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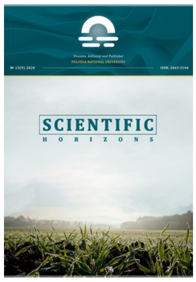

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Improving feed efficiency in Kazakh white-headed cattle: The role of residual feed intake, growth, and dry matter intake

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Abstract. The aim of this study was to investigate the influence of residual feed intake on key technological parameters involved in the rearing of Kazakh white-headed cattle. The experimental research was carried out at four large-scale breeding enterprises raising this breed: the limited liability partnership "Zhana Bereke" (Akmola Region), the limited liability partnership "Galitskoe" (Pavlodar Region), the communal farm "Sabit" (West Kazakhstan Region), and the limited liability partnership "Shalabai" (Abai Region). Data collection and continuous monitoring were implemented using the automated livestock monitoring system known as Vytelle-sense technology. Following a two-week adaptation period, 64 steers of the Kazakh white-headed breed were selected at each enterprise. Over the course of 60 days, measurements were taken for residual feed intake, average daily weight gain, and daily dry matter consumption. Results showed that, across all four enterprises, approximately half of the animals exhibited negative residual feed intake values. The mean average daily weight gain was 0.95 kilograms, while the mean daily intake of dry matter per steer was 11.03 kilograms. A positive correlation was observed between residual feed intake and average daily weight gain, whereas no significant correlation was found with dry matter consumption. Bulls demonstrating negative residual feed intake values along with high feed consumption are recommended for selection in breeding programmes due to the potential for genetically favourable traits. Additionally, the recorded average daily weight gain ranged from 0.1 to 1.81 kilograms, with dry matter intake ranging from 7.82 to 13.91 kilograms per day

Keywords: Kazakh white-headed breed; technological parameters; Vytelle-sense technology; beef cattle breeding; heredity

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INTRODUCTION

The relevance of the study is that the growth of the world population contributes to the need for beef production and the search for improvement of cattle reproduction. Therefore, in countries such as Kazakhstan, the introduction of new cattle breeding technologies to minimise feed costs with excellent technological performance is a priority. According to the data obtained during the study of statistical indicators, G. Kassenbayev *et al.* (2024) noted that the growth of cattle population is 2-4% from year to year. It was also noted that maintenance feed requirements can be up to 75% of the total cost of feeding and care of beef cattle breeds per year. Crop production as an industry for beef cattle feedstock is very dependent on weather conditions, as a result feed price can fluctuate, and this figure can be even higher. At the same time, it is noted that the majority of beef cattle are in small farms that compete with large enterprises. This means that only the introduction of new technologies, which can only be done on large farms, will allow large enterprises to change the situation. In order to realise these trends and to comply with age-old traditions, the Republic of Kazakhstan pays considerable attention to ensuring food security.

S.K. Abugaliyev *et al.* (2019) and A.T. Bissembayev *et al.* (2023) note that beef and its source in Kazakhstan – beef cattle breeding, it is an essential and necessary food product and fulfils a leadership role for obtaining affordable food. I. Baltenweck *et al.* (2020) and R.G. Alders *et al.* (2021) conclude that the use of modern technologies in the field of programming and information has simplified and accelerated the collection of data for genetic evaluation of herds and technological parameters of feeding. Genetic improvement extends to the production of new and improvement of existing breeds, species, lines of beef cattle. After all, the basis of any animal breeding is selection. For this purpose, it is necessary to collect reliable information on productive indicators of animals. Kazakhstan is an ideal platform for utilising the potential to increase meat production because beef cattle breeds have valuable biological and economic features. Studies by L. Cavani *et al.* (2024) showed that feed intake is an inherited trait and can serve to improve the efficiency of cattle breeding by selection of beef animals. Thus, feed conversion ratios and residual feed intake (RFI) is a heritable trait. The costs of feed production and animal feeding are now being realised by consumers as a personal health, environmental and animal welfare issue rather than just an economic issue (Montayeva *et al.*, 2023).

Cattle feed consumption must create a sustainable beef production model. As noted by C. Davison *et al.* (2021), even small changes in feeding technology affect feed intake and feed conversion. Three indicators give a complete and correct picture of understanding these processes, these are RFI by individual cattle, average daily live weight gain and dry matter intake (DMI). The use of RFI in beef cattle selection is a more effective method of breeding cattle for feed productivity than selection for feed inputs per unit of live weight gain (Kropyvka *et al.*, 2024). This indicator, actively used in the technology of selection of beef cattle, makes it possible to accurately and purposefully put into practical use the fattening of beef cattle with increasing the productive effect of feed and increasing the profitability of the livestock industry. In fact, in addition to a selection tool, RFI can be a tool to measure the efficiency of animal feeds (Montayev *et al.*, 2023). At the same time, the continued use of RFI for selection will result in progeny consuming the minimum amount of feed at the same level of productivity as progeny consuming more feed but with the same level of productivity.

There are inaccurate and outdated models for predicting feed intake based on eating behaviour, live weight and age, but their use is subjective and inaccurate. Specialised software now collects individual and daily information using cloud-based technologies, digital animal identification, etc. Such opportunities allow collecting quickly and qualitatively all technological information, minimising the human factor with its inherent errors. Objective of the work was to study the effect of process parameters like RFI, ADG, DMI on each other. The tasks to fulfil this goal were collecting and analysing information on RFI indicator, experimentally using Vytelle-sense technology and analysing the data obtained with its help.

LITERATURE REVIEW

Until now, many small and large farms in Kazakhstan use inefficient ways of determining feed efficiency indicators (Kassenbayev *et al.*, 2024). These are such well-known indicators as feed conversion ratio and DMI. These indicators can be used only for short-term analyses of growing technology for a period of not more than two months, while growing technology for a longer period gives a lot of factors that distort these indicators. These factors are feed quality, microclimate and some parasitic diseases which distort the real conversion rate. N. Kazhgaliyev *et al.* (2020) noted that, given the fact that regardless of the conditions of cattle breeding development, the main direction of development is to get the greatest profit from the largest number of the most productive animals, which are bred in specific conditions. At the same time, the official assessment of the breeding value of animals in beef cattle, which is applied at the present stage in the Republic of Kazakhstan, always implies two qualities: breeding and productive, and therefore they cannot be separated. This statement is considered controversial because it was considered as an axiom in the first half of the last century, which does not correspond to modern scientific approaches. This axiom can be destroyed by the genetics of quantitative traits, or modern socio-economic conditions of the agro-industrial complex of the republic.

Quantitative determinations of breeding qualities of bulls of the Kazakh white-headed breed by assessing the indicators of their productivity were carried out by A. Nugmanova *et al.* (2024). Productivity indicators were evaluated by the dynamics of live weight, daily growth rate, efficiency of feed conversion and morphological quality of meat, as well as in the use of complex indices "A" to assess breeding potential. These indices allowed selection of the best 10% of bulls for further utilisation of their genetic potential, the remaining bulls also performed well and only 10% of bulls were culled. Such studies allow saving forage by not spending it on bulls with poor performance, and manipulating heritability by obtaining progeny from bulls with good performance. L.F. Benfica *et al.* (2020) noted in their works the same idea: RFI is also a breeding quality of the breed, because it is a measure of feed productivity, which is the difference between the feed that was consumed by the animal actually and that which the animal should have consumed according to the norms established on the farm and according to the technological regulations. P. Guarnido-Lopez *et al.* (2021) note that RFI is a complex and versatile indicator under the control of many biological processes, including nutritional selection, feed conversion, metabolism at the cellular level, and catabolism. B.N. Baban *et al.* (2020) noted in their studies that the organism of an animal with this low index spends less energy on heat production and protein metabolism. This index is heritable and does not depend on growth rate and body weight. Therefore, J.R. Johnson *et al.* (2019), A. Foroutan *et al.* (2021) consider subjectivity to use only this index for selection without ADG and DMI, this immediately improves the profitability of beef producers by as much as 33%. An inverse proportional consistency with the DMI indicator is observed.

RFI is very useful for controlling feed digestibility and converting it into live weight (Pogranichniy *et al.*, 2023). Thus, G.F. Moraes *et al.* (2019) and P. Martin *et al.* (2024) experimented with cattle with different productivity. Data were obtained that cows with high productivity and lower RFI gave similar reproductive performance to cows with low productivity and higher RFI. It was concluded that selection for heifer and heifer efficiency gave poor results for lactation performance and questionable results for reproductive soundness. Thus, the use of RFI alone to evaluate cows for calf and milk production is questionable, although it was noted that selection for a favourable RFI increases gestation. However, in the study of F.M. Rouquette *et al.* (2023), low RFI coincided with a decrease in subcutaneous fat. This is what the producer needs (within reasonable limits of course): to get more meat and less fat. Low RFI results in low blood cortisol, which means that animals with low RFI are less stressed and therefore have stronger immunity and are easier to vaccinate.

The reverse research experience is also possible, in which phenotype and genotype data or genetic markers, as in the work of I. Beishova *et al.* (2024), can be used to predict and improve the productivity of meat of the Kazakh white-headed breed of cattle. The efficiency of meat production in this case is carried out by supplementing the base of genetic knowledge of this particular breed using selection by diplotypes for which identified those that had a phenotypic effect of rapid and stable live weight gain. There are information technologies for measuring RFI mentioned in the studies of V.K. Sharma *et al.* (2021), C. Yang *et al.* (2022): Vytelle-sense – feed logging system provides an opportunity to engage in efficient selection of beef cattle. In fact, it is a simple mathematical and genetic correlation between feed intake and production performance based on heritability. Vytelle-sense technology can continuously record weight and feed intake and accurately identify cattle with high or low RFI values in minimal time and faster than traditional RFI testing. This technology provides the ability to accurately present weight gain charts in a short period of time. The system, by collecting information quickly, allows the farmer to get several more tests per year. The database currently contains data on 140,000 animals of 24 breeds and over 32,000 RFI phenotypes. The review concludes that RFI is recommended for beef cattle producers with small operation requirements as a beef cattle sampling tool to reduce feed requirements and identify those herds with high feed conversion efficiency, but does not consider development, carcass quality, reproductive and lactation performance.

MATERIALS AND METHODS

The study was conducted on the basis of four farms: Zhana Bereke Limited Liability Partnership (LLP) (Akmola Region), Galitskoe LLP (Pavlodar Region), Sabit communal farm (West Kazakhstan Region) and Shalabai LLP (Abai Region). Zhana Bereke LLP (Akmola Region) is a closed-cycle agricultural company (i.e., the company has agricultural fields, a feed mill, meat cattle breeding and a meat processing complex). Galitskoe LLP (Pavlodar Region) is a large agricultural enterprise engaged in crop production, dairy and beef cattle breeding, horse breeding, and fodder production. Thus, beef cattle breeding is provided with fodder of own production. Communal farm "Sabit" (West Kazakhstan region) is a communal farm, the main activity of which is breeding of pedigree cattle of Kazakh white-headed breed. LLP "Shalabai" (Abai region) is an enterprise engaged in breeding of sheep, horses, and cattle of meat breeds, as well as crop production and fodder production.

The survey was conducted with the help of Vytelle-sense technology. This is a system that allows the weight of cattle to be measured without stressful factors such as being put on special scales or being held for measurement. The system also allows the measurement of feed intake. When the animal drinks water through the In-pen Weighing System (IPW) drinker, the system collects information on the live weight of the animal, and the collected information is collected in the Vytelle-sense Systems software analytical system. At the same time, indicators such as RFI, DMI, and ADG are measured simultaneously and accurately. Before the beginning of the experiment, the experimental animals were given 14 days to adapt to the new feeding conditions. According to the manufacturer (Canada), the equipment can be used for up to 60 days. The largest bulls were selected from four farms, as it was planned to use them for breeding. Bulls at weaning age were selected. Housing conditions: cold loose housing, access to feed and water 24 hours a day. The trial lasted 60 days during November 2023 – March 2024 on the farms in question.

Bulls were marked by RFI data, also data collected included Wt1 – weighing on the first day of the experiment and Wt60 – weighing on the last day of the experiment.; ADG: average daily gain; DMI: average daily DMI during the test. The experiment was also conducted, and groups of steers were formed at the enterprises Zhana Bereke LLP (Akmola Region) (29 bulls), Galitskoe LLP (Pavlodar Region) (29 bulls), Sabit communal farm (West Kazakhstan Region) (38 bulls) one group each, at the enterprise Shalabai LLP (Abai Region) two experimental groups (20 and 30 bulls). For the purity of the experiment, all animals on all four farms received the same diet for the main parameters (Table 1).

***Table 1**. Basic requirements for diets in experimental animals of farms of Zhana Bereke LLP (Akmola Region), Galitskoe LLP (Pavlodar Region), Sabit communal farm (West Kazakhstan Region) and Shalabai LLP (Abai Region)*

Indicators	Hay	Straw (barley)	Silage (corn)	Barley grain
Humidity, %	17	12.2	67	11.2
Dry matter, %	83	87.8	33	88.8
Crude protein, g	6.5	3.77	8.33	14.7
Exchange energy, MJ	1.91	1.48	2.32	2.92
Starch, %	1	1.3	22.54	52.99
Sugar, %	4	3.52	1.9	2.65
Crude fat, %	2.88	1.75	3.16	2.4
Ca, %	0.36	0.38	0.28	0.09
R, %	0.21	0.11	0.26	0.45
Mg, %	0.15	0.13	0.18	0.13
K, %	1.29	1.5	1.23	0.58
Na, %	0.23	0.11	0.04	0.02

***Source:** created by the authors*

All procedures performed in studies involving animals were in accordance with the European convention for the protection of vertebrate animals used for experimental and other scientific purposes (1986).

RESULTS AND DISCUSSION

The study was conducted in parallel on four farms (Tables 2-6) and similar data were obtained. The results from these farms revealed similar patterns in RFI, ADG, and DMI, providing a comprehensive overview of feed efficiency and growth performance in the steers. The data from Table 2 reveals significant variability in RFI across the experimental steers, ranging from negative to positive values. Better feed efficiency is indicated by negative RFI values, which imply that certain steers grow at comparable or superior rates while consuming less feed than anticipated. This demonstrates how breeding programmes can increase feed efficiency by selecting for low RFI. Nonetheless, the existence of both negative and positive RFI values in the same group indicates significant genetic variation and implies that a variety of factors affect feed efficiency.

***Table 2**. Results of the experiment on individual steers of Zhana Bereke LLP (Akmola region)*

Experimental animal number	RFI	Wt1	Wt60	ADG	DMI
KZC160257597	-1.9	358.92	374.42	0.31	10
KZC160257685	-1.63	292.89	321.39	0.57	7.82
KZC160257623	-1.5	279.3	315.8	0.73	8.4
KZC160257193	-1.26	251.66	287.66	0.72	10
KZC160257481	-1.07	339.79	368.79	0.58	10.2
KZC160257172	-0.98	299.5	339	0.79	10.2
KZC160257187	-1.2	275.79	319.29	0.87	10.05
KZC160257465	-0.78	339.1	357.1	0.36	10.3
KZC160257500	-0.61	382.97	417.97	0.7	11.11

Table 2. Continued

Experimental animal number	RFI	Wt1	Wt60	ADG	DMI
KZC160257504	-0.37	259.26	283.76	0.49	10.27
KZC160257195	-0.36	283.56	314.06	0.61	12
KZC160257579	-0.23	350.4	403.4	1.06	12
KZC160257634	-0.2	330.34	364.34	0.68	9.8
KZC160257562	-0.08	365.13	407.13	0.84	11.04
KZC160257642	-0.17	365.05	397.05	0.64	14
KZC160257615	0.22	370.66	406.16	0.71	10
KZC160257620	0.38	304.61	359.61	1.1	11.37
KZC160257572	0.38	263.38	278.38	0.3	10.94
KZC160257683	0.38	295.61	353.11	1.15	12.35
KZC160233434	0.39	310.15	310.65	0.01	10.69
KZC160233356	0.4	389.96	413.46	0.47	9
KZC160233369	0.41	310.67	313.67	0.06	8.8
KZC160233374	0.42	324.76	334.76	0.2	14.58
KZC160233416	0.45	344.88	396.38	1.03	13.84
KZC160233414	0.47	313.95	367.45	1.07	11.69
KZC160233349	0.5	298.02	325.02	0.54	13.11
KZC160233344	0.51	369.18	396.18	0.54	16.95
KZC160233367	0.6	222.12	257.62	0.71	10.72
KZC160233397	0.9	339.93	374.43	0.69	12.75

Note: *date of experiment: 2024-02-03*
Source: *created by the authors*

An in-depth examination of the data in Table 2 indicates a significant variation in residual feed intake among the 29 steers, ranging from -1.9 to +0.9. Among them, 14 steers demonstrated negative RFI values, signifying enhanced feed efficiency, but the remaining 15 steers exhibited positive RFI values, indicating subpar efficiency. The average daily gain varied from a minimum of 0.01 kg/day (KZC160233434, RFI = 0.39) to a maximum of 1.15 kg/day (KZC160257683, RFI = 0.38), with a mean ADG of roughly 0.65 kg/day across all steers. Significantly, steers KZC160257683 and KZC160257620, both exhibiting an RFI of 0.38, attained ADG values beyond 1.1 kg/day, despite their inferior RFI classification, illustrating that feed efficiency and weight growth are not tightly associated. In steers exhibiting negative RFI (n = 14), the ADG varied from 0.31 kg/day (KZC160257597) to 1.06 kg/day (KZC160257579). The mean ADG in this cohort was almost 0.69 kg/day, which is slightly greater than the average of 0.61 kg/day noted in the positive RFI group. This slight disparity underscores the intricacy of the relationship between RFI and growth performance. For instance, steer KZC160257579 (RFI = -0.23) achieved an ADG of 1.06 kg/day with a dry matter intake of 12 kg/day, while KZC160257193 (RFI = -1.26) exhibited a comparable DMI of 10 kg/day but a reduced ADG of 0.72 kg/day, indicating interindividual heterogeneity in feed conversion efficiency.

The dry matter intake values varied from 7.82 to 16.95 kg per day. The mean DMI for the group was roughly 10.7 kg/day. Notably, steer KZC160233344, with a mild RFI of 0.51, demonstrated the highest DMI at 16.95 kg/day, although achieved only an average ADG of 0.54 kg/day, signifying low efficiency. Conversely, steer KZC160257683 (RFI = 0.38) exhibited a very low DMI of 12.35 kg/day alongside the greatest ADG of 1.15 kg/day, indicating efficient nutrient utilisation despite the elevated RFI. This contrast highlights the complex factors influencing growth performance. The statistical analysis of this sample indicates the absence of a definitive linear correlation between RFI and ADG, as well as between RFI and DMI. The relationship between RFI and ADG is erratic, while DMI values fluctuate independently of RFI levels. Consequently, the data suggest that selecting for feed efficiency based exclusively on RFI may neglect steers exhibiting substantial growth potential and efficient feed utilisation in practical environments. A comprehensive selection method that integrates RFI with ADG and DMI is advised to improve productivity and resource efficiency in Kazakh white-headed cattle breeding operations.

The RFI values for the steers at Galitskoe LLP are shown in Table 3 and range from -2.01 to 0.68. Many of the steers with negative RFI levels were more feed-efficient, using less feed than anticipated while still growing at a similar rate. This implies that these steers could be selected for in breeding programmes that try to increase feed efficiency since they may be genetically inclined to have higher feed conversion.

***Table 3**. Results of the experiment on individual bulls of Galitskoe LLP (Pavlodar region)*

Experimental animal number	RFI	Wt1	Wt60	ADG	DMI
KZS180430872	-1.07	331.47	376.83	0.56	6.98
KZS180430919	-1	340.73	369.89	0.36	6.89
KZS180430433	-2	228.7	299.17	0.87	6.06
KZS180430931	-2.01	358.02	426.88	0.85	8.21
KZS180430972	-1.55	352.78	390.04	0.46	7.92
KZS180430968	-1.38	395.44	414.88	0.24	8.21
KZS180430485	-1	324.96	382.46	0.71	8.11
KZS180430446	-1.37	315.26	341.98	0.33	7.46
KZS180430946	-1.09	409.6	494.66	1.05	9.73
KZS180438080	-1.63	284.5	330.66	0.57	7.49
KZS180438083	-0.99	383.18	423.68	0.5	8.9
KZS180430402	-1.09	283.88	324.38	0.5	7.68
KZS180430195	-0.99	307	346.68	0.49	8.01
KZS180438176	0.68	356.73	388.32	0.39	8.57
KZS180438088	0.55	357.33	380.01	0.28	8.6
KZS180438002	0.52	303.79	340.24	0.45	8.16
KZS180430962	0.38	363.3	388.42	0.31	8.81
KZS180438016	0.38	313.09	364.93	0.64	8.7
KZS180438126	0.37	334.6	353.24	0.23	8.57
KZS180438140	0.37	376.95	419.88	0.53	9.57
KZS180430945	0.21	362.1	420.42	0.72	9.63
KZS180430845	0.16	364.08	425.64	0.76	9.7
KZS180430125	0.08	342.02	388.18	0.57	9.17
KZS180438098	0.2	314.14	334.4	0.25	8.49
KZS180438026	0.21	360.14	403.88	0.54	9.52
KZS180430938	0.36	361.2	413.84	0.65	9.69
KZS180430985	0.37	350.56	377.28	0.33	9.14
KZS180430192	0.61	367.75	417.97	0.62	9.8
KZS180438034	0.77	327.71	372.26	0.55	9.18

***Note:** experiment date: 2023-11-06/2024-01-26*
***Source:** created by the authors*

Significant variance can be seen in the data when looking at the ADG; the greatest ADG was 1.05 kg/day, while the lowest was 0.24 kg/day. It's interesting to note that although lower RFI values are generally linked to better ADG, the data also reveals that some animals with negative RFI had comparatively slow growth rates, suggesting that feed efficiency and growth performance are not always correlated. This disparity implies that the diversity in ADG may also be influenced by other environmental factors and genetic factors, such as growth potential. The steers' DMI ranged from 6.06 kg/day to 9.73 kg/day, and there was no discernible pattern linking DMI and RFI. The heterogeneity in ADG and the absence of a clear correlation between RFI and DMI imply that feed intake is not the only factor influencing growth outcomes. Other elements, such the feed's nutritional value, metabolic effectiveness, and overall health, probably have a big impact. These results highlight the intricacy of feed growth and efficiency, suggesting that a more comprehensive strategy that takes into account other variables in addition to RFI may be required to maximise breeding tactics.

The RFI values of the steers from the Sabit communal farm are displayed in Table 4 and vary from -2.17 to 1.34. A subset of the steers may be more feed-efficient, using less feed in relation to their performance, based on the negative RFI levels. The large range of RFI levels, however, suggests that the steers' feed efficiency varies significantly, most likely as a result of a combination of environmental and genetic factors. Although the positive RFI values imply that other factors, like feeding practices or metabolic variations, may also be impacting feed intake, this variation offers a chance to investigate genetic selection for feed efficiency.

***Table 4**. Results of the experiment on individual steers of Sabit communal farm (West Kazakhstan region)*

Experimental animal number	RFI	Wt1	Wt60	ADG	DMI
KZL102204595	-2.17	201.53	283.43	1.17	5.15
KZL102204543	-1.52	262.79	357.29	1.35	7.45
KZL102204461	-0.89	199.6	271	1.02	5.98
KZL102204531	-0.87	205.43	262.83	0.82	5.58
KZL102204497	-0.84	266.22	352.32	1.23	7.88
KZL101734419	-0.71	280.17	395.67	1.65	9.39
KZL102204511	-0.71	237.72	260.12	0.32	5.03
KZL101734321	-0.58	223.5	326.4	1.47	7.97
KZL101734393	-0.43	241.36	317.66	1.09	7.44
KZL102204605	-0.36	220.76	255.06	0.49	5.51
KZL102204493	-0.32	220.39	298.09	1.11	7.2
KZL102204503	-0.29	261.05	362.55	1.45	8.92
KZL101734305	-0.27	287.98	383.18	1.36	9.2
KZL101734315	-0.25	251.3	338.1	1.24	8.23
KZL102204373	-0.2	222.91	298.51	1.08	7.3
KZL102204473	-0.12	287.28	348.88	0.88	8.07
KZL102204539	-0.03	186.33	261.93	1.08	6.74
KZL102204377	0	259.25	353.75	1.35	8.92
KZL102204485	0.04	213.02	281.62	0.98	7.07
KZL102204483	0.04	280.62	339.42	0.84	8
KZL102204593	0.05	227.5	306.6	1.13	7.76
KZL102204467	0.11	252.64	349.24	1.38	8.97
KZL101734331	0.18	237.12	298.02	0.87	7.39
KZL101734395	0.21	243.21	330.71	1.25	8.55
KZL102204529	0.21	265.76	329.46	0.91	8.08
KZL102204513	0.21	267.91	347.01	1.13	8.7
KZL102204389	0.34	254.19	359.19	1.5	9.56
KZL101734403	0.46	219.69	321.19	1.45	8.89
KZL102204615	0.47	239.09	316.79	1.11	8.35
KZL101734311	0.48	232.77	312.57	1.14	8.33
KZL102204581	0.65	267.12	368.62	1.45	9.98
KZL101734317	0.7	232.85	311.25	1.12	8.49
KZL102204359	0.8	205.16	253.46	0.69	6.89
KZL102204499	0.84	215.26	307.66	1.32	8.82
KZL102204601	0.92	227.59	294.09	0.95	8.16
KZL101734323	1.25	247.04	300.24	0.76	8.35
KZL102204465	1.29	198.7	298.1	1.42	9.22
KZL102204353	1.34	253.34	335.24	1.17	9.67

***Note:** experiment date: 2024-01-06/2024-03-16*
***Source:** created by the authors*

An analysis of the experimental data from Sabit communal farm indicates that residual feed intake values for the 38 steers varied from -2.17 to +1.34. Seventeen steers had negative RFI values, signifying exceptional feed efficiency, whereas twenty-one steers displayed positive RFI values, indicative of worse feed conversion efficiency. The steer exhibiting the highest feed efficiency was KZL102204595, characterised by a RFI of -2.17, an average daily gain of 1.17 kg/day, and a remarkably low DMI of 5.15 kg/day. In contrast, the least efficient steer, KZL102204353 (RFI = 1.34), had an ADG of 1.17 kg/day while necessitating 9.67 kg/day of DMI, or 88% more feed than the most efficient animal for the equivalent growth rate. The average ADG for steers exhibiting negative RFI was 1.14 kg/day, whereas those with positive RFI averaged 1.12 kg/day, demonstrating only a negligible disparity in growth rate despite significantly divergent feed efficiency. Steer KZL101734419 (RFI = -0.71) attained the highest average daily gain in the cohort at 1.65 kg/day, accompanied with a dry matter intake (DMI) of 9.39 kg/day, so demonstrating that certain animals exhibit substantial development alongside comparatively modest feed consumption. In contrast, KZL102204511 (RFI = -0.71) had a very low ADG of

0.32 kg/day, despite a comparably low DMI of 5.03 kg/day, underscoring individual diversity in nutrition utilisation.

