestock System (ILS) has been implemented to enable accurate livestock accounting, monitor animal health, and control product movement. This contributes to enhanced biosecurity and improved product quality – critical factors for accessing international markets. Additionally, mobile applications such as VETMOBILE for veterinary professionals and TORTTULIK for livestock owners have been developed to facilitate the registration, monitoring, and management of livestock farms. To ensure full traceability of agricultural products from farm to consumer, the Ministry of Agriculture has initiated the development of the Plant Production Traceability Information System (PPIS). This system aims to monitor the entire production and distribution cycle of plant-based agricultural products, ensure compliance with international standards, and foster greater trust from foreign trade partners (Modern digital solutions..., 2025). State support remains a key factor in the development of agricultural exports. As a member of the Eurasian Economic Union (EAEU), Kazakhstan benefits from simplified trade procedures and reduced tariffs on exports to other member states. In addition, the government is actively engaged in negotiations to establish new trade corridors and free trade agreements, thereby improving conditions for agricultural exports. One of the government's priority areas is the enhancement of financial support mechanisms for exporters, including subsidies, export risk insurance, and the provision of preferential loans.

Despite these positive developments, Kazakhstan's agricultural exports continue to face several challenges. A high dependence on natural conditions contributes to unstable crop yields, which in turn affects export volumes. Furthermore, the issue of underdeveloped processing capacity remains unresolved: the lack of modern production facilities limits the ability to increase exports of higher value-added products. Logistics and infrastructure constraints also pose ongoing barriers, particularly in transporting goods to distant foreign markets. Another critical factor is the need to meet international standards of product quality and safety, which requires sustained investment in the modernisation of production processes and certification systems. Addressing these challenges calls for a comprehensive approach, including strengthened financial support, the introduction of modern risk management tools, and expanded access to international capital markets.

The financial stability of Kazakhstan's agricultural exporters is a cornerstone of the sector's successful development. It influences not only the global competitiveness of domestic agricultural products but also contributes to broader economic growth. In the context of global instability, exchange rate fluctuations, trade barriers, and high transport costs, exporters must employ a diverse range of financial instruments and strategies to minimise risks and enhance profitability. This requires improvements to preferential lending systems, the development of export risk insurance mechanisms, diversification of export products, better logistics infrastructure, reduced transport costs, and the continued digitalisation of export operations. State support programmes, such as financing through the Agrarian Credit Corporation and the Baiterek Venture Fund (n.d.), should be expanded. Increasing the availability of long-term loans – ranging from 7 to 10 years – with reduced interest rates would enable export-oriented enterprises to plan their activities more effectively. The introduction of a system of state guarantees and subsidies for export loans would reduce the lending risks faced by banks, thereby improving access to credit for farmers. It is also essential to enhance leasing mechanisms for the acquisition of modern agricultural machinery and equipment, supported by state-subsidised interest rates.

The establishment of a specialised fund to support agricultural exports – providing preferential loans for the modernisation of processing facilities and logistics infrastructure – would allow Kazakhstani agricultural exporters to access cheaper and longer-term financial resources. This is particularly important in light of growing competition in the global market. A dedicated agency for export risk insurance should be created to protect exporters from potential losses arising from the insolvency of foreign counterparties. The introduction of a state programme to subsidise insurance premiums for agricultural exporters would reduce the financial burden on companies and increase the accessibility of insurance services. Additionally, the development of mechanisms for hedging currency risks would help minimise losses resulting from sharp fluctuations in the tenge's exchange rate against major world currencies. The active development of insurance infrastructure would enable agricultural exporters to operate in foreign markets with reduced risks and greater confidence in the financial stability of their operations.

A key factor in ensuring financial stability is reducing dependency on a single product type or sales market. Kazakhstan's current export portfolio is largely composed of raw materials, such as grain and oilseeds, making it vulnerable to global price volatility. Product diversification and increased exports of processed goods would help mitigate these risks. Expanding domestic processing capacities – for products such as flour, vegetable oils, canned meat, powdered milk, and other high value-added goods – is essential. Promoting organic products in export markets also presents a promising opportunity, as there is rising demand in the European Union, China, and the Middle East for organic grain, honey, meat, and dairy products (Faichuk *et al.*, 2022). Another important step in strengthening Kazakhstan's export position involves the development of finished food exports and the promotion of Kazakhstani brands in international markets. Participation in trade exhibitions and marketing programmes will be crucial to raising brand visibility and enhancing competitiveness abroad.

Kazakhstan's landlocked geography presents significant challenges for export logistics. In this context, the development of transport and logistics centres in key regions of the country is essential. Such infrastructure would reduce transportation time and lower logistics costs for exporters. In addition, subsidising railway tariffs for agricultural exporters – particularly for shipments to China, Europe, and the Gulf countries – would enhance cost-efficiency. The expansion of international transport corridors, including the One Belt – One Road initiative, will facilitate Kazakhstan's deeper integration into global supply chains. Optimising logistics will improve the competitiveness of Kazakhstani agricultural products by reducing delivery costs. The development of electronic platforms for product certification is equally important, as it will help minimise bureaucratic delays and accelerate market entry for exporters. The application of blockchain technologies for supply chain traceability will build trust among foreign buyers by ensuring product authenticity and compliance with international quality standards. Furthermore, the introduction of digital marketplaces for agricultural trade will enable exporters to access new partners directly, expanding market reach while lowering transaction costs. Digitalisation will streamline administrative procedures, reduce operational expenses, and improve oversight of logistics and financial transactions.

In summary, the financial sustainability of Kazakhstan's agricultural exporters depends on a complex set of factors, including access to financing, effective risk mitigation, product diversification, logistics development, and the digitalisation of operations. Comprehensive measures – such as affordable long-term lending, export risk insurance, support for value-added processing, reduced transportation costs, and the integration of digital technologies – are essential to strengthening the global competitiveness of Kazakhstani agricultural companies and ensuring the long-term, stable growth of agricultural exports.

DISCUSSION

The results of the study demonstrate that Kazakhstan's agricultural sector possesses substantial untapped export potential, although it faces a number of structural and operational limitations. Analysis of statistical data reveals that, in recent years, the volume of agricultural exports has shown steady growth; however, the export structure remains insufficiently diversified. The principal export commodities continue to be grain crops, sunflower oil, and meat products, while high value-added goods are represented in relatively small volumes. This highlights the urgent need to expand deep processing of agricultural raw materials, which would not only increase export revenues but also enhance the competitiveness of Kazakhstan's products in international markets. Climatic factors exert a significant influence on the stability of agricultural exports. Extreme temperature fluctuations, uneven precipitation distribution, and severe weather events introduce considerable uncertainty for producers, complicating the planning of export deliveries. W. Xie *et al*. (2020), in a study based on long-term meteorological and trade data, demonstrated that global warming is causing shifts in agricultural production zones, which will ultimately alter the structure of agricultural exports. While W. Xie *et al*. study focuses on long-term climate zone shifts and their implications for global trade, the present research centres on short-term climate risks. Sudden weather anomalies, such as unexpected droughts or frosts, can sharply reduce crop yields and disrupt export schedules, thereby contributing to increased volatility in agricultural markets.

Infrastructure constraints also represent a major limiting factor in the development of Kazakhstan's export potential. Analysis of the country's transport and logistics systems indicates that high transportation costs, insufficient warehouse and export infrastructure, and dependency on transit routes through neighbouring countries pose serious challenges to exporters. Although several investment projects have been launched to modernise logistics – such as the development of international transport corridors and the establishment of logistics hubs – current data show that transport costs in Kazakhstan remain higher than those in competing export-oriented economies. This underscores the need for continued investment in infrastructure, the development of multimodal transport systems, and improvements in logistics efficiency. H.H. Park and S.J. Cho (2021) examined the influence of logistics-related factors on agricultural exports, focusing on transportation costs, infrastructure limitations, and disruptions in global supply chains. Their study concluded that inadequate transport networks, the absence of modern ports, and a lack of cold chain infrastructure are among the principal barriers to exporting perishable agricultural goods. The findings of the present study align with these conclusions, particularly with regard to the cost of logistics. However, unlike H.H. Park and S.J. Cho global analysis, this study identifies Kazakhstan-specific, seasonal challenges, such as peak logistical pressures during harvest seasons, limited storage capacity, and border delays linked to customs procedures.

Financial mechanisms to support exports also play a critical role in the development of the agricultural sector (Mamasydykov *et al*., 2019). The findings of this study indicate that existing programmes providing subsidies and loans to exporters have had a positive effect on industry growth; however, the scale of support remains insufficient. Kazakhstani farmers and processing enterprises continue to face limited access to affordable credit, which restricts their ability to expand production and enter foreign markets. A comparison with government support frameworks in other countries suggests that Kazakhstan must enhance its incentive structures for exporters by expanding preferential financing schemes and developing comprehensive export risk insurance mechanisms. R. Zhang *et al*. (2021) examined the influence of government subsidies and agricultural support programmes on export performance. His study considered a range of models, including production-based subsidies, compensation for transport costs, and the provision of export loans. Similarly, M. Springmann and F. Freund (2022) found that countries which actively subsidise their agricultural sectors tend to record higher export volumes than those with minimal government support. Programmes targeting small-scale farms were found to be especially important, as they enable these producers to compete with large agricultural holdings. The current study also confirms the importance of state support but highlights the issue of unequal resource distribution. Subsidy programmes in Kazakhstan are predominantly directed toward large agribusinesses, whereas small and medium-sized farms often struggle to access financial assistance. Addressing this imbalance is essential to achieving more inclusive and sustainable growth in agricultural exports.

Another key issue is the influence of international trade agreements on agricultural export performance. The data show that Kazakhstan is actively cultivating trade relations with China, Central Asian countries, and the European Union. However, the country's export policy still requires further adaptation to meet evolving international requirements. Major barriers include challenges with product certification, compliance with phytosanitary and veterinary standards, and restricted access to new markets. In this context, it is necessary to enhance state support in the areas of certification and quality control, including the establishment of laboratory centres and the simplification of procedures for entering foreign markets (Tyukhtenko *et al*., 2024). J.H. Grant *et al*. (2021) analysed the impact of trade barriers on agricultural exports, showing that even minor changes in customs tariffs and quotas can significantly affect export volumes. The findings of L. Zhai *et al*. (2022) similarly demonstrate that countries facing trade restrictions experience an average 15-20% decline in agricultural exports due to reduced competitiveness. This study also explored the effects of trade barriers, though with a particular focus on sanitary and veterinary regulations rather than tariff-based measures. It is the difficulty in meeting international food safety standards that most significantly constrains the export potential of Kazakhstan's agricultural sector.

E.M. Meemken *et al.* (2021) investigated the impact of certification and compliance with international standards on agricultural exports. Their study demonstrated that certified products gain access to premium market segments, enabling exporters to achieve higher prices. They also observed that consumers in developed countries show a strong preference for products with verified quality and environmental safety assurances. The present study confirms the critical importance of certification but also highlights additional challenges, particularly the high cost of obtaining international certification. This factor presents a dual effect: while certification enhances competitiveness, it simultaneously limits opportunities for small-scale producers lacking the financial capacity to undertake complex certification procedures.

In addition, the study revealed that modern agricultural technologies can significantly increase Kazakhstan's export potential. The adoption of precision farming, digital trading platforms, and blockchain technologies for product traceability can enhance the competitiveness of Kazakhstani agricultural goods. However, the current level of technological implementation remains insufficient, indicating the need for stronger state support. This should include measures aimed at digitalising the agricultural sector, fostering agricultural start-ups, and facilitating the adoption of advanced production techniques. J. Liu and J. Xie (2020) explored the role of technological innovation in strengthening the competitiveness of agricultural exports. Their research examined the implementation of automated production management systems, digital trading platforms, and traceability technologies. Similarly, M. Matthess and S. Kunkel (2020) found that countries investing heavily in the digitalisation of the agro-industrial sector tend to outperform those that rely on traditional production methods. The findings of the present study confirm the importance of technological progress, while also pointing to disparities in its adoption. Large-scale producers derive tangible benefits from digitalisation, but for small and medium-sized farms, the high cost of advanced technologies remains a major barrier to entry.

Overall, the analysis revealed that logistics, digitalisation, and compliance with environmental and quality standards are among the key determinants of agricultural export performance. While the study aligns with broader international trends, it also identifies specific barriers, including logistical bottlenecks, financial constraints, and the challenges producers face in adapting to evolving trade conditions. These findings underline the necessity of a comprehensive strategy for enhancing Kazakhstan's export potential – one that considers both macroeconomic factors and the real-world challenges encountered by producers at the micro level.

CONCLUSIONS

Developing the export potential of the agricultural sector plays a vital role in Kazakhstan's economic growth by generating foreign exchange earnings, improving the trade balance, and stimulating the development of related industries. In recent years, Kazakhstan has demonstrated positive trends in agricultural exports, particularly in the segments of grains, oilseeds, and processed goods. Access to financial resources remains a key success factor for agricultural enterprises. State support programmes – such as loan subsidies, tax incentives, and export risk insurance – contribute to export growth, but require further refinement. Long-term loans with low interest rates, offered by specialised financial institutions such as the Agrarian Credit Corporation and KazAgroFinance, are particularly important for enabling export-oriented investment. Nevertheless, infrastructure development continues to pose a significant challenge. Despite Kazakhstan's strategic geographical location between Europe and Asia, high transportation costs and underdeveloped logistics infrastructure hinder the full realisation of export potential. International trade relations also have a major influence on export performance. Kazakhstan actively participates in regional integration through the Eurasian Economic Union (EAEU) and is strengthening trade ties with China, the Middle East, and Europe. However, successful expansion into these markets requires product adaptation to international quality standards, necessitating greater investment in certification, quality assurance, and biosafety systems.

Technological development, including the introduction of digital platforms and innovative solutions, enhances the competitiveness of Kazakhstan's agricultural exports. The implementation of automated accounting systems – such as IFA for livestock and GISS for subsidies – has improved transparency and administrative efficiency in the sector. In 2023 alone, 240,000 applications for subsidies were submitted via the GISS platform, with over 177,500 approved, demonstrating strong farmer engagement with state support mechanisms. An analysis of Kazakhstan's agricultural export potential confirms its strategic importance to the national economy. Between 2019 and 2024, agricultural export volumes exhibited a generally positive trajectory, despite isolated periods of decline. Notably, crop exports nearly tripled, rising from USD 1,102.7 million in 2015 to a peak of USD 3,070.2 million in 2022, followed by a modest decrease in 2023-2024. Livestock exports also expanded, reaching USD 226.5 million in 2024. Processed agricultural products showed the most stable growth, increasing to USD 2,655.0 million in 2024. Overall, the total volume of agricultural exports more than doubled – growing by over 2.4 times during the review period – indicating strong and growing international demand for Kazakhstani agricultural products. Kazakhstan's main agricultural export items include grain crops, flour and cereal products, oilseeds, meat, and dairy products. Wheat and flour constitute the largest share of these exports, with the primary importers being countries in Central Asia – Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan – as well as Afghanistan, Iran, and China. Exports to China have shown particularly strong growth, rising from USD 351 million in 2019 to USD 954 million in 2023.

Thus, the export potential of Kazakhstan's agricultural sector plays a vital role in the country's economic development by enhancing the global competitiveness of its products and supporting sustainable growth. The development of agricultural exports is influenced by a wide range of factors, including financial mechanisms, state support, infrastructure quality, and international trade relations. A limitation of this study lies in the limited availability of comprehensive statistical data, which may not fully capture the current situation due to the volatility of external markets and the influence of broader macroeconomic conditions. Promising directions for future research include the development of strategies to diversify agricultural exports, analysis of the effects of climate change on agricultural productivity, evaluation of government support mechanisms, and the implementation of digital technologies to optimise export processes.

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Експортний потенціал аграрної продукції: Фінансові аспекти

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Анотація. Робота спрямована на аналіз фінансових механізмів, що стимулюють розвиток експортного потенціалу аграрної продукції, для зміцнення позицій країни на світових ринках. У роботі досліджувався експортний потенціал аграрного сектору Казахстану, його роль в економічному розвитку країни та фактори, що впливають на його конкурентоспроможність на міжнародних ринках. Для оцінки експортного потенціалу аграрного сектору розглянуто ключові фінансові механізми, включно з державними програмами субсидування, податковими пільгами та механізмами страхування експортних ризиків. Було виокремлено роль спеціалізованих фінансових організацій, таких як Агрокредитна корпорація та КазАгроФінанс, які забезпечують аграріїв доступом до кредитування та лізингу для модернізації виробництв і розвитку експортних можливостей. Розглядався вплив інфраструктури, включно з транспортними та логістичними коридорами, на вартість і терміни поставок сільськогосподарської продукції. Одним із важливих чинників, що визначають розвиток експорту, є технологічний прогрес в агропромисловому комплексі. Також підкреслюється значущість державних програм, спрямованих на поліпшення макроекономічної політики, стабілізацію валютних ризиків і розвиток фінансових інститутів. Розглядалися дані про динаміку обсягу сільськогосподарського експорту Казахстану. Обсяг експорту всієї продукції сільського господарства збільшився з 2,1 млрд доларів у 2015 році до 5,1 млрд доларів у 2024 році. Незважаючи на позитивні тенденції, відзначались проблеми, такі як нестабільність урожайності, дефіцит переробних потужностей і високі транспортні витрати. Особливу увагу приділено експорту сільськогосподарської продукції до Китаю, який збільшився з 351 млн доларів у 2019 році до 954 млн доларів у 2023 році. Основні висновки роботи включали необхідність розширення фінансових інструментів підтримки, таких як пільгове кредитування, страхування експортних ризиків та субсидування транспортних витрат. Інвестиції в переробку сільськогосподарської продукції, розвиток нових експортних маршрутів і цифровізація процедур сертифікації допоможуть зміцнити позиції Казахстану на міжнародних ринках і збільшити обсяги аграрного експорту

Ключові слова: міжнародна торгівля; продовольча безпека; торговельні бар'єри; субсидії та дотації; валютні ризики

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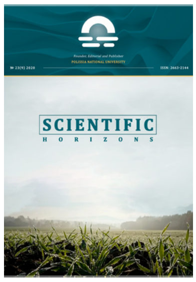

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Bioeconomy as a strategic direction for sustainable development of the agricultural sector

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Abstract. The study aimed to identify the key principles of bioeconomy and their impact on the environmental, economic and social sustainability of the agro-industrial complex. A comprehensive analysis of existing practices of applying Environmental, Social, Governance (ESG) strategies and bioeconomy in the agricultural sector, including the study of successful cases and a comparative analysis of the effectiveness of innovative technologies, was conducted. The study determined that the introduction of bioeconomy principles in the agricultural sector significantly contributes to strengthening the sustainability and efficiency of the agricultural sector. Between 2021 and 2024, there was an increase in the area used for sustainable agriculture, from 43 to 47 million hectares, as well as an increase in the share of organic fertilisers in the total, from 5% to 7%. The use of drip irrigation has also increased, from 1.5 to 3 million hectares. At the same time, food losses in the agricultural sector decreased from 16% to 13%, and the efficiency of water use increased from 3.5 to 4 km^3. The development of circular technologies has brought significant results: the share of recycled waste in agricultural production increased from 22% to 30%, and the number of companies using such solutions increased from 90 to 150. The use of biotechnology has also had a positive impact – the share of GM crops has increased from 5% to 9%, and the carbon footprint has been reduced from 5 to 3 million tonnes of CO_2. A study of the successful implementation of ESG approaches in agribusiness, including in Kazakhstan, Germany and the Netherlands, showed a reduction in the use of chemical fertilisers, improved product quality and reduced greenhouse gas emissions. For instance, Olzha Agro reduced the use of agrochemicals by 12% while achieving an 18% increase in yields. EcoMilk has reduced its CO_2 emissions by 25% by

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using biodegradable packaging and installing solar panels. In general, the results of the analysis confirmed the importance of integrating bioeconomic and ESG principles for the sustainable development of the agro-industrial complex and increasing its social significance

Keywords: ecological footprint; precision agriculture; circular economy; biofermentation; ESG strategies

INTRODUCTION

The bioeconomy is becoming increasingly strategic for the sustainable development of the agricultural sector. It is central in ensuring food security, increasing agricultural productivity and minimising the negative impact on the environment. In the context of global climate change, growing demand for food and limited natural resources, the transition to a bioeconomic model of production and consumption is not just relevant, but vital. The bioeconomy is based on the rational use of renewable bioresources, the introduction of advanced biotechnologies and the application of closed (circular) cycle principles, which provides environmentally friendly and more efficient production. Integration of Environmental, Social, Governance (ESG) approaches (environmental, social and governance aspects) is also important, as they help to reduce the carbon footprint, improve working conditions and ensure transparency of management in the agricultural sector.

In the context of climate change and the need to move to a bioeconomic model, the problem of sustainable development of the agricultural sector is relevant. N. Khan *et al.* (2021) emphasised that the use of innovative agricultural technologies has significantly increased the sustainability of crops and reduced dependence on chemical fertilisers. The study demonstrated how modern technologies not only increase yields but also reduce the environmental impact of agricultural production. J. de Carvalho *et al.* (2022) addressed the use of renewable bioresources, such as biofuels and biopolymers in the agricultural sector, defining them as substantial for the reduction of the carbon footprint and strengthening the sustainability of production systems. A similar was highlighted by N. Patel *et al.* (2022), emphasising the role of biotechnology in shaping sustainable agricultural production models. The authors emphasised the importance of using biopolymers and biofuels to reduce pressure on the ecosystem and increase economic profitability. B. Koul *et al.* (2022) consider the principles of the circular economy as strategically important for agricultural waste management. The study suggested ways to recycle agricultural waste, such as biogas and compost, to create closed production cycles and minimise losses. P. Singh and A. Sharma (2022) analysed the introduction of precision farming technologies, including drones and Internet of Things (IoT) systems. Following the study, such solutions can significantly increase the efficiency of the agricultural sector and reduce its environmental impact.

A. Gamage *et al.* (2023) highlighted the important role of organic farming in improving soil condition and reducing chemical pollution. The study emphasised the resilience of organic practices to changing climatic conditions. U. Hafeez *et al.* (2023) analysed the use of genetic engineering to develop plant varieties that are resistant to climate stress. Following the study, such varieties can significantly increase crop yields and the adaptability of agricultural production to adverse conditions. R. Azis *et al.* (2024) considered biofermentation as a potential method for producing environmentally friendly feed and fertilisers. The study demonstrated that these technologies reduce the need for chemical additives and improve the quality of agricultural products. J. Ramos-Teodoro *et al.* (2021) emphasised the importance of introducing solar panels and other renewable energy sources in the agro-industry, demonstrating how such solutions contribute to reducing energy consumption and carbon emissions. K. Refsgaard *et al.* (2021) studied the social dimension of the bioeconomy, particularly its impact on job creation and improving working conditions in rural areas. The study highlighted the role of the bioeconomy in strengthening social stability and rural development. However, there are still unresolved issues related to the limited attention paid to the social aspects of the bioeconomy, including employment and the improvement of working conditions in rural areas. In addition, specific mechanisms for integrating biotechnology into various agricultural systems have not been well developed, indicating a need for further scientific research in this area.

The study aimed to analyse the application of bioeconomy principles in agribusiness, identify successful examples of their implementation and assess the impact of these approaches on sustainable agricultural development.

MATERIALS AND METHODS

The study analysed and evaluated the main components of the bioeconomy and sustainable development of the agro-industrial complex in the context of the introduction of innovative technologies and principles of sustainable agriculture, based on data covering the period from 2021 to 2024. The study addressed the efficient use of bioresources to improve crop sustainability and yields. The research analysed innovative agricultural technologies, including new biotechnologies and environmentally friendly fertilisers, which improve product quality and reduce negative environmental impact. The study also analysed ways to use biodegradable fertilisers and biological products to reduce soil and water pollution. Data on the area under sustainable agriculture, the share of organic fertilisers, the use of drip irrigation, levels of food losses and water efficiency were studied (according to the Bureau of National Statistics Agency for Strategic planning and reforms of the Republic of Kazakhstan (n.d.)).

The study also analysed the principles of circular economy and waste-free production in the agro-industrial complex. The processes of recycling agricultural waste, such as biogas and compost, as well as the use of agricultural by-products to produce biofuels and biopolymers, were considered. Data were analysed on the share of recycled waste, the volume of recycled organic materials, the number of enterprises that have implemented circular technologies, as well as the use of by-products and emission reductions in the agricultural sector (Ministry of Industry and Construction of the Republic of Kazakhstan, 2024). The study examined biotechnologies, including genetic engineering methods for creating resistant plant varieties, as well as biofermentation and biocatalysis for developing new feeds, fertilisers and food additives. Data on the share of genetically modified crops, the production of biotechnology products, the reduction of the carbon footprint in agricultural production, and the use of biotechnology to increase yields and reduce dependence on chemical fertilisers were analysed (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021).

The study analysed the reduction of the carbon footprint. Precision farming technologies, such as drones, Iot and Big Data, which optimise the use of resources in agriculture and reduce carbon emissions, were addressed. The growth of organic farming and the use of alternative energy sources, such as biogas and solar panels, to reduce carbon emissions and minimise the climate impact of the agricultural sector were also analysed. As part of the analysis, examples of Kazakhstani companies Olzha Agro (n.d.) and EcoMilk (n.d.) were considered, which demonstrate the introduction of precision farming technologies, increased yields, reduced use of agrochemicals, reduced CO_2 emissions and the use of renewable energy sources. Foreign cases were also studied: the German company BioEconomy Cluster (n.d.) and the Dutch company Van der Knaap (Reiley, 2023). Additionally, examples of other Kazakhstani enterprises involved in the development of the bioeconomy were analysed. In particular, the activities of Zharkent Starch Packing Plant (n.d.), which processes agricultural raw materials into feed additives, Biofert (n.d.), a producer of bio-organic fertilisers, and Agrofarm (n.d.), an agricultural enterprise that implements sustainable agricultural technologies.

The projects in the field of bioenergy implemented by Partner-Agro (n.d.) and Zorg Biogas (n.d.), the activities of KazAgro Green (n.d.) in the field of environmental innovation, as well as eco-packaging solutions from GreenPack (n.d.) were studied. The role of the KazAgro-Expo exhibition (n.d.) as a platform for agricultural innovation, fermentation of feed in Kostanay region (Agro-Bio-Auliekol, n.d.), development of enzyme complexes at the National Centre for Biotechnology (n.d.), digitalisation of rural areas (Digital Villages of…, 2020), and renewable energy projects by Farmers of Chilik (n.d.) were analysed. The analysis included official data from the Ministry of Agriculture of the Republic of Kazakhstan (n.d.) on the growth of organic land, research on the use of *Trichoderma* as a biofungicide (Yerpasheva *et al.*, 2022), and social aspects of the bioeconomy presented in Astana TV reports (Under the "Green…, 2019). These companies were selected for their successful application of bioeconomic technologies, such as agricultural waste recycling and vertical farming, which have significantly improved the environmental and economic efficiency of their farms. Their selection was based on their leading positions in agricultural innovation and sustainable environmental approaches.

RESULTS

The bioeconomy is a system of economic activity based on the use of renewable biological resources, advanced biotechnologies and circular production principles. In the agro-industrial complex, it plays a key role in ensuring food security, improving agricultural efficiency and reducing environmental impact. At the end of 2022, the permanent rural population in the Eurasian Economic Union countries was about 52 million people, accounting for 28% of the total population of the region. The total area of agricultural land in the same year was 112.7 million hectares, of which 59.4% was occupied by cereals and legumes. Agricultural production in 2022 grew by 10.4% compared to 2021, reaching USD 166 billion (Fernández-Puratich *et al.*, 2021).

Implementation of ESG principles in the agricultural sector contributes to the sustainable development of the industry, reduction of negative environmental impact, improvement of social conditions and increase of management transparency. 70% of companies in the agricultural sector recognise the importance of the environmental component, of which 80% implement projects for waste recycling and reduction, and 77% focus on energy efficiency. Social aspects of ESG are covered by 74% of companies, of which 96% develop the skills and competences of their employees, and 92% provide decent remuneration for labour. The managerial part of ESG is covered by 72% of companies, of which 90% are devoted to the reduction of business risks and 80% monitor compliance with ethical standards. This data confirms that the integration of ESG principles into corporate strategies contributes to their sustainable development and increased competitiveness in the agricultural sector (Leite de Almeida *et al*., 2024). In the context of global challenges such as climate change, depletion of natural resources and the need to ensure food security for a growing population, the effective use of biological resources is becoming one of the key tasks for the agro-industrial complex (Akanmu *et al*., 2023). Modern agricultural technologies are the foundation of sustainable agriculture, as they not only increase crop yields but also contribute to improving crop resilience. These innovations support the agricultural sector in adapting to changing environmental conditions while reducing negative impacts on the ecosystem (Table 1).