Regarding DMI, intake varied from 5.03 kg/day (KZL102204511) to 9.98 kg/day (KZL102204581), with a mean of roughly 7.95 kg/day. Of the 10 steers exhibiting the greatest DMI (⩾ 8.89 kg/day), only four presented negative RFI values, indicating that elevated intake alone does not dictate superior feed efficiency. KZL102204503 (RFI = −0.29) exhibited a substantial ADG of 1.45 kg/day and a DMI of 8.92 kg/day, while KZL102204389 (RFI = 0.34) attained a similar ADG of 1.50 kg/day, albeit with a higher RFI and a comparable DMI of 9.56 kg/day. The data indicate an absence of a consistent linear correlation between RFI and ADG. Multiple steers exhibiting elevated positive RFI values (e.g., KZL102204465, RFI = 1.29; ADG = 1.42 kg/day) had comparable weight increase to those with negative RFI values (e.g., KZL102204543, RFI = −1.52; ADG = 1.35 kg/day), underscoring the multifaceted character of growth. Similarly, the association between RFI and DMI is diverse. KZL102204497 (RFI = −0.84) and KZL102204581 (RFI = 0.65) had comparable ADG values (1.23 and 1.45 kg/day, respectively); however, the latter ingested 2.1 kg more dry matter daily, signifying much inferior feed efficiency.

The RFI levels of the steers from Group 1 at Shalabai LLP are reflected in the data in Table 5. The significant variation in feed efficiency among the steers is highlighted by the presence of both negative and positive RFI values in this group. Certain steers with negative RFI values are more effective in turning feed into weight gain, indicating that they are making better use of their feed resources. Conversely, positive RFI readings indicate less efficient feed usage, with steers ingesting more feed than is necessary for their growth. This range in RFI values indicates the presence of genetic variations in feed efficiency, but it also highlights the possible impact of management and environmental factors, including housing circumstances, food composition, and health status.

***Table 5**. Results of the experiment on individual steers of Shalabai LLP (Abai region) (Group 1)*

Experimental animal number	RFI	Wt1	Wt60	ADG	DMI
KZF193688117	-1.56	268.42	272.82	0.09	6.12
KZF194601515	-1.08	196.45	200.37	0.08	5.38
KZF194764568	-1.03	204.94	216.2	0.23	6.08
KZF194601487	-0.73	207.44	227.04	0.4	6.99
KZF194764514	-0.6	194.96	201.82	0.14	6.02
KZF194601551	-0.48	213.8	227.02	0.27	6.92
KZF194761909	-0.36	219.24	226.1	0.14	6.69
KZF193688161	-0.13	240.01	266.47	0.54	8.6
KZF194761920	-0.11	219.54	226.89	0.15	6.98
KZF194601482	-0.04	249.23	264.91	0.32	8.09
KZF193688001	0	271.89	291.49	0.4	8.75
KZF194761906	0.08	230.22	235.12	0.1	7.18
KZF194601497	0.21	242.96	258.16	0.31	8.21
KZF193688152	0.25	260.35	272.11	0.24	8.29
KZF194764502	0.63	260.98	277.15	0.33	8.97
KZF194764507	0.66	202.92	206.34	0.07	7.19
KZF194764587	0.74	230.32	235.72	0.11	7.87
KZF193688131	0.79	227.34	228.32	0.02	7.57
KZF193688153	1.35	217.21	228.97	0.24	8.69
KZF194764545	1.41	198.62	209.9	0.23	8.4

***Note:** experiment date: 2023-12-17/2024-02-04*
***Source:** created by the authors*

ADG readings range from a very low 0.02 kg/day to a higher 1.72 kg/day of ADG. The steers' diverse growth rates demonstrate that there isn't always a clear correlation between ADG and RFI. It's interesting to note that while some steers with greater RFI values showed better growth, others with lower or negative RFI values showed low ADG. This suggests that the variation in growth rates cannot be explained by feed efficiency alone. ADG is probably influenced by a number of factors, including the animal's metabolic efficiency, genetic propensity for growth, and the calibre of the feed it consumes. As a result, concentrating solely on RFI might not account for all the elements that influence an animal's growth performance.

The steers' daily consumption ranged from 6.12 kg to 9.72 kg in terms of DMI. The data shows a more nuanced relationship between RFI and DMI than one may anticipate. The diversity in DMI across steers with similar RFI values indicates that there are individual differences in intake, even though steers with lower RFI values tended to consume less feed. These variations may be caused by the metabolic rates of the cattle, the feed's digestibility, or variations in appetite. This makes the connection between feed efficiency and intake even more difficult to understand. The results imply that other biological or environmental elements must be taken into account when evaluating the steers' overall performance because DMI alone cannot adequately explain feed efficiency.

RFI levels for steers at Shalabai LLP (Abai region) in Group 2 range from -1.59 to 1.89, with both positive and negative values present, according to the data in Table 6. Better feed efficiency is indicated by negative RFI readings, which show that steers are using their feed resources more efficiently by consuming less feed in relation to their growth. But as the range of positive RFI readings shows, some steers are less productive and use more feed than is necessary for their growth. The genetic variability in feed efficiency within the group is highlighted by this range in RFI values, which also raises the possibility that environmental factors like feed quality, management techniques, and health may have a big impact on feed utilisation.

***Table 6**. Results of the experiment on individual steers of Shalabai LLP (Abai region) (Group 2)*

Experimental animal number	RFI	Wt1	Wt60	ADG	DMI
KZF194601607	-1.59	177.24	196.36	0.39	4.73
KZF194601732	-1.34	197.39	207.19	0.2	5.26
KZF194602286	-1.02	225.66	244.28	0.38	6.68
KZF194601642	-0.97	264.9	277.14	0.25	7.6
KZF194601705	-0.92	242.03	261.63	0.4	7.26
KZF194601648	-0.84	210.67	227.33	0.34	6.37
KZF194601637	-0.81	243.66	260.32	0.34	7.32
KZF194601582	-0.73	215.59	222.45	0.14	6.29
KZF194601640	-0.73	253.51	263.31	0.2	7.45
KZF194601562	-0.61	234.38	240.76	0.13	6.93
KZF194764492	-0.53	247.69	258.47	0.22	7.52
KZF194601592	-0.44	214.24	222.56	0.17	6.58
KZF194602438	-0.18	213.68	220.06	0.13	6.77
KZF194601722	0.11	243.58	251.9	0.17	7.96
KZF194601576	0.17	201.62	213.38	0.24	6.95
KZF194601634	0.17	218.93	242.45	0.48	7.85
KZF194601657	0.23	215.36	224.68	0.19	7.33
KZF194602370	0.26	267.96	279.22	0.23	8.88
KZF194602400	0.33	213.97	223.77	0.2	7.4
KZF194601798	0.41	242.67	265.21	0.46	8.72
KZF194602390	0.46	234.1	242.42	0.17	8.05
KZF194601569	0.68	221.44	235.16	0.28	8.1
KZF194601720	0.76	227.02	229.48	0.05	7.95
KZF194602290	0.76	198.74	215.4	0.34	7.63
KZF194602324	0.76	204.19	224.77	0.42	7.93
KZF194601571	0.82	214.22	229.9	0.32	8.1
KZF194601659	0.86	214.54	227.78	0.27	8.06
KZF194602419	0.92	195.68	205	0.19	7.45
KZF194601646	1.14	234.82	253.92	0.39	9.11
KZF194601563	1.89	237.17	249.91	0.26	9.72

***Note:** experiment date: 2023-12-17/2024-02-04*
***Source:** created by the authors*

The values for ADG vary significantly in growth performance, ranging from 0.02 kg/day to 1.8 kg/day. It's interesting to note that while some steers with greater RFI values shown superior growth, others with negative RFI values had comparatively low ADG. This implies that ADG is not solely determined by feed efficiency as determined by RFI. The variation in growth rates suggests that when assessing growth performance, additional elements including genetics, feed quality, and general animal health must also be taken into account. The DMI values, which range from 6.29 kg/day to 8.72 kg/day, thus lend credence to the notion that growth and feed efficiency are influenced by factors other than feed intake. This highlights how difficult it is to choose animals only on the basis of RFI and implies that in order to maximise cattle productivity, a more thorough approach that takes into account additional physiological and environmental aspects is required.

Thus, the essence of the experiment is to empirically assess the relationship between residual feed intake, average daily weight gain, and dry matter intake in Kazakh white-headed bulls under identical feeding conditions in order to identify animals that convert feed into body weight with optimal efficiency. The main advantage of this feeding strategy, controlled by Vytelle-sense technology, is its ability to identify bulls with negative RFI values that achieve comparable or higher weight gain while consuming less feed, thereby reducing production costs without compromising growth. This method improves economic sustainability, especially on large farms where feed costs account for up to 75% of total production costs. However, a significant drawback is that high-performing bulls do not always demonstrate the most efficient RFI values, as growth results are additionally influenced by genetic, metabolic, and environmental variables. Therefore, although this approach is a reliable selection tool, it should be used in conjunction with comprehensive genetic and phenotypic evaluations. Scalability is ensured by automated monitoring systems that reduce labor intensity and increase accuracy, making it suitable for both industrial and medium-sized enterprises. This strategy facilitates data-driven breeding stock selection, contributing to sustainable improvements in herd productivity and resource efficiency in beef production.

The benefits of this feeding strategy are evident from the data: choosing animals with lower RFI can minimise feed expenses without sacrificing growth. Cattle farming can be made more sustainable by using steers that grow as well or better while consuming less feed. The lack of a distinct, reliable relationship between RFI and ADG, as well as the variation in DMI among steers with comparable RFI values, are additional drawbacks that the findings also highlight. This implies that growth success cannot be predicted just by feed efficiency. This implies that, in order to maximise cow productivity, RFI should be used in conjunction with other elements like genetics, health, and feed quality, even though it is a helpful tool for identifying animals that use feed efficiently. This approach can be applied universally across beef cattle farms, especially those aiming to improve feed efficiency and reduce costs. By selecting animals with lower RFI values, farmers can potentially enhance the profitability of their operations. Furthermore, as the study demonstrates, using advanced technologies like Vytelle-sense for continuous monitoring of RFI, ADG, and DMI can provide more accurate and timely data, allowing for more informed decision-making in breeding programmes. The results underscore the importance of a holistic approach to cattle breeding, one that integrates feed efficiency with other productivity indicators to ensure the sustainable and profitable growth of beef production.

The following results were obtained, which were identical on all four farms: RFI varied on the enterprises from -2 to 2.01; ADG was 0.95 kg; average daily DMI per experimental steer was 11.03 kg/day. The most efficient feed utilisation was in steers with an RFI of -2. A very interesting positive correlation between ADG and DMI indices was found ($P = 0.011$). Thus, it is necessary to conclude that intensive DMI provoked intensive weight gain in steers, with a parallel absence of any correlation between RFI and ADG. The total number of steers with excellent RFI values (those with negative values) was 52, of which 24 had above average daily gain. These 24 steers had DMI which varied from 9.59 to 12 kg/day. Thus, out of 116 experimental bulls only 24 had outstanding RFI and excellent DMI, these experimental bulls can be kept separately to produce progeny with the same performance in future. But also, the range of recorded average daily gains ranged from 0.1 to 1.81 kg/day and the average ADG was 0.95 kg/day. DMI varied from 7.82 kg/day to 13.91 kg/day, with a median value of 11.03 kg/day obtained.

This efficient way of identifying the most cost-effective steers is easy to use in practice, because this Vytelle-sense continuous weight and feed monitoring technology makes it possible to accurately identify representatives of the total cattle breeding herd with the performance required by the company where these animals are reared. Another important positive aspect of using such a system in daily practice is the possibility to do it in a short time. This makes it possible to make accurate weight gain charts and even to forecast the profit made. The system is not labour-intensive and allows the owner to carry out even several such calculation tests per year. A separate positive phenomenon of using such a system is the influence on the qualitative and quantitative composition of the rations, because by calculating the sufficiency of dry matter in the feed and the index breeding value it is possible to adjust the ration to the RFI needs of the animal.

RFI is a moderately inherited measure of feed efficiency, actually a technological index used to select for more productive beef cattle (Dossybayev *et al.*, 2024). Evaluation of the various weight changes of the animals experimented on, both long term and short term, provided information that steers with low RFI values gave better performance than animals with higher RFI values. Observations of experimental animals gave information that herd members with low RFI values were calmer, rested more, and if these animals did not have the opportunity to lie down, they became restless. Using RFI as a genetic selection tool, it is possible to predict that offspring purchased from cattle with low RFI will eat less without weight loss. In this case, RFI is not related to sex, height, body parameters, quality of carcasses obtained. Calm cattle are an outward sign of low RFI. Unsatisfactory housing and feeding, as well as high density of animals can change these genetic properties. The obtained data suggest that bulls of Kazak Akbas or Kazakh white-headed cattle breed have lower indicators of average daily gain than representatives of other cattle breeds.

This means that improvement of this indicator using RFI as a selection tool will allow reaching the indicators of such breeds as Angus-Hereford or Simmental. Thus, obtaining improved daily weight gain should be seen as the most important objective of breeding programmes that will aim to improve the breeding performance of this breed. But, if Table 6 is scrutinised, it can be seen that DMI for the Kazakh Whitehead cattle breed has advantages over other varieties of beef, dairy, and meat and dairy cattle breeds. There is also noted mutual correlation on ADG and DMI indicators, but complete absence of similar correlation on ADG and RFI indicators. It turns out that outdated concepts that good weight of cattle is an outstanding economic and technological indicator, do not reflect the actual state of modern technology and the efficiency of feed utilisation is much more important in beef cattle breeding. Now technologists in Kazakhstan are faced with the task of breeding temperamentally calm cattle that consume less feed but are feed efficient while spending the least amount of time on feed consumption (Korbych, 2023). The easiest way to achieve this, as practical research has shown, is to select bulls by their RFI. L. Cavani *et al.* (2024) find that RFI has a moderate heritability, with a range of 26% to 58%. This would mean that selected bulls will either consume less feed than unselected bulls while achieving the same ADG, or they will consume more feed but achieve higher ADG. The purpose of such selection is to select animals for beef cattle breeds, but in parallel, according to D.P. Berry *et al.* (2019), the production of greenhouse gases by animals will be reduced. And at the current growth of beef production in Kazakhstan, it can be of great importance.

Data of average daily growth according to L.S. Brunes *et al.* (2021) are a simple mathematical way to check the effectiveness of selected technological strategies. But this method is controversial and cannot be considered in the modern technological process of cultivation as the main argument in the choice of cultivation strategy. These indicators, according to S.R. Chacko Kaitholil *et al.* (2024), depend largely on many factors such as the number of years a farmer has been involved in dairy farming, reduction in the quality and quantity of milk given to calves, the presence of diseases that could be transmitted with this milk, problems of postvaccinal reactions and diseases of contagious and non-contagious aetiology. Technological parameters, according to S.C. Archer (2021), which can also affect the indicators of average daily gains of calves are the time of pre-weaning, as well as technological parameters of cows from which calves were obtained: what weight of the cow was at the first insemination, the number of calvings and the age of the cow, the stability of cow production indicators on a particular farm. The calves that became the object of the study are not much affected by environmental temperature conditions, because their genetic potential made it possible to easily tolerate the climate of Kazakhstan. However, the ambient temperature and when calves were born and developed in the first three months of life should be taken into account when analysing technological indicators. That is, comparing the performance of calves born in winter and summer will be incorrect. The presence of adequate nutrition will influence ADG performance. Thus, ADG is certainly an important technological argument, but should only be considered in conjunction with RFI, as demonstrated in this study.

In addition to the economic costs of raising beef cattle, consumer demand should always be considered. This implies the meat quality requirements of beef cattle. Every large enterprise with a closed cycle of agricultural production has a sales department for finished products and a network of shops. The data obtained in the course of the study emphasise the reliability and stability of the RFI indicator to physiological and technological nuances of production, but the question of how the selection of animals with low RFI affects the quality of meat, how this indicator affects the ratio (or content) of fat in meat, the marbling of meat of elite breeds of cattle should be studied in more detail. It is an indicator of carcass composition and should also be evaluated holistically, because while technological research is important, sales and consumer demand data can be an important economic study of whether the quality of carcasses from cattle with low RFI meets consumer demand.

The use of seemingly simple and modern methods such as Vytelle-sense as well as the data obtained in this study has a drawback. It is that during summer grasing this programme may not be effective. The essence of the research is that all animals receive a certain amount of feed, the qualitative composition of which is known. When grasing, animals consume different quality and quantity of food, so the programme calculations will be incorrect. The research of this problem is promising. In addition, the use of Vytelle-sense technology with different diets, rather than one diet as in this study, could provide interesting information for research.

CONCLUSIONS

In this study, Vytelle-sense technology was used on the basis of four farms: Zhana Bereke LLP (Akmola Region), Galitskoe LLP (Pavlodar Region), Sabit communal farm (West Kazakhstan Region) and Shalabai LLP (Abai Region). With the help of this technology the data of direct correlation of RFI indicator and ADG indicator with complete absence of correlation of RFI and DMI were obtained. The following results were obtained: RFI indicator varied on the enterprises from -2 to 2.01; ADG indicator was 0.95 kg; average daily DMI intake per experimental steer was 11.03 kg/day. The most efficient feed utilisation was in steers with RFI -2; a positive correlation between ADG and DMI was observed (P = 0.011). The interval of recorded average daily gains ranged from 0.1 to 1.81 kg/day and the mean ADG was 0.95 kg/day. The DMI varied from 7.82 kg/day to 13.91 kg/day and a median value of 11.03 kg/day was obtained.

The experiment shows that choosing cattle according to RFI can lower feed expenses and increase feed efficiency. However, the inconsistent correlation between RFI and ADG implies that RFI is insufficient on its own to forecast growth performance. Other important factors are health, feed quality, and genetics. The intricacy of cattle performance is highlighted by the weak association found between DMI and growth. Therefore, to maximise productivity and guarantee sustainable and economical beef production, a more thorough breeding strategy that incorporates RFI with other parameters is required. To improve selection criteria, future studies should concentrate on determining the physiological and genetic elements that affect growth performance as well as feed efficiency. Furthermore, enhancing beef production methods will need examining the long-term impacts of RFI-based breeding programmes on cow health, meat quality, and environmental sustainability.

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Підвищення ефективності використання кормів у казахської білоголової худоби: роль залишкового споживання корму, приросту та споживання сухої речовини

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Анотація. Метою даного дослідження було вивчення впливу залишкового споживання корму на ключові технологічні параметри вирощування казахської білоголової худоби. Експериментальне дослідження проводилося на чотирьох великих племінних підприємствах, що розводять цю породу: товаристві з обмеженою відповідальністю «Жана Береке» (Акмолинська область), товаристві з обмеженою відповідальністю «Галицьке» (Павлодарська область), комунальному господарстві «Сабіт» (Західно-Казахстанська область) та товаристві з обмеженою відповідальністю «Шалабай» (Абайська область). Збір даних та постійний моніторинг здійснювалися за допомогою автоматизованої системи моніторингу худоби, відомої як технологія Vytelle-sense. Після двотижневого періоду адаптації на кожному підприємстві було відібрано 64 бички казахської білоголової породи. Протягом 60 днів проводилися вимірювання залишкового споживання корму, середньодобового приросту ваги та добового споживання сухої речовини. Результати показали, що на всіх чотирьох підприємствах приблизно половина тварин мала від'ємні значення залишкового споживання корму. Середній добовий приріст ваги становив 0,95 кілограма, а середнє добове споживання сухої речовини на бичка – 11,03 кілограма. Була виявлена позитивна кореляція між залишковим споживанням корму та середнім добовим приростом ваги, тоді як значущої кореляції зі споживанням сухої речовини виявлено не було. Биків, які демонструють негативні значення залишкового споживання корму разом з високим споживанням корму, рекомендується відбирати для програм розведення через потенціал генетично сприятливих ознак. Крім того, середній щоденний приріст ваги становив від 0,1 до 1,81 кілограма, а споживання сухої речовини – від 7,82 до 13,91 кілограма на день

Ключові слова: Казахська білоголова порода; технологічні параметри; технологія Vytelle-sense; м'ясне скотарство; спадковість

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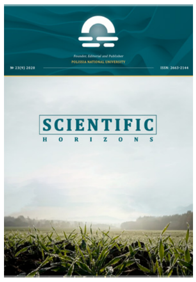

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Impact of anthropogenic factors on the population structure of non-fish seafood in reservoirs of Azerbaijan

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Abstract. The aim of the study was to establish the impact of anthropogenic factors on population size and structure. The article presented the results of a comprehensive empirical study aimed at assessing the influence of anthropogenic factors on the structure and abundance of shrimp (*Palaemon elegans, Palaemon adspersus*) and freshwater crayfish (*Astacus leptodactylus, Pontastacus eichwaldi*) populations in the conditions of Shamkir and Mingachevir reservoirs of Azerbaijan. In the period from June to August 2024, field surveys were conducted at sites with different degrees of pollution. The assessment included analyses of the density of individuals, age and sex composition, juvenile abundance and mortality, and spatial distribution of populations. For freshwater crayfish, the average density of *Astacus leptodactylus* ranged from 12 individuals/m^2 (clean zones of the Shamkir reservoir) to 5 individuals/m^2 (polluted zones of the Mingachevir reservoir). The number of *Pontastacus eichwaldi* varied from

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7 to 2 individuals/m^2. The share of juveniles in the population structure in clean areas reached 42% (*Palaemon elegans*) and 40% (*Astacus leptodactylus*), while in polluted areas it decreased to 15-20%. Mortality of juveniles up to 40% was recorded in sites with organic pollution. An imbalance in the sex composition was observed in areas with high levels of pollution: in *Palaemon adspersus* and *Pontastacus eichwaldi* the proportion of males exceeded 55%, while in clean areas females predominated or an equal ratio was maintained. The greatest decrease in the abundance of all species was observed in the Mingachevir reservoir – up to 60% for *Pontastacus eichwaldi*, which indicates the high sensitivity of the species to complex anthropogenic impact. The results showed that chemical pollution, recreational load and poaching are the determining factors of population degradation. A direct correlation between the level of anthropogenic impact and the decrease in abundance, disturbance of age and sex structure was established. Indicator indicators for monitoring the state of freshwater ecosystems were proposed. The obtained results can be used for development of monitoring programmes and ecological-restoration measures in aquatic ecosystems of Azerbaijan

Keywords: bottom invertebrates; monitoring of environment; technogenic load; freshwater ecosystems; bioindication

INTRODUCTION

The relevance of this study is due to the need to assess the impact of anthropogenic factors on aquatic ecosystems, which is especially important in the context of accelerated pollution of water bodies and climate change. The Shamkir and Mingachevir reservoirs, which are important ecosystems for the region, are exposed to various pollutants such as heavy metals and organic substances, which leads to changes in the abundance and population structure of aquatic inhabitants. Shrimp and freshwater crayfish, being sensitive indicators of water quality, are good subjects for studying the effects of pollutants. The problematic issue of the study is the insufficient assessment of the impact of anthropogenic pollutants on the state of populations of these species in specific water bodies of Azerbaijan, which limits the development of effective methods for the protection of water body ecosystems and sustainable use of their resources. It is important not only to quantify the populations, but also to analyse the impact of pollutants on age and sex structure, as well as on mortality of juveniles, which allows a deeper understanding of ecological changes in these reservoirs and the formation of recommendations for their protection.

Thus, F.R. Gulieva and L.V. Gulieva (2021) revealed that economic activities in the area of Mingachevir and Varvarinskoye reservoirs contributed to the reduction of species diversity of non-fish aquatic organisms. According to the results, the disruption of trophic relationships and reduction in the number of key invertebrates occurred under the influence of pollution and changes in the hydrological regime. In a study by S. Hasanova (2024) recorded the deterioration of aquatic environment as a result of wastewater and industrial emissions. The author found that anthropogenic pressure led to changes in the species composition and decrease in the abundance of certain groups of non-fish organisms. In the generalised analysis presented by R. Abbasov *et al.* (2022), it was shown that urbanisation and expansion of agricultural areas increased the pressure on water bodies in Azerbaijan. The authors stated that such processes reduced the stability of aquatic ecosystems and caused structural changes in hydrobiont populations. Based on data on Lake Naivasha, E. Mutethya and E. Yongo (2021) analysed the consequences of anthropogenically caused penetration of invasive species and recorded their impact on native invertebrate populations. The researchers found that the introduction of alien organisms contributed to the displacement of native species and disrupted the balance of the ecosystem.