***Table 1**. Rational use of biological resources in the agricultural sector of Kazakhstan*

Metric	2021	2022	2023	2024
Area of agricultural land used for sustainable farming (million hectares)	43	44	45	47
Share of organic fertilisers in total volume (in %)	5%	5.5%	6%	7%
Application of drip irrigation technologies (million hectares)	1.5	2	2	3
Level of food losses in agricultural sectors (in %)	16%	15%	15%	13%
Water use efficiency (km^3)	3.5	3.6	3.8	4

***Source:** compiled by the authors based on the Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.)*

The agro-industrial complex is showing positive dynamics in various aspects of sustainable development. The area of agricultural land used for sustainable farming is increasing, reflecting the growing interest in environmentally friendly farming methods. The share of organic fertilisers is also growing, reflecting a desire to reduce dependence on chemicals. At the same time, drip irrigation technologies, which contribute to more efficient use of water resources, are becoming increasingly popular. Food waste is decreasing, which may indicate improvements in logistics and processing. All of these changes are aimed at increasing environmental sustainability and more efficient use of natural resources in agricultural production. In Kazakhstan's agricultural sector, the development of new agricultural technologies is manifested through the introduction of IoT-based soil moisture monitoring systems, the use of Netafim precision irrigation systems, and the use of DJI AGRAS drones for the precise application of fertilisers and plant protection products. These technologies reduce water consumption by 25-40%, and the dosage of agrochemicals is optimised depending on the actual soil conditions and phytosanitary status of the fields. For instance, Zharkent Starch Packing Plant (n.d.) recorded an 18% reduction in mineral fertiliser costs and a 12% increase in corn yields after implementing drone monitoring and spot fertilisation.

As part of the transition to the sustainable use of bioresources, the practice of using biodegradable fertilisers based on sapropel, peat and fermented plant residues is actively developing. For example, BioFert (n.d.) produces liquid organo-mineral fertilisers obtained using anaerobic fermentation products, which not only improve the physical and chemical characteristics of the soil but also contribute to an increase in humus levels. After two seasons of applying such fertilisers, Agrofarm (n.d.) increased the organic matter content of the soil by 0.3-0.5%, which stabilised winter wheat yields at over 42 c/ha. In addition to fertilisers, biological products based on *Bacillus subtilis*, *Trichoderma harzianum* and *Streptomyces* spp. are actively used as substitutes for chemical fungicides and pesticides in vegetable cultivation. Research by the Institute of Soil Science and Agrochemistry has shown that the use of these biological products in greenhouse farms in the Almaty region reduces tomato blight by 60% and increases the dry matter content of fruits by 8-10%, which improves their market quality. The use of organic fertilisers such as biohumus, compost from agricultural waste and fermented manure shows high carbon efficiency. For example, at the Partner-Agro farm (n.d.), the use of compost from plant residues reduced the carbon footprint per hectare by 1.2 tonnes of CO_2 per season compared to traditional nitrate fertiliser application. This approach not only increases soil productivity but also contributes to the environmental sustainability of agricultural landscapes.

The circular economy, or closed-loop economy, is a model in which waste is recycled into resources, and the production process becomes as sustainable and efficient as possible (Barros *et al*., 2023). This concept is becoming increasingly relevant in the agro-industrial complex, where traditional production methods often lead to the generation of significant amounts of waste, such as agricultural residues, packaging and chemical emissions. The implementation of circular economy principles in the agricultural sector contributes to a significant improvement in the environmental situation, a reduction in losses and an increase in resource efficiency. This not only minimises the negative impact on the environment but also opens new prospects for creating added value and sustainable growth in the industry (Table 2).

***Table 2**. Circular economy and waste-free production in the agricultural sector of Kazakhstan*

Metric	2021	2022	2023	2024
Share of recycled agricultural waste in agricultural production (%)	22%	23%	25%	30%
Volume of organic waste processed (million tonnes)	1.0	1.2	1.5	2.0
Number of enterprises that have implemented circular technologies	90	100	120	150
Level of utilisation of agricultural by-products (%)	55%	58%	60%	65%
Reduction of waste emissions in the agricultural sector (thousand tonnes)	250	270	300	350

***Source:** compiled by the authors based on the Ministry of Industry and Construction of the Republic of Kazakhstan (2024)*

Improvement in the recycling and utilisation of agricultural waste is notable. The share of recycled waste in agricultural production and the volume of organic materials recycled have been steadily increasing, reflecting improved sustainable production and processing practices in the agricultural sector. The growing number of companies adopting circular technologies also confirms the growing interest in closed production cycles, which contributes to more efficient use of resources and reduced waste. The increased use of agricultural by-products and reduced waste emissions in the agricultural sector indicates improved environmental policies and the introduction of new technologies to minimise environmental impact. These trends support the transition of agricultural production to more sustainable and environmentally friendly models.

One example of the implementation of circular economy principles in Kazakhstan's agro-industrial sector is the construction of local biogas plants for the processing of organic livestock waste. For instance, on farms in the South Kazakhstan region, the company Zorg Biogas (n.d.) has installed bioreactors with a capacity of up to 300 m^3, which use cattle manure and silage residues to produce methane. The biogas produced is used to heat greenhouses and generate electricity, which has reduced coal consumption by 40% during the heating season. At the same time, methane emissions into the atmosphere have been reduced, and energy costs have been cut. Composting of organic residues is actively used in agricultural enterprises in Central Kazakhstan. For instance, KazAgro Green (n.d.) has implemented a multi-stage system of crop residue processing, including shredding, fermentation and maturation of compost with the addition of EM crops. The resulting compost is used on the fields as an organic fertiliser, which has reduced dependence on mineral fertilisers by 25% and increased humus content by 0.4% over two years. This improves the water-holding capacity of the soil and helps to stabilise yields under changing climatic conditions.

Another important area is the production of biopolymers from plant materials. In collaboration with scientists from Nazarbayev University, the start-up GreenPack (n.d.) has developed biodegradable packaging made from corn starch and sunflower husks, which is used to pack seeds and vegetables. This material completely decomposes within 90 days in the soil, leaving no toxic residues. Thanks to such projects, agribusinesses can simultaneously reduce dependence on plastic packaging and their environmental footprint. Modern biotechnologies are substantial in the transformation of the agro-industrial complex, creating new opportunities to improve the quality of agricultural production and increase its sustainability (Rosero-Delgado *et al.*, 2021). Genetic engineering, bio-fermentation, and biocatalysis technologies significantly increase the efficiency of the agricultural sector, making it more adaptable to changing climate conditions, improving product quality and reducing environmental impact. These innovative approaches ensure the sustainability of agriculture in response to global challenges such as climate change, soil degradation and growing food demand (Table 3).

***Table 3**. Application of biotechnology and reduction of carbon footprint in the agricultural sector of Kazakhstan*

Metric	2021	2022	2023	2024
Share of genetically modified (GM) crops (in %)	5%	6%	7%	9%
Production of biotechnology products (million tonnes)	1.0	1.1	1.2	1.5
Reduced carbon footprint in agricultural production (million tonnes of CO_2)	3	3.5	4	5
Use of biotechnology to increase yields (in %)	4%	5%	5%	6%
Reduced use of chemical fertilisers (in %)	3%	4%	4%	6%

***Source:** compiled by the authors based on the Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan (2021)*

There is a gradual increase in the use of biotechnology in agricultural production, which is reflected in the growing share of genetically modified crops and the production of biotechnology products. This not only increases yields but also reduces the carbon footprint of the agricultural sector, which has a positive impact on environmental sustainability. The use of biotechnology to increase yields and reduce the use of chemical fertilisers reflects the desire for more efficient and environmentally friendly agriculture. The introduction of these technologies optimises production processes and minimises the negative impact on the environment, which is substantial in the sustainable development of the agricultural sector. One of the most promising areas of biotechnology in Kazakhstan's agriculture is genetic engineering aimed at creating stress-resistant crop varieties. Since 2021, the KazAgroExpro project (n.d.) has been developing drought-resistant maize and wheat hybrids with integrated DREB1 and CBF genes that activate plant defence mechanisms in the face of water shortages and temperature changes. Field trials in the Zhambyl region have shown that yields of these crops remain at 45-48 cwt/ha at moisture levels below 60% of the long-term norm. This minimises crop losses in the context of climate change and reduces the need for irrigation by 30-35%.

At the same time, the area of biofermentation is developing, especially in livestock production. The Agro-Bio-Auliekol feed mill (n.d.) in Kostanay region has introduced technologies for the microbiological conversion of grain processing waste into high-protein feed additives with a crude protein content of up to 32%. The technology is based on microorganisms of the genera *Lactobacillus* and *Bacillus subtilis*, which ferment straw, molasses and meal. Thanks to these technologies, the company has reduced the purchase of soybean meal by 22%, which has reduced total feed costs by 18% per year. At the same time, biocatalysis is widely used in the production of fermented premixes for ruminants. The National Centre for Biotechnology (n.d.) in Astana has developed enzyme complexes that promote the breakdown of fibre in feed, increasing the digestibility coefficient by 12-15%. This reduces concentrate consumption, lowers methane emissions from the rumen and improves feed conversion, which is important from both an environmental and economic point of view.

The reduction of the carbon footprint is a key aspect of sustainable agricultural production, especially considering that Kazakhstan's agriculture generates more than 15 million tonnes of CO_2 equivalents annually. Precision farming technologies play a significant role in this context. In 2023, as part of the Digital Villages of Kazakhstan programme, around 120 farms in the Pavlodar and Akmola regions gained access to Trimble GPS navigation and IoT sensors for measuring soil moisture and composition. This has reduced the use of mineral fertilisers by 20-25% and water consumption for irrigation by 30%, which in turn has contributed to a reduction in greenhouse gas emissions of 1.7 million tonnes of CO_2 equivalent per year (Digital Villages of…, 2020). Alternative energy sources, including biogas plants and solar panels, are also being actively introduced in the agricultural sector. For example, Farmers of Chilik (n.d.) in southern Kazakhstan use up to 40% of its electricity from biogas plants powered by cattle manure. This reduced diesel fuel consumption by 9.2 tonnes per year and CO_2 emissions by 110 tonnes. Solar panels installed on the roofs of farm buildings generate an additional 22-25 kW of energy per day, which fully covers the energy needs for cooling and lighting systems.

In Western Kazakhstan, especially in the Ural and Atyrau regions, organic farming based on the use of green manure, manure, compost and crop rotation is actively developing. According to the Ministry of Agriculture of the Republic of Kazakhstan (n.d.), the area of certified organic land increased from 35,000 ha in 2020 to 58,000 ha in 2024, while the overall carbon balance in these areas remains positive. The application of ESG principles in the agricultural sector is becoming increasingly popular as companies and farms realise that sustainable development contributes to competitiveness and long-term stability. Examples of ESG strategies implemented both in Kazakhstan and abroad demonstrate marked improvements in environmental sustainability, economic efficiency and social responsibility. These examples demonstrate how innovation and responsible business practices can transform the agricultural sector (Table 4).

***Table 4**. Successful cases of implementing ESG strategies in the agricultural sector*

Case	Technologies used	Increase in crop yields	Savings (percentage)	Reduction of CO_2 emissions	Reduced use of chemicals	Additional information
Kazakhstan: Olzha Agro Holding	Precision farming, minimal tillage	18%	12% on agricultural chemicals	-	20%	Reduced use of chemical fertilisers by 20%
Kazakhstan: EcoMilk LLP	Biodegradable packaging, solar panels	-	30% on energy costs	25%	-	500 solar panels on 20 farms
Germany BASF programme	Renewable energy sources, biogas plants	-	35-50% on electricity	40%	-	Processing of 50 thousand tonnes of agricultural waste per year
Netherlands: Van der Knaap vertical farming technology	Hydroponic and aeroponic systems for growing vegetables	20%	60% on pesticides	-	30%	Saves up to 95% of water, reduces chemical consumption by 30%

***Source:** compiled by the authors based on Olzha Agro (n.d.), EcoMilk (n.d.), BioEconomy Cluster (n.d.), L. Reiley (2023)*

An example of the implementation of ESG strategies in Kazakhstan is the agricultural holding Olzha Agro (n.d.), which in 2023 began using precision farming and minimum tillage systems. These innovations have significantly reduced the use of chemical fertilisers and pesticides, which has contributed to an 18% increase in yields. Thanks to the use of modern technologies, the agricultural holding saved 12% on agrochemicals, which not only reduced the environmental burden but also improved the company's financial performance. This approach contributes to the sustainable development of agriculture and reduces the negative impact on the environment, in line with ESG principles. Another successful example is EcoMilk (n.d.), an organic dairy producer that actively integrates sustainability principles into its operations. The use of biodegradable packaging and solar panels on its farms has significantly reduced the company's environmental footprint. Thanks to these measures, the company has reduced CO_2 emissions by 25% and cut energy costs by 30%. These steps not only contribute to environmental protection but also reduce operating costs, which increases the company's competitiveness in the market.

International experience also demonstrates the successful application of ESG strategies in the agricultural sector. In Germany, the Bioeconomy Strategy programme actively uses renewable energy sources and biogas plants to process agricultural waste. These innovations can significantly reduce energy costs by 35-50%. In addition, the use of such technologies leads to a 40% reduction in CO_2 emissions. This approach not only reduces the carbon footprint but also increases the energy independence of farmers, which contributes to their economic sustainability. A vivid example of the successful implementation of such technologies is the BioEconomy Cluster (n.d.). The Netherlands is a leader in the introduction of innovative technologies in agriculture, and vertical farming is one of the most prominent examples. Dutch farmers are actively using hydroponic and aeroponic systems to grow vegetables, which saves up to 95% of water, a critical resource in the context of climate change and water shortages. The use of vertical farms contributes to sustainable food production, reduces water and fertiliser costs, and enables indoor vegetable growth, minimising the need for pesticides and chemicals. An example of the successful implementation of such technologies is Van der Knaap (Reiley, 2023).

Examples from Kazakhstan, Germany and the Netherlands demonstrate how the implementation of ESG principles in the agricultural sector not only increases environmental sustainability but also improves economic efficiency. The use of innovative technologies such as precision farming systems, renewable energy sources and the development of organic agriculture ensures significant progress in reducing their carbon footprint, increasing yields and reducing operating costs. These examples are an important benchmark for other countries and companies seeking sustainable development and innovative solutions in the agricultural sector. The bioeconomy is a model of sustainable development based on the efficient and rational use of renewable biological resources. The agro-industrial complex offers many advantages, helping to balance the environmental, economic and social aspects of agriculture. The implementation of bioeconomic principles not only reduces the negative impact on nature, but also improves companies' financial results, creates jobs and develops rural areas. According to forecasts, by 2030, the value of the closed-loop bioeconomy could reach USD 7.7 trillion. At the same time, the World Bioeconomy Forum estimates the value of the global bioeconomy at USD 4 trillion, with a forecast of growth to USD 30 trillion or more by 2050 (Cano-Gómez *et al.,* 2024).

One of the important aspects of the bioeconomy in Kazakhstan's agro-industrial sector is achieving environmental sustainability by reducing the chemical load on soil, water bodies and the atmosphere. For instance, using biological products based on *Trichoderma viride* and *Bacillus subtilis* on farms in the Akmola region helped cut down on fungicide use by 30%, which led to a 45% drop in wheat disease compared to control plots. At the same time, the use of biodegradable organo-mineral fertilisers produced from sapropel and chicken manure on farms in the Karaganda region has reduced nitrate content in the soil by 17% and improved the phytosanitary condition of rapeseed crops (Yerpasheva *et al.,* 2022).