In a study by C. Waldock *et al.* (2025) documented that pollution of water bodies caused changes in the trace element composition of tropical fish communities, affecting the entire trophic structure. The authors emphasised that similar processes may have occurred in other ecosystems, including reservoirs, where anthropogenic interference was observed. When analysing the consequences of the transformation of coastal landscapes, T. Pšeničková and J. Horák (2022) found a reduction in abundance and simplification of the structure of hydrobiont populations. The researchers recorded that deforestation and the creation of artificial reservoirs had a long-term negative impact on the ecological parameters of aquatic communities. In particular, A. Febriana and B.I. Utary (2024) found that conversion of mangrove forests in the Tanjung Luar village area caused habitat degradation and reduction of biological resources. According to the authors, the disturbance of the natural balance was accompanied by the loss of breeding habitat for many invertebrate species, affecting the entire structure of coastal ecosystems. A large-scale study by W.M. Jubb *et al.* (2023) analysed the effects of hydraulic structures and water level fluctuations on fish migrations in river systems. The authors found that combined anthropogenic impacts disrupted the reproduction and movement of aquatic organisms, contributing to changes in the spatial structure of their populations, including invertebrate's dependent on stable hydrological regimes.

In analysing the relationship between natural resources and socio-economic behaviour of communities, S. Gaja-Svasti *et al.* (2022) documented that in the Mun River Basin, wild fish and invertebrates remained the most important element of the diet and source of income for villagers. The authors emphasised that changes in the aquatic environment caused by anthropogenic interventions were directly reflected in the decreasing availability of these resources and the transformation of traditional lifestyles. Summarising data from the Mekong region, I.G. Baird and Z.S. Hogan (2023) noted that the construction of hydropower plants entails a significant reduction in fish biodiversity and degradation of aquatic habitat. As part of their review, it was shown that non-fish species, particularly those sensitive to water level fluctuations and bottom substrate quality, were also at risk of extinction under the impact of regulated flows. Sustainable aquaculture production was addressed in a study by S.M. Colombo *et al.* (2023), which examined the potential for closed-loop feed systems for "blue" food resources. The authors found that feed rationalisation and reduction of pressure on natural aquatic populations can contribute to the recovery of non-fish organisms subjected to anthropogenic depletion.

In the context of fisheries conservation, I. Mayer and M. Pšenička (2024) examined the use of reproductive technologies to conserve teleosts in the face of declining abundance. The researchers demonstrated that technological reproduction can serve as a compensatory mechanism for the loss of natural populations, including non-fish components of ecosystems that are closely related to spawning conditions and microenvironment. The aim of the study was to analyse changes in the structure of non-fish seafood populations under the influence of anthropogenic factors in reservoirs of Azerbaijan. The objectives of the study were to identify key anthropogenic factors, assess their impact on non-fish seafood and analyse changes in population structure.

MATERIALS AND METHODS

The study was conducted from June to August 2024 in the Shamkir and Mingachevir reservoirs of Azerbaijan. The climate of the region was characterised by dry and hot summers with average daily air temperatures from +28 to +35°C and night temperatures from +20 to +25°C. The average annual precipitation was 200-300 mm, most of which occurred in the spring months. The hydrological regime of both reservoirs is subject to significant anthropogenic influence due to the presence of large industrial enterprises, recreational areas and settlements in the adjacent territories. This was the reason for selecting these reservoirs as sites for assessing the impact of anthropogenic factors on aquatic ecosystems and hydrobiont populations. Shrimp: stone shrimp (*Palaemon elegans*) and grass shrimp (*Palaemon adspersus*), as well as freshwater crayfish: Slender-clawed crayfish (*Astacus leptodactylus*) and Caspian crayfish (*Pontastacus eichwaldi*) were selected as research objects. The species were selected due to their high sensitivity to changes in the hydrochemical regime of water bodies and widespread occurrence in aquatic ecosystems of Azerbaijan. These species have indicator properties that allow to objectively assess the level of ecological state of water bodies and the degree of anthropogenic impact.

To assess the impact of anthropogenic factors, two categories of sites were studied: clean (control sites with minimal human impact) and heavily polluted. Sampling was carried out monthly from June to August 2024 by hand collection and using standard invertebrate traps. Each site was surveyed in three replicates and then the mean population density (number of individuals per square metre) was calculated. Shrimp and crayfish densities were determined by counting the number of captured specimens in a defined area of the reservoir bottom (1 m^2). The authors adhered to the standards of the Guidelines for the treatment of animals in behavioural research and teaching (2012). For this purpose, a control area (1 × 1 metre square) was allocated at each site, after which the captured individuals were counted, recorded and then the average density was calculated using the formula (1):

$$D = \frac{N}{S}, \tag{1}$$

where D – population density (individuals/m^2); N – number of captured individuals in the study area; S – plot area (m^2).

The sex composition of populations (proportion of females and males) was determined by visual examination of each specimen using a "Leica EZ4" binocular microscope (Germany). The sex of each captured specimen was recorded, and then the proportion of individuals of each sex (% of the total population size) was calculated (2):

$$P = \frac{n_p}{N} \times 100\%, \tag{2}$$

where P – proportion of females or males (%); n_p – number of individuals of a particular sex (females or males); N – total number of individuals surveyed.

To assess the age structure, morphometric analysis was carried out using electronic caliper "Mitutoyo" (model CD-15APX, Japan) with measurement accuracy up to 0.01 mm and electronic scales "Ohaus Scout STX2202" (USA) with accuracy up to 0.01 g. The obtained data allowed to distinguish age groups: juveniles, adults and older individuals. Mortality of juveniles was assessed by comparing the number of juveniles in contaminated sites and control (clean) zones. The number of juveniles was recorded separately for each site (individuals per m^2). Mortality was calculated according to the following formula (3):

$$M = \frac{(N_c - N_p)}{N_c} \times 100\%, \tag{3}$$

where M – juvenile mortality (%); N_c – number of juveniles in control (clean) areas (individuals/m^2); N_p – number of juveniles on polluted areas (individuals/m^2).

For quantitative assessment of anthropogenic pollution, water and bottom sediment samples taken monthly at each location were used. Concentration of heavy metals (Pb, Zn, Cu) was determined by atomic absorption spectrophotometer "Analytik Jena novAA 400P" (Germany). The content of pollutants in water and bottom sediments was measured by infrared spectrometer "Infracal ATR-SP" (USA). Organic pollution (nitrates, nitrites and ammonium nitrogen) was analysed using a spectrophotometer "Hach DR3900" (USA). Noise impact from recreational activities (motor boats, fishing and tourism) was measured with a noise meter model "Testo 815" (Germany). Measurements were made monthly during daytime (from 10:00 to 16:00) at each study site, after which the average noise level in decibels (dB) was calculated. The obtained data were processed by analysis of variance (ANOVA) in Statistica 12 software. For visualisation it was used graphs built in Microsoft Excel and Python with Matplotlib library, showing population density, mortality of juveniles and reduction of species abundance at polluted areas.

RESULTS

Quantitative indicators of shrimp populations in Shamkir and Mingachevir reservoirs. The average density of *Palaemon elegans* shrimp in the Shamkir Reservoir varied from 12 to 25 individuals per square meter. The highest number of individuals was observed in coastal areas with aquatic vegetation and minimal pollution, where the density reached 25 individuals/m². In contrast, areas located near industrial enterprises and recreational zones were characterised by a lower abundance of this species – approximately 12-15 individuals/m². In the Mingachevir Reservoir, the density of *Palaemon elegans* was lower, ranging from 8 to 18 individuals per m². The maximum density of 18 individuals was observed in areas with low anthropogenic impact, far from populated areas, whereas near sites of intensive fishing and industrial activity, the population density decreased to minimal values – 8-10 individuals per m². The species *Palaemon adspersus* showed a noticeably lower population density in both reservoirs. In the Shamkir Reservoir, the density of this species varied from 9 to 17 individuals per m². The highest concentration of individuals was characteristic of coastal, shallow-water areas with shelters and a rich food base. In moderately polluted areas, the density decreased to 10-12 individuals/m², while in zones of pronounced anthropogenic pollution, it was less than 9 individuals/m².

In the Mingachevir Reservoir, the situation proved even less favourable for *Palaemon adspersus*: the population density ranged from 6 to 14 individuals per m². The lowest abundance of this species was noted in areas with high levels of industrial and domestic effluent pollution (6-7 individuals/m²), indicating a pronounced sensitivity of this species to the negative impact of pollutants. When studying the age and sex structure of the shrimp, differences in the distribution of age groups and sex ratio of the populations were revealed. For *Palaemon elegans* in the Shamkir Reservoir, juveniles (less than one year old) accounted for 42%, adults (1 to 2 years old) – 48%, and the proportion of older individuals (over 2 years old) was low – only about 10%. A similar pattern was observed in the Mingachevir Reservoir, however, the proportion of juveniles was smaller (35%), while adults constituted up to 55%. *Palaemon adspersus* demonstrated a different pattern of age distribution. In the Shamkir Reservoir, juveniles accounted for approximately 30%, while adults were the dominant age group, reaching 60%. Older age groups were rarely encountered (10%). In the Mingachevir Reservoir, the proportion of juveniles was even lower (25%), and adults higher (65%), indicating difficult reproduction and premature aging of the population.

In addition to abundance and age composition, significant differences in the sex ratio of shrimp were identified. In *Palaemon elegans*, a predominance of females was observed – on average 55-60% of the total population in both reservoirs. *Palaemon adspersus* had an almost equal sex ratio (50:50%), however, in areas with increased pollution, a slight predominance of males was noted (up to 55%). A comparative analysis of individual distribution showed unevenness in populations across the reservoir areas. The highest abundance of both species was characteristic of remote and ecologically clean zones with low levels of anthropogenic impact. Areas with intensive human economic activity were characterised by a decrease in the total shrimp abundance by 25-40% from the average values across the reservoirs (Table 1).

***Table 1**. Quantitative indicators of shrimp populations in Shamkir and Mingachevir reservoirs*

Type of shrimp	Reservoir	Density (individuals/m²)	Juveniles	Adults	Older individuals	Proportion of females	Proportion of males
Palaemon elegans	Shamkir	12-25	42%	48%	10%	60%	40%
	Mingachevir	8-18	35%	55%	10%	55%	45%
Palaemon adspersus	Shamkir	9-17	30%	60%	10%	50%	50%
	Mingachevir	6-14	25%	65%	10%	45%	55%

***Source:** developed by the authors*

Thus, it was found that anthropogenic impacts significantly change the quantitative indicators and structure of shrimp populations in Shamkir and Mingachevir reservoirs, with *Palaemon adspersus* species being the most vulnerable. The results obtained can be used to develop measures for the protection and rational use of shrimp resources in water bodies of Azerbaijan.

Indicators of freshwater crayfish populations in Shamkir and Mingachevir reservoirs. The average population density of freshwater crayfish, *Astacus leptodactylus*, in the Shamkir Reservoir ranged from 5 to 12 individuals per square metre. The maximum density for this species (12 individuals/m²) was recorded in areas with clean water and natural shelters – such as stones, snags, and dense aquatic vegetation. In territories affected by sewage and domestic waste, the crayfish abundance decreased to 5-6 individuals per m². In the Mingachevir Reservoir, the average density of *Astacus leptodactylus* was lower, varying between 3 and 9 individuals per m². The highest abundance was observed in areas remote from industrial influence, whereas zones of intense pollution were characterised by a minimal abundance – 3-4 individuals per m². The density of the second species studied, *Pontastacus eichwaldi*, in the Shamkir Reservoir was within the range of 3 to 7 individuals per square metre. A high density (7 individuals/m²) was recorded only in isolated areas with minimal anthropogenic impact and the presence of a good food base. Areas with pollution and constant human presence showed a sharp decrease in density to 3-4 individuals/m². In the Mingachevir Reservoir, the density of *Pontastacus eichwaldi* was the lowest, amounting to only 2 to 5 individuals per m². The lowest abundance (2 individuals/m²) was recorded in zones with significant domestic waste pollution.

The age structure of the *Astacus leptodactylus* population in the Shamkir Reservoir was characterised by a high proportion of juveniles (up to 2 years old) – 40%. Adults (from 2 to 4 years old) constituted about 45%, and older individuals (over 4 years old) – 15%. In the Mingachevir Reservoir, the percentage of juveniles decreased to 30%, adults increased to up to 50%, and the proportion of older individuals increased to 20%, reflecting negative conditions for successful juvenile reproduction. The age composition of the *Pontastacus eichwaldi* population in the Shamkir Reservoir consisted of 25% juveniles, 60% adults, and 15% older individuals. In the Mingachevir Reservoir, juveniles accounted for only 20%, adults – 65%, and older individuals – 15%. The sex composition of crayfish populations was close to an equal ratio. In the Shamkir Reservoir, both species studied had an equal proportion of females and males – approximately 50:50%. However, in the Mingachevir Reservoir, especially in polluted areas, an increase in the proportion of males to 55% was observed, likely due to different resistance of the sexes to pollution. During the annual observation period, the *Astacus leptodactylus* population in the Shamkir Reservoir decreased by 15%. In the Mingachevir Reservoir, the decline in the abundance of this species reached 20%. The *Pontastacus eichwaldi* population decreased even more significantly – by 20% in the Shamkir Reservoir and by 25% in the Mingachevir Reservoir. The main factors for this reduction were the deterioration of water quality and the destruction of natural habitats due to anthropogenic pollution and fishing. In areas with high levels of organic and chemical pollution, an increase in juvenile mortality of both species by 25-30% was recorded compared to clean areas. This led to a sharp imbalance in age structure and a deterioration of reproductive potential (Table 2).

***Table 2**. Indicators of freshwater crayfish populations in Shamkir and Mingachevir reservoirs (for the observation period 2024)*

Type of crayfish	Reservoir	Density (individuals/m²)	Juveniles	Adults	Older individuals	Proportion of females	Proportion of males	Annual population decline	Juvenile mortality in polluted areas
Astacus leptodactylus	Shamkir	5-12	40%	45%	15%	50%	50%	-15%	25%
	Mingachevir	3-9	30%	50%	20%	45%	55%	-20%	30%
Pontastacus eichwaldi	Shamkir	3-7	25%	60%	15%	50%	50%	-20%	25%
	Mingachevir	2-5	20%	65%	15%	45%	55%	-25%	30%

***Source:** developed by the authors*

The results indicate the critical impact of pollution and poaching on the structure and abundance of freshwater crayfish in both reservoirs. The greatest damage was caused to juveniles, which significantly reduced the ability of populations to natural recovery and sustainable development.

Effects of specific anthropogenic factors on the abundance and population structure of shrimp and freshwater crayfish populations. Among the main factors, industrial wastewater containing heavy metals (lead, zinc, copper), domestic organic effluents, and intensive poaching caused the greatest damage. The abundance of *Palaemon elegans* shrimp in areas of the Shamkir Reservoir with elevated heavy metal content (especially lead and zinc) decreased from 25 to 17 individuals/m² (a 32% reduction). A similar situation was observed in the Mingachevir Reservoir, where pollution caused a reduction in the abundance of this species from 18 to 11 individuals/m² (a 39% reduction). Furthermore, domestic organic effluents discharged into the water body also caused a 25-30% reduction in the population abundance of this species compared to clean areas (Khudiiash *et al.*, 2023).

For the grass shrimp, *Palaemon adspersus*, the greatest reduction in abundance was recorded in areas polluted by organic domestic effluents. In the Shamkir Reservoir, the abundance of this species decreased from 17 to 11 individuals/m² (a 35% reduction), and in the Mingachevir Reservoir – from 14 to 8 individuals/m² (a 43% reduction). This indicated the species' high sensitivity to organic pollutants (Koretsky & Kononenko, 2024). The age structure of both shrimp species also underwent significant changes under the influence of pollution. For instance, the proportion of juveniles of the grass shrimp in polluted areas of the Mingachevir Reservoir decreased from 25% to 15%, while the juvenile mortality increased to 40% compared to 15% in control areas. In the Shamkir Reservoir, for *Palaemon elegans*, the proportion of juveniles decreased from 42% to 30%, and mortality increased from 15% to 32%. The populations of freshwater crayfish were also significantly reduced under the influence of anthropogenic factors. For example, the abundance of the slender-clawed crayfish (*Astacus leptodactylus*) in the Shamkir Reservoir, due to the impact of heavy metals and poaching, decreased from 12 to 8 individuals per m² (a 33% reduction). In the Mingachevir Reservoir, domestic organic effluents had an even greater impact, reducing the population abundance of this species from 9 to 5 individuals per m² (a 44% reduction).

Anthropogenic factors had the most significant negative impact on the population of the Caspian crayfish (*Pontastacus eichwaldi*). In the Shamkir Reservoir, under the influence of organic pollutants (nitrates and nitrites), the abundance decreased from 7 to 4 individuals per m² (a 43% reduction). In the Mingachevir Reservoir, characterised by high levels of domestic organic effluents, the abundance of the Caspian crayfish decreased most sharply – from 5 to 2 individuals per m² (a 60% reduction). Besides water pollution, a significant negative factor was noise pollution from recreational activities (fishing, tourism) (Shumka *et al.*, 2020). In areas with high noise levels, the abundance of freshwater crayfish additionally decreased by 15-20%, and the proportion of older and adult individuals decreased by 40-50%, which indicated the negative influence of noise and fishing on the reproductive potential of populations (Table 3).

***Table 3**. Effects of specific anthropogenic factors on the abundance and population structure of shrimp and freshwater crayfish populations*

Type	Reservoir	Anthropogenic factor	Numbers, clean areas (individuals/m²)	Numbers, polluted areas (individuals/m²)	Headcount reduction	Main pollutants	Proportion of juveniles in clean areas	Proportion of juveniles in polluted areas	Juvenile mortality in polluted areas
Stone shrimp (Palaemon elegans)	Shamkir	Heavy metals (Pb, Zn, Cu)	25	17	32%	Lead (Pb), Zinc (Zn)	42%	30%	32%
Stone shrimp (Palaemon elegans)	Mingachevir	Petroleum products, domestic wastewater	18	11	39%	Organics	35%	20%	35%
Grass shrimp (Palaemon adspersus	Shamkir	Organic domestic wastewater	17	11	35%	Organics	30%	18%	32%
Grass shrimp (Palaemon adspersus)	Mingachevir	Domestic wastewater	14	8	43%	Organics	25%	15%	40%
Slender-clawed crayfish (Astacus leptodactylus)	Shamkir	Heavy metals, poaching of fish	12	8	33%	Lead, Zinc, Poaching	40%	30%	35%
Slender-clawed crayfish (Astacus leptodactylus)	Mingachevir	Organic domestic wastewater	9	5	44%	Organics	30%	20%	40%
Caspian crayfish (Pontastacus eichwaldi)	Shamkir	Nitrates, nitrites	7	4	43%	Nitrates, nitrites	25%	15%	35%
Caspian crayfish (Pontastacus eichwaldi)	Mingachevir	Domestic wastewater	5	2	60%	Organics	20%	10%	40%

***Source:** developed by the authors*

Thus, water pollution and anthropogenic factors had a significant negative impact on the quantitative indicators and population structure of the studied species. Freshwater crayfish and shrimp species *Palaemon adspersus* were the most sensitive to pollution.

Distribution of shrimp and crayfish populations in relation to anthropogenic impacts. In the clean areas of the Shamkir and Mingachevir Reservoirs, a uniform distribution of *Palaemon elegans* shrimp was observed. The maximum density (25 individuals per m²) was noted in areas of the Shamkir Reservoir little affected by anthropogenic factors, characterised by the presence of natural shelters and a rich food base. In areas with a moderate level of pollution and increased anthropogenic pressure, the density of this species decreased to approximately 17 individuals per m², while the most polluted areas subjected to active recreational activity were characterised by a reduction in abundance to 10-12 individuals per m². *Palaemon adspersus* exhibited even greater sensitivity to pollution and other anthropogenic factors, including poaching and noise pollution (Shumka *et al.*, 2023). The maximum abundance of this species was recorded in the coastal zones of the Shamkir Reservoir (17 individuals/m²), where favourable habitat conditions, such as clean water and abundant shelters, were observed. In polluted areas, the shrimp abundance decreased to 11 individuals/m², and in the most polluted areas of the Mingachevir Reservoir, the density was only 8 individuals/m².

For freshwater crayfish, the spatial structure of populations was even more sensitive to anthropogenic impact (Kurovska, 2024). The slender-clawed crayfish (*Astacus leptodactylus*) reached maximum density in clean zones of the Shamkir Reservoir, distant from industrial facilities, where the abundance was up to 12 individuals per m². In areas with water polluted by heavy metals and organic substances, the abundance decreased to 8 individuals per m², and in the Mingachevir Reservoir – to 5 individuals per m². The Caspian crayfish (*Pontastacus eichwaldi*) showed the most pronounced dependence on anthropogenic impact among the studied crayfish species. In the Shamkir Reservoir, its density varied from 7 individuals/m² in clean areas to 4 individuals/m² in polluted territories. In the Mingachevir Reservoir, this indicator was even lower, amounting to only 2-3 individuals per m² in areas with high levels of oil and organic pollution. This indicated that the Caspian crayfish proved to be the most sensitive to the negative influence of anthropogenic pollution.

Analysis of the spatial distribution showed that the most vulnerable were the juveniles of all investigated species. In polluted areas, the proportion of juveniles significantly decreased, leading to a noticeable imbalance in the age structure and a deterioration of reproductive potential (Bilyalov *et al.*, 2025). In the most polluted zones of the Mingachevir Reservoir, the mortality of shrimp and crayfish juveniles exceeded the figures in clean areas by 2-2.5 times. It was also established that noise pollution caused by active human recreational activity (boating, fishing, tourism) intensified the negative impact of pollution. In areas with high noise levels, the density of shrimp and crayfish populations additionally decreased by 15-20%, and the abundance of older age groups – by up to 50% (Fig. 1).

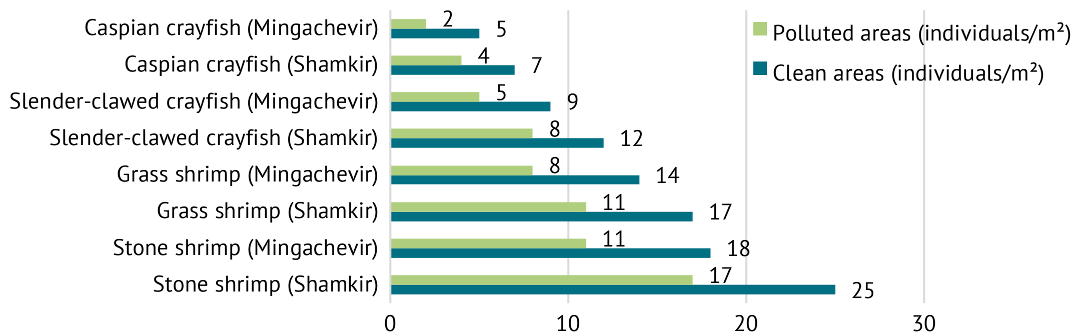

Figure 1*. Distribution of shrimp and crayfish populations in relation to anthropogenic impacts*
Source: *developed by the authors*

Thus, the results clearly demonstrated a direct dependence of spatial structure and population size on the level and type of anthropogenic impact. The greatest changes were observed in areas with complex impact of pollution (oil products, heavy metals, organics) and active recreation. The results of the study showed a significant decrease in the number of shrimp and crayfish populations in the polluted areas of the Shamkir and Mingachevir reservoirs, especially in the species *Palaemon adspersus* and *Pontastacus eichwaldi*, where the influence of anthropogenic factors led to a decrease in juveniles, imbalance of sex ratios. The greatest changes were observed in Mingachevir reservoir, where the level of pollution reached critical indicators for the ecosystem.

DISCUSSION

The conducted study established that anthropogenic factors exert a significant negative impact on the structure and abundance of shrimp (*Palaemon elegans,* *Palaemon adspersus*) and freshwater crayfish (*Astacus leptodactylus, Pontastacus eichwaldi*) populations in the Shamkir and Mingachevir Reservoirs. In polluted areas of both water bodies, the density of all studied species was significantly lower compared to clean zones: for *Palaemon elegans* in polluted areas of the Shamkir Reservoir, density decreased from 25 to 17 individuals/m² (by 32%), and for *Palaemon adspersus* – from 17 to 11 individuals/m² (by 35%). In the Mingachevir Reservoir, the abundance of *Palaemon elegans* decreased from 18 to 11 individuals/m² (by 39%), and *Palaemon adspersus* – from 14 to 8 individuals/m² (by 43%). The Caspian crayfish proved particularly vulnerable, with its abundance in heavily polluted areas of the Mingachevir Reservoir dropping to 2 individuals/m², representing a 60% reduction. The proportion of juveniles in polluted areas also significantly decreased for all species: for *Palaemon elegans* and *Palaemon adspersus*, the proportion of juveniles in polluted areas of Mingachevir decreased from 35-42% to 15-18%, accompanied by increased mortality (up to 50%). Simultaneously, shifts in sex structure were observed: males predominated in polluted areas, especially for *Palaemon adspersus* and *Pontastacus eichwaldi*, which may indicate differential resistance of sexes to toxicants. Thus, the spatial distribution, age, and sex composition of populations clearly correlated with the intensity of anthropogenic impact, confirming its destructive influence on the water bodies' ecosystem.