From a social perspective, the bioeconomy is substantial in the development of rural areas and the creation of new jobs. In 2023, 260 new jobs were created in the fields of bioengineering, compost production and organic fertilisers as part of the state programme "Жасыл ауыл". A biogas plant using livestock manure began operating in the Talas district, providing energy for 14 greenhouse farms and creating more than 40 jobs. At the same time, the development of organic farming has encouraged young people to return to rural areas, and in 2022-2024, 18% of agronomy graduates started small farms using bioeconomic practices (Under the "Green…, 2019). Thus, bioeconomy in the agricultural sector of Kazakhstan emphasises the relationship between environmental sustainability, economic benefits and social integration of rural residents. Its implementation contributes to the creation of an adaptive and efficient model of agricultural production that not only reduces the burden on natural ecosystems but also stimulates economic growth in the regions, improving the quality of life in rural areas.

DISCUSSION

Bioeconomy, as a key area of sustainable development in the agricultural sector, has become increasingly important. The study demonstrated that ESG principles focusing on environmental, social and governance sustainability significantly affect the development of the agricultural sector. Environmental practices, such as reducing carbon footprint and rational use of natural resources, improving the ecological situation and reducing environmental impact. Social initiatives, including improving working conditions and creating new jobs, are becoming the basis for social progress and improving the quality of life of rural residents. In addition, the introduction of transparent management approaches improves trust between producers and consumers, which has a positive impact on the economic situation in the industry. This issue was also studied by B. Wang *et al.* (2024), whose results confirmed that ESG strategies play a key role in the development of the agro-industrial complex. They reduce the negative impact on the environment by introducing energy-efficient technologies and reducing greenhouse gas emissions. In addition, ESG-oriented companies have more opportunities to attract investment and receive government subsidies.

P. Vrabcová and H. Urbancová (2023) also demonstrated that sustainable business practices in agriculture include the rational use of natural resources and the use of precision farming technologies. The social component of ESG aims to improve the working conditions of farmers and support local communities. Effective ESG management increases the transparency of supply chains and reduces the risks associated with climate change. Notably, the implementation of ESG strategies in the agricultural sector requires significant investments and reworking of business models, which can be difficult for small and medium-sized agricultural enterprises (Hopka & Kovtun, 2024). However, in the long run, such changes contribute to the sustainability of agriculture by reducing dependence on climate risks and fluctuations in resource prices. Furthermore, consumers and investors increasingly prefer companies that adhere to the principles of sustainable development, making the ESG approach not only ethically justified but also economically beneficial.

The rational use of biological resources has become a key factor in ensuring sustainability and increasing crop yields (Khrystenko *et al.*, 2025). The study analysed new agricultural technologies, such as the use of biodegradable fertilisers and biopreparations, which contribute to improving plant resilience and protecting them from disease. These innovative methods, including environmentally friendly fertilisers, reduce the negative impact on the environment while increasing agricultural efficiency. Such practices are fully consistent with the principles of sustainable development, providing long-term environmental and economic benefits. D. Wang *et al.* (2023) concluded that the efficient use of bioresources in agriculture is aimed at preserving ecosystems and increasing productivity without depleting natural resources. This includes crop rotation, organic farming and the use of biological plant protection methods. These approaches help restore soil fertility and reduce the negative environmental impact of the agricultural sector.

E. Duncan *et al.* (2021) determined that innovative agricultural technologies, including precision farming, biotechnology and automation, contribute to more efficient use of resources. Drones and sensors can be used to monitor the condition of crops and optimise irrigation and fertiliser management. The introduction of digital solutions reduced costs, increased yields and improved the resilience of agriculture to climate change. The findings confirm the results of previous studies, showing that innovative agricultural technologies do indeed contribute to more efficient use of biological resources. Precision farming and biological plant protection methods help minimise losses and reduce environmental impact. As a result, agricultural enterprises not only gain economic benefits but also achieve long-term environmental sustainability, which correlates with the principles of rational use of natural resources.

The circular economy and zero-waste production have become key trends in the agricultural sector (Ciuła *et al.*, 2024). Recycling of agricultural waste, such as biogas, composting and feed additives, contributes to the efficient use of resources, reducing waste and the negative impact on the environment. The use of agricultural by-products in the production of biofuels and biopolymers also reduces dependence on fossil energy sources and promotes the development of environmentally friendly technologies (Shumka *et al.*, 2021). Such approaches not only increase economic efficiency but also significantly strengthen the environmental sustainability of agribusiness. The study by L. Rojas *et al.* (2022), emphasising that the circular economy in the agro-industrial complex prioritises minimisation of waste and maximising the use of by-products, is noteworthy. In agriculture, this is manifested in the processing of organic waste into biochar, biogas or compost, which helps to reduce the environmental impact. This approach not only helps farmers reduce costs but also contributes to the creation of closed production cycles, increasing the sustainability of the agricultural sector.

A. Taghizadeh-Alisaraei *et al.* (2023) concluded that zero-waste production in agriculture is based on the full use of resources and the recycling of by-products. For instance, straw is used to produce feed, fertiliser or biofuel, and food waste is processed into feed or organic fertiliser. The introduction of such technologies reduces the negative impact on the environment and increases the profitability of agricultural production. These results confirm the conclusions outlined in the previous section, as the circular economy and zero waste production not only reduce resource waste but also increase the efficiency of the agricultural sector. Examples of successful use of by-products show that closed production cycles can reduce costs and improve the environmental sustainability of agriculture (Shebanin *et al.*, 2024). Thus, the introduction of circular economy principles in the agricultural sector is a key factor for increasing the competitiveness and sustainable development of the industry.

The use of biotechnology, such as genetic engineering and biofermentation, has proven to be a crucial factor in increasing the resilience of crops to various stresses, including drought and disease. Studies have shown that the introduction of new plant varieties adapted to adverse conditions, as well as the development of new types of feed, fertilisers and food additives using biocatalysis, improves production results and contributes to the sustainability of the agricultural sector. These biotechnological innovations have significantly increased both agricultural efficiency and food security. A. Tyczewska *et al.* (2023) confirmed that biotechnology in the agricultural sector contributes to increased yields, improved plant resistance to stressful conditions and reduced need for chemical fertilisers. Modern methods, such as biofermentation and the use of beneficial microorganisms, help to improve soil conditions and protect crops from diseases. These technologies not only increase agricultural productivity but also contribute to its environmental sustainability.

R. Govindasamy *et al.* (2022) also concluded that genetic engineering and biofermentation are key in creating new plant varieties with improved characteristics, as well as in developing more efficient methods of biomass processing. Genetic modification makes it possible to create crops that are resistant to drought, pests and diseases, which helps to reduce crop losses. Biofermentation, in turn, is used to produce biofertilisers, biofuels and fermented feed, which contributes to more efficient use of resources in agriculture. Comparing the data obtained during the research, it can be noted that biotechnology is an important factor in improving the efficiency and sustainability of the agricultural sector. Genetic engineering and biofermentation not only improve the characteristics of crops but also help reduce the use of chemical fertilisers and pesticides. This improves productivity while reducing the environmental footprint.

Reduction of the carbon footprint has become a key aspect of the sustainable development of the agricultural sector. The introduction of precision farming technologies, including the use of drones, IoT and Big Data, has significantly reduced the consumption of resources such as water, fertilisers and energy. This has not only reduced carbon emissions but also increased economic efficiency by cutting costs. The development of organic farming and the use of alternative energy sources, such as solar panels and biogas plants, have become additional measures to reduce carbon emissions and mitigate climate impact. J. Rajakal *et al.* (2021) concluded that reducing the carbon footprint in the agricultural sector is achieved by optimising production processes, using renewable energy sources and reducing greenhouse gas emissions. The introduction of precision farming technologies, the use of biological fertilisers and energy-saving equipment helps to reduce the negative impact on the environment. In addition, carbon farming practices, such as green manure and minimum tillage, improve CO_2 sequestration.

U. Bhatti *et al.* (2024) noted that the greening of agriculture is aimed at creating a balance between agro-industrial processes and natural ecosystems. This includes the use of organic fertilisers, the reduction of chemicals and the introduction of conservation technologies. Such approaches not only preserve biodiversity but also increase the resilience of the agricultural sector to climate change. The analysis of the study results demonstrated that the reduction of the carbon footprint and greening agriculture are important components of the sustainable development of the agro-industrial complex. The introduction of environmentally friendly technologies and the use of alternative energy sources leads to a significant reduction in greenhouse gas emissions and improved soil conditions (Parkhomets *et al.*, 2023). Thus, the transition to more environmentally friendly agricultural practices not only reduces the negative impact on the environment but also contributes to improving the economic efficiency of the agricultural sector.

The benefits of the bioeconomy for the agricultural sector include improved environmental sustainability, increased economic efficiency and social relevance. Environmental benefits, such as reduced soil, water and air pollution, contribute to improving the environment and preserving natural resources. Economic efficiency is achieved by reducing the cost of raw materials and energy resources, which strengthens the competitiveness of enterprises. The social significance of the bioeconomy is manifested in the creation of new jobs and the improvement of the lives of rural residents, which is a key element of sustainable development and social stabilisation. All these factors underline the role of the bioeconomy as a strategic direction for the long-term sustainable development of the agro-industrial complex.

CONCLUSIONS

The results of the study demonstrated that the bioeconomy is an important aspect of the sustainable development of the agricultural sector. Implementation of ESG strategies in the agricultural sector helps to reduce the carbon footprint, efficiently use natural resources and improve the social responsibility of business. By following ESG principles, companies gain competitive advantages, strengthen investor and consumer confidence, and increase their economic sustainability. The rational use of biological resources contributes to increased agricultural productivity while reducing environmental impact. The use of biodegradable fertilisers and biopreparations improves soil quality and reduces water and air pollution. The circular economy and waste-free technologies for processing agricultural waste create added value, including biogas, biofuels and organic fertilisers. The use of biotechnology, such as genetic engineering and biofermentation, contributes to the creation of plant varieties that are resistant to stress factors and to the development of innovative feeds and fertilisers. These technologies increase yields, reduce the need for chemicals and reduce the cost of agrochemicals. The use of precision farming, drones and IoT technologies helps to use resources efficiently, and the transition to renewable energy sources reduces the environmental impact of agriculture on the climate.

In Kazakhstan, the area of agricultural land designated for sustainable farming increased from 43 million hectares to 47 million hectares, and the use of organic fertilisers increased from 5% to 7%. The area covered by drip irrigation increased from 1.5 million hectares to 3 million hectares. Food losses decreased from 16% to 13%. The share of recycled waste in agricultural production increased from 22% to 30%, and the volume of recycled organic waste increased from 1 to 2 million tonnes. In the biotechnology sector, the share of genetically modified crops increased from 5% to 9%, and the carbon footprint decreased by 5 million tonnes of CO_2. Examples from Kazakhstan, Germany and the Netherlands show that the bioeconomy increases the efficiency of agriculture and reduces its environmental footprint. Olzha Agro reduced chemical use and increased yields by 18%, while EcoMilk reduced CO_2 emissions by 25%. In Germany, biogas plants have reduced energy costs by 50%, and in the Netherlands, vertical farms have reduced water consumption by 95%. These technologies make the agricultural sector sustainable and competitive. The long-term impacts of biotechnology on agroecosystems and socio-economic development in rural areas are not well understood, which is a limitation of this study. To determine the economic efficiency of bioeconomic technologies, additional research is required in different climatic and geographical conditions.

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CONFLICT OF INTEREST

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Біоекономіка як стратегічний напрям сталого розвитку агропромислового комплексу

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Анотація. Дослідження спрямоване на виявлення ключових принципів біоекономіки та їхнього впливу на екологічну, економічну та соціальну стійкість агропромислового комплексу. Під час дослідження було проведено комплексний аналіз наявних практик застосування Environmental, Social, Governance (ESG)-стратегій і біоекономіки в агропромисловому комплексі, включно з вивченням успішних кейсів і порівняльним аналізом ефективності впровадження інноваційних технологій. Під час проведеного дослідження було встановлено, що впровадження принципів біоекономіки в агропромисловий комплекс істотно сприяє зміцненню стійкості та підвищенню ефективності сільськогосподарського сектору. У період з 2021 по 2024 рік спостерігалося зростання площ, що використовуються для сталого землеробства – з 43 до 47 млн гектарів, а також збільшення частки органічних добрив у загальному обсязі – з 5 % до 7%. Використання крапельного зрошення також зросло – з 1,5 до 3 млн гектарів. Паралельно з цим відбулося зниження продовольчих втрат в агросекторі з 16 % до 13 %, а ефективність використання водних ресурсів збільшилася з 3,5 до 4 км^3. Розвиток циркулярних технологій приніс помітні результати: частка перероблених відходів в агровиробництві зросла з 22 % до 30 %, а кількість підприємств, що застосовують такі рішення, збільшилася з 90 до 150. Застосування біотехнологій також справило позитивний вплив – частка ГМ-культур зросла з 5 % до 9 %, а вуглецевий слід було скорочено з 5 до 3 млн тонн CO_2. Вивчення успішного впровадження ESG-підходів в агробізнесі, зокрема в Казахстані, Німеччині та Нідерландах, засвідчило зниження застосування хімічних добрив, поліпшення якості продукції та зменшення викидів парникових газів. Наприклад, агрохолдинг «Олжа Агро» знизив використання агрохімікатів на 12%, домігшись при цьому зростання врожайності на 18 %. А компанія «EcoMilk» завдяки використанню біорозкладного паковання та встановленню сонячних панелей скоротила викиди CO_2 на 25 %. Загалом, результати аналізу підтвердили значущість інтеграції біоекономічних та ESG-принципів для сталого розвитку агропромислового комплексу та підвищення його соціальної значущості

Ключові слова: екологічний слід; точне землеробство; циркулярна економіка; біоферментація; ESG-стратегії

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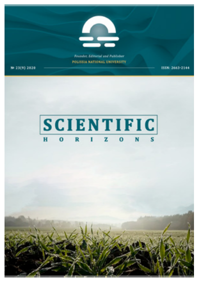

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Trends in global grain and seed trade, Ukrainian position on the global market

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Abstract. The study aimed to comprehensively analyse the Ukrainian grain market during the war and its prospects after its end, as well as an assessment of key trends in the global grain market in 2020-2024. The research methodology was based on the collection of data from reports of international organisations and open sources, their processing through statistical, comparative and forecasting analysis, as well as the synthesis of quantitative and qualitative indicators. The results demonstrated that global production in 2023/24 totalled 789.8 million tonnes of wheat, 1.22 billion

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tonnes of corn, 149 million tonnes of barley and 57 million tonnes of sunflower seeds, led by China, the US, the EU and Ukraine. The study determined that in Ukraine, the war reduced the area under crops from 15.4 million hectares in 2021 to 9.1-10.2 million hectares in 2024, while yields reduced from 47.8 hwt/ha in 2021 to 38.3 hwt/ha in 2022, before recovering to 43.8 hwt/ha in 2023. The study also determined that exports decreased from 85 million tonnes (in the 2021/22 marketing year) to 46-50 million tonnes (2022/23) but increased to 67.4 million tonnes (2023/24) thanks to the Solidarity Roads and the humanitarian corridor. Analysis of wheat prices determined that the price ranged from 6000-6500 UAH/t (USD 210-230/t FOB) in 2020/21 to 5500-6000 UAH/t (USD 200-220/t) in 2022/23 and 8191-9500 UAH/t (USD 220-250/t) in 2024. The sector's losses included machinery (4.7 billion USD) and irrigation (225 million USD), while logistics costs increased by 30-50%, affecting global prices (12-13 USD per bushel for wheat in 2022, 8-9 USD in 2024). The analysis of the prospects for the development of the Ukrainian grain market after the war found that the restoration of infrastructure worth 29 billion USD, modernisation of elevators, expansion of markets to the EU, Africa and Asia, as well as investments supported by international organisations and the World Bank will return exports to 85 million tonnes and potentially reach 100 million tonnes annually, strengthening Ukraine's role in global food security

Keywords: crop exports; planted areas; yields; logistics; infrastructure destruction and reconstruction; agricultural sector

INTRODUCTION

Agriculture, in particular the grain sector, is the backbone of Ukraine's economy and is key in ensuring global food security, which determines the relevance of an analysis of its state and prospects in the context of a full-scale Russian invasion that began in 2022. The war caused significant losses in agricultural infrastructure, a reduction in acreage, disruption of supply chains, and a drop in exports, which not only weakened Ukraine's position on the global market but also exacerbated the problem of access to grain in countries in Africa, Asia, and the Middle East that depend on its supplies (Panfilova *et al.*, 2025). At the same time, the resilience of Ukraine's agricultural sector, adaptation to wartime conditions, and support from international organisations open up prospects for recovery and modernisation after the war, which requires a detailed study of the current state, assessment of losses, and forecasting of future development to identify strategies that could return Ukraine to its pre-war status as one of the world's leading grain exporters.