Research by L. Sehnal *et al.* (2021) and D.D. Backović and N. Tokodi (2024) addressed two different directions related to the response of aquatic organisms to technogenic loads. D.D. Backović and N. Tokodi focused on the biotoxicological aspect, investigating the spread of cyanobacteria and cyanotoxins in freshwater bodies, including aquaculture systems. It was emphasised that these compounds significantly disrupt metabolic functions and reduce the reproductive activity of aquatic organisms. Meanwhile, L. Sehnal *et al.* dedicated their work to the analysis of the microbiome of aquatic vertebrates, focusing on its role in immune defence and adaptation to polluted environments. Both approaches covered molecular and physiological levels but did not include population or spatial parameters. In contrast to these authors, the presented study allowed for establishing quantitative relationships between environmental pollution and the demographic structure of shrimp and crayfish populations, which enhances the applied significance of the obtained results in the context of bioindication and monitoring.

On the other hand, studies by R.N. Wanjari *et al.* (2024) and C. Zanghi and C.C. Ioannou (2025) concentrated on the physicochemical properties of the environment and their impact on ecosystem stability and functioning. C. Zanghi and C.C. Ioannou demonstrated that an increase in water turbidity leads to disruption of visual signals in fish, which entails a decrease in hunting efficiency and changes in the structure of trophic networks. At the same time, R.N. Wanjari *et al.* applied ecological modelling methods to analyse reservoir stability and interactions between abiotic and biotic components. Both studies presented important systemic conclusions but did not address specific changes in the structure of individual populations. Unlike these authors, the current work examined the quantitative parameters of indicator species populations and recorded patterns of decline in abundance and juveniles depending on the degree of pollution, which expands the possibilities for assessing the real vulnerability of aquatic ecosystems.

In a series of works by M.J. Thorstensen *et al.* (2022) and X. Miao *et al.* (2023), approaches aimed at studying the physiological state of aquatic organisms depending on environmental conditions were implemented. M.J. Thorstensen *et al.* developed non-invasive data collection methods for assessing the physiological state and movement of freshwater fish, reducing stress on the study subjects. X. Miao *et al.*, in turn, demonstrated that short-term keeping of silver carp in a clean natural environment improves its organoleptic and biochemical characteristics. Both works focused on physiological indicators; however, demographic characteristics and population stability were not assessed. The conducted study, however, allowed for recording a sharp decrease in density of up to 60-80%, an increase in juvenile mortality, and a distortion of sex structure in benthic crustaceans, which provides a more complete picture of the consequences of pollution at the population level.

Similarly, the works of D. Pandit *et al.* (2023) and A.G. Tacon *et al.* (2024) raised issues concerning the degradation of aquatic ecosystems from different perspectives. D. Pandit *et al.* investigated the decline in species diversity in Bangladesh water bodies and noted its impact on food security and the sustainability of small-scale fisheries, especially in socially vulnerable areas. A.G. Tacon *et al.* conducted an annotated literature review on the benefits and risks of consuming fish and seafood, drawing attention to the content of heavy metals and other pollutants. Despite their relevance and broad scope, neither study touched upon specific population changes due to pollution. This work filled that gap by establishing quantitative dependencies between the intensity of anthropogenic impact and population viability parameters – density, age composition, and sex structure – thereby creating a scientific basis for biomonitoring and restoration of aquatic bioresources.

Of particular note are the studies by K. Amoah *et al.* (2024) and L. Zhang *et al.* (2024), which considered two different approaches to assessing the state of aquatic organisms. K. Amoah *et al.* conducted molecular and immunobiological characterisation of four *Bacillus* strains isolated from the gut of hybrid grouper, demonstrating their antagonistic action against pathogens and their potential to improve fish health in aquaculture systems. Meanwhile, L. Zhang *et al.* focused their efforts on monitoring fish species diversity in coastal waters using DNA metabarcoding technology and passive water sampling. While both studies made significant contributions to the development of molecular ecology and monitoring, neither covered the analysis of spatial and age structure of populations under conditions of chemical pollution. In contrast, the presented study provides a clear focus on changes in the demographics and structure of crayfish and shrimp populations depending on the level of water body pollution, including an assessment of density, sex composition, and juveniles, which allows for conclusions to be drawn at the ecosystem sustainability level.

Among the works concerning the adaptation of organisms to changing conditions, the research by H.C. Vieira *et al.* (2022) and S. Rahayu *et al.* (2024) are noteworthy. S. Rahayu *et al.* analysed the current state and prospects of probiotic application in Chinese aquaculture, highlighting their impact on immune resistance, growth, and reduction of pathogen load in aquatic organisms. At the same time, H.C. Vieira *et al.* proposed a method of transplant testing for fish in field conditions to assess the toxicological load of the aquatic environment. Although both approaches are aimed at studying the response of organisms to external factors, they remain limited to the analysis of physiological and behavioural parameters at the level of individual organisms. In contrast, the present study presents spatial and quantitative indicators of populations in natural conditions, allowing for the consideration of the sustainability not of individual organisms, but of entire biocoenoses and their ability to self-maintain under conditions of complex pollution.

Equally interesting and conceptually significant are the studies by O.A. Anyanwu *et al.* (2023) and M. Reverter *et al.* (2025), which address the socio-ecological consequences of anthropogenic pressure on water resources. M. Reverter *et al.* presented a retrospective review of the aquaculture industry's contribution to the development of antimicrobial resistance, linking this to the excessive use of antibiotics and the global spread of resistant strains. O.A. Anyanwu *et al.*, in turn, conducted an interdisciplinary study dedicated to the perception of fish consumption in polluted marine environments in Indonesia. The authors showed that the population experiences an internal conflict between the traditional value of fish as a food source and the awareness of potential contamination risks. Both studies focus on the global and social aspects of ecological degradation but do not include a specific analysis of the consequences of pollution for population dynamics and structure. In contrast, the conducted study complements general assessments with empirical data on real changes in the spatial distribution, mortality, and reproduction of indicator species, which increases the accuracy of diagnosing the ecological state of freshwater bodies.

In the works of F.C. Sarker *et al.* (2022) and C. Van Driessche *et al.* (2024), issues concerning the conservation of freshwater biodiversity and the monitoring of fishing communities in a transformed environment were considered. F.C. Sarker *et al.* conducted an inventory of the ichthyofauna of the floodplain ecosystems of Sylhet (Bangladesh), highlighting the richness of species composition and the environment's susceptibility to seasonal and anthropogenic stress. Measures to strengthen the protection and management of water resources were proposed. In turn, C. Van Driessche *et al.* used DNA metabarcoding to assess spatio-temporal changes in the composition of fish communities in the Scheldt estuary. Trends of species shifting in response to environmental changes were identified; however, the analysis did not include the structural characteristics of individual populations. Unlike these works, the presented study provided an assessment of the density, sex, and age composition of benthic invertebrates, demonstrating a direct correlation of these parameters with the level of pollution and recreational pressure, which significantly expands the applied value of the obtained data.

In the studies by A.A. Mamun *et al.* (2021), and T.O. Sogbanmu and A.B. Dauda (2024), the consequences of industrial aquaculture and the possibilities of using local fish species in toxicological assessments were considered. A.A. Mamun *et al.* showed that export-oriented coastal fish farming can benefit vulnerable populations in terms of food security, but if uncontrolled, it can be accompanied by ecological risks. In turn, T.O. Sogbanmu and A.B. Dauda systematised the use of local Nigerian fish species in laboratory ecotoxicological tests, emphasising their significance for assessing the impact of pollutants. Both approaches were oriented towards economic or experimental practice but did not include field assessments of population stability under conditions of real pollution. Unlike them, the presented study applied a comprehensive population-ecological approach, documenting structural changes and demographic consequences of pollution for benthic invertebrates in freshwater ecosystems. The reviewed studies covered a wide range of aspects from biodiversity and physiology to food security and molecular monitoring methods. However, most of them either focused on individual organisms or described general ecosystem processes without analysing population structure and dynamics.

CONCLUSIONS

As a result of this study, a comprehensive assessment of the influence of anthropogenic factors on the structure, abundance and spatial distribution of shrimp (*Palaemon elegans, Palaemon adspersus*) and freshwater crayfish (*Astacus leptodactylus, Pontastacus eichwaldi*) populations in the Shamkir and Mingachevir reservoirs was carried out. In areas with minimal anthropogenic load (control zones) the density of shrimp populations varied from 12 to 25 individuals/m^2 for *Palaemon elegans* and from 9 to 17 individuals/m^2 for *Palaemon adspersus* in the Shamkir reservoir. In Mingachevir reservoir, the densities of these species ranged from 8 to 18 individuals/m^2 for *Palaemon elegans* and 6 to 14 individuals/m^2 for *Palaemon adspersus*. For freshwater crayfish in the Shamkir reservoir, population densities of *Astacus leptodactylus* ranged from 5 to 12 individuals/m^2 and *Pontastacus eichwaldi* from 3 to 7 individuals/m^2. In Mingachevir reservoir, the density of *Astacus leptodactylus* ranged from 3 to 9 individuals/m^2 and *Pontastacus eichwaldi* from 2 to 5 individuals/m^2. In polluted areas near sewage and recreational sources, shrimp abundance decreased to 11-17 individuals/m^2 and crayfish abundance to 2-5 individuals/m^2, representing a 32-60% reduction in density compared to control sites. The age structure of the populations showed significant changes: the proportion of juveniles in control conditions ranged from 25% to 42%, while in polluted areas it decreased to 15-20%. The mortality rate of juveniles in polluted areas reached 40-50%, especially in *Palaemon adspersus* and *Pontastacus eichwaldi*. A change in the sex composition was also recorded: the proportion of males was 55-78% in contaminated areas, while in clean areas it was 40-56%. The spatial structure of the populations showed a tendency towards habitat reduction and fragmentation, especially in the coastal zones of the Mingachevir reservoir, where maximum concentrations of organic pollutants were detected. Noise pollution, household rubbish and poaching also had an impact. Thus, a direct correlation between the level of anthropogenic impact and demographic characteristics of populations was established. The study confirmed that the decrease in density, mortality of juveniles and disturbance of the sex structure are reliable indicators of ecological disadvantage of water bodies. The prospects for further research on this topic include the development of more detailed monitoring programmes aimed at studying the long-term effects of anthropogenic impact on the ecosystems of Azerbaijan's reservoirs, as well as investigating the effectiveness of restorative measures to support the sustainability of non-fish seafood populations in these conditions.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Вплив антропогенних чинників на структуру популяції нерибних морепродуктів у водосховищах Азербайджану

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Анотація. Метою дослідження було встановити вплив антропогенних чинників на чисельність і структуру популяцій. У статті представлено результати комплексного емпіричного дослідження, спрямованого на оцінку впливу антропогенних чинників на структуру та чисельність популяцій креветок (*Palaemon elegans*, *Palaemon adspersus*) і річкових раків (*Astacus leptodactylus*, *Pontastacus eichwaldi*) в умовах Шамкірського та Мінгечаурського водосховищ Азербайджану. У період із червня до серпня 2024 року було проведено польові обстеження на ділянках із різним ступенем забруднення. Оцінка включала аналіз щільності особин, вікового та статевого складу, чисельності молодняка та його смертності, а також просторового розподілу популяцій. Для річкових раків середня щільність *Astacus leptodactylus* коливалася від 12 особин/м^2 (чисті зони Шамкірського водосховища) до 5 особин/м^2 (забруднені зони Мінгечаурського). У *Pontastacus eichwaldi* чисельність варіювала від 7 до 2 особин/м^2. Частка молодняка в структурі популяцій на чистих ділянках досягала 42 % (*Palaemon elegans*) і 40 % (*Astacus leptodactylus*), тоді як на забруднених ділянках – знижувалася до 15-20 %. Зафіксовано смертність молодняка до 40 % на ділянках з органічним забрудненням. На ділянках з високим рівнем забруднень спостерігався дисбаланс статевого складу: у *Palaemon adspersus* і *Pontastacus eichwaldi* частка самців перевищувала 55 %, тоді як на чистих ділянках переважали самки або зберігалося рівне співвідношення. Найбільше зниження чисельності всіх видів відзначено в Мінгечаурському водосховищі – до 60 % у *Pontastacus eichwaldi*, що свідчить про високу чутливість виду до комплексного антропогенного впливу. Результати засвідчили, що хімічне забруднення, рекреаційне навантаження та браконьєрство є визначальними чинниками деградації популяцій. Встановлено пряму залежність між рівнем антропогенного впливу та зниженням чисельності, порушенням вікової та статевої структури. Запропоновано індикаторні показники для моніторингу стану прісноводних екосистем. Отримані результати можуть використовуватися для розробки програм моніторингу та еколого-реставраційних заходів у водних екосистемах Азербайджану

Ключові слова: донні безхребетні; моніторинг середовища; техногенне навантаження; прісноводні екосистеми; біоіндикація

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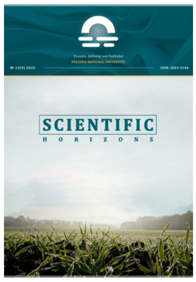

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Potential of leguminous crops for sustainable development of the agricultural sector

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Abstract. The purpose of the present study was to determine the agro-ecological advantages of growing leguminous crops compared to conventional cereals, particularly their impact on soil quality, biological activity, and productivity of agro-ecosystems. The study investigated the impact of leguminous crops – peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*) – on soil physicochemical properties, microbiological composition, biological nitrogen fixation, yield and stability of agroecosystems in the arid conditions of southern Ukraine. The study was conducted in comparison with control plots sown with wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), which allowed assessing the effectiveness of leguminous crops in improving soil fertility and their contribution to maintaining agroecosystem sustainability. The results showed that the cultivation of leguminous crops contributed to an increase in humus content, increased soil capillary porosity, and improved water retention

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properties, while these indicators stayed lower in the control plots with cereals. The study also recorded a significant increase in the number of nitrogen-fixing (*Bradyrhizobium, Azotobacter*) and phosphorus-mobilising (*Pseudomonas, Bacillus*) bacteria in the plots with leguminous crops, which indicated an increase in biological processes in the soil. Yields of wheat and barley were dependent on the level of mineral nutrition, while leguminous crops provided a stable level of productivity without additional nitrogen fertilisation. The findings confirmed the feasibility of integrating leguminous crops into crop rotations to maintain soil fertility, improve microbiological balance, and reduce dependence on mineral fertilisers. It was found that biological nitrogen fixation by peas, lentils, and beans increases the level of available nitrogen in the soil, which positively influences the productivity of agroecosystems compared to conventional cereals

Keywords: fertility; nitrogen fixation; organic recovery; environmental sustainability; microbiological activity

INTRODUCTION

The relevance of the present study was driven by the growing need for sustainable development of the agricultural sector and rational use of natural resources. The intensification of agriculture is accompanied by gradual soil depletion, decreasing humus levels, degradation of agroecosystems, and increased dependence on mineral fertilisers. Leguminous crops such as peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*) play an essential role in maintaining soil fertility due to their ability to biologically fix nitrogen, improve soil structure, increase water retention capacity, and enhance microbiological processes. The cultivation of these crops helps to reduce the use of mineral nitrogen fertilisers, which reduces the environmental burden on agroecosystems (Tereshchenko & Tarabrina, 2025).

The research problem is related to the need to develop effective agricultural technologies that will reduce the negative impact of intensive farming on the environment. Conventional farming methods cause excessive use of mineral fertilisers, which leads to soil acidification, nutrient imbalances, and a decrease in biodiversity. One solution to this problem is to integrate leguminous crops into crop rotations, which will contribute to the natural enrichment of soil with nitrogen, improve its structural properties, and reduce the need for synthetic fertilisers. The study of the impact of peas, lentils, and beans on agroecosystems allows assessing their contribution to maintaining ecological balance, increasing the yield of subsequent crops, and improving soil biological activity (Panfilova *et al.*, 2023). According to V.A. Mazur *et al.* (2021), modern cultivation technologies for leguminous crops contribute to an increase in the level of humus and biological activity of the soil, which improves its water-holding capacity and reduces the risk of degradation. According to A. Movchaniuk (2021), the integration of leguminous crops into crop rotations can reduce the need for nitrogen fertilisers by up to 40%, which reduces the financial burden on agricultural producers. According to I.V. Tomashuk and R.O. Horobchuk (2024), the use of leguminous crops in crop rotations increases the yield of subsequent crops by 15%-20%, which is explained by the improvement of soil structure and its enrichment with nitrogen. As proven by R.D. Semba *et al.* (2021), leguminous crops contain 20%-28% protein and a significant amount of micronutrients, making them a valuable element of food security.

As confirmed by the findings of M.M. Rahman *et al.* (2022), growing leguminous crops helps reduce greenhouse gas emissions and improves the water balance of agroecosystems, which is a crucial factor in climate change adaptation. According to L. Ditzler *et al.* (2021), leguminous crops help to increase the number of beneficial soil microorganisms and reduce erosion by 15%-20%, which positive influences soil fertility. According to H. Ferreira *et al.* (2021), leguminous crops are a key element of sustainable agriculture, as biological nitrogen fixation reduces the need for mineral fertilisers and reduces the environmental burden of the agricultural sector. As K.R. Ramya *et al.* (2022) emphasised, pigeon pea (*Lathyrus sativus*) has a particular potential, as it is characterised by high nutritional value and resistance to drought conditions.

According to M.A. Uebersax *et al.* (2023), dry beans (*Phaseolus vulgaris* L.) are an essential element of sustainable agricultural production due to their high protein content and ability to improve soil characteristics. As confirmed by the findings of E. Kebede (2021), biological nitrogen fixation by leguminous crops reduces the need for fertilisers and improves soil quality. According to J. Jena *et al.* (2022), leguminous crops increase biodiversity, water balance, and prevent the degradation of arable land, making them a vital component of sustainable agricultural technologies. According to G. Cusworth *et al.* (2021a), the massive adoption of leguminous crops in Europe will help reduce the impact of the agricultural sector on climate change and develop sustainable food systems. The analysis of studies confirmed that leguminous crops play an essential role in maintaining soil fertility, improving environmental sustainability and food security. The purpose of this study was to assess the influence of growing peas, lentils, and beans on soil physicochemical properties, biological nitrogen fixation, soil microbiological composition, yields, and stability of agroecosystems in the arid conditions of southern Ukraine. The principal objectives of the study were to determine the impact of peas, lentils, and beans on soil physicochemical properties and microbiological composition, to assess the efficiency of biological nitrogen fixation and its contribution to soil fertility, and to analyse the yield of these crops in comparison with wheat and barley.

MATERIALS AND METHODS

The study was conducted in April-October 2024 at the National Research and Production Centre of Mykolaiv National Agrarian University in Mykolaiv region, southern Ukraine. The experimental plots were located in the steppe zone on ordinary black soil with a total area of 2 ha. The climatic conditions of the study area were characterised by high average annual temperatures, precipitation deficit, and frequent dry periods, which allowed assessing the resistance of leguminous crops to stress factors and their influence on the stability of agroecosystems. The object of the study was leguminous crops, namely peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*), which were grown from May to August, as well as control crops – wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*), which were sown in April. The key aspects of the study included soil physicochemical parameters, the impact of biological nitrogen fixation, changes in soil microbiological composition, yield, and agronomic characteristics of leguminous and cereal crops, and the impact of leguminous crops on agroecosystem stability.

The study was conducted on two plots: a control plot and an experimental plot. The control plot was sown with wheat and barley grown in a conventional way without biostimulants. The experimental plot included peas, lentils, and beans, which were actively biologically fixed with nitrogen. To increase productivity, mineral fertilisers were applied to the control plot: ammonium nitrate (N_{34}) at a dose of 90 kg/ha and superphosphate (P_2O_{546}) at a dose of 60 kg/ha. No mineral fertilisers were applied on the experimental plot, which allowed assessing the effectiveness of biological nitrogen fixation and improvement of soil characteristics under the influence of leguminous crops. The physicochemical parameters of the soil were analysed according to the following parameters: acidity (pH), humus content, macro- and microelements, soil density, moisture, capillary porosity, water permeability, and nitrate and ammonium nitrogen content. Acidity was measured using a Hanna HI 98130 pH meter. The humus content was estimated by the Turin method, while macro- and microelements were determined by spectrophotometric method (Shimadzu UV-1800). The content of total nitrogen was estimated by the Kjeldahl method, while nitrate and ammonium nitrogen – by ion-selective electrodes (Bremner, 1960). Soil density was determined by the ring sample method, moisture content – by the gravimetric drying method, capillary porosity – by the laboratory permeability method, and soil erosion resistance – by the Savvinov method (DSTU No. 4138-2002, 2002).

The effect of biological nitrogen fixation was determined by analysing the activity of nodule bacteria (*Rhizobium leguminosarum*), the number of which was estimated by the method of serial dilutions. The level of accumulation of available nitrogen in the soil was studied, specifically, the content of mineral, organic, and available nitrogen in the soil solution. The determination was carried out using the spectrophotometric method and the Kjeldahl method. The study also analysed the activity of nitrogenase, which is a key indicator of the efficiency of biological nitrogen fixation, using the acetylene reduction method. The ammonium nitrogen content was determined by the colorimetric method, and the nitrate nitrogen content was determined by ion-selective electrodes. The nitrogen balance in the plant-soil system was also assessed by determining the nitrogen utilisation factor. Changes in the microbiological composition of the soil were assessed according to the number of nitrogen-fixing bacteria (*Bradyrhizobium, Azotobacter*), phosphorus-mobilising bacteria (*Pseudomonas, Bacillus*), and the total number of soil microorganisms. The analysis was performed using the colony forming units (CFU/g soil) method. The detection of changes in the microbiological composition helped to assess the impact of leguminous crops on the activation of beneficial microflora and the improvement of soil biological activity.

Yields and agronomic characteristics of leguminous and cereal crops were assessed by measuring average yield (t/ha), thousand-kernel-weight, protein content in grain, starch content, germination energy and field germination, plant height, leaf area, number of productive stems, and plant biomass. The yield was determined by direct weighing of the grain after harvest. Protein content was analysed by the Kjeldahl method. Starch content was determined by the polarimetric method. The thousand-kernel-weight was measured on a RADWAG AS 220.R2 analytical balance. Field germination was evaluated according to the standard methods of DSTU No. 4138-2002 (2002). Morphological parameters of plants, such as height, leaf area, and number of productive stems, were determined using a Mitutoyo IP54 calliper and an electronic leaf area meter. The biomass was determined by weighing the dry matter after drying in a thermostat at 105°C. Drought tolerance was assessed on a 10-point scale, where 1 point corresponded to very low tolerance and 10 points – to complete tolerance to drought conditions. The evaluation was carried out by determining the relative water loss in the leaves, as well as by visual criteria – the degree of wilting and inhibition of plant growth during drought. Disease resistance was also determined on a 10-point scale, where 1 point indicated complete instability of the crop, and 10 points – high resistance to major pathogens. Disease diagnostics was carried out by visual monitoring of plants and identification of lesions according to the method of phytopathological analysis.

The impact of pulses on the stability of the agroecosystem was assessed by analysing soil erosion resistance, capillary porosity, biological activity, and the overall balance of organic matter. Erosion resistance was determined by the level of water resistance of soil aggregates using the Savvinov method (DSTU No. 4744:2007, 2007), and capillary porosity was determined by the laboratory permeability method (Richards, 1954). The biological activity of the soil was assessed by the level of respiratory activity of microorganisms using the Bazir method, and the total balance of organic matter was determined by the content of humus and total nitrogen (Anderson & Domsch, 1978). Statistical processing of the data was performed using Statistica 12 software (StatSoft, Inc.). To determine the reliability of the differences between the control and experimental parameters, the methods of analysis of variance (ANOVA) and Student's t-test ($p < 0.05$) were used. The statistical analysis helped to assess the efficiency of biological nitrogen fixation by leguminous crops, their influence on changes in physical, chemical, and microbiological parameters of the soil, as well as the significance of these changes for the stability of the agroecosystem and improvement of crop yields. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS

Physical and chemical characteristics of the soil. The soil pH analysis showed that in the control plots (wheat, barley) the acidity stayed within 5.5-6 pH, while in the experimental plots sown with peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*), it increased to pH 6.2-6.8. This indicated a decrease in soil acidity during the cultivation of leguminous crops. The key factor that influenced this indicator was the biological fixation of nitrogen by nodule bacteria, which reduced the need for mineral fertilisers that cause acidification. The humus content in the experimental plots with peas, lentils, and beans increased by 0.4%-0.6%, while in the control plots it stayed stable (2.4%-2.8%). This increase was explained by the high biomass of leguminous crop root residues, which contributed to the accumulation of organic matter and its transformation into stable humus compounds. The assessment of the soil structure showed that the share of agronomically valuable aggregates (0.25-10 mm) in the control plots was 65%-70%, while in the experimental plots with peas, lentils, and beans this figure increased to 77%-83%. This indicated an improvement in the aggregate structure of the soil, which contributed to a reduction in soil compaction, improved water permeability, and increased erosion resistance.

The study of soil water permeability showed that in the control plots this indicator fluctuated between 10-15 mm/h, while in the experimental plots it increased to 13-20 mm/h (an increase of 25%-30%). This indicates a decrease in surface water runoff, which is a significant factor for preserving soil moisture and preventing erosion processes. Soil density indicators confirmed that the cultivation of peas, lentils, and beans contributed to a reduction in soil compaction. In the control plots, the soil density was 1.3-1.45 g/cm^3, while in the experimental plots it was 1.1-1.3 g/cm^3. This meant that leguminous crops improved soil aeration and water permeability, which is critical for the development of the plant root system. The analysis of nitrogen content showed that in the control plots its concentration was 0.12%-0.16%, while in the experimental plots sown with peas, lentils, and beans it was 0.18%-0.22%, which meant an increase of 30%-40%. This proved the effectiveness of symbiotic nitrogen fixation, which accumulated available nitrogen in the soil, reducing the need for nitrogen fertilisers.

The phosphorus content in the control plots was 18-25 mg/kg, while in the plots with peas, lentils, and beans it was 24-32 mg/kg, an increase of 20%-28%. The potassium content increased by 10%-20% (180-220 mg/kg in the control plots versus 220-260 mg/kg in the experimental plots). The increased concentration of phosphorus and potassium in the experimental samples indicated the activation of microbiological processes that contributed to the mobilisation of these elements from soil reserves and improved their availability to plants. The study of the organic carbon content showed that its concentration in the control plots was 1.8%-2.2%, while in the plots with peas, lentils, and beans it increased to 2.4%-2.8% (an increase of 30%-35%). This indicated an improved accumulation of organic matter and higher biological activity of the soil, which contributed to the stabilisation of its fertility. The assessment of soil capillary porosity showed that its level in the control plots was 42%-48%, while in the plots with peas, lentils, and beans this figure reached 50%-57% (an increase of 8%-12%). This meant that the experimental plots retained moisture better, which positively influenced the water balance and ensured stable conditions for plant growth (Table 1).

***Table 1**. Physical and chemical characteristics of the soil*

Indicator	Control (grain crops, 2024)	Leguminous crops (experimental plots, 2024)	Change (%)	Months of research
soil pH (hydrogen index, characterises the acidity or alkalinity of the soil)	5.5-6 (wheat, barley)	6.2-6.8 (peas, lentils, beans)	+0.5-0.8	May-August

Table 1. Continued

Indicator	Control (grain crops, 2024)	Leguminous crops (experimental plots, 2024)	Change (%)	Months of research
Humus content (%)	2.4-2.8 (wheat, barley)	2.8-3.4 (peas, lentils, beans)	+0.4-0.6	May-August
Agronomically valuable aggregates (%)	65-70 (wheat, barley)	77-83 (peas, lentils, beans)	+12-18	May-August
Water permeability (mm/h)	10-15 (wheat, barley)	13-20 (peas, lentils, beans)	+25-30	May-August
Soil density (g/cm3)	1.3-1.45 (wheat, barley)	1.1-1.3 (peas, lentils, beans)	-0.1-0.2	May-August
Nitrogen content (%)	0.12-0.16 (wheat, barley)	0.18-0.22 (peas, lentils, beans)	+30-40	May-August
Phosphorus content (mg/kg)	18-25 (wheat, barley)	24-32 (peas, lentils, beans)	+20-28	May-August
Potassium content (mg/kg)	180-220 (wheat, barley)	220-260 (peas, lentils, beans)	+10-20	May-August
Total organic carbon content (%)	1.8-2.2 (wheat, barley)	2.4-2.8 (peas, lentils, beans)	+30-35	May-August
Capillary soil porosity (%)	42-48 (wheat, barley)	50-57 (peas, lentils, beans)	+8-12	May-August

Source: *developed by the authors of this study*

Thus, the results of the 2024 study confirmed that peas (*Pisum sativum*), lentils (*Lens culinaris*), and beans (*Phaseolus vulgaris*) helped to reduce soil acidity, increase humus content, improve its structural stability, increase the concentration of macronutrients (nitrogen, phosphorus, potassium), and improve water holding capacity.

Impact of biological nitrogen fixation. The content of available nitrogen in the soil in the experimental plots was 30%-40% higher than in the control samples, which confirmed the effectiveness of symbiotic nitrogen fixation. In the control plots, its level was 0.12%-0.16%, while in the experimental plots it was 0.18%-0.22%. The high efficiency of biological nitrogen fixation was conditioned by the vigorous activity of nodule bacteria of the genus *Rhizobium*, which formed symbiotic relationships with leguminous crops, providing them with nitrogen without mineral fertilisers. Assessment of root system morphology showed a significant difference in the number of nodules between control and experimental plants. In wheat and barley, this figure did not exceed 5-10 nodules per plant, indicating low nitrogen fixation activity. At the same time, 60-100 nodules per plant were formed on the roots of peas, lentils, and beans, which confirmed their high ability to fix atmospheric nitrogen. An increase in the number of nodules by 900-1,100% compared to the control samples indicated the effectiveness of using leguminous crops to improve the nitrogen balance of the soil. The weight of nodules on the control crops was only 0.1-0.3 g/plant, suggesting their low activity in nitrogen fixation processes. However, in the experimental plots, the nodule weight varied between 1.2-2.5 g/plant, which meant an increase of 400-700%. This emphasised the value of peas, lentils, and beans as effective nitrogen fixers that can substantially increase the level of nitrogen in the soil.

Thanks to biological nitrogen fixation, the need for nitrogen fertilisers was reduced by up to 40%. This not only reduces the financial cost of nitrogen fertilisation, but also helps to reduce the environmental burden, as excess mineral nitrogen can cause water pollution. Increased nitrogen levels directly affected the yield of subsequent crops in the rotation. Control plots with wheat or barley as a predecessor yielded 4.5-5 t/ha of wheat and 3.8-4.2 t/ha of barley. At the same time, in the experimental plots, wheat yields increased to 5.2-6 t/ha and barley yields to 4.2-5 t/ha, which indicated a 15%-20% increase in productivity. Another significant consequence of effective nitrogen fixation was a reduction in nitrogen leaching into groundwater. On the control plots, the leaching level was 2.5-3 mg/L, which is an indicator of extensive nitrogen losses due to leaching. In the experimental plots, where nitrogen fixation occurred naturally, this figure dropped to 1.2-1.5 mg/l (a 40%-50% reduction). This means that nitrogen fixed in a biological form is better retained in the soil and continues to be available to plants for a long time. The number of beneficial microflorae, including nitrogen-fixing bacteria and microorganisms involved in the transformation of organic nitrogen, also increased pronouncedly. In the control plots, the number of soil microorganisms was 1.8×10^6 CFU/g soil, while in the experimental plots it was 3.5×10^6 CFU/g soil, which indicated an increase in microbiological activity by 90-100%. This contributed to more intensive decomposition of organic matter and increased overall soil fertility.

The increase in nitrogen levels also positively influenced humus content. In the control plots, the humus content stayed at 0.2%-0.3%, while in the experimental plots it increased to 0.4%-0.6% (an increase of 100-200%). This indicated an improvement in the structure of organic matter in the soil and an increase in its stability, which contributed to the long-term preservation of fertility. The physical characteristics of the soil also changed as a result of biological nitrogen fixation. The cultivation of leguminous crops contributed to a decrease in soil density from 1.3-1.45 g/cm^3 in the control plots to 1.1-1.3 g/cm^3 in the experimental plots, which indicated a 10-12% reduction in compaction. This improved water permeability and air permeability, which contributed to the development of the root system of plants and increased the efficiency of nutrient absorption (Table 2).

***Table 2**. Impact of biological nitrogen fixation*

Indicator	Control (wheat, barley)	Experiment (peas, lentils, beans)	Change (%)
Available nitrogen in the soil (%)	0.12-0.16	0.18-0.22	+30-40
Number of nodules on the roots (pcs./plant)	5-10	60-100	+900-1,100
Total nodule weight (g/plant)	0.1-0.3	1.2-2.5	+400-700
Reduced demand for nitrogen fertilisers (%)	0	Up to 40	Reduced costs
Post-crop wheat yield (t/ha)	4.5-5	5.2-6	+15-20
Post-crop barley yield (t/ha)	3.8-4.2	4.2-5	+12-18
Nitrogen leaching into groundwater (mg/l)	2.5-3	1.2-1.5	-40-50
Number of soil microorganisms (CFU/g soil)	1.8×10^6	3.5×10^6	+90-100
Increase in humus level (%)	0.2-0.3	0.4-0.6	+100-200
Reduced soil compaction (g/cm^3)	1.3-1.45	1.1-1.3	-10-12

***Source:** developed by the authors of this study*

The obtained results confirmed the high efficiency of biological nitrogen fixation with peas, lentils, and beans. Not only does it increase the level of available nitrogen in the soil, but it also improves its microbiological properties, reduces the need for mineral fertilisers, and contributes to the environmental sustainability of agricultural systems. The use of these crops in crop rotation is an effective measure to preserve and improve soil fertility, optimise agricultural technologies, and increase yields of subsequent crops.

Changes in the microbiological composition of the soil. On the control plots, the number of nitrogen-fixing bacteria (*Rhizobium leguminosarum*, *Bradyrhizobium japonicum*, *Sinorhizobium meliloti*) was 2.1×10^6 CFU/g soil, which indicated a low natural activity of symbiotic processes. In the experimental plots, the number of these bacteria reached 4.8×10^6 CFU/g soil, which meant a 128% increase. Such a pronounced difference was explained by the fact that the root system of peas, lentils, and beans actively attracted nodule bacteria, which entered into symbiosis with plants and contributed to the biological fixation of atmospheric nitrogen. The number of phosphate-mobilising bacteria (*Pseudomonas fluorescens*, *Bacillus megaterium*, *Penicillium bilaii*) involved in the conversion of insoluble forms of phosphorus into those available to plants in the control plots was 1.5×10^6 CFU/g soil. In the experimental plots, this figure reached 3.2×10^6 CFU/g soil, which was an increase of 113%. This indicated that leguminous crops contributed to the activation of microorganisms capable of decomposing organophosphorus compounds and increasing the availability of phosphorus to plants, which is a vital factor for increasing yields.

The number of actinomycetes (*Streptomyces* spp., *Micromonospora* spp.), which play a major role in the decomposition of organic matter and the synthesis of biologically active compounds, was 0.8×10^6 CFU/g soil in the control plots. In the experimental plots, this figure doubled and reached 1.6×10^6 CFU/g soil, which confirmed a considerable improvement in the decomposition of organic matter. The high number of actinomycetes indicated the active formation of stable humus compounds in the soil. The study of the dynamics of fungi-reducers (*Trichoderma* spp., *Aspergillus* spp., *Fusarium oxysporum*) involved in the decomposition of complex organic matter and transformation of nutrients showed that in the control plots their number was 0.6×10^6 CFU/g soil. In the experimental plots, this figure increased to 1.2×10^6 CFU/g soil, indicating a doubling of the fungal biota activity. The total number of microorganisms in the soil also changed substantially. In the control plots, it was 4.5×10^6 CFU/g soil, while in the experimental plots it was 9.8×10^6 CFU/g soil, which was a 118% increase. This indicator confirmed that plant residues of peas, lentils, and beans stimulated the activation of microorganisms responsible for the decomposition of organic matter, which directly affected the increase in soil fertility (Fig. 1).

The results showed that the cultivation of peas, lentils, and beans contributed to the stabilisation of the soil microbial composition, an increase in the number of nitrogen-fixing and phosphate-solubilising bacteria, and an increase in overall biological activity. This ensured better availability of nutrients for plants and contributed to greater yields of subsequent crops in the rotation.

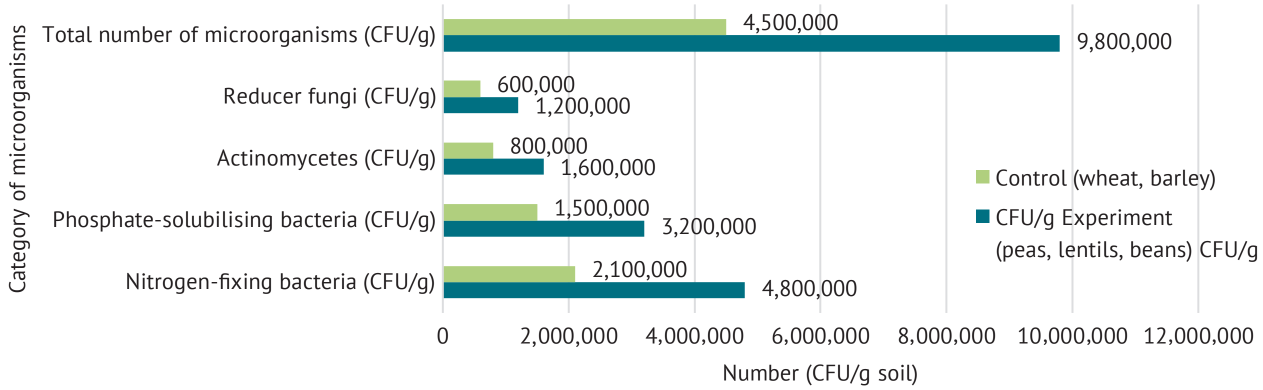

***Figure 1**. Changes in the microbiological composition of the soil*
***Source:** developed by the authors of this study*

Yields and agronomic characteristics of leguminous and grain crops. Average yields of grain crops were greater compared to leguminous crops. Wheat demonstrated the greatest yields (4-5.5 t/ha), while barley had yields within 3.5-4.8 t/ha. This was explained by the greater adaptability of cereals to different climatic conditions and their intensive selection. Among the leguminous crops, peas showed the greatest yields (2.8-3.5 t/ha), while lentils had the lowest yields (1.8-2.5 t/ha), which was explained by their sensitivity to moisture deficit and slow development in the early stages of the growing season. Plant height varied considerably between the crops under study. Wheat had the greatest height (80-110 cm), which contributed to its high competitiveness in closed crops. Barley had a height of 70-100 cm, which made it less vulnerable to lodging. Peas and beans were 60-85 cm and 50-70 cm tall, respectively, which allowed them to produce stable yields even under unfavourable conditions. Lentils were the shortest crop (40-55 cm), which limited their ability to compete effectively for light. The thousand-kernel-weight (TKW) was the highest for beans (250-350 g), which indicated the high energy value of its seeds. Peas had average TKW values (200-250 g), while lentils had the lowest TKW (30-45 g), making them a less energy-intensive crop. By comparison, wheat and barley had TKW values of 40-55 g and 45-60 g, respectively, which reflected their compact seed structure, which contributed to uniform maturation and reduced losses during harvesting.

The protein content of leguminous crops was significantly higher than that of grain crops. Lentils contained 24%-28% protein, making them a valuable crop for the production of vegetable protein concentrates. Peas had 22%-25% protein, while beans had 20%-23%, which also indicated their high nutritional value. In comparison, wheat and barley had 10%-14% and 9%-13% protein, respectively, confirming their primary function as a source of carbohydrates in the food industry. The vegetation period was the longest for wheat (210-230 days) and barley (180-200 days), which indicated that they needed a long development period to form a stable harvest. Among pulses, peas had the shortest growing season (85-100 days), making them the best crop for short-term crop rotations. Lentils had a vegetation period of 90-110 days, while beans had a vegetation period of 95-120 days, making them less adaptable to the conditions of a short vegetation period. Drought tolerance was highest in beans (9 points out of 10), which confirmed their ability to effectively use soil moisture. Peas had a strong level of resistance (8 points), while lentils showed 7 points, indicating their greater sensitivity to moisture deficit. Wheat and barley had scores of 6 and 7, respectively, indicating their relative resistance to drought, but lesser adaptability compared to leguminous crops. Disease resistance varied between crops. Lentils demonstrated the highest resistance (8 points), which confirmed their lower vulnerability to fungal and bacterial infections. Peas and wheat had analogous scores (7 points), making them relatively resistant crops. Beans and barley demonstrated the lowest level of resistance (6 points), which was explained by their tendency to develop bacterial and fungal diseases (Table 3).

***Table 3**. Yields and agronomic characteristics of leguminous and grain crops*

Parameter	Peas (Pisum sativum)	Lentils (Lens culinaris)	Beans (Phaseolus vulgaris)	Wheat (Triticum aestivum)	Barley (Hordeum vulgare)
Average yield (t/ha)	2.8-3.5	1.8-2.5	2.2-3	4-5.5	3.5-4.8
Plant height (cm)	60-85	40-55	50-70	80-110	70-100
Thousand-kernel weight (g)	200-250	30-45	250-350	40-55	45-60
Protein in seeds (%)	22-25	24-28	20-23	10-14	9-13

Table 3. Continued

Parameter	Peas (Pisum sativum)	Lentils (Lens culinaris)	Beans (Phaseolus vulgaris)	Wheat (Triticum aestivum)	Barley (Hordeum vulgare)
Vegetation period (days)	85-100	90-100	95-120	210-230	180-200
Resistance to drought (points, 1-10)	8	7	9	6	7
Disease resistance (points, 1-10)	7	8	6	7	6

Source: *developed by the authors of this study*

The results showed that leguminous crops are valuable elements of agricultural systems, as they not only provide high-quality protein products, but also contribute to soil fertility and crop stability in crop rotation. Compared to grain crops, they have lower yields but higher biological value due to their high protein content and ability to fix atmospheric nitrogen.

Impact of leguminous crops on agroecosystem stability. Improvement of soil structure accounted for 25% of the total impact, which confirmed the effectiveness of leguminous crops in improving the mechanical composition of the soil. This was explained by the high biomass of the root systems and an increase in the number of stable soil aggregates. Compared to the control plots, the content of agronomically valuable aggregates in the soil increased by 12%-18%, which reduced its tendency to compaction and improved water permeability. A 15% reduction in erosion was another prominent result of the use of leguminous crops. Improved soil structure and increased organic matter content contributed to a reduction in water and wind erosion. Better retention of moisture and organic material in the topsoil markedly reduced the risk of soil degradation. Moisture retention accounted for 20% of the overall impact of leguminous crops on the agroecosystem. The high porosity of the soil and the increased water-holding capacity contributed to reduced evaporation and better moisture accumulation in the topsoil. As a result, the capillary porosity in the experimental plots increased by 8%-12% compared to the control plots.

The increase in organic matter accounted for 18% of the total impact. The humus content in the experimental plots increased by 0.4%-0.6%, which confirmed the effectiveness of leguminous crops in improving the organic balance of the soil. The introduction of a significant amount of root and plant residues contributed to the improvement of humification processes, which positively influenced the biological activity and productivity of agroecosystems. The 12% increase in biodiversity was caused by improved conditions for the development of microbiota, beneficial insects, and soil fauna. The study of the number of microorganisms in the soil confirmed that their total number in the experimental plots increased by 118% compared to the control samples. Specifically, the number of nitrogen-fixing bacteria (*Rhizobium leguminosarum*, *Bradyrhizobium japonicum*) and phosphate-solubilising bacteria (*Pseudomonas fluorescens*, *Bacillus megaterium*) increased by 128% and 113%, respectively. Reduced fertiliser requirements accounted for 10% of the total impact. Thanks to the active biological nitrogen fixation, the need for mineral nitrogen fertilisers was reduced by up to 40%, which contributed to environmental safety and reduced financial costs for agricultural production. The improved absorption of phosphorus and potassium by microorganisms also reduced the need for phosphorus and potassium fertilisers (Fig. 2).

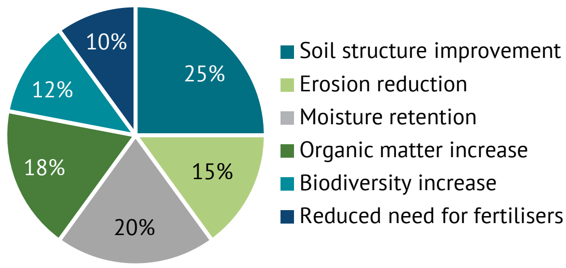

Figure 2*. Impact of leguminous crops on agroecosystem stability*

Source: *developed by the authors of this study*

The obtained results confirmed that the cultivation of leguminous crops contributed to increasing the sustainability of agroecosystems, reducing the negative impact of agricultural production on the environment and optimising biological processes in the soil. This demonstrated the valuable role of peas, lentils, and beans in maintaining ecological balance and increasing agricultural efficiency.

DISCUSSION

The results of the study confirmed the positive influence of leguminous crops on the agroecosystem. Compared to the control plots sown with wheat and barley, the experimental pea, lentil, and bean crops contributed to an increase in soil nitrogen content, which was explained by active biological nitrogen fixation by nodule bacteria. There was an improvement in the physical and chemical properties of the soil, including an increase in humus content and capillary porosity, which contributed to the improvement of water retention capacity. Microbiological analysis revealed an increase in the number of nitrogen-fixing and phosphorus-solubilising bacteria, which indicated the activation of beneficial microflora under the influence of leguminous crops. The yields of leguminous crops were stable, and their impact on the agroecosystem was manifested in the reduction of erosion processes and improvement of soil biological activity. These findings confirmed the effectiveness of growing leguminous crops to improve soil fertility and agroecosystem sustainability.

M.V. Conti *et al*. (2021) and U. Sahoo *et al*. (2023) confirmed that leguminous crops contributed to the improvement of the physical and chemical properties of the soil through the accumulation of organic compounds and increased activity of soil microflora. Biological nitrogen fixation by leguminous crops was shown to reduce the use of mineral fertilisers, which positively influenced soil structure and fertility. Another significant factor is the improvement of the soil's water-holding capacity, which is crucial in arid regions (Laposha *et al*., 2020; Zymaroieva *et al*., 2021). The findings obtained are consistent with the present study, which observed an increase in humus content and activation of nitrogen fixation processes. However, unlike these studies, the present study assessed the direct influence of individual leguminous crops without intercropping, which allowed for more accurate data on soil changes. G. Cusworth *et al*. (2021b) and A. Raihan *et al*. (2024) confirmed that the inclusion of leguminous crops in crop rotation improves the sustainability of the agroecosystem by increasing the microbiological activity of the soil and reducing dependence on chemical fertilisers. These studies showed that leguminous crops increase the number of nitrogen-fixing and phosphorus-solubilising bacteria, which improves plant nutrient uptake. These findings were confirmed by the present study, which also recorded an increase in the activity of microbial groups in the soil in experimental plots with peas, lentils, and beans. However, unlike the cited studies, the present study analysed not only the impact of leguminous crops on microbiological parameters, but also the relationship between these changes and crop productivity, which allows for a comprehensive assessment of their agroecological effect.

According to S. Kuyah *et al*. (2021) and M. Ahmed *et al*. (2022), the use of leguminous crops in agriculture contributed to the improvement of soil quality by increasing the level of organic matter and improving its physical and chemical properties. Leguminous crops were shown to markedly reduce the dependence on mineral fertilisers due to their high nitrogen fixing capacity, which contributed to improved soil quality. Furthermore, the study confirmed that in the context of climate change, the use of leguminous crops in crop rotations reduced the risk of soil degradation and helped to maintain soil fertility in the long term. The present study was consistent with these findings, as it was found that the cultivation of peas, lentils, and beans positively influenced humus levels, soil capillary porosity, and biological activity. However, unlike the study by M. Ahmed *et al*., the present study focused on concrete regional characteristics, which enabled more applied conclusions on the effectiveness of leguminous crops in southern Ukraine. As shown by K. Singh *et al*. (2021) and K. Jones *et al*. (2023), the active interaction of leguminous crops with symbiotic bacteria helped to improve the nitrogen balance of the soil and ensured more efficient absorption of macro- and microelements. It was found that an increase in the number of nitrogen-fixing bacteria of the genus *Rhizobium* and phosphorus-solubilising microorganisms contributed not only to the improvement of the physical and chemical properties of the soil, but also to an increase in the yield of leguminous crops. This study also recorded an analogous trend – the number of beneficial microorganisms increased in the experimental plots with peas, lentils and beans, which positively impacted the agroecosystem. However, unlike these studies, the present study considered not only the overall impact of microorganisms, but also the concrete effects of certain types of leguminous crops on the microbiological composition of the soil, which helped to obtain practical recommendations for their use in regions with an arid climate.

According to the findings of S. Kumar *et al*. (2022) and A. Nord *et al*. (2022), the cultivation of leguminous crops greatly affected food security and nutrition, while also contributing to improved soil fertility through biological nitrogen fixation. Leguminous crops were found to improve diets through their high protein, vitamin, and micronutrient content, and to positively influence soil fertility through biological nitrogen fixation. However, in some regions, insufficient adoption of agricultural technologies and low adaptation to specific climatic conditions continued to be limiting factors (Kiurchev *et al*., 2020; Didur *et al*., 2023). The present study confirmed the positive impact of leguminous crops on improving soil characteristics and yields but focused on assessing the effectiveness of distinct types of leguminous crops in a regional perspective. This allowed drawing conclusions on their adaptation to the arid conditions of southern Ukraine and identifying the most effective crops for restoring soil fertility. As emphasised by B. Balázs *et al*. (2021) and K.Y. Belachew *et al*. (2022), the use of leguminous crops in agricultural systems contributed to increasing the productivity of agri-food complexes and reducing the yield gap between different regions. It was found that the integration of leguminous crops into modern agricultural technologies could substantially increase production efficiency by improving soil structure and reducing dependence on mineral fertilisers. The study also confirmed that different leguminous crops showed uneven yields depending on local climatic and agronomic conditions. The present study also found pronounced differences between pea, lentil, and bean yields depending on soil type and moisture levels. However, unlike the above studies, the present study assessed not only the yield potential of crops, but also their impact on the stability of the agroecosystem, which enabled a comprehensive assessment of their environmental performance.