One of the main challenges is the lack of studies that comprehensively cover the impact of the war on the grain market and offer specific recovery scenarios. L. Osipova (2022) noted that the war caused a significant reduction in grain exports, but the analysis was limited to general data, without a detailed consideration of logistical changes and their impact on pricing, and forecasts for post-war development. I. Lynnyk (2024) assessed the loss of infrastructure, such as elevators and ports, noting their importance to the sector, but without the potential of alternative routes and the role of international support, which reduces its practical value. L. Pobochenko *et al.* (2023) highlighted changes in global grain trade due to the war, noting the critical importance of Ukraine in these processes, but ignoring the impact on domestic prices and prospects for market expansion, leaving gaps in the analysis of local factors.

Another important aspect of highlighting the impact of the war in Ukraine on food security in the world, as well as determining its investment potential and the role of international organisations in the recovery of the agricultural sector, requires additional research to fully understand the prospects. X. Wang *et al.* (2023) analysed global grain trends, which traced the impact of external market factors on trade, but without considering the specifics of the war in Ukraine, in particular its impact on the processing industry and domestic logistics, which reduces the relevance to the local context. A. Abu Hatab (2022) analysed in detail the impact of the war on food security in Africa, highlighting the global consequences of the decline in Ukrainian exports, but not the prospects for the recovery of these exports and adaptation to new conditions, leaving gaps in the analysis of future development. T. Ben Hassen and H. El Bilali (2022) assessed the impact of the war on global food security in detail, providing a valuable basis for analysis, but without a detailed analysis of global trends in world trade, leaving the overview incomplete for assessing post-war prospects.

Another important aspect is the insufficient coverage of global trends in the grain sector related to geopolitical factors and their impact on trade flows (Cheremisina *et al.*, 2025). A. Lukyanova and A. Zeynalov (2022) discussed in detail the redistribution of grain markets due to sanctions against Russia, assessing new opportunities for other exporters, but they do not address the long-term consequences of these changes for importing countries, which limits their predictive depth. S. Nate *et al.* (2024) analysed the impact of geopolitical tensions on logistics in the Black Sea region, emphasising its importance for global supply, but not considering the potential of alternative logistics corridors outside the region, which narrows the scope of the results. L. Liu *et al.* (2023) analysed the growth of competition between key grain exporters such as Argentina and Brazil during the crises, but did not address the role of developing countries as new players in the market, which reduces the completeness of the findings.

The study aimed to provide a comprehensive analysis of the Ukrainian grain market, incorporating changes in the global grain sector in 2020-2024. To achieve this goal, several key tasks were set, including: studying the dynamics of production, exports and prices for major grains (wheat, corn, barley) and sunflower seeds in the world and Ukraine, analysing the impact of the war on these indicators; assessing direct losses of the Ukrainian agricultural sector and changes in global grain logistics caused by the conflict; developing scenarios for the post-war recovery of the Ukrainian market, addressing the role of infrastructure, investment and international support, as well as the state of the industry and its potential in the future.

MATERIALS AND METHODS

The methodology of this study was based on a comprehensive approach to the analysis of the Ukrainian and global grain market for the period of 2020-2024, emphasising the impact of the war on the Ukrainian agricultural sector and its development prospects. To achieve these goals, various sources of information, methods of data collection, data processing and analysis were used, ensuring the objectivity and reliability of the findings. The main principles of the study were systematic, comparative analysis and synthesis of quantitative and qualitative data, adapted to the specifics of the subject of the study – grain production, logistics, prices and trade relations.

The information base is based on official reports of international organisations, in particular the Food and Agriculture Organisation (n.d.a; n.d.b; 2024; 2025), as well as data from the U.S. Department of Agriculture (2025a; 2025b) and FAOSTAT statistical databases (n.d.). For the analysis of the Ukrainian market, it was used the materials of the Ministry of Agrarian Policy and Food of Ukraine (n.d.), as well as estimates of losses in the agricultural sector by the Kyiv School of Economics (Neyter *et al.*, 2024) and the World Bank (2025). Additionally, analytical reports from private agricultural companies such as UkrAgroConsult (n.d.) and SuperAgronom (n.d.) were used to provide data on prices, yields and logistics on the domestic market. Primary data was supplemented with information from open sources – press publications, and regulatory documents, such as Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions No. COM/2022/217 “An Action Plan for EU-Ukraine Solidarity Lanes to Facilitate Ukraine’s Agricultural Exports and Bilateral Trade with the EU” (2022). To update the information for 2024, preliminary forecasts and press releases from the Ukrainian Grain Association and the U.S. Department of Agriculture were used, given that full annual reports were not yet available as of February 2025.

Data was collected through a systematic review of statistical reports and databases available online, followed by verification through cross-checking sources. For example, global grain production figures for 2022/23 and 2023/24 were taken from the Food and Agriculture Organisation and the U.S. Department of Agriculture and then updated through FAOSTAT to ensure consistency of figures. For Ukraine, data on planted areas, yields, and exports for 2020-2024 were collected from official reports of the Ministry of Agrarian Policy and the Ukrainian Grain Association, supplemented by estimates of war losses by the Kyiv School of Economics (Neyter *et al.*, 2024). Prices for cereals and sunflower seeds were based on weighted averages from UkrAgroConsult and SuperAgronom reports, incorporating the exchange rate (27-40 UAH/USD for the period) and logistics costs obtained from the Grain Corridor and Solidarity Roads publications. In cases of discrepancies (for example, between the export estimates of the U.S. Department of Agriculture and the Ukrainian Grain Association for 2023/24), the average value was preferred. For the qualitative analysis of the prospects, the method of expert estimates based on the forecasts of the World Bank and the Food and Agriculture Organisation was used.

Data processing included quantitative and qualitative analysis. Quantitative indicators, including production volumes, planted areas, yields, exports, and prices, were systematised in tables and converted into percentages to compare the contribution of individual countries (e.g. Ukraine’s share of global corn exports) or dynamics over the years. For this purpose, statistical processing methods were used: calculation of averages, determination of price ranges and trend-based forecasting. Currency conversions were made based on the official exchange rate of the National Bank of Ukraine for the respective years (27-28 UAH/USD in 2020-2021, 36-38 UAH/USD in 2022-2023, 38-40 UAH/USD in 2024). The qualitative analysis included an assessment of logistical changes, infrastructure losses (machinery, irrigation), and development prospects, for which a synthesis and summary of information from various sources were used. Data on prices on global markets were taken from the Chicago Mercantile Exchange and correlated with Ukrainian conditions.

The analysis was conducted in several areas. The comparative method was used to compare Ukraine’s performance with that of global leaders (China, the US, and the EU). Historical analysis traced the dynamics of sown areas and prices. A systematic approach was used to assess the relationship between logistics, prices and markets. The forecasting method was based on data extrapolation and estimates of international organisations. Scenario analysis was used to draw qualitative conclusions about development prospects:

infrastructure rehabilitation, market expansion and the role of the Food and Agriculture Organisation were assessed through potential development scenarios. All methods were combined to create a holistic picture adapted to the conditions of war and post-war recovery.

RESULTS

The global grain trade is a strategically important segment of the agricultural economy that determines food security, influences macroeconomic indicators of countries and shapes the balance of power in international trade relations. In 2020-2024, the global grain market will show steady growth driven by several factors. Firstly, there is a steady increase in the global population, which stimulates the growth of demand for food. In addition, changes in consumption patterns in many countries, including increased demand for meat and dairy products, have increased the need for feed grains. The dynamics of global grain production in 2020-2024 were characterised by overall growth, although there were periodic declines due to adverse weather conditions, political factors and logistical problems. The total grain production in the 2023/24 marketing year reached 2.854 billion tonnes, slightly higher than the average for the last five years (2.7 billion tonnes) and the previous year (2.8 billion tonnes). One of the key trends is the strengthening of the position of major producers such as the US, China, Brazil, India and the EU, which together account for about 70% of global production of major grains (Fig. 1).

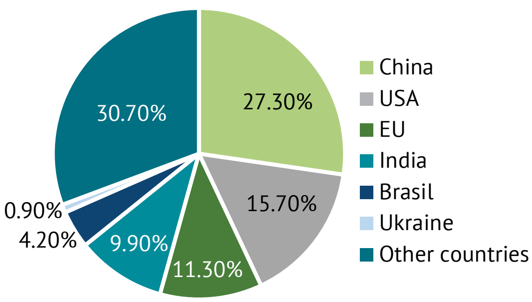

***Figure 1**. Leading countries in grain production (2023/24 marketing year)*
***Source:** compiled by the authors*

Wheat remains one of the most important crops in the world, key in meeting the food needs of billions of people, through its use in the production of bread, flour products and other staple foods (Panfilova *et al.*, 2023). In the 2023/24 marketing year, global wheat production reached 789.8 million tonnes, one of the highest levels on record, reflecting sustained growth driven by improved agricultural technologies and favourable weather conditions in several regions (Fig. 2).

China remains the leading producer, annually supplying around 135 million tonnes of wheat, which accounts for a significant portion of its domestic food market, although the country is rarely a major exporter. The EU, with 125 million tonnes of wheat, is second, being substantial in both domestic supply and exports, particularly to North Africa and the Middle East. India, with 108 million tonnes, ranks third, demonstrating steady production growth to meet the needs of its huge population and build up strategic reserves. This trend is affecting traditional trade routes, forcing producers to adapt to new market conditions that include both logistical challenges and price fluctuations due to geopolitical factors and climate change. Corn also remains one of the most important cereals, playing an indispensable role in both the food and feed industries, where it serves as the main source of energy for livestock and poultry, as well as a feedstock for bioethanol and other industrial products (Bulgakov *et al.*, 2020). In the 2023/24 marketing year, global corn production reached an impressive 1.22 billion tonnes, reflecting steady growth driven by both higher yields thanks to modern technologies and expanding acreage in key regions (Fig. 3).

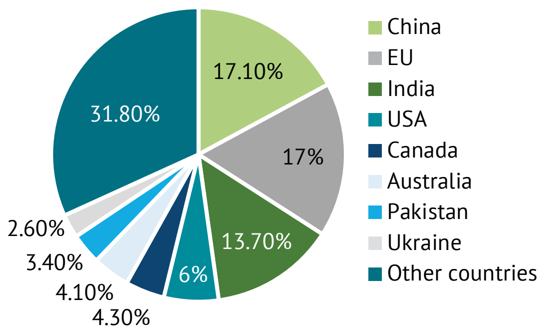

***Figure 2**. World leaders in wheat production (2023/24 marketing year)*
***Source:** compiled by the authors*

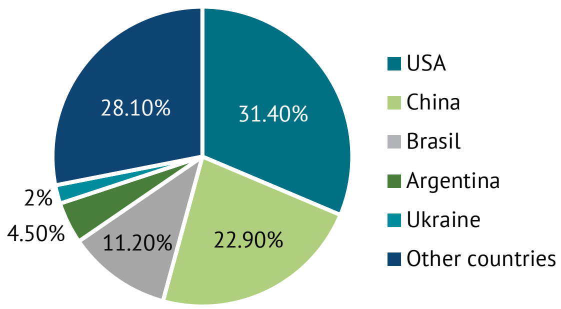

***Figure 3**. World leaders in corn production (2023/24 marketing year)*
***Source:** compiled by the authors*

The United States remains the undisputed leader in this area, with an annual corn harvest of more than 383 million tonnes, accounting for almost a third of global production; a significant portion of this volume is used for domestic consumption, particularly in the livestock and biofuel industries, and the rest is exported, strengthening the US position in the global market. China, with 279 million tonnes, is the second largest producer, but its production is mainly focused on domestic needs, particularly the rapidly growing livestock industry, which supports demand for feed, as well as food and industrial purposes, and therefore the country exports only a small part of the harvest (Kulazhanov *et al.*, 2024). Brazil, with 137 million tonnes, and Argentina, with 55 million tonnes, have seen significant production increases, thanks to the expansion of cultivated areas in favourable climates, the introduction of advanced agricultural technologies such as precision farming and drought-resistant hybrids, and improved infrastructure for grain storage and transportation. These South American countries are not only meeting their demand, but are also increasingly competing on the international market, supplying corn to Asia, Africa and Europe, which strengthens their position as leading players in global trade in this crop.

Barley is significant among cereals, remaining an indispensable component of global trade due to its wide use in the food industry, in particular to produce malt, beer and some types of bakery products, and in the feed sector, where it is an important source of nutrients for livestock and poultry. In the 2023/24 marketing year, global barley production reached 149 million tonnes, reflecting stable demand for the crop and its adaptability to different climatic conditions (Fig. 4).

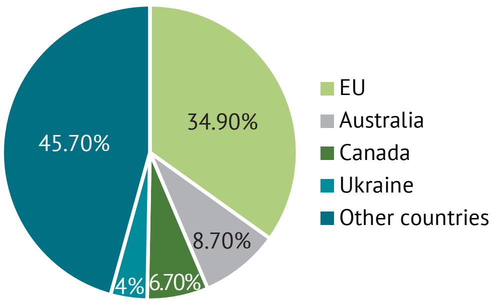

Figure 4. *World leaders in barley production (2023/24 marketing year)*
Source: *compiled by the authors*

The EU remains the leading barley producer, with 52 million tonnes of barley, thanks to countries such as Germany, France and Spain, where advanced farming techniques and favourable weather conditions contribute to high yields; much of Europe's barley is used for domestic consumption, particularly in brewing, and for export. Australia, which harvested 13 million tonnes, benefits from an arid climate ideal for barley cultivation and is a key exporter focused on Asian markets such as China and Japan. Canada, with 10 million tonnes, is known for its high-quality barley, which is in demand in the North American brewing industry and beyond, making it a consistent leader. Despite the war, Ukraine has managed to produce about 6 million tonnes of barley, although this is less than pre-war levels; its contribution is still valuable, especially for exports to the Middle East. Barley is a strategically important export product, particularly for countries such as Saudi Arabia, where it is in steady demand in the feed industry for livestock feeding and in processing, which maintains its importance on the global market even in the face of competition from other cereals.

Sunflower seeds have a special place in the agricultural sector due to their key role in the production of sunflower oil – a strategic product that is not only a staple of the food basket in many countries, but also an important component in cosmetics, pharmaceuticals and other industries, making it economically significant on a global scale. In the 2023/24 marketing year, global sunflower seed production reached 57 million tonnes, reflecting stable demand for the crop and its adaptability to different agricultural and climatic conditions (Fig. 5).

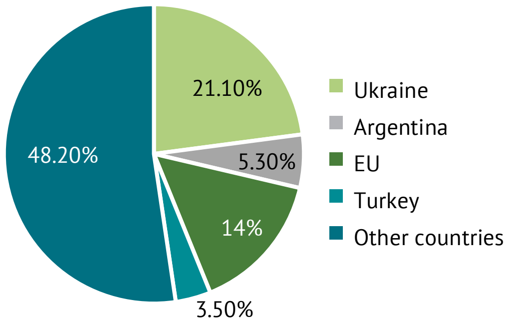

Figure 5. *World leaders in sunflower seed production (2023/24 marketing year)*
Source: *compiled by the authors*

Analysing the top sunflower seed producing countries, it is worth noting that over 21% of this volume is accounted for by Ukraine, which holds a dominant position in the global market due to its fertile soils, large, planted areas and developed processing infrastructure. Despite the substantial challenges posed by the war, including the occupation of some agricultural land and disruption of supply chains, Ukraine managed to harvest around 12 million tonnes of sunflower seeds, an achievement made possible by the resilience of the agricultural sector and its focus on growing this highly profitable crop, which provides a significant portion of the country's foreign exchange earnings through the export of sunflower oil – a product in demand in Europe, Asia and the Middle East.

Concerning Ukraine's position on the global market, Ukraine has traditionally been one of the key players on the global grain market, playing an important role in ensuring global food security. Thanks to its fertile black soil, which covers a large part of the national territory, and favourable climatic conditions for growing grain crops such as wheat, corn and barley, Ukraine is consistently among the leading exporters of these products

(Pichura *et al.*, 2024). Despite the challenges posed by the full-scale invasion in 2022, the country has managed to maintain its position on the international stage by adapting to the new conditions through alternative logistics routes and support from international partners. In the 2023/24 marketing year, Ukraine exported over 67.4 million tonnes of grains and oilseeds, which is a significant figure given the temporary occupation of some agricultural land and disruption of traditional export routes through the Black Sea. The dynamics of crop areas in Ukraine have undergone significant changes due to the war and economic factors (Fig. 6).

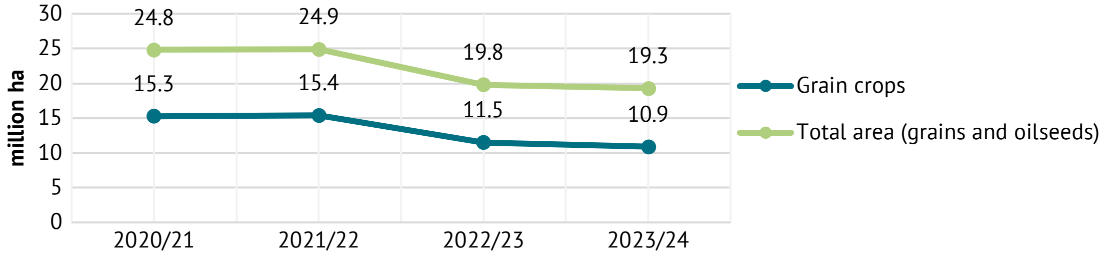

***Figure 6**. Dynamics of grain crops planted areas in Ukraine, million ha (2020-2024)*
***Source:** compiled by the authors based on the Ministry of Agrarian Policy and Food of Ukraine (n.d.)*

In the pre-war period, Ukraine demonstrated impressive results in the agricultural sector, particularly in 2021, when the country achieved a record harvest of 100 million tonnes of grain and oilseeds, made possible by the expansion of grain crop acreage to over 15 million hectares, and the total area under crops to 24.9 million hectares. This success was due to optimal weather conditions, high yields, and access to resources such as fertilisers and machinery, which enabled the fertile black soil to be used to its full potential. However, Russian full-scale invasion in February 2022 drastically changed the situation: the area under grain crops reduced substantially to 11-12 million hectares, which is 10-22% less than in 2021, depending on the region and estimates (Food and Agriculture Organisation (n.d.a; n.d. b) and the Ukrainian Grain Association indicate a range of reductions). The main reasons were the temporary occupation of approximately 20% of agricultural land (about 5 million hectares), the mining of fields, and logistical disruptions that hampered the spring sowing campaign, especially for spring crops such as maize and barley. In 2023, Ukrainian farmers managed to partially adapt to the war conditions, restoring grain crops to approximately 11 million hectares, although the total area under all crops was 19.3 million hectares; however, significant areas of over 174,000 km^2 remained mined, and 109,000 km^2 were under occupation, limiting access to land, especially in the east and south of the country, where crops were traditionally grown. km^2 remained mined, and 109,000 km^2 were under occupation, limiting access to land, especially in the east and south of the country, where a significant part of the grain was traditionally grown. For 2024/25, a reduction in the area under grain crops, in particular winter wheat, to 9.1-10. This shift in crop structure is a strategic response by farmers to high global prices for oilseeds (e.g., sunflower oil remains a key export product). This shift in the crop structure is a strategic response by farmers to high global prices for oilseeds (for example, sunflower oil remains a key export product) and to the difficulties in grain exports, which require larger volumes and more stable transport access. As a result, sunflower acreage in 2024/25 may remain at 4.8-5 million hectares, while soybean and rapeseed acreage may increase to 1.6-1.8 million hectares and 1.5-1.6 million hectares, respectively, reflecting farmers' desire to maximise profits amid uncertainty and war. Notably, grain and oilseed yield in Ukraine are stable even under difficult conditions (Fig. 7).

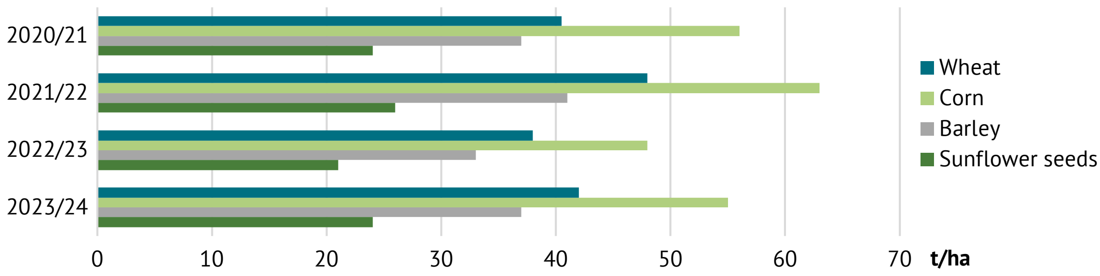

***Figure 7**. Dynamics of grain and sunflower yields in Ukraine, t/ha (2020-2024)*
***Source:** compiled by the authors based on the Ministry of Agrarian Policy and Food of Ukraine (n.d.)*

In 2022/23, the Ukrainian agricultural sector faced unprecedented challenges due to Russia's full-scale invasion, which began in February, as well as unfavourable weather conditions, particularly drought in the southern and eastern regions, which further complicated the cultivation of grain crops. Despite this, the average grain yield was 3.83 t/ha, which was significantly lower than the pre-war level of 2021 (4.78 t/ha), but still demonstrated the resilience of farmers in extreme conditions. Wheat yielded about 3.78 tonnes per hectare, maize 4.76 tonnes per hectare, and barley 3.35 tonnes per hectare, but the gross harvest of cereals and oilseeds reduced to 56 million tonnes, of which cereals accounted for approximately 53.1 million tonnes. In 2023/24, the situation improved slightly as farmers adapted to the realities of war. They optimised their use of resources, for example by increasing the application of available fertilisers where possible and returned to cultivating some of the deoccupied land in the Kharkiv, Mykolaiv and Kherson regions. Better weather conditions, including a mild winter and sufficient rainfall in the spring, contributed to an increase in yields to 4.38 tonnes per hectare: wheat reached 4.25 tonnes per hectare, maize 5.5 tonnes per hectare, and barley 3.7 tonnes per hectare. As a result, the total harvest increased to 70 million tonnes, of which grain crops accounted for about 60 million tonnes, with the rest being oilseeds such as sunflower (12.2 million tonnes). This 25% increase compared to 2022 demonstrated the agricultural sector's ability to recover even in crisis conditions. According to estimates for 2024/25, yields may decline slightly to 4.05-4.2 tonnes/ha due to less favourable weather conditions and the gradual depletion of soils in regions of intensive agriculture, such as the Poltava and Cherkasy regions, where, according to a report by the Kyiv School of Economics, no proper crop rotation has been carried out for years due to economic priorities (Neyter *et al.*, 2024). It is estimated that wheat yields will be around 4-4.2 t/ha, corn 5-5.3 t/ha, and barley 3.4-3.6 t/ha, which, together with a reduction in acreage to 9.1-10.2 million hectares, will result in a gross grain harvest of 65-69 million tonnes. These figures highlight the extraordinary resilience of Ukrainian agriculture, which, despite the war, the mining of over 174,000 km^2 of land and the occupation of 109,000 km^2, continues to produce significant volumes. At the same time, a full return to pre-war levels, such as 86 million tonnes of grain in 2021, remains unattainable without the cessation of hostilities, demining of territories and restoration of logistics infrastructure, in particular Black Sea ports, which are critical for exports. Exports of grain and oilseeds are the backbone of Ukraine's agricultural economy, providing a significant portion of foreign exchange earnings and supporting the stability of the national currency even in wartime, as the agricultural sector traditionally accounts for up to 40% of the national export earnings (Fig. 8).

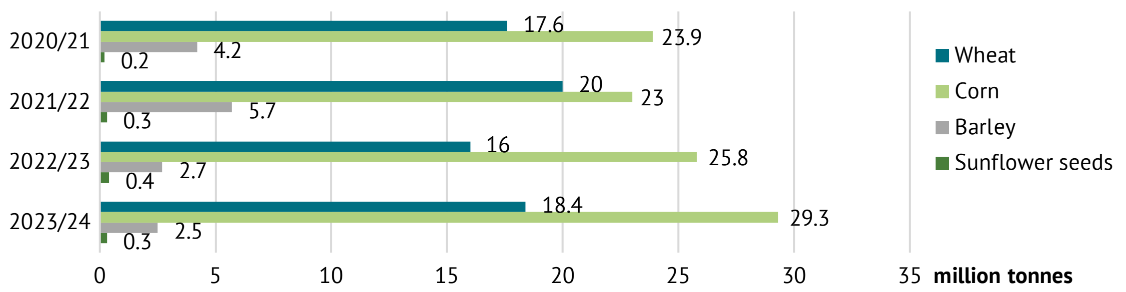

***Figure 8**. Dynamics of exports of grain crops and sunflower in Ukraine in 2020-2024, mln tonnes*
***Source:** compiled by the authors based on the Ministry of Agrarian Policy and Food of Ukraine (n.d.)*

In the 2021/22 marketing year (July 2021 to June 2022), Ukraine achieved a record high, exporting 85 million tonnes of grain and oilseeds to foreign markets, including 48.6 million tonnes of grain (20 million tonnes of wheat, 23 million tonnes of corn, 5 million tonnes of barley) and significant volumes of sunflower oil and seeds, which was made possible by the developed infrastructure of Black Sea ports such as Odesa, Chornomorsk and Pivdennyi, as well as the high harvest in 2021 (106 million tonnes). However, in 2022/23 (July 2022 to June 2023), exports redu substantially to 46-50 million tonnes due to Russian full-scale blockade of Black Sea ports, which paralysed traditional sea routes, which transported up to 90% of agricultural products; this caused accumulation of grain in warehouses, increased transport costs and a drop in incomes of farmers, although a partial resumption of exports became possible through land routes via Poland, Romania and Hungary, as well as thanks to the launch of a "grain corridor" in August 2022, brokered by the United Nations (UN) and Turkey. In 2023/24 (July 2023 to June 2024), the situation improved: thanks to the extension of the "grain corridor" until September 2023, and subsequently the creation of a humanitarian sea route along the coast after Russia's withdrawal from the agreement, as well as the development of alternative routes through EU countries, rail and river routes through the Danube (Romania) and transhipment points in Poland, Ukraine exported 67. 4 million tonnes of grain and oilseeds, including 23.1 million tonnes of corn, 16.6 million tonnes of wheat and 4.2 million tonnes of barley, as well as significant volumes of sunflower oil (over 5 million tonnes), demonstrating its adaptation to the war conditions and the support of international partners.

According to the forecasts for 2025 (July 2024 – June 2025), exports of grains and oilseeds are expected to reach 50-60 million tonnes, depending on logistical capacities, in particular, the capacity of the western borders, where delays on the Polish-Ukrainian border periodically create bottlenecks, – and the geopolitical situation, including the stability of sea routes and potential attacks on port infrastructure; estimates vary from 50 million tonnes to 60 million tonnes depending on the harvest (65-69 million tonnes). The main markets remain Asia, such as China (corn and soybeans) and Indonesia (wheat), North Africa, in particular Egypt (wheat), and the EU, where Spain (corn) and the Netherlands (oilseeds) are key importers, although competition is increasing from Russia, which is actively dumping wheat prices, and Latin American countries, such as Brazil and Argentina, which are increasing their corn supplies. Despite these challenges, Ukraine maintains its global leadership in sunflower and sunflower oil exports (over 50% of the global market), fourth place in corn (after the US, Brazil and Argentina) and sixth in wheat (after the EU, US, Canada and Australia), which underscores its strategic importance in the global grain market and the resilience of agricultural exports even during the war, when every million tonnes is the result of heroic efforts of farmers and logisticians.