According to S.K. Upa- dhyay *et al*. (2023) and K. Dave *et al*. (2024), climate change considerably affected the growth and productivity of leguminous crops, which required the use of adaptive technologies to maintain their yields. It was proved that rising temperatures and changes in precipitation patterns considerably affected the growth and productivity of leguminous crops, which required adaptive approaches to their cultivation. The use of rhizobacteria, which can stimulate plant growth, proved to be an effective way to maintain the productivity of leguminous crops under climate change (Kyselov, 2024). The present study confirmed that leguminous crops helped improve the microbiological composition of the soil by activating nitrogen-fixing and phosphorus-solubilising bacteria, which positively influenced soil fertility. However, in contrast to these studies, the present study focused on the direct impact of various leguminous crops on soil indicators and their potential for use in arid regions. According to M.F. Desire *et al*. (2021) and S. Kumari and S.K. Maiti (2022), cultivation of leguminous crops played a valuable role in improving soil fertility and ensuring food security. The researchers found that biological nitrogen fixation not only contributed to soil enrichment with nutrients but also provided the possibility of reclaiming degraded land. Additionally, these studies proved that leguminous crops can be an effective source of micronutrients and protein, which made them promising for food fortification in nutrient-poor regions. The results obtained in the present study generally supported these findings, as they also revealed positive effects of leguminous crops on humus content and soil structure. At the same time, unlike S. Kumari *et al*. and M.F. Desire *et al.*, the present study focused on determining the concrete influence of each leguminous crop on individual soil parameters, which helped to obtain a more detailed picture of their effectiveness in the conditions of southern Ukraine.

As confirmed by K. Kumara *et al*. (2023) and J.R. Lamichhane *et al*. (2023), the introduction of leguminous crops into crop rotations contributed to a marked increase in the carbon balance of agroecosystems and improved the overall environmental sustainability of agricultural land. The use of leguminous crops in farming systems was shown to increase the organic carbon content of the soil, which reduced degradation and improved its water-retaining properties. Furthermore, studies showed that the use of relay-cropping methods with leguminous crops improved the use of soil resources and increased the efficiency of agroecosystems. The findings of the present study were consistent with these conclusions, as it was confirmed that the physical and chemical characteristics of the soil improved, the level of microbiological activity increased, and yields increased. However, unlike these studies, the present study analysed distinct types of leguminous crops in greater detail, which allowed assessing their adaptive efficiency in the face of climate change and draw practical conclusions regarding their use to restore soil fertility in arid regions. The findings confirmed the general conclusions of previous studies on the positive impact of leguminous crops on soil fertility, yields, and the stability of agroecosystems, specifically through biological nitrogen fixation and improved soil microbiological composition.

CONCLUSIONS

The study analysed the impact of growing leguminous crops on the key agroecological indicators of the soil and the productivity of agroecosystems in arid conditions. Peas, lentils, and beans were found to not only improve the physical and chemical properties of the soil, but also activate microbiological processes, which ensures their role in maintaining the stability of agricultural landscapes. Changes in the physical and chemical parameters of the soil confirmed the improvement of its structure in the experimental plots. Increased humus levels and improved capillary porosity contributed to effective moisture retention, which is a key factor in arid regions. This suggested that leguminous crops can play a valuable role in improving soil water management and preventing soil degradation. The study revealed a marked increase in the number of nitrogen-fixing and phosphorus-solubilising bacteria in the soil, which confirmed its biological activation under the influence of leguminous crops. Nitrogen uptake improved, reducing the need for mineral fertilisers. This is an essential environmental and economic factor that can help reduce the cost of agrochemicals and increase the environmental sustainability of agroecosystems. A comparative analysis of yields revealed that leguminous crops demonstrated a stable level of productivity regardless of moisture supply, while wheat and barley were significantly dependent on mineral nutrition. This indicated a greater adaptability of leguminous crops to stressful conditions, which can be a crucial factor in planning crop rotations in regions with a changing climate. The findings confirmed the prospects of leguminous crops for maintaining soil fertility, increasing its biological activity, and reducing dependence on mineral fertilisers. The cultivation of peas, lentils, and beans can play a key role in sustainable farming strategies, contributing to the long-term conservation of soil resources and increasing the environmental sustainability of agro-systems in arid conditions. A limitation of the study was that it was conducted within a single region with an arid climate, which may affect the generalisability of the findings to other agroclimatic zones. Further research should be aimed at assessing the long-term impact of leguminous crops on soil characteristics and their efficiency in different crop rotation systems and climatic conditions.

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Потенціал зернобобових культур для сталого розвитку аграрної галузі

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Анотація. Метою дослідження було визначити агроекологічні переваги вирощування зернобобових культур у порівнянні з традиційними зерновими, зокрема їхній вплив на якість ґрунту, біологічну активність та продуктивність агроекосистем. У статті досліджено вплив зернобобових культур – гороху (*Pisum sativum*), сочевиці (*Lens culinaris*) та квасолі (*Phaseolus vulgaris*) – на фізико-хімічні властивості ґрунту, мікробіологічний склад, біологічну фіксацію азоту, урожайність та стабільність агроекосистем у посушливих умовах Півдня України. Дослідження проводилося у порівнянні з контрольними ділянками, засіяними пшеницею (*Triticum aestivum*) та ячменем (*Hordeum vulgare*), що дозволило оцінити ефективність зернобобових у покращенні родючості ґрунту та їхній внесок у підтримку стійкості агросистем. Результати показали, що вирощування зернобобових сприяло збільшенню вмісту гумусу, підвищенню капілярної пористості ґрунту та покращенню його водоутримувальних властивостей, тоді як на контрольних ділянках зі злаковими культурами ці показники залишалися нижчими. Також було зафіксовано значне зростання чисельності азотфіксувальних (*Bradyrhizobium, Azotobacter*) та фосформобілізуючих (*Pseudomonas, Bacillus*) бактерій на ділянках із зернобобовими, що свідчило про активізацію біологічних процесів у ґрунті. Урожайність пшениці та ячменю виявилася залежною від рівня мінерального живлення, тоді як зернобобові забезпечували стабільний рівень продуктивності без додаткового внесення азотних добрив. Отримані результати підтверджують доцільність інтеграції зернобобових у сівозміни для підтримки родючості ґрунтів, покращення мікробіологічного балансу та зниження залежності від мінеральних добрив. Встановлено, що біологічна фіксація азоту горохом, сочевицею та квасолею забезпечує підвищення рівня доступного азоту в ґрунті, що позитивно впливає на продуктивність агроекосистем у порівнянні з традиційними зерновими культурами

Ключові слова: родючість; азотфіксація; органічне відновлення; екологічна стійкість; мікробіологічна активність

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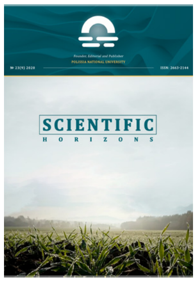

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Optimisation of dosages and application methods for Agrobion granulated soil improver in combination with mineral fertilisers for grain crops on southern chornozems in Northern Kazakhstan

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Abstract. The study aimed to identify effective ratios of the biological product and mineral fertilisers to increase yields and soil activity. The study presented the results of a comprehensive study of the effect of the granular preparation "Agrobion" and different doses of mineral fertilisers (NP) on the agrobiological parameters of oats and spring wheat in the southern black soil of Northern Kazakhstan. The experiment covered 18 variants of fertiliser combinations, including an absolute control, a standard dose of NP, as well as different doses of Agrobion (100-300 kg/ha) and their combinations with ¼, ½, ¾ and full NP norms in the main and pre-sowing methods of application. The highest biological activity of the soil was observed in

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the variant with 200 kg/ha of "preparation" and ½ NP, which was accompanied by a fivefold increase in the number of nitrogen fixers, actinomycetes and cellulose-degrading bacteria compared to the control. The yield of oats in the earing phase reached 49.52 g/vessel with this combination, and the maximum field germination (72.14%) was recorded at the pre-sowing application of 100 kg/ha of Agrobion with a full dose of NP. Analysis of the chemical properties of the soil showed a decrease in electrical conductivity and maintenance of optimal pH with a moderate reduction in NP and the use of the product. The results demonstrated that the optimal doses of Agrobion (100-200 kg/ha) in combination with ½ or ¾ of the calculated NP rate provide the highest yield, microbiological activity and germination. Excessive doses (300 kg/ha) or a sharp decrease in NP led to a decrease in efficiency. A correlation was found between the dose of Agrobion, yields and soil fertility indicators. The recommended combination to increase agroecological efficiency is 200 kg/ha of "granular preparation" with ½ NP at the main application. The practical value of this study is the substantiation of the optimal doses of Agrobion and NP, which reduces the mineral load without loss of yield, which contributes to resource conservation and environmental protection of agriculture

Keywords: soil microorganisms; yield; soil acidity; methods of application; bioactivity

INTRODUCTION

The research relevance is determined by the need to increase the efficiency of mineral nutrition of grain crops on the chornozems of Northern Kazakhstan while reducing the environmental and economic burden on agroecosystems. Given the shortage of high-quality fertilisers and rising agricultural production costs, the use of biological products capable of increasing the availability of nutrients and stabilising agrobiological processes in the soil is of particular importance. The granular forms of such products, particularly Agrobion, demonstrate the potential to be integrated into traditional fertilisation schemes, providing a more uniform distribution of the active ingredient and the ability to adapt doses to specific conditions (Mohylevska, 2025). The problem of this study is caused by the lack of scientifically based recommendations on dose regulation and the choice of the method of applying biological products in combination with mineral fertilisers when growing grain crops on chornozems. Insufficient knowledge of the joint impact on soil microbiota, plant germination and productivity of oats and spring wheat limits the widespread adoption of such technologies in agricultural practice (Drobitko & Kachanova, 2023). In addition, the impact of different fertiliser combinations on agrochemical and microbiological soil parameters requires systematic analysis to develop optimal solutions for sustainable agriculture (Tonkha *et al.*, 2024).

According to the results presented by A.T. Khusainov *et al.* (2021), the use of a "granular biological product" on black soil contributed to an increase in agroecological sustainability and soil microflora activity in barley cultivation. The study recorded a positive effect of the preparation on crop yields even with reduced doses of mineral nutrition. As noted by S. Turebayeva *et al.* (2022), the introduction of no-till tillage in combination with biologically active agents ensured sustainable winter wheat production in the conditions of Southern Kazakhstan. According to the authors, the combination of biological and technological factors increased the biological activity of the soil and improved its water regime on chornozem plots.

According to the observations described by S.B. Kenenbaev *et al.* (2023), the agricultural sector of Kazakhstan continues to employ an irrational approach to the use of mineral fertilisers, which is exacerbated by insufficient microbiological activity of soils. The researchers emphasised the need to combine mineral components with biological products to compensate for agrochemical degradation, especially in arid regions. As demonstrated by M. Dugalić *et al.* (2025), the systematic application of mineral fertilisers in combination with organic matter and corrective agents such as lime improved the agrophysical and chemical properties of the soil under maize cultivation. The results obtained indicate a high sensitivity of yields to an integrated approach including biological regulation.

Based on the analysis performed by K. Pycia *et al.* (2024), the study determined that changes in the composition of fertilisers used on different soil types directly affect the structural and heat-resistant properties of cereal starch. The study emphasised the importance of considering the specifics of soil nutrition when using organic and mineral compounds, especially against the backdrop of growing interest in biomass by-products. According to Ch. Srinivasarao *et al.* (2024), organomineral fertilisers help restore microbial balance in the soil, improving agrochemical parameters and increasing nutrient availability. The study emphasises the potential of such systems as an element of sustainable agriculture in regions with a high level of agro-environmental risk. As confirmed by V. Kavvadias *et al.* (2023), the use of chemical fertilisers, compost and zeolite has different effects on yields, nutrient composition and soil properties in the short term. The study determined that the integration of organic and mineral components stabilises soil acidity (pH) and increases the utilisation of macronutrients. According to the analysis by M. Kulhánek *et al.* (2023), modern approaches to plant nutrition should incorporate the historically accumulated knowledge of the interaction of fertilisers with agroecosystems. The study emphasised the importance of returning to combined nutrition models in which organic and mineral elements are used synergistically.

As demonstrated by F. Cheţan *et al.* (2022), the response of soils and maize yields to tillage systems is significantly modified by climatic factors and the type of fertiliser applied. The study determined that crop sustainability is enhanced using gentle tillage technologies in combination with biostimulants and mineral additives. According to the observations of E.G. Magnucka *et al.* (2023), different forms of sulphur have a complex effect on the composition of organic matter and microbiota activity in models of vegetation experience. The authors noted that the use of available forms of macronutrients activates the growth of symbiotic bacteria and promotes the biotransformation of carbon fractions in the soil. According to M. Knežević *et al.* (2021), automated databases and tools are substantial in processing and systematising soil profiles, especially when analysing the dynamics of indicators under the influence of fertilisers. The authors emphasised the importance of digitalisation and structural interpretation of soil data when conducting comprehensive agrochemical research. According to the trials by M. Kozłowski *et al.* (2023), the use of agrarian reclamation with the alternation of wheat and rapeseed crops on techno-soils in Central Poland helps improve the water and physical properties of disturbed soils. The authors recorded an increase in water-holding capacity and a decrease in soil density with the systematic use of organomineral fertilisers.

The study aimed to substantiate the optimal rates and methods of applying Agrobion with mineral fertilisers to increase grain yields and improve the properties of the black soil of Northern Kazakhstan. The objective of the study was to identify the agrobiological effects of the combined use of different doses of the "granular biological product" and mineral fertilisers, as well as to determine the impact on the productivity of crops, the state of microflora and changes in the agrochemical parameters of black soils.

MATERIALS AND METHODS

The study was conducted between May and September 2024 on the territory of the Limited Liability Partnership "Kokshetau Experimental Production Farm" (Zereninsky District, Akmola Region, Republic of Kazakhstan) on southern chornozems with a neutral reaction (pH 7.24-7.75). The experiment included field and vegetation parts, corresponding to the agrotechnical requirements for the cultivation of grain crops. Oats (*Avena sativa* L.) and spring wheat (*Triticum aestivum* L.) were used as test objects. The meliorative preparation "Agrobionov" was applied in the conditions of the vegetation experiment in doses of 0, 100, 120, 200, 240 and 300 kilograms per hectare (kg/ha) in combination with mineral fertilizers (NP) in full and fractional doses of ¾, ½ and ¼ of the calculated rate (denoted as NPcalc, ¾ NPcalc, ½ NPcalc, ¼ NPcalc). Vegetation experiments were conducted in plastic cylindrical vessels of 5 litres, 28 cm high and 19 cm in diameter, filled with 4 kg of air-dry soil, and placed in a climate chamber at a temperature of +20…+25 °C and humidity of 60-65%.

The yield of the green mass of oats at the end of tillering and the earing stage was determined in vegetative vessels by cutting the aboveground mass and weighing it on analytical scales Sartorius CPA225D (Germany) with an accuracy of ±0.01 g. The yield of the green mass of spring wheat in the tube stage was determined in the field on an area of 1 m² in triplicate with the subsequent weighing of the biomass on an Ohaus Scout Pro Balance (USA). In the field experiment, fertilisers and the preparation were applied in two ways: main (in autumn before sowing) and pre-sowing (simultaneously with sowing). A total of 18 experimental variants were laid out, including an absolute control (without fertiliser and preparation) and a control with a full rate of NP without ameliorative preparation. Field plots of 21×2.1 m, or 44.1 m², were laid out in triplicate. Soil samples for determining the microbiological activity of the soil were taken with a soil drill in the phase of spring wheat emergence in the root zone at a depth of 0-20 cm.

To determine the number of soil microorganisms, the seeding method was applied using selective nutrient media. The number of bacteria consuming organic nitrogen was determined on meat-peptone agar, bacteria using inorganic nitrogen on starch-ammonium agar; actinomycetes on Gauze medium; aerobic nitrogen fixers on Ashby medium; cellulose-degrading bacteria on Hutchinson medium; and microscopic fungi on Chapek medium. Samples were taken from the rhizosphere of plants at a depth of 0-10 cm, soil suspensions were prepared in sterile saline, and 0.1 ml was applied to Petri dishes. Incubation was conducted at +28°C for 5-7 days. The colonies were counted manually under a Nikon SMZ745 binocular microscope (Japan), expressing the results in colony forming units per 1 g of dry soil. In 2024, meteorological conditions in Shagalaly village, Zerendy district, Akmola region, were characterised by increased precipitation rates in May and August 2024, and during the critical phase of the growing season, precipitation and moisture reserves were optimal. In general, the year was favourable for grain cultivation in Northern Kazakhstan (Table 1).

***Table 1**. Meteorological conditions for the growing season of 2024 on the territory of Kokshetau Experimental Production Farm Limited Liability Company, Shagalaly of Zerendy District, Akmola Region*

Parameters	20-31 May	June	July	August	September	Sum
The sum of precipitation, mm	65.1	65	67.5	56	21.8	
Annual average, mm	30.7	44.2	63.9	39.7	27	
Average monthly temperature in 2024, t °C	9	20.9	19.5	17.1	10.5	
Average annual t °C	11.7	17	18.8	17.1	12	
The average annual sum of active temperatures, t °C	18.7	210	272.8	220.1	60	781.6
Total active temperatures in 2024, t °C		327	294.5	220.1	15.5	857.1

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

In the third decade of September 2024, harvesting was carried out, and wheat yield data were obtained for 18 experimental variants. The harvesting was conducted using a continuous method with a WinterSteiger grain selection combine, the accounting area of the plot was 21×1.6 m. The yield of spring wheat in tonnes per hectare (t/ha) was recorded based on the results of harvesting plots with a selection combine, converted to hectares and adjusted for standard moisture according to ISO 712:2009 (2009). The effectiveness of fertilisers in combination with Agrobion 120 kg/ha was assessed by a set of parameters: yield of dry vegetative mass of oats for haylage), soil pH, electrical conductivity (EC), content of available forms of nitrogen (N), phosphorus (P) and potassium (K) in the soil-plant system. The pH was measured with a portable pH meter Hanna HI98103 (Italy), and the electrical conductivity with a conductivity meter Mettler Toledo FiveEasy (Switzerland). The concentration of N, P, and K in the soil and plant mass was determined by the method of wet mineralisation followed by spectrophotometric analysis using a Shimadzu UV-1800 (Japan). The results were statistically processed using Statistica 12 (StatSoft, USA). To assess the reliability of differences between the variants, one-factor analysis of variance (ANOVA) was used at a significance level of $p < 0.05$. The least significant difference ($LSD_{0.05}$) was calculated for each indicator. To evaluate the strength of the relationship between Agrobion doses and the resulting traits, Pearson's correlation coefficient (R) was calculated. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

The application of Agrobiones at a dose of 100 kg/ha in combination with a full dose of NP (options 2 and 3) did not result in a significant increase in the number of microbial communities compared to option 1. In the control variant (variant 1), the number of actinomycetes was 54.66×10, and aerobic nitrogen fixers were 1×10. In variant 2 (basic application), the number of actinomycetes was 46.3×10, and nitrogen fixers 2×10; in variant 3 (pre-sowing application), 40.67×10^4 and 2.33×10, respectively. Thus, in both cases, the increase compared to the control was insignificant and did not exceed the statistical error, which indicated weak biological activity. This confirms that a dose of 100 kg/ha in the presence of complete mineral fertilisation does not have a pronounced stimulating effect on the development of key functional groups of microorganisms.

The most significant changes were observed in variant 10, which combined 200 kg/ha of "granulated biopreparation" (basic application) and ½ of the NP norm. In this variant, the number of bacteria consuming organic nitrogen reached 12.33; bacteria using inorganic nitrogen 14.3×10; actinomycetes 108.67×10; aerobic nitrogen fixers 17×10^6; cellulose-degrading bacteria 39.3×10; microscopic fungi 2.33×10. These indicators significantly exceeded the values of control variant 1: the number of bacteria consuming organic nitrogen was 3.4 times higher (12.33 vs. 3.66); bacteria using inorganic nitrogen was 7.15 times higher (14.3×10 vs. 2×10); actinomycetes was 99 times higher (108.67×10 vs. 54.66×10); aerobic nitrogen fixers were 17 times higher (17×10 vs. 1×10).99 times (108.67×10 vs. 54.66×10); aerobic nitrogen fixers 17 times (17×10 vs. 1×10); microscopic fungi 3.5 times (2.33×10 vs. 0.66×10).

The variants with a dose of 300 kg/ha of the "preparation" (variants 14-16) did indeed demonstrate contradictory results in terms of microbiological indicators. The contradiction was that at high doses of Agrobion, there was an increase in the activity of certain functional groups (e.g., bacteria that use mineral nitrogen), but at the same time, other important groups of actinomycetes and nitrogen fixers, which play a key role in the formation of a stable and balanced microbial community. Thus, in variant 14 (at full NP rate), the number of bacteria using inorganic nitrogen reached 28×10^6, which is 14 times higher than in the control (2×10^6). However, at the same time, the number of actinomycetes decreased to 71.67×10^4 compared to 108.67×10^4 in variant 10, and aerobic nitrogen fixers decreased to 8×10^6 compared to 17×10^6. Variant 15 (½ NP) showed an even more dramatic decrease: actinomycetes 69.67×10^4, aerobic nitrogen fixers 2.1×10^7, and cellulose-degrading bacteria only 4.3×10^4, which is significantly lower than 39.3×10^4 in variant 10. Option 16 (¼ NP) yielded an extremely high number of bacteria utilising inorganic nitrogen (153×10^6), but the number of actinomycetes (33.3×10^4) and aerobic nitrogen fixers (12.3×10^6) was below optimal values.

Variants 12 and 13 (200 kg/ha of "granular biopreparation" at ¼ NP, applied by the main and pre-sowing methods, respectively) demonstrated pronounced differences in microbiological indicators depending on the method of application. In variant 12, the number of aerobic nitrogen fixers reached 10.3×10^6, which was significantly higher than in variant 13 (6.67×10^6). At the same time, in both variants, the number of bacteria using inorganic nitrogen remained high (22.3×10^6 and 17×10^6, respectively), and actinomycetes 104.3×10^4 and 46.3×10^4. This confirmed the importance of the application method for the activation of certain microbial groups, in particular spore-forming forms. The absolute control (variant 17) demonstrated the lowest number of most groups of microorganisms: organotrophic bacteria 0.33; aerobic nitrogen fixers 0.67×10^6; actinomycetes 66×10^4. However, the number of bacteria using inorganic nitrogen reached an abnormally high level (153×10^6), which is possibly determined by the accumulation of mineral residues from previous seasons and the lack of competition from active microflora.

Variant 18, which included only Agrobion at a dose of 100 kg/ha, without mineral fertilisers, showed a sharp surge in organotrophic bacteria (217), but other groups, including actinomycetes and nitrogen fixers, remained at a low level. This indicates a short-term stimulating effect, not accompanied by structural changes in microbial communities. A comparison of the main and pre-sowing applications showed that the first method often provided a higher number of microorganisms. For instance, at a dose of 200 kg/ha and full NP (variants 8 and 9), the total number of bacteria using organic nitrogen was 4.33 (main) versus 10.0 (pre-sowing), but the number of actinomycetes and fungi was higher in the main method, 76.3×10^4 and 0.33×10^4, respectively (Table 2).

***Table 2**. Quantitative indicators of microorganisms in 18 variants of the experiment to study the doses and timing of application of the granular preparation Agrobion on different nutrient media*

	Variant	Microorganisms that consume organic nitrogen	For the detection of actinomycetes and bacteria that consume inorganic nitrogen	Number of actinomycetes	Number of aerobic nitrogen fixers	For aerobic bacteria that use cellulose	Number of microscopic fungi
		MPA	SAA	Gauze	Ashby	Hutchinson	Chapeka
NPcalc control	1	3.66×10^6	2×10^6	54.66×10^4	1×10^6	45×10^4	0.66×10^4
A100base+NPcalc	2	2.33	6.3×10^6	46.3×10^4	2×10^6	40.67×10^4	0.66×10^4
A100prep+NPcalc	3	1	1×10^6	40.67×10^4	2.33×10^6	46×10^4	0.66×10^4
A100base+1/2NPcalc	4	1	1.67×10^6	32×10^4	1.33×10^6	30×10^4	0.66×10^4
A100prep+1/2 NPcalc	5	3	6.3×10^1	28.67×10^4	1×10^6	25×10^4	0.33×10^4
A100base+1/4 NPcalc	6	5	3.67×10^6	27.3×10^4	2×10^6	38.3×10^4	0.66×10^4
A100prep+1/4 NPcalc	7	3	1.67×10^6	80.67×10^4	1×10^6	42.67×10^4	0.33×10^4
A200base+NPcalc	8	4.33	3×10^6	76.3×10^4	6.3×10^1	52.3×10^4	0.33×10^4
A200prep+NPcalc	9	10	3.67×10^6	35.3×10^4	6.3×10^0	44.67×10^4	1.33×10^4
A200base+1/2 NPcalc	10	12.33	6.3×10^{14}	108.67×10^4	17×10^6	39.3×10^4	2.33×10^4
A200prep +1/2NPcalc	11	7	7.67×10^6	78.67×10^4	6.3×10^{10}	18.67×10^4	0.33×10^4
A200base+1/4 NPcalc	12	17.66	6.3×10^{22}	104.3×10^4	6.3×10^{10}	26.67×10^4	0.66×10^4
A200prep+1/2NPcalc	13	11.66	17×10^6	46.3×10^4	16×10^6	26.67×10^4	1×10^4
A300base+NPcalc	14	27	28×10^6	71.67×10^4	8×10^6	34×10^4	2×10^4
A300base+1/2 NPcalc	15	67.33	7.67×10^6	69.67×10^4	21×10^6	4.3×10^4	0.33×10^4
A300base+1/2NPcalc	16	57.33	153×10^6	4.3×10^{33}	6.3×10^{12}	26×10^4	0.66×10^4
abs control	17	0.33	153×10^6	66×10^4	0.67×10^6	35.67×10^4	4×10^4
A100 kg/ha	18	217	153×10^6	45×10^4	1×10^6	36.67×10^4	2×10^4

Note: *MPA – meat-peptone agar; SAA – starch-ammonium agar*
Source: *compiled by the authors*

Thus, the greatest microbiological effect was recorded in variant 10 (200 kg/ha of "granular biological product" + ½ NP, main application). A moderate decrease in the mineral load with active biostimulation ensured a balanced development of microbial groups. Exceeding the dose (300 kg/ha) or excessive reduction of NPs led to a decrease in biological activity. The obtained data recommended variant 10 as the most effective from the agrobiological point of view for use in the conditions of southern chornozems of Northern Kazakhstan. The control variant (NP calculated, variant 1), which used the full calculated dose of mineral fertilisers without biological additives, provided an average yield of green mass of oats at the level of 6.13 g/vessel.

This indicator was taken as the base for the comparative analysis of the other variants. The variants involving a reduction in the dose of mineral fertilisers to ¾ of the calculated dose and the simultaneous application of the "preparation" at a dose of 120 kg/ha showed a moderate decrease in yield. Thus, the average value for variant 2 was 5.76 g/vessel, which is 0.37 g less than in the control case. Even though the result was lower than the baseline, the difference was within the error margin ($LSD_{0.05}$ = 0.99 g/vessel), and therefore not statistically significant. This fact indicated that part of the mineral fertilisation could be effectively replaced by a biological preparation without significant yield loss.

The variant with half the dose of NP and the same amount of Agrobion (variant 3) gave an even lower yield of 5.31 g/vessel, which was 0.82 g less than the control. At the same time, the result was closer to the limit of statistical significance. Consequently, when NP was reduced by 50%, the potential of the biological preparation became insufficient to fully compensate for the missing mineral elements. The most pronounced decrease in yield was observed when ¼ NP was applied together with 120 kg/ha of "granular biopreparation" (variant 4). The average value was only 4.45 g/vessel, which is 1.68 g lower than in the control variant. The difference was significantly higher than the $LSD_{0.05}$, and therefore statistically significant. This indicates that excessive reduction of mineral load, even in the presence of a biological stimulant, negatively affected the productivity of oats in the early stages of vegetation. Probably, under these conditions, the plants experienced a deficiency of key macronutrients (nitrogen and phosphorus), especially during the period of active growth of vegetative mass (Romanchuck *et al.*, 2017). Comparison of the data between the experimental variants revealed a clear correlation between the level of yield and the degree of NP reduction. When 75% of the calculated dose was preserved, yield losses were not statistically confirmed, but when reduced to 50% and below, the losses became pronounced. This concludes that there is a threshold dependence below which the effect of the biological product cannot provide full compensation for the missing mineral elements. Notably, the use of the "biopreparation", even with a significant reduction in NP, still provided a significant yield of green mass (Yeraliyeva *et al.*, 2017) In practical farming conditions, this may indicate the high agronomic flexibility of the biopreparation, which can be used to adapt the nutrition technology to specific economic and climatic conditions (Table 3).

***Table 3**. Yield of green mass of oats in the phase of the end of tillering in the conditions of vegetation experience with the application of different doses of fertilizers in combination with Agrobion at a dose of 120 kg/ha (g/vessel)*

Variants	1	2	3	4	average	Difference from control
Ncalc control	5.34	7.18	6.40	5.58	6.13	
3/4 NPcalc+A120	6.52	5.40	6.14	4.98	5.76	-0.37
1/2 NPcalc+A120	6.83	3.35	5.52	5.52	5.31	-0.82
1/4 NPcalc+A120	5.51	3.40	4.68	4.21	4.45	-1.68
$LSD_{0.05}$, g/vessel					0.99	

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

Thus, according to the results of the tillering phase, the best option in terms of efficiency and resource consumption was the variant with a ¾ dose of mineral fertilisers in combination with 120 kg/ha of Agrobion. It provided yields that were statistically indistinguishable from the control at lower mineral inputs. Therefore, it is possible to consider this combination as an economically and environmentally feasible alternative to full mineral fertilisation in oat cultivation on the black soil of Northern Kazakhstan. In the control variant with the full calculated dose of NP without the addition of the "preparation" (NP calculation, variant 1), the pH value was 7.24, which corresponded to a slightly alkaline reaction. The electrical conductivity of the soil reached 306 μS/cm, reflecting the presence of a standard level of salts in the soil solution for chornozem conditions. At the same time, the yield of the green mass of oats was 6.13 g/vessel. The balance of the elements was as follows: nitrogen 181.02 milligrams per kilogram (mg/kg), phosphorus 18.30 mg/kg, and potassium 382.51 mg/kg.

Reducing the dose of mineral fertilisers to ¾ of the calculated rate in combination with 120 kg/ha of "granulated biopreparation" (variant 2) resulted in an increase in soil pH to 7.6. Electrical conductivity decreased to 167.9 μS/cm, indicating a decrease in the total dissolved salt content. Yield decreased slightly to 5.76 g/vessel. Nitrogen content decreased to 171.93 mg/kg and potassium to 263.74 mg/kg, while phosphorus content increased to 20.79 mg/kg. This indicated more active nitrogen uptake by plants and stabilisation of phosphorus availability under the influence of Agrobion. In the variant with ½ of the calculated dose of NP and the same dose of "preparation" (variant 3), the pH increased to 7.71, which corresponded to the tendency of mild alkalisation of the soil. The electrical conductivity was 202 μS/cm, which remained within the normal range. Yields decreased to 5.31 g/vessel and nitrogen content was 162.01 mg/kg. The potassium content was 302.52 mg/kg, indicating a more economical use of potassium resources with a reduced mineral load. The phosphorus content remained at 18.19 mg/kg, which almost correlated with the benchmark.

The most significant decrease was recorded in the variant with ¼ of the calculated dose of NP with the addition of 120 kg/ha of Agrobion (variant 4). The yield in this variant was 4.45 g/vessel, which was significantly lower than the control level. The pH value increased to 7.75, but the electrical conductivity decreased to 158.3 μS/cm. Nitrogen concentration in the soil decreased to 142.94 mg/kg, potassium to 263.53 mg/kg, and phosphorus remained at 18.23 mg/kg. These data indicated a lack of mineral nutrition with a too strong reduction in the dose of NP, despite the presence of biostimulation. Correlation analysis revealed a negative relationship between yield and soil electrical conductivity (correlation coefficient R = -0.90), indicating that a decrease in salt pressure had a favourable effect on plant development. At the same time, a moderately negative relationship between soil pH and yield (R = -0.78) was found, which reflected the optimal weakly alkaline reaction in the range of 7.2-7.6 for oat growth (Table 4).

Table 4. *Efficiency of fertiliser application in combination with Agrobion 120 kg/ha*

Variant	pH	Electrical conductivity (EC)	Yield, g/vessel	Nutrient balance of oats, mg/kg in the soil-plant system at the end of the tillering phase		
				N	P	C
NPcalc (control)	7.24	306	6.13	181.02	18.30	382.51
¾ NPcalc+A120 kg/ha	7.6	167.9	5.76	171.93	20.79	263.74
½ NPcalc+A120 kg/ha	7.71	202	5.31	162.01	18.19	302.52
¼ NPcalc+A120 kg/ha	7.75	158.3	4.45	142.94	18.23	263.53
Correlation coefficient, R	-0.78	-0.9	$LSD_{0.05}$=0.99 g/vessel	0.98		

Source: *compiled by the authors*

Thus, an increase in the dose of "preparations" combined with a moderate decrease in mineral fertilisation contributed to an improvement in the balance of macroelements in the soil without salt accumulation, which was confirmed by a decrease in electrical conductivity. The best balance between the level of available nitrogen, phosphorus and potassium, as well as the optimal yield, was recorded when using ¾ dose of mineral fertilisers in combination with 120 kg/ha of "granular biological product" (variant 2). With a further reduction of the NP dose to ½ and even more so to ¼, the effectiveness of the biostimulant decreased, especially concerning the nitrogen supply of plants. The yield of oats in the earing phase varied depending on the combination of doses of the "preparation" and mineral fertiliser rates. In the control variant with the full calculated dose of NP, the yield was 26.4 g/vessel. With a reduction in the rate of mineral fertilisers to ½ NP and the application of 100 kg/ha of Agrobion, the yield reached 38.23 g/vessel, which exceeded the control value. When 120 kg/ha was applied, the yield decreased to 30.24 g/vessel, remaining above the baseline. A dose of 200 kg/ha at ½ NP provided a yield of 35.23 g/vessel. The highest rate was recorded at a dose of Agrobion 300 kg/ha in combination with ½ NP, where the yield was 49.52 g/vessel.

When applying ¾ NP, the yield of oats also varied depending on the dose of the "granular biopreparation". When 100 kg/ha was applied, the yield was 22.7 g/vessel, which was below the control level. When the dose was increased to 120 kg/ha, the yield increased to 29.16 g/vessel. At 200 kg/ha, the yield was 24.6 g/vessel. The variant with a dose of 300 kg/ha provided a yield of 35.41 g/vessel, which exceeded the control indicator. The differences between the variants at ½ NP were more pronounced than at ¾ NP. At a dose of 100 kg/ha of Agrobion, the yield increased by 11.83 g/vessel compared to the control. At a dose of 120 kg/ha, the difference was 3.84 g/vessel. The application of 200 kg/ha provided a yield increase of 8.83 g/vessel. The dose of 300 kg/ha contributed to an increase in yield by 23.12 g/vessel compared to the control variant. At ¾ NP, the application of 100 kg/ha of the "preparation" was accompanied by a decrease in yield by 3.7 g/vessel compared to the control. The variant with a dose of 120 kg/ha gave a yield increase of 2.76 g/vessel. At 200 kg/ha, the yield remained at the control level. A dose of 300 kg/ha provided a yield increase over the control by 9.01 g/vessel.

The analysis demonstrated that at ½ NP, the application of 300 kg/ha of the "granular biopreparation" provided a significant increase in yield, exceeding the $LSD_{0.05}$ of 10.2 g/vessel. The differences between the 100 kg/ha and 200 kg/ha doses also exceeded the significance threshold. The variant with 120 kg/ha at ½ NP showed an increase but within the statistical error. At ¾ NP, a significant difference in yield was recorded only at 300 kg/ha of Agrobion. At a dose of ½ NP, an increase in the dose of Agrobion from 100 to 300 kg/ha was accompanied by an increase in yield from 38.23 to 49.52 g/vessel. At a dose of ¾ NP, a similar increase in yield was observed from 22.7 to 35.41 g/vessel. The lowest yields at ¾ NP were recorded at 100 and 200 kg/ha of the "preparation". The correlation coefficient between the dose of Agrobion and yield at ½ NP was 0.70, reflecting a strong positive relationship. At ¾

NP, the correlation coefficient was 0.5, indicating a less pronounced dependence between the level of biostimulation and yield. The highest yield in the experiment was recorded in the variant with the introduction of 300 kg/ha of "granular biopreparation" and ½ of the calculated dose of NP (Table 5).

***Table 5**. Yield of green mass of oats in the conditions of vegetation experience in the eating phase*

Agrobions, kg/ha	0.00	100	120.00	200	240.00	300	R
Fertiliser rates							
½NPcalc		38.23	30.24	35.23	35.86	49.52	0.70
¾NPcalc		22.7	29.16	24.6	35.41	28.5	0.5
$N_{22}P_{100}$calc average	26.4	$LSD_{0.05}$=10.2 g/vessel					

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

The obtained data on the yield of oats in the earing phase showed that the maximum values were recorded when the dose of mineral fertilisers was reduced to ½ NP and the dose of the "biopreparation" was increased to 300 kg/ha. At ¾ NP, the best results were also observed at a dose of 300 kg/ha, but the overall yield level remained lower than at ½ NP. Field germination at the main application of the full calculated dose of NP (1 NP) without Agrobion was 61.07%. With the addition of 100 kg/ha of Agrobion, germination increased to 62.19%, and at 200 kg/ha to 64.82%, indicating a positive effect of the preparation. However, with a further increase in the dose of Agrobion to 300 kg/ha, germination decreased to 56.43%, which was lower than the control (61.07%). When using ½ NPcalc, the field germination rate without "preparations" was 59.64%. The application of 100 kg/ha of Agrobion increased the index to 70.36%, which was the maximum value for the main application at this NP rate. A dose of 200 kg/ha of the "granular biopreparation" gave a germination rate of 60.71%, which was slightly higher than the control. At ¼ NPcalc, the germination rate without Agrobion was 58.93%, increasing to 64.82% at 100 kg/ha and 67.14% at 200 kg/ha of the "granular biopreparation", which demonstrated a stable positive effect of the preparation at low NP doses. In the variant without fertilisers and "preparations" (absolute control), the field germination rate was 67.50%, which was higher than the number of variants with low doses of NPs, probably due to natural soil fertility.

At pre-sowing application, the full rate of NP (1 NP) without "selected preparation": provided germination of 61.07%, identical to the main application. The application of 100 kg/ha of "Agrobion" increased the indicator to 72.14%, which was the maximum value in the entire experiment, indicating the high efficiency of the pre-sowing application. A dose of 200 kg/ha of the "selected preparation" gave a germination rate of 67.86%, which also exceeded the control. For ½ NPcalc, germination without the "selected product" was 54.46%, which was lower than all other variants. The application of 100 kg/ha of Agrobion increased the index to 61.96%, demonstrating the restoration of germination to the control level. At ¼ NPcalc, germination without "preparation" was 61.79%, and with 100 kg/ha of "preparation" – 64.82%, which corresponded to the data of the main application for this dose. The analysis demonstrated that the smallest significant difference ($LSD_{0.05}$) was 5.6%, therefore it is possible to define the differences between the variants as significant when this threshold was exceeded. The correlation coefficient (R) for the main application was 0.73 and for the pre-sowing application 0.67, indicating a moderate relationship between the doses of the "granular biopreparation" and field germination. The greatest increase in germination was observed at the pre-sowing application of 100 kg/ha of the "granular biopreparation" with the full rate of NP (+11.07% compared to the control), while the dose of 300 kg/ha at the main application reduced germination by 4.64% compared to the control. Variants with ½ and ¼ NPcalc showed less stability, especially at pre-sowing application, where low doses of NP without "granular biopreparation" reduced germination to the lowest values (54.46%) (Table 6).

***Table 6**. Field germination depends on the timing and doses of mineral fertilisers and Agrobion*

	Main				**Pre-sowing**		
Agrobions, kg/ha / NPcalc	0	100	200	300	0	100	200
1 NP	61.07	62.19	64.82	56.43	61.07	72.14	67.86
1/2.NPcalc		59.64	70.36	60.71		54.46	61.96
¼NPcalc		58.93	64.82	67.14		61.79	64.82
0		67.50					
$LSD_{0.05}$=5.6%		Correlation coefficient R				0.73	0.67

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

The data obtained showed that pre-sowing application of Agrobion at a dose of 100 kg/ha with the full rate of NP provided the highest field germination (72.14%), while high doses of the preparation (300 kg/ha) at the main application reduced the indicator. Moderate doses of Agrobion (100-200 kg/ha) stably increased germination at both application rates, especially at low NP doses, which emphasised the role of optimising germination conditions on southern black soil. With the main application of the full design dose of NP (1 NP) without the "granular biopreparation", the yield of green mass was 510 grams per square metre (g/m²). The application of 100 kg/ha of the "granular biopreparation" increased the indicator to 560 g/m², and a dose of 200 kg/ha provided the maximum yield for this variant of 664 g/m². However, with a further increase in the dose to 300 kg/ha, the yield decreased to 566 g/m², indicating possible growth inhibition at high concentrations of the product. For the ½ NPcalc, the yield without the "preparation" was 565 g/m², which was higher than the control with the full rate of NP. The application of 100 kg/ha of "preparations" increased the yield to 587 g/m², and 200 kg/ha to 566 g/m², which was below the maximum. A dose of 300 kg/ha of "biopreparations" yielded 676 g/m², which was the highest for ½ NPcalc with the main application. At ¼ NPcalc, the yield without the "granular biopreparation" reached 728 g/m², which was the highest value among all variants of the main application. However, the addition of 100 kg/ha of the "granular biopreparation" reduced the figure to 499 g/m², 200 kg/ha to 425 g/m², and 300 kg/ha to 702 g/m², indicating an unstable effect of the preparation at low NP doses. The variant without fertilisers and "biological products" (absolute control) showed a yield of 319 g/m², which was the minimum value for the main application.

At the pre-sowing application, the full rate of NP (1 NP) with 100 kg/ha of Agrobion provided a yield of 733 g/m², which was the maximum value in the entire experiment. The dose of 200 kg/ha of Agrobion yielded 664 g/m², which corresponded to the maximum of the main application for this NP rate. For ½ NPcalc, the yield with 100 kg/ha of Agrobion was 676 g/m², and with 200 kg/ha 555 g/m², which was below the maximum. At ¼ NPcalc, 100 kg/ha of Agrobion provided a yield of 702 g/m², while 200 kg/ha reduced the yield to 402 g/m², which was the minimum value for pre-sowing application. The variant without "preparations", but with pre-sowing application (0 kg/ha), showed a yield of 646 g/m², which exceeded the control of the main application. The analysis revealed the smallest significant difference ($LSD_{0.05}$) at 98 g/m², which confirmed the significance of differences between the variants when this threshold was exceeded. The correlation coefficient (R) for the main application was 0.85, indicating a strong relationship between Agrobion doses and yield. The greatest increase in yield was observed at the pre-sowing application of 100 kg/ha of "biopreparations" with the full rate of NP (+223 g/m² compared to the control of the main application). At the same time, high doses of "preparations" (200-300 kg/ha) at ¼ NPcalc reduced the yield, especially when applied at pre-sowing (-326 g/m² at 200 kg/ha compared to ¼ NPcalc without "granular biological product") (Table 7).

***Table 7**. Influence of doses and timing of "Agrobion" application in combination with mineral fertilisers (NP) on the yield of spring wheat green mass in the critical phase of heading (g/m²)*

Method of application	Main				Pre-sowing	
Agrobions, kg/ha / Full norm $N_{40}P_{45}$	0	100	200	300	100	200
1 NP	510.00	560.00	664.00	566.00	733.00	664.00
1/2.NPcalc		565.00	587.00	566.00	676.00	555.00
¼NPcalc		728.00	499.00	425.00	702.00	402.00
0	319				646.00	
	($LSD_{0.05}$ = 98 g)				R 0.85	

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

The obtained data showed that the pre-sowing application of 100 kg/ha of Agrobion with full NP rate provided the highest yield of spring wheat green mass (733 g/m²). Moderate doses of the "granular biopreparation" (100-200 kg/ha) stably increased the yield at full and half NP rates, while at low NP doses (¼ NPcalc) the preparation more often reduced the indicators, especially when applied at pre-sowing. With the main application of the full calculated dose of NP (1 NP) without "selected preparations", the yield was 2.40 t/ha. The application of 100 kg/ha of the "preparation" increased the yield to 2.57 t/ha, which was the maximum value for the main application at this NP rate. A dose of 200 kg/ha of "selected preparations" reduced the yield to 2.36 t/ha, and 300 kg/ha to 1.98 t/ha, indicating a negative effect of high doses of the preparation. For ½ NPcalc, the yield with 100 kg/ha of "preparation" was 2.23 t/ha, with 200 kg/ha 2.10 t/ha, and with 300 kg/ha 1.45 t/ha, which demonstrated a consistent decrease in yield with increasing dose of the preparation. At ¼ NPcalc, 100 kg/ha of the "granular biopreparation" yielded 1.93 t/ha, 200 kg/ha 1.67 t/ha, and 300 kg/ha 1.25 t/ha, which was the lowest value among the fertiliser variants at the main application. The absolute control (no fertiliser and "biopreparation") yielded 2.09 t/ha, which was higher than several variants with low NP rates and high doses of the "preparation".

At the pre-sowing application, the full rate of NP (1 NP) with 100 kg/ha of the "granular biopreparation" provided a yield of 2.76 t/ha, which was the maximum value in the entire experiment. A dose of 200 kg/ha of the "biopreparation" yielded 2.44 t/ha, which also exceeded the control of the main application (2.40 t/ha). For ½ NPcalc, the yield with 100 kg/ha of Agrobion was 2.24 t/ha, and with 200 kg/ha 2.17 t/ha, which was comparable to the results of the main application for this NP rate. At ¼ NPcalc, 100 kg/ha of Agrobion provided a yield of 1.96 t/ha, and 200 kg/ha 1.67 t/ha, which corresponded to the data of the main application for this dose of the preparation. Statistical analysis revealed the smallest significant difference ($LSD_{0.05}$) at the level of 0.2 t/ha, which confirmed the significance of differences between the variants when this threshold was exceeded. The correlation coefficient (R) for the main application was -0.99 for the full NP rate, -0.9 for ½ NPcalc and -0.99 for ¼ NPcalc, indicating a strong negative relationship between increasing doses of the "granular biopreparation" and yield. For pre-sowing application, R was 0.91 for 100 kg/ha and 0.94 for 200 kg/ha, showing a positive correlation at moderate doses of the product. The highest yield increase was observed at 100 kg/ha of the "granular biopreparation" with the full rate of NP (+0.36 t/ha compared to the control of the main application). At the same time, high doses of "Agrobion" (300 kg/ha) at the main application reduced the yield by 0.42 t/ha for 1 NP and by 0.84 t/ha for ½ NPcalc compared to the control (Table 8).

***Table 8**. Influence of doses and timing of Agrobion application in combination with NP fertilisers on the yield (t/ha) of spring wheat*

		Main contribution					Pre-sowing	
NPcalc (total calculated dose)	**Agrobions, kg/ha**	**0**	**100**	**200**	**300**	**Correlation coefficient R**	**100**	**200**
1 NP	1	2.40	2.57	2.36	1.98	-0.99	2.76	2.44
1/2.NPcalc	0.5		2.23	2.1	1.45	- 0.9	2.24	2.17
¼NPcalc	0.25		1.93	1.67	1.25	-0.99	1.96	1.67
0	0						2.09	
($LSD_{0.05}$=0.2 t/ha)						Correlation coefficient R	0.91	0.94
1 NP	1	2.40	2.57	2.36	1.98	-0.99	2.76	2.44

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

The obtained data showed that the pre-sowing application of 100 kg/ha of Agrobion with full NP rate provided the highest yield of spring wheat (2.76 t/ha). Moderate doses (100-200 kg/ha) steadily increased the yield at full NP rate, while high doses (300 kg/ha) and low NP rates (¼ NPcalc) reduced the yield, especially at the main application. The effectiveness of the product depended on the method of application and dosage, with the advantage of pre-sowing application (Shuvar *et al.*, 2022). The results obtained confirmed that the effectiveness of the granular preparation Agrobion in combination with mineral fertilisers (NP) depends on their doses and method of application. At full NP rate (variant 1) without biostimulation, moderate biological activity and average yield levels were maintained, while absolute control (variant 17) showed degradation of the microbiota and a decrease in productivity. The addition of Agrobion at a dose of 100 kg/ha at full NP rate (variants 2 and 3) did not provide a noticeable increase in microbiological activity, indicating the low efficacy of the preparation in the presence of excess mineral nutrition. The maximum indicators of microorganism activity and oat yield in the tillering phase were recorded in variant 10 (200 kg/ha of "granulated biopreparation" + ½ NP, main application), where a synergistic effect of biological and mineral stimulation was observed. Variants with 300 kg/ha of the preparation showed a tendency to suppress certain microbial groups, especially actinomycetes and nitrogen fixers, which may be associated with substrate oversaturation. Similar patterns were observed in the analysis of spring wheat yield: the highest values were recorded with a pre-sowing application of 100 kg/ha of Agrobion with a full NP rate. Thus, the effectiveness of the preparation depends significantly on the dosage and application technology.

Furthermore, S.V. Nallanthighal (2024) and C.O. Adetunji *et al.* (2024) considered approaches to increasing crop yields using organic compounds and nanotechnology. S.V. Nallanthighal demonstrated that humanite can improve plant nutrition, but the study was limited to two crops and did not consider microbiological changes in the soil. The review by C.O. Adetunji *et al.* addressed nanobiofertilisers, the structure and potential benefits, but lacked information on dosages, application methods and practical results in real agricultural systems. In contrast, the present study is based on a vegetation and field experiment with 18 normalised variants, including Agrobion doses, fractional NP rates and different application methods. It covers not only oat and wheat yields but also the dynamics of microbial groups (actinomycetes, nitrogen fixers, fungal microflora), as well as agrochemical parameters (pH, EC, NPK content), making it more applicable and representative of the conditions of the black soils of Northern Kazakhstan.

According to the results of M. Aguiar *et al.* (2023) and M. Liu *et al.* (2025), biological processes in the rhizosphere directly affect nutritional efficiency and crop productivity. M. Liu *et al.* found a correlation between phosphorus-sensitive bacteria and canola growth, but the study was limited to molecular analysis without the use of fertilisers or agronomic practices. M. Aguiar *et al.* studied the impact of agroecosystem edge zones on microbial community structure, but the study addressed spatial gradients rather than managed agronomic practices. In contrast, the present study is based on targeted variation of doses and methods of application of a "granular biopreparation" with mineral fertilisers and enables a direct impact on the abundance of key microbial groups. It was found that the combination of 200 kg/ha of Agrobionts and ½ NP (variant 10) provides a multiple increase in microbiological activity and balanced nutrition, which is not covered by M. Liu *et al*. and M. Aguiar *et al*. Thus, the study offers not just monitoring of the microbiota, but specific ways of its targeted regulation.

Moreover, the studies by A. Botero (2021) and F.C. Schilt (2023) considered aspects indirectly related to soil fertility but in a different context. F.C. Schilt conducted geoarchaeological research aimed at reconstructing the Late Pleistocene environment and anthropogenic impact but without agronomic objectives and evaluation of soil processes in modern systems. A. Botero addressed phytopathological aspects and plant resistance to the keel pathogen, without considering soil microbiota, mineral nutrition and agrochemical parameters. In contrast to these studies, the present work combines agrochemical, microbiological and yield approaches. It presents data on the impact of "biological products" and mineral fertilisers on grain yields, microbial numbers, and soil chemistry, and establishes threshold dose levels beyond which a decrease in efficiency is observed. Such complexity and experimental representativeness distinguish this study from theoretical reconstructive and specialised phytopathological works.

Furthermore, R. Siuda *et al.* (2021) and G. Izydorczyk *et al.* (2022) addressed the technological aspects of fertiliser pelletisation. R. Siuda *et al.* developed and verified the method of lime-gypsum granulation, confirming its industrial applicability, but did not conduct agrobiological tests in the field. G. Izydorczyk *et al.* emphasised the importance of granulation to increase the efficiency of fertiliser application, including reducing losses and leaching, but the work was limited to laboratory analysis of the physical properties of the granules. In contrast to these technological approaches, the present study combines the granular form of Agrobion with graded doses of NPs, recording both chemical (pH, conductivity), biological (microbiota population) and yield parameters. This comprehensiveness not only confirms the suitability of the granules but also determines the biologically and economically optimal schemes of the use, which was not presented by R. Siuda *et al.* and G. Izydorczyk *et al.*

In addition, studies by A. Lisowska *et al.* (2022) and M. Ferrari *et al.* (2025) addressed alternative forms of macronutrient application. A. Lisowska *et al.* investigated granular sulphur fertilisers and their effect on sandy soils, finding an increase in sulphur content and improved substrate structure, but did not assess yield or soil biological activity. M. Ferrari *et al.* compared foliar fertilisation with traditional nitrogen application and concluded that gradual foliar application can be effective in conditions of moisture deficiency. In contrast to thematically narrow studies, the present paper covers several crops (oats and wheat), different doses of "granulated biopreparation" and NP, and includes an assessment of germination, yield and microbiological parameters. This can be used for the development of specific fertilisation schemes adapted to chornozems, in contrast to the studies by A. Lisowska *et al.* and M. Ferrari *et al.*, which were limited to certain nutrient forms.

In this context, studies by B.R. Sahoo *et al.* (2024) and C.O. Asadu *et al.* (2024) addressed promising approaches to improving fertilizer efficiency. B.R. Sahoo *et al.* showed that nanoforms of fertilisers have a positive effect on rice yield and soil health, but the study was mainly laboratory-based and did not address interactions with mineral fertilisation. C.O. Asadu *et al.* presented an overview of slow-release fertilisers, emphasising mechanisms and potential benefits, but without specific dose gradations or analysis of application methods. In contrast, the present study is based on field and vegetation experiments with clear variations in fertiliser rates, which identified threshold values at which a sharp decline in biological activity or yield occurs. Thus, the results obtained not only complement but also expand the understanding of the rational use of fertilisers in practice, offering reproducible solutions for the conditions of Northern Kazakhstan.

In addition, J. Hou *et al.* (2025) and A.R.S. Viana *et al.* (2025) investigated the effectiveness of alternative types of organo-mineral fertilisers. J. Hou *et al.* demonstrated that the application of mixed straw-chemical fertiliser increases nitrogen nutrition in sweet corn; however, the study was limited to a single crop and did not evaluate soil microbiological parameters. A.R.S. Viana *et al.* studied the effect of wastewater sludge-based fertilisers on chickpea yield and soil properties, recording increased yields and higher available phosphorus content. In contrast to the mentioned study, the present paper covered several crops (oats, wheat), uses combinations of "biopreparations" and mineral fertilisers that differ in method and dose, and evaluates not only productivity but also the state of the microbiota (actinomycetes, nitrogen fixers, fungi) and agrochemical indicators. This provides grounds for a comprehensive assessment of the interactions between "preparation-fertiliser-soil-plant", which was not conducted in the studies. The experiment must establish threshold doses and application methods.

Furthermore, D. Shanmugavel *et al.* (2023) and A. Jasińska *et al.* (2023) addressed promising strategies for sustainable fertilisation. D. Shanmugavel *et al.* presented a synthesis review of smart fertilisers, focusing on controlled release and new carriers, but practical data in field crops was minimal. A. Jasińska *et al.* analysed the use of digestate from anaerobic digestion as a fertiliser, identifying agronomic potential but not considering microbiological activity and interaction with mineral components. In contrast to these approaches, the present study provides experimentally confirmed data on the combination of a "biological product" and NPs, quantifying the response of microbial communities and yields at different doses. This not only theoretically substantiates the effectiveness of the combined approach but also proposes specific practical solutions for the chornozems of Northern Kazakhstan, including in conditions of limited use of mineral components.

In turn, the studies by T. Srisawat *et al.* (2024) considered alternative models of agriculture and biowaste conversion. T. Srisawat *et al.* demonstrated that natural (subsistence) agriculture can reduce vegetative mass but does not affect the yield and quality of rice, while not studying microbiological processes and agrochemical changes in the soil. K. Chojnacka *et al.* (2024) presented the practical aspects of converting biological waste into fertilisers, emphasising the technological value of the raw material, but the efficiency in terms of soil microbiota and agrocenosis productivity was not assessed. In contrast to the mentioned studies, the present paper addressed the granular biopreparation not only in terms of form and source but also in an agro-functional context: how it affects growth, nutrition, microbial composition and yield. This makes it possible to adapt Agrobion doses depending on the goal (increasing yield, activating microbiota, saving NPs), which makes the study highly applicable.

CONCLUSIONS

A comprehensive assessment of the effectiveness of the granular biological product Agrobion in combination with nitrogen-phosphorus mineral fertilisers (NP) in different doses and methods of application was made in a vegetation and field experiment on the southern black soil of Northern Kazakhstan. The study covered 18 experimental variants, including absolute control (no fertiliser), control with full NP rate, and combinations of biological products at doses of 100, 200 and 300 kg/ha with mineral fertilisers applied at doses of ¼, ½, ¾ and 1.0 of the calculated rates. Based on microbiological analyses, the study determined that the most favourable option for activating the rhizosphere microbiota was a combination of 200 kg/ha of the "granular biological product" with a ½ dose of NP at the main application (variant 10). In this variant, the maximum values of the number of actinomycetes, aerobic nitrogen fixers, and organotrophic and cellulose-degrading bacteria were recorded. This confirms that a moderate reduction in the mineral load during biostimulation can achieve a synergistic effect and activate the soil microbiota. On the contrary, high doses of the "granular biological product" (300 kg/ha) at the full dose of NP caused inhibition of certain microbial groups, probably due to substrate oversaturation.

The analysis of oat yields in the tillering and earing phases showed that at a dose of 300 kg/ha and a reduction of NP to ½, the yield reached maximum values (49.52 g/vessel), exceeding the control values by more than 20 g/vessel. At ¾ NP, a similar ratio also had a positive effect, but the yield level was slightly lower than at ½ NP. When the dose of NP was reduced to ¼, the compensating effect of the "preparations" became less pronounced, especially at a dose of 120 kg/ha. The field germination of oats and spring wheat also responded positively to moderate doses of the "preparation". The highest values of germination (72.14%) and yield (733 g/m^2) of wheat green mass were achieved at the pre-sowing application of 100 kg/ha of the "granular biopreparation" with the full dose of NP. For the grain productivity of spring wheat (t/ha), the same variant provided a yield of 2.76 t/ha, the maximum among all experimental combinations. At the same time, an increase in the dose of the "selected preparation" to 300 kg/ha at low NP rates led to a decrease in yield, which indicates a possible stressful effect of excessive biological load. In the future, it is planned to expand the tests on different soil types and under-production crops to assess the stability of the effect of the "preparations".

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CONFLICT OF INTEREST

None.

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Оптимізація дозувань та методів внесення гранульованого меліоративного препарату Агробіонів у поєднанні з мінеральними добривами для зернових культур на південних чорноземах Північного Казахстану

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Анотація. Метою дослідження було визначення ефективних співвідношень біопрепарату та мінеральних добрив для підвищення врожайності та активності ґрунту. У дослідженні представлені результати комплексного вивчення впливу гранульованого препарату «Агробіон» та різних доз мінеральних добрив (МД) на агробіологічні показники вівса та ярої пшениці на південному чорноземі Північного Казахстану. Дослід охоплював 18 варіантів комбінацій добрив, включаючи абсолютний контроль, стандартну дозу МД, а також різні дози Агробіону (100-300 кг/га) та їх комбінації з ¼, ½, ¾ та повною нормою МД за основного та передпосівного способів внесення. Найвища біологічна активність ґрунту спостерігалася у варіанті з 200 кг/га «препарату» та ½ МД, що супроводжувалося п'ятикратним збільшенням кількості азотфіксаторів, актиноміцетів та целюлозорозкладаючих бактерій порівняно з контролем. Урожайність вівса у фазі колосіння за цієї комбінації досягла 49,52 г/посудину, а максимальна польова схожість (72,14 %) зафіксована при передпосівному внесенні 100 кг/га Агробіону з повною дозою МД. Аналіз хімічних властивостей ґрунту показав зниження електропровідності та підтримку оптимального pH при помірному зниженні МД та використанні препарату. Результати демонструють, що оптимальні дози Агробіону (100-200 кг/га) у поєднанні з ½ або ¾ розрахункової норми NP забезпечують найвищу врожайність, мікробіологічну активність та схожість. Надмірні дози (300 кг/га) або різке зниження NP призвели до зниження ефективності. Виявлено кореляцію між дозою Агробіону, врожайністю та показниками родючості ґрунту. Рекомендована комбінація для підвищення агроекологічної ефективності – 200 кг/га «гранульованого препарату» з ½ МД при основному внесенні. Практична цінність цього дослідження полягає в обґрунтуванні оптимальних доз Агробіону та МД, що зменшує мінеральне навантаження без втрати врожайності, що сприяє ресурсозбереженню та захисту навколишнього середовища сільського господарства

Ключові слова: ґрунтові мікроорганізми; врожайність; кислотність ґрунту; способи внесення; біоактивність

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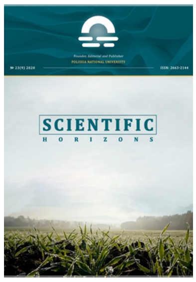

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Biotechnological aspects of sawflies number control in blackcurrant plantations

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Abstract. The study aimed to compare the effectiveness of biotechnological methods of controlling the *Pristiphora rufipes* sawfly population on black currant (*Ribes nigrum*) in the forest-steppe zone of Ukraine and to identify environmental factors affecting effectiveness. The study was conducted using 20 plots (0.1 hectares each) divided into four groups: treatment with the biological product *Bacillus thuringiensis*, entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*), a combination of fungi with pheromone traps and control without treatment. The effectiveness was

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assessed through weekly monitoring of pest numbers, the degree of leaf damage according to the scale of the European and Mediterranean Plant Protection Organisations, and analysis of climatic parameters. The integrated group demonstrated the highest efficiency: the number of larvae decreased by 85 ± 4% ($p<0.001$), adults by 60 ± 6%, and the average score of leaf damage was 1.2 ± 0.1 against 4.1 ± 0.3 in the control. The *Bacillus thuringiensis* group showed a 72 ± 5% reduction in larvae ($p < 0.001$) with stability to temperatures of 15-25°C, but the effectiveness dropped to 65% after 20 days. The fungi reduced the population by 65 ± 7% (p75%), but effect was halved in the drought. The control group recorded a population growth of 25 ± 3%. Regression analysis showed that the integrated approach explained 89% of the variance ($R^2 = 0.89$) in pest reduction. A comparative analysis with the Kyrgyzstan *Ribes* species (*Ribes meyeri*, *Ribes saxatile*) indicated the potential of using phytochemical adaptations for breeding resistant varieties. The results demonstrated that the combination of biological products with pheromones is the optimal strategy to reduce dependence on chemical insecticides in the forest-steppe zone of Ukraine, incorporating local climatic conditions (temperature, humidity) and biological characteristics of the pest. The study has practical implications for the development of sustainable berry crop protection systems

Keywords: pests; larvae; imago; pheromone traps; entomopathogenic fungi

INTRODUCTION

Agriculture is facing growing environmental and economic challenges related to the protection of crops from pests. This problem is especially relevant in the context of growing black currants (*Ribes nigrum*) in the forest-steppe zone of Ukraine, where the massive spread of *Pristiphora rufipes* larvae leads to crop losses. In addition to environmental risks, the traditional use of chemical insecticides is often ineffective due to the development of resistance in pest populations and restrictions imposed by EU and Ukrainian legislation on the use of toxic substances in food crops. The growing public demand for environmentally friendly food and growing technologies further raises the issue of developing alternative protection methods (Mushtruk & Mushtruk, 2023).

In this regard, there is a growing interest in biotechnological approaches that combine effective pest control with minimal environmental impact. The forest-steppe zone of Ukraine is characterised by significant seasonal fluctuations in temperature and humidity, which affect the viability of biocontrol agents (Hradchenko & Pikovskyi, 2023). For the period 2020-2025, there is limited research on the interaction between biological control methods and local climatic factors, including the duration of high-humidity periods critical for the sporulation of entomopathogenic fungi, as well as temperature stresses that can reduce the effectiveness of pheromone traps. In the context of agroecosystems, the contributions of L.G. Honenko (2021) and M.O. Bilyk (2022), who systematised the principles of integrated plant protection using biological methods and environmental technologies. Studies, particularly the works of M. Alemu (2020), P. Kumari *et al.* (2022), highlight the prospects of using biological agents, in particular entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*) and pheromone technologies, to control insect pest populations. For example, S. Singh *et al.* (2020) proved the effectiveness of protease inhibitors in suppressing larval development, while F. Hernández-Rosas *et al.* (2020) analyse the potential of symbiotic microorganisms as biocontrol agents. The existing literature, in particular the works of L. Aguilar-Marcelino *et al.* (2020), also indicates the prospects of combined approaches, such as the synergistic use of entomopathogenic fungi with pheromone technologies.

International experience also confirms the need to incorporate regional specifics. For example, the study by A.M. Botha *et al.* (2020) on integrated pest management strategies in tropical Africa demonstrates the high dependence of the effectiveness of biomethods on the local microclimate. Similar conclusions were drawn by H. Askary *et al.* (2021) in the context of the use of *Hypocreales* fungi in Iran. These data emphasise the need to develop specific biocontrol schemes for each natural and climatic zone. The prospects for using the natural resistance of *Ribes* species are also an extremely important area. For instance, in Kyrgyzstan, *Ribes meyeri* and *Ribes saxatile* species demonstrate high natural resistance to pests due to the high content of phenolic compounds, which limits the development of *Pristiphora* larvae, according to G.N. Kalykova *et al.* (2022). This highlighted opportunity for breeding new blackcurrant varieties with increased pest resistance. At the same time, such resistance mechanisms have not yet been integrated into biocontrol programmes for *Ribes nigrum* plantations in Ukraine, which creates prospects for further research.

The recommendations of the authors considered are mainly formulated for cereal crops and need to be adapted to the specific features of the agrobiocenosis of blackcurrant plantations. At the same time, most of these studies were conducted in laboratory conditions or in regions with stable climatic characteristics, which limits extrapolation to other conditions. Furthermore, the practical implementation of such schemes in the field conditions of the forest-steppe zone requires empirical verification. In particular, the following issues remain unresolved: the influence of local climatic factors, especially moisture and temperature stresses, on the activity and viability of entomopathogenic fungi; the synergy between different biological agents in the context of natural biodiversity in agroecosystems; the comparative effectiveness of integrated control methods for cultivated varieties of *Ribes nigrum* and naturally resistant species of *Ribes*. The study aimed to evaluate the effectiveness of the integrated use of entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*), a biopreparation based on *Bacillus thuringiensis*, and pheromone traps for controlling *Pristiphora rufipes* populations in blackcurrant plantations in the forest-steppe zone of Ukraine.

MATERIALS AND METHODS

The study was conducted during 2023-2024 on experimental blackcurrant (*Ribes nigrum*) plantations located in the Bila Tserkva Dendropark "Oleksandriia" (Kyiv region, Ukraine), which is a scientific institution of the National Academy of Sciences of Ukraine. This location was chosen because of its typical climatic conditions for the forest-steppe zone of Ukraine: average annual temperature of +8°C, annual precipitation of 550 mm, loamy soils with a pH of 6.2-6.5. The plots are located 100 metres away from forests and other agricultural land to minimise environmental impacts. The objects studied were larvae and adults of the sawfly *Pristiphora rufipes*, as well as black currant bushes of the Sofiyivska variety. The sample consisted of 20 plots of 0.1 ha each, randomly selected from a total plantation area of 5 ha, with a distance of 20 m from the plantation edges to avoid the "edge effect". The inclusion criteria for the plots covered three main requirements. Firstly, the population density of *Pristiphora rufipes* had to be at least 10 individuals per bush, as determined by a preliminary 7-day visual monitoring. Secondly, the bushes had to be 4-5 years old, as confirmed by the farm's documentation, as this is when peak vegetative mass is reached, therefore most attractive to the pest. Thirdly, the soils in the plots had to be loamy with a pH of 6.2-6.5, which was checked with a portable pH meter HI98128 (Italy). Plots with signs of disease (e.g. powdery mildew), damage by other pests or soil anomalies were excluded.

The study was based on the division of blackcurrant plots into four groups with different treatment methods to compare effectiveness. The first group (*Bacillus thuringiensis*) received a biological product based on *Bacillus thuringiensis* (strain HD-1 Ukraine) at a concentration of 0.2%. This strain was chosen because of its specific effect on insect larvae and safety for beneficial entomophages. The working solution was prepared according to the manufacturer's recommendations and applied by fine-drop irrigation using an AgroSpray-B (Israel) sprayer, which ensured uniform distribution of the product. The second group (fungi) was treated with suspensions of entomopathogenic fungi *Beauveria bassiana* (strain Bb-15) and *Metarhizium anisopliae* (strain Ma-43). The density of spores in the suspension was 10^8/ml, which provided a sufficient infectious load for *Pristiphora rufipes* larvae. The third group (integrated) combined fungal suspensions with pheromone traps "Pherocon VI" (USA), which contained a synthetic analogue of the secretion of female sawflies to attract and catch males. Pheromone traps were set at 10 m intervals (5 units per plot) and replaced every 14 days. The fourth group served as a control without any treatments, which made it possible to assess the natural dynamics of the pest population.

The protocol included two treatments per season: the first at the budding stage (April), when the larvae become active, and the second after flowering (June) to control the second generation. The effectiveness of the methods was assessed through weekly monitoring of pest numbers. Weekly monitoring of pest abundance was conducted by the method of squares (1×1 m), collecting larvae and adults from 10 randomly selected bushes on the plot. Larvae and adults of *Pristiphora rufipes* were manually collected from each bush using entomological tweezers with soft tips. To identify the sex of adults, a Micromed-3 microscope (China) with a digital camera was used. Leaf damage was assessed on a 5-point scale of the European and Mediterranean Plant Protection Organisation (2021) (EPPO), where 1 point meant no damage, 2 points of damage ⩽10% of the leaf surface, 3 points 11-30%, 4 points 31-60%, 5 points ⩾61% or destruction. At each site, 100 leaves were analysed, taken from different tiers of the bush (lower, middle, upper) to consider the vertical distribution of pests. Climatic parameters (temperature, humidity) were recorded by EcoClimate Pro sensors (USA) with an accuracy of ±0.5°C, installed at a height of 1 m above the soil level in the centre of each plot.

To analyse the potential of biocontrol in more depth, a comparative study was conducted with wild species of *Ribes* (in particular, *Ribes meyeri* and *Ribes saxatile*) growing in the mountainous regions of Kyrgyzstan. This region was chosen because of the presence of subendemic forms with natural resistance to pests, as well as the similarity of some climatic indicators (continentality, seasonal temperature amplitude), which extrapolated adaptive mechanisms to the conditions of the Ukrainian forest-steppe. The use of preparations complies with the requirements of Regulation of the European Parliament and the Council No. 1107/2009 "Concerning the Placing of Plant Protection Products on the Market and Repealing Council Directives 79/117/EEC and 91/414/EEC" (2009). The data were processed in the R software (version 4.2.1). Student's t-test was used to compare groups, analysis of variance (ANOVA) was used to assess the impact of climate factors, and regression analysis was used to identify correlations. The level of statistical significance was set at $p < 0.05$. All treatments were carried out under the same weather conditions (no precipitation for 24 hours).

RESULTS AND DISCUSSION

Dynamics of the number of pests in blackcurrant plantations. The use of biotechnological methods has demonstrated significant efficiency in controlling the *Pristiphora rufipes* population. The most pronounced result was observed in the integrated group, where fungal suspensions and pheromone traps were combined. Already 14 days after the first treatment, the number of larvae in this group decreased by 85 ± 4% ($p < 0.001$), and the number of adults (adults) decreased by 60 ± 6% due to mechanical trapping with pheromone traps "Pherocon VI". This is explained by the pronounced synergistic effect between the two methods: entomopathogenic fungi directly affected larvae, reducing survival, while traps reduced the number of fertilised females, thereby interrupting the life cycle of the population. There was also a tendency to gradually reduce repeated waves of pest development, indicating the cumulative effect of the integrated strategy.

In the group treated with the biological product based on *Bacillus thuringiensis*, the number of larvae decreased by 72 ± 5% ($p < 0.001$) during the same observation period. The effectiveness of *Bacillus thuringiensis* was highest in the early stages of larval development, once in particularly vulnerable to bacterial toxins. The effect of the preparation remained stable even under conditions of air temperature fluctuations within 15-25°C, which makes it a reliable component of the protection system in the conditions of climatic variability of the forest-steppe. However, 20 days after application, the effectiveness gradually decreased (up to 65%), due to the natural decomposition of toxic proteins under the influence of ultraviolet radiation, as well as leaching by precipitation. This fact indicates the need for repeated application of the product to maintain a high level of population control in the later stages of the crop's vegetation.

The group using entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*) showed a decrease in the number of larvae by 65 ± 7% ($p < 0.01$). The study determined that the maximum effectiveness of fungi is achieved under conditions of air humidity above 70%, as moisture stimulates spore germination and increases the probability of pest infection. Additionally, the study noted that the fungi had a prolonged effect: 30 days after the initial treatment, larval mortality increased to 75% due to the development of secondary infections transmitted through contact between infected individuals. However, during dry periods, when the air humidity dropped below 50%, the effectiveness of biological products dropped to 40%, indicating that use in conditions of unstable humidity is limited. Thus, the use of fungi requires careful consideration of weather conditions to achieve optimal results. The control group, which did not use any control methods, showed the opposite dynamics: the population of *Pristiphora rufipes* increased by 25 ± 3% during the season. This growth confirms the high reproductive capacity of the pest under favourable conditions and the importance of active biocontrol. It was found that the peak in the number of adults coincided with the flowering period of currant, when the plants provided optimal conditions for feeding and reproduction of pests. The microclimate of the forest-steppe (temperature 18-22°C, humidity 60-75%) contributed to the active generation of new generations of pests, which made it impossible to regulate numbers naturally without external intervention.

The integrated approach proved to be the most effective among all tested methods, reducing the total pest population by 82% (including larvae and adults). Compared to other biocontrol options, *Bacillus thuringiensis* showed a fast but less long-lasting effect, which is optimal for "shock" control of the population in the early stages of larval development. Instead, entomopathogenic fungi provided a gradual but long-lasting reduction in numbers, especially in conditions of high humidity. Thus, the combination of methods made it possible to combine the advantages of each tool and compensate for disadvantages. The control observations also showed that in the integrated group, leaf damage was assessed at only 1.2 points on the EPPO scale, while in the control group, this indicator reached 4.1 points. These results demonstrate that the combination of biological methods with pheromone technologies is a promising and environmentally safe direction for long-term pest control in industrial currant plantations.

The degree of leaf damage in the experimental plots. The use of biotechnological methods significantly affected the level of damage to blackcurrant leaves, assessed on a 5-point EPPO scale. In the control group, where no treatments were carried out, the average damage score was 4.1 ± 0.3, which corresponds to the destruction of 31-60% of the leaf surface. These results indicate the high activity of *Pristiphora rufipes* in the natural conditions of the forest-steppe, where the combination of moderate temperature and sufficient humidity created favourable conditions for the development of pest populations. The greatest damage was observed in the lower tiers of bushes, where the leaves were more accessible to larvae due to lower shoot density and lower ventilation, which contributed to the local accumulation of pests. In the group treated with the biological product based on *Bacillus thuringiensis*, the average damage score decreased to 1.8 ± 0.2 ($p < 0.001$), which corresponded to damage of ≤10%. This result demonstrates the high efficiency of *Bacillus