Notably, the direct losses of the Ukrainian agricultural sector as a result of the full-scale Russian invasion that began in 2022 cover a wide range of destruction and damage, going far beyond grain theft or the destruction of elevators and storage infrastructure. One of the most critical blows was the massive destruction and damage to agricultural machinery, which is essential for proper farming. According to estimates by the Kyiv School of Economics in cooperation with the Ministry of Agrarian Policy, as of mid-2023, the loss of equipment – tractors, combines, seeders, cultivators and other specialised machinery – reached a value of over USD 4.7 billion (Neyter *et al.*, 2024). Southern regions, such as Kherson, Zaporizhzhia and Mykolaiv regions, were particularly affected, where Russian forces targeted or seized equipment in the occupied territories, and in some cases took it to Russia or to temporarily controlled lands. In the government-controlled areas of the south, such as the Mykolaiv region, farmers lost equipment due to artillery strikes, making it impossible to harvest crops or prepare for new sowing campaigns in a timely manner. Restoring this fleet requires not only significant financial resources, but also time, which is almost unattainable for most farms, especially small and medium-sized ones, in times of war.

The destruction of irrigation systems has also caused significant losses to the agricultural sector, which has become a critical problem for the southern regions of Ukraine – Kherson, Zaporizhzhia, Mykolaiv and Odesa regions, where irrigated agriculture was the basis for growing grain, vegetables and fruits in an arid climate. The World Bank (2025) estimates that as of 2023, the value of damaged or destroyed irrigation infrastructure exceeds 225 million USD, but the actual losses could be much higher due to the long-term impacts. These losses culminated in the explosion of the Kakhovka hydroelectric power station in June 2023, which led to catastrophic flooding of thousands of hectares of land on the right bank of the Kherson region, destruction of crops in the fields and disruption of irrigation canals that supplied up to 580,000 hectares of farmland in the south. For instance, the North Crimean Canal, which supplied water not only to the occupied Crimea but also to a large part of Kherson and Zaporizhzhia regions, stopped functioning, leaving farmers without access to irrigation in the face of natural drought. This has caused soil degradation, salinisation and loss of productivity, which will require years of effort and billions of dollars in investments to restore, significantly undermining the agricultural potential of the southern regions.

The loss of processing capacity has been another painful aspect for the agricultural sector, with southern Ukraine being particularly hard hit. Plants producing sunflower oil, flour, sugar and other processed products located in cities such as Mykolaiv, Kherson and Melitopol (Zaporizhzhia region) were repeatedly targeted by Russian attacks or occupied. According to a report by the Kyiv School of Economics, direct losses to the processing infrastructure exceed 1 billion USD, and this does not include lost value added, as farmers are forced to export raw materials (e.g. sunflower seeds) at lower prices due to a lack of processing capacity within the country (Neyter *et al.*, 2024). In the south, where processing has traditionally been an important part of the economy, these losses have led to economic decline, job losses and a deterioration in the financial health of farms, which, together with other factors, creates a complex picture of the devastation that the region will be recovering from for decades after the war.

Notably, the war in Ukraine caused major changes in global grain logistics, disrupting the traditional export routes of one of Ukraine's largest grain suppliers (Penkova & Kharenko, 2023). Before the full-scale invasion, the country transported up to 90% of its wheat, corn and barley through Black Sea ports such as Odesa, Chornomorsk and Pivdennyi, from where the products were shipped to countries in Asia, Africa and Europe. Russian blockade of these ports in the first months of the invasion led to the accumulation of millions of tonnes of grain in warehouses, causing not only economic losses for Ukraine but also a threat to global food security, especially in countries dependent on Ukrainian imports, such as Egypt, Turkey and the Middle East. In response, the international community and Ukraine were forced to look for alternative transport routes, which led to the restructuring of logistics chains and increased transport costs, affecting global grain markets. One of the key decisions to resume exports was the creation of alternative routes through EU countries, through the so-called "Solidarity Corridors" initiated by the EU in May 2022. These routes involved transporting grain by rail, road and river through Poland, Romania, Slovakia, Hungary and other countries to European ports such as Constanta (Romania), Gdansk (Poland) and the Baltic ports. The EU played a decisive role: in the first months of the Solidarity Corridors, around 20 million tonnes of grain were exported via these routes, partially compensating for the loss of Black Sea routes. The port of Constanta became particularly important, becoming the main hub for transhipment of Ukrainian grain, handling over 8 million tonnes in 2022. In addition, from August 2022 to September 2023, the Black Sea Grain Initiative, mediated by the UN and Turkey, was in effect, which enabled another 32.9 million tonnes to be exported through partially unblocked ports. After its completion, Ukraine created its humanitarian corridor along the western coast of the Black Sea, which added another 27 million tonnes to exports in the 2023/24 marketing year. However, these alternatives proved to be more expensive and less efficient due to limited railway capacity, track gauge incompatibility (Ukrainian gauge is wider than European gauge) and border congestion, which increased logistics costs by 30-50% compared to the pre-war period.

Internal logistics in Ukraine faced numerous challenges due to the war, which complicated the delivery of grain from fields to export terminals (Shevchuk, 2024). One of the main obstacles was the physical destruction of transport infrastructure: bridges, railways and roads, especially in the east and south, were severely damaged by shelling, disrupting links between agricultural regions and logistics hubs. For instance, in the Mykolaiv and Kherson regions, key roads to ports became impassable, forcing farmers to seek detours through western regions. The shortage of rolling stock and locomotives added to the problems, as a significant part of the railway fleet was destroyed or remained in the occupied territories; according to estimates by Ukrzaliznytsia (n.d.), up to 15% of freight cars were lost in 2022. At the same time, the war has stimulated the development of river logistics: according to the Ukrainian Sea Ports Authority (2024), transport on the Danube increased from 1 million tonnes in 2021 to 4 million tonnes in 2023, thanks to the modernisation of ports in Izmail and Reni. The prospects for domestic logistics are related to investments in railway infrastructure (e.g., electrification and track expansion projects), the expansion of river terminals, and the creation of temporary storage facilities closer to the western borders. However, these initiatives require billions of dollars and time, which remain limited resources in the context of the war. Changes in Ukrainian grain logistics significantly affected international logistics chains, forcing global traders and carriers to revise routes and optimise costs. The blockade of the Black Sea has forced importing countries such as Egypt and Turkey to switch to other suppliers in the United States and Argentina or wait for slow deliveries via European ports, extending delivery times from 10-15 days to 30-40 days when using the "Solidarity Routes". Transportation costs have increased due to the need to use several modes of transport (rail, road, barges), transhipment at borders and insurance of cargo in the conflict zone. For example, before the war, transporting a tonne of grain from Ukraine to Egypt cost 20-25 USD, but in 2022, the price jumped to 70-100 USD, depending on the route. This led to congestion in European ports such as Constanta, where cargo handling times doubled, and put additional pressure on global freight rates, which rose by 15-20% in 2022 due to a shortage of vessels in the Black Sea region. At the same time, competition from Russia, which increased exports through its ports (Novorossiysk, Rostov), exacerbated the imbalance in logistics flows, shifting part of Ukraine's traditional markets to eastern routes. The restructuring of grain logistics due to the war in Ukraine affected pricing on world markets, causing initially sharp price increases and subsequently volatility (Fig. 9).

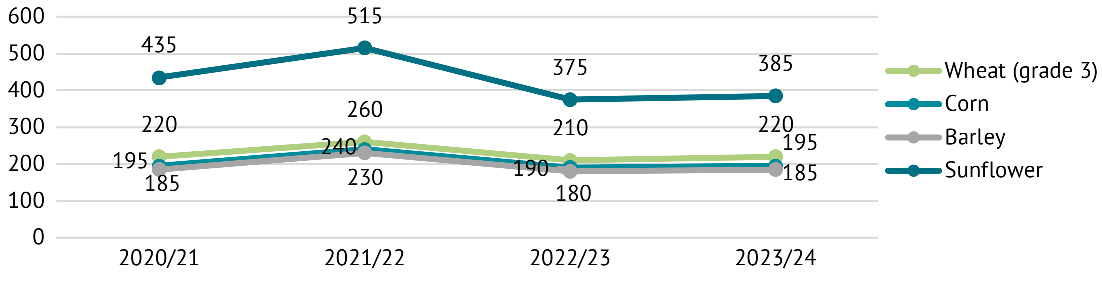

Figure 9. *Dynamics of grain prices for sunflower seeds after the start of the full-scale invasion of Ukraine – average (USD/t)*

Source: *compiled by the authors based on UkrAgroConsult (n.d.) and SuperAgronom (n.d.)*

Prices for grain and sunflower seeds in Ukraine during the 2020/21-2023/24 marketing years have undergone significant changes under the influence of yields, global demand, logistical conditions and the war. In the 2020/21 marketing year (July 2020 to June 2021), average purchase prices on the domestic market were 6,000-6,500 UAH/t (USD 210-230/t FOB in Black Sea ports) for wheat (grade 3), This was facilitated by a stable harvest (65 million tonnes of grain) and high export demand (17.6 million tonnes) from Egypt, Indonesia and Turkey; prices rose at the end of the season due to drought in the southern regions and the revival of global trade after the pandemic. Corn costs 5,500-5,800 UAH/t (190-200 USD/t FOB), with an increase in the second half of the year, thanks to China, which actively imported (exports of 23.9 million tonnes) for feed needs after the resumption of pig farming. Barley remained at 5,200-5,500 UAH/t (180-190 USD/t FOB), supported by exports of 4.2 million tonnes to Saudi Arabia and China, where it was in demand for livestock farming. Sunflower seeds cost 12,000-13,000 UAH/t (420-450 USD/t), with an upward trend due to demand for sunflower oil (oil exports of 5.5 million tonnes) and average yields (15.1 million tonnes); only 0.2 million tonnes of raw materials were exported, with the rest being processed domestically. The dollar exchange rate remained stable (27-28 UAH/USD), but rising freight rates due to global logistics problems added pressure on export prices.

In the 2021/22 marketing year (July 2021 to June 2022), a record harvest of 106 million tonnes kept prices somewhat subdued, but global demand and fears of war pushed them to a peak: wheat (grade 3) reached 7,000-7,500 UAH/t (250-270 USD/t FOB), with a peak in December-January due to exports of 20 million tonnes to Asia (Indonesia, Pakistan) and Africa (Egypt); corn 6,500-7,000 UAH/t (230-250 USD/t FOB), driven by Chinese demand (over 8 million tonnes) and high yields, which ensured exports of 23 million tonnes by February 2022; barley 6,200-6,700 UAH/t (220-240 USD/t FOB), with growth due to exports of 5.7 million tonnes to Turkey and a reduction in supply from Russia; sunflower seeds 14,000-15,000 UAH/t (500-530 USD/t), with a peak due to a harvest of 17 million tonnes and oil exports of 5.7 million tonnes, while only 0.3 million tonnes of raw materials were exported. In the 2022/23 marketing years (July 2022 to June 2023), the war and the blockade of ports caused prices to fall: wheat 5,500-6,000 UAH/t (200-220 USD/t FOB after August), corn 5,000-5,500 UAH/t (180-200 USD/t), barley 4,800-5,200 UAH/t (170-190 USD/t), sunflower 10,000-11,000 UAH/t (350-400 USD/t); the "grain corridor" aided in export of 46-50 million tonnes, but the devaluation of the hryvnia to 36-37 UAH/USD and the increase in transport costs (to 70-100 USD/t) reduced profitability. In the 2023/24 marketing years (July 2023 to June 2024), prices recovered thanks to a harvest of 79 million tonnes and logistics: wheat 5,700-8,191 UAH/tonne (210-230 USD/tonne), corn 5,570-6,721 UAH/tonne (190-210 USD/tonne), barley 4,383-6,597 UAH/tonne (170-200 USD/tonne), sunflower seeds 11,000-14,500 UAH/t (370-400 USD/t), with exports of 67. 4 million tonnes; an exchange rate of 36-40 UAH/USD and competition from Russia (230-250 USD/t for wheat) influenced price dynamics, while world prices stabilised (9-10 USD per bushel for wheat).

Once the war in Ukraine is over, the key task for the development of the grain market will be to rebuild the destroyed infrastructure, including ports, railways, bridges and storage facilities, which have suffered significant damage as a result of the hostilities. Black Sea ports such as Odesa, Chornomorsk and Pivdennyi, which accounted for up to 90% of grain exports before the war, will require significant investment to resume full operations, while the de-occupied ports of Mykolaiv and Kherson will need additional modernisation to return to their pre-war capacities (7-10 million tonnes per month). The modernisation of the elevator industry will also be a priority, as many elevators in eastern and southern Ukraine have been destroyed or damaged, and their total capacity has been reduced by 20-30%. Post-war recovery will also involve not only reconstruction, but also the introduction of modern technologies for automated storage systems, energy-efficient dryers and digital platforms for monitoring stocks. This will improve grain storage efficiency, reduce losses (which reached 10-15% before the war due to outdated infrastructure) and make the Ukrainian market more competitive. The development of river logistics, particularly through the Danube ports (Izmail, Reni), which grew from 100,000 tonnes to 2.5 million tonnes per month during the war, could be a long-term solution for diversifying transport capacity.

The war has forced Ukraine to review its trade relations and seek new markets, which opens prospects for expanding the geography of grain exports after the war is over. Until 2022, the main markets were Asia (China, Indonesia), North Africa (Egypt) and the EU (Spain, the Netherlands), but the blockade of the Black Sea and logistical difficulties have increased dependence on European routes such as the Solidarity Road. In the post-war period, Ukraine could strengthen its position in the EU, where its grain has already been integrated into supply chains, but this requires harmonising quality standards with European norms (e.g., pesticide content and certification). At the same time, African countries are a promising destination, where demand for grain is growing due to demographic growth and the need for affordable products; according to the Food and Agriculture Organisation (2022), Ukraine could increase its supplies to 5-7 million tonnes annually to countries such as Nigeria or Kenya, subject to the development of trade agreements. The Asian market, in particular India and South Korea, could also become a new focus due to their needs for corn and wheat, if Ukraine invests in marketing and logistics. Changes in trade relations with Poland, Slovakia, and Hungary, which imposed temporary bans on imports of Ukrainian grain in 2023, will require diplomatic efforts and the establishment of export verification mechanisms to avoid conflicts and ensure stable access to EU markets. Expanding sales markets will help diversify and reduce dependence on certain regions, which will be a lesson learned from wartime.

The investment potential of the Ukrainian agricultural sector after the war is significant, as the country has unique natural resources (33% of the world's black soil) and a proven ability to adapt to crisis conditions, as demonstrated by exports of 67.4 million tonnes in the 2023/24 marketing year despite the war. Foreign direct investment will be directed towards rebuilding infrastructure, modernising production and increasing added value through grain processing (e.g. flour, compound feed, bioethanol). According to government estimates, the needs for the restoration of the agricultural sector exceed 29 billion USD, which creates opportunities for international investors, particularly from the US, Canada and the EU, who had already expressed interest in Ukrainian projects before the war, as noted in the report of the Ministry of Agrarian Policy and Food of Ukraine (2023). Domestic investors, such as large agricultural holdings (Kernel, MHP), may also become more active if the state provides transparent conditions, tax incentives, security guarantees and risk insurance. The development of the processing industry, where margins on value-added products (oil, cereals) are 20-50% higher than on raw materials, could attract capital to medium and small enterprises, which have proved more resilient during the war than large holdings. Furthermore, innovative technologies such as precision farming, drones and IT solutions for crop monitoring will increase the sector's attractiveness to technology companies. However, the implementation of this potential will depend on land clearance (over 174,000 km^2), political stability and access to credit, as the war has destroyed the financial capacity of many farmers.

International organisations will be central in the post-war recovery of the Ukrainian grain market, providing financial, technical and humanitarian support. The UN, through the Black Sea Grain Initiative, has already proven its ability to unblock exports, exporting 32.9 million tonnes in 2022-2023, and could become a coordinator of logistics projects after the war, contributing to the stability of supplies. The Food and Agriculture Organisation (2024; 2025) prioritises support for farmers and restoration of production: in 2022-2024, the organisation funded 17 million USD in projects to provide seed, fertiliser and small grants to farms in the frontline areas, and after the war, its role will be to modernise agricultural technologies and adapt to climate change (e.g. breeding drought-resistant varieties). The World Bank, which is assessing the sector's losses and needs, has already allocated more than $1 billion for agricultural projects in Ukraine since 2022 and plans large-scale infrastructure reconstruction programmes (ports, elevators) and farm loans worth up to 5 billion USD in the post-war period (National Institute for Strategic Studies, 2024). These organisations will also facilitate Ukraine's integration into EU standards through technical assistance and funding for green initiatives such as bioenergy and energy efficiency. Their cooperation with the Ukrainian government and the private sector will be crucial to attracting donor funds and creating a sustainable development model that will enabled Ukraine not only to return to pre-war volumes (85 million tonnes of exports) but also to exceed them, reaching 100 million tonnes annually if all projects are implemented.

DISCUSSION

The study analysed the positions of global leaders in the production of grain crops and sunflower seeds for the 2023/24 marketing year, as well as key trends shaping the global market, providing insight into the dynamics of the global grain sector and its response to current challenges. The results demonstrated that China (24% of global grain production, 135 million tonnes of wheat), the United States (16%, 383 million tonnes of corn), and the EU (11%, 52 million tonnes of barley) remain the dominant players, while Ukraine holds significant positions with 2% of corn (25 million tonnes) and 21% of sunflower seeds (12 million tonnes). These figures highlight the high concentration of production among a few countries, which makes the global market vulnerable to geopolitical shocks such as sanctions or regional conflicts and also point to growing demand in Asia and Africa, increased competition due to price dumping by Russia, and the reorientation of logistics to alternative routes. These trends signify a gradual shift in trade flows from traditional routes to new logistics corridors and the growing role of Latin American and Asian countries in compensating for deficits, which affects the stability of global supplies and pricing. A study by J. Clapp (2023) also analysed in detail the concentration of grain production among key countries, highlighting their vulnerability to crises such as supply disruptions, but did not consider the impact of local conflicts on global prices, which limits the depth of the results obtained. R. Sendhil *et al.* (2022) addressed the growth in demand for grain crops in Asia, providing important data on consumption and highlighting the demographic and economic factors behind this trend, but ignoring competition between exporters such as the United States and Australia, which reduces the practical value of the conclusions for assessing market dynamics. M. Aghayev (2023) highlighted changes in logistics due to geopolitical factors, highlighting the role of sanctions against Russia in redirecting flows through Caspian ports, but without considering the potential of developing countries as alternative suppliers, which narrows the scope of the results obtained. S. Erol (2024) analysed the impact of full-scale war on the situation in the Black Sea, noting the importance of logistical changes in the region, but without addressing Ukraine's adaptation capabilities, which limits the predictive potential of the study. A comparison of the results of these studies with the results of this study reveals a common recognition of the concentration of production and geopolitical influence on the market. However, this study is distinguished by its broader coverage of trends, including an analysis of changes in global trends, trade and logistics, which provides a more comprehensive understanding of global shifts and their implications for the global grain sector.

The study also included a detailed analysis of the dynamics of grain acreage, yields and exports in Ukraine for 2020-2024 to assess the impact of the war on the agricultural sector and its adaptation capabilities. The results demonstrated that grain sowing areas decreased from 15.4 million hectares in 2021 to 9.1-10.2 million hectares in 2024 due to occupation (109,000 km^2 of land), mining (174,000 km^2) and the transition to oil crops such as sunflower and soybeans, reflecting economic expediency in the context of difficult grain exports; yields reduced from a record 47.8 hwt/ha in 2021 to 38.3 hwt/ha in 2022 due to hostilities and resource shortages, but recovered to 43.8 hwt/ha in 2023 thanks to farmers' adaptation and better weather conditions. Grain exports reduced from 85 million tonnes in 2021/22 to 46-50 million tonnes in 2022/23 due to the blockade of ports but reached 67.4 million tonnes in 2023/24 thanks to the "Solidarity Routes" and the humanitarian corridor. These results demonstrate a significant impact on the productivity of the sector but also highlight its resilience: reductions in area and yields were offset by logistical solutions, which stipulated exports at a level close to pre-war levels. For Ukraine, this highlights the potential for reorientation towards oilseeds as a strategic direction in the short term, which could strengthen its position in the global market in competition with other players. T. He *et al.* (2023) analysed in detail the decline in grain production in Ukraine due to the war, with accurate statistical data on losses, but without considering the impact of these processes on domestic prices and crop redistribution, which limits the breadth of the conclusions drawn. W. Martin and N. Minot (2022) examined the decline in grain exports in 2022, noting the role of the war in the global crisis, but without touching on the recovery processes of 2023, which reduces its relevance for a full cycle analysis. D. Özocakli *et al.* (2024) provided a detailed overview of export changes through the "grain corridor" supported by an analysis of its impact on grain prices, but did not consider the long-term logistical prospects, which narrows the predictive value of the results obtained. Thus, compared to these studies, the study is notable for a comprehensive approach that covers not only the dynamics of area, yield and exports, but also their interrelationship with other indicators of the global grain market, providing a broader basis for assessing the current state and future development of Ukraine's agricultural sector.

An analysis of price trends for grain crops and sunflower seeds in Ukraine for the 2020/21-2023/24 marketing years revealed significant fluctuations caused by the war, global demand and logistical challenges, assessing the impact of these factors on the agricultural sector's economy. The results indicated that wheat prices rose from 6,000-6,500 UAH/t (210-230 USD/t FOB) in 2020/21 marketing year to 7,000-7,500 UAH/t (250-270 USD/t) in 2021/22 marketing year thanks to a record harvest, dropped to 5,500-6,000 UAH/t (200-220 USD/t) in 2022/23 marketing year due to excess stocks and port blockades, but recovered to 8,191-9,500 UAH/t (220-250 USD/t) in 2024 due to reduced production and drought; corn fluctuated from 5,500-5,800 UAH/t (190-200 USD/t) to 10,150 UAH/t (210-212 USD/t), barley from 5,200-5,500 UAH/t (180-190 USD/t) to 8,000 UAH/t (200-220 USD/t), and sunflower seeds from 12,000-13,000 UAH/t (420-450 USD/t) to 14,500-15,000 UAH/t (400-420 USD/t). These data indicate an initial rise in prices due to high demand, a sharp decline in 2022 due to military restrictions, and a gradual recovery peaking in 2024 due to climatic and market factors, although competition with Russia (230-250 USD/t for wheat) has held back potential. For Ukraine, this means that the war has increased dependence on logistics (costs have risen by 30-50%), but steady demand for grain and oil has kept the sector profitable; High prices in 2024 (up 21-68% compared to 2023) underscore the need to stabilise production and exports to avoid volatility that could affect competitiveness in the global market amid dumping and rising supply from Latin America. Z. Zhang *et al.* (2023) analysed in detail the impact of global crises on grain prices, highlighting their vulnerability to supply disruptions, but did not consider the impact of regional conflicts on global trade flows, which limits its depth. G. Mustafa and A. Iqbal (2021) examined trends in sunflower seed production and trade in the global market, noting the important role of Asian markets in this segment, but ignoring the role of competition between key exporters, which reduces its completeness. S. Devadoss and W. Ridley (2024) addressed wheat price fluctuations on global exchanges, noting the impact of sanctions against Russia, but did not sufficiently account for the growth in supply from Latin American countries, which narrows its practical context. E.M. Kacperska *et al.* (2025) presented a detailed analysis of wheat price volatility in the global market related to the Black Sea Agreement, but did not address the impact of other factors on freight rates, which limits its predictive value. Thus, compared to these studies, this paper is distinguished by its approach, which combines an analysis of local price trends in Ukraine with a broader global context, considering competition, logistics and market factors, providing a comprehensive overview of the economic implications and stabilisation strategies at the national and international levels.

In summary, the study synthesised the main aspects of the grain sector development, integrating the analysis of global trends and changes in the Ukrainian agro-industrial complex in the context of the war, which provides a basis for assessing its future opportunities. The study covered the positions of major producing countries, global market trends and the dynamics of Ukrainian production, prices and exports, providing a holistic view of the current state and development potential. After the end of the war, Ukraine has significant prospects for recovery and growth, including rebuilding infrastructure, improving logistics and strengthening its position in international markets with the support of the international community. These efforts could return it to a leading role in the grain sector, as well as contribute to broader progress in ensuring the stability and development of the global food system in the face of current challenges.

CONCLUSIONS

An in-depth analysis of key trends in the global grain market for the period 2020-2024, as well as the Ukrainian grain market in the context of the war, was conducted, and its prospects after the war were outlined. In particular, the study determined that global production in the 2023/24 marketing year amounted to 789.8 million tonnes of wheat, 1.22 billion tonnes of corn, 149 million tonnes of barley and 57 million tonnes of sunflower seeds, with China, the United States, the EU and Ukraine occupying the leading positions. In Ukraine, the war caused a significant reduction in grain acreage from 15.4 million hectares in 2021 to 9.1-10.2 million hectares in 2024, while yields ranged from a record 47.8 hwt/ha in 2021 to 38.3 hwt/ha in 2022, with a subsequent recovery. Grain exports reduced from 85 million tonnes in 2021/22 to 46-50 million tonnes in 2022/23 due to the blockade of ports but increased to 67.4 million tonnes in the 2023/24 marketing year thanks to the adaptation of logistics. Domestic prices reflected these changes: wheat cost 6,000-6,500 UAH/t (210-230 USD/t FOB) in 2020/21 marketing year, reduced to 5,500-6,000 UAH/t (200-220 USD/t) in 2022/23 marketing year due to excess stocks, and increased to 8,191-9,500 UAH/t (220-250 USD/t) in 2024 due to reduced harvest and logistical difficulties.

Direct losses in Ukrainian agriculture, in addition to reduced crop areas, included the destruction of agricultural equipment worth 4.7 billion USD, the destruction of irrigation systems worth 225 million USD (especially after the bombing of the Kakhovka hydroelectric power plant in 2023), and damage to processing facilities, which most affected southern regions such as Mykolaiv and Zaporizhzhia. The war has radically changed global grain logistics, forcing Ukraine to reorient itself to land routes through Poland, Romania and the Danube ports, which has increased transport costs by 30-50% (from 20-25 USD/tonne to 70-100 USD/tonne) and affected global prices. The prospects for the development of the Ukrainian grain market after the war are linked to the restoration of infrastructure, which requires 29 billion USD, the modernisation of elevators to reduce grain losses, the expansion of sales markets to Africa and Asia, the strengthening of positions in the EU, and the attraction of investment with the support of international organisations such as the UN, the Food and Agriculture Organisation and the World Bank. Notably, the study has some limitations in terms of focusing on cereals and sunflower seeds, which omitted a wider range of agricultural products, such as pulses or industrial crops. Further research could focus on analysing the impact of geopolitical changes and trade agreements on the long-term competitiveness of the Ukrainian agricultural sector in the world, which could be used to compile strategies to strengthen positions in the international arena and adapt to new economic realities.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Тренди у світовій торгівлі зерном і насінням, позиція України на глобальному ринку

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Анотація. Дане дослідження було спрямоване на комплексний аналіз українського зернового ринку в умовах війни та його перспектив після її завершення, а також оцінку ключових тенденцій світового ринку зернових за 2020-2024 роки. Методологія дослідження ґрунтувалася на зборі даних із звітів міжнародних організацій та відкритих джерел, їх обробці шляхом статистичного, порівняльного та прогнозного аналізу, а також синтезі кількісних і якісних показників. Результати роботи показали, що світове виробництво у 2023/24 році склало 789,8 млн тонн пшениці, 1,22 млрд тонн кукурудзи, 149 млн тонн ячменю та 57 млн тонн насіння соняшнику, де лідирують Китай, США, ЄС та Україна. В результаті дослідження було встановлено, що в Україні війна скоротила посівні площі з 15,4 млн га в 2021 році до 9,1-10,2 млн га в 2024 році, урожайність впала з 47,8 ц/га в 2021 році до 38,3 ц/га в 2022 році, після чого відновилася до 43,8 ц/га в 2023 році. Також було визначено, що експорт знизився з 85 млн тонн (у 2021/22 маркетинговому році) до 46-50 млн тонн (2022/23), але зріс до 67,4 млн тонн (2023/24) завдяки «Шляхам солідарності» та гуманітарному коридору. При аналізі цін на пшеницю було встановлено, що ціна коливалася від 6000-6500 грн/т (USD 210-230/т FOB) у 2020/21 до 5500-6000 грн/т (USD 200-220/т) у 2022/23 і 8191-9500 грн/т (USD 220-250/т) у 2024 році. Втрати сектору включали техніку (4,7 млрд доларів) і зрошення (225 млн доларів), а логістичні витрати зросли на 30-50 %, вплинувши на світові ціни (USD 12-13 за бушель для пшениці у 2022 році, USD 8-9 у 2024 році). При аналізі перспектив розвитку українського зернового ринку після війни встановлено, що відновлення інфраструктури вартістю 29 млрд доларів, модернізація елеваторів, розширення ринків збуту до країн ЄС, Африки та Азії, а також інвестиції за підтримки міжнародних організацій і Світового банку дозволять повернути експорт до 85 млн тонн і потенційно досягти 100 млн тонн щорічно, зміцнюючи роль України у світовій продовольчій безпеці

Ключові слова: експорт культур; посівні площі; урожайність; логістика; руйнування та відновлення інфраструктури; аграрний сектор

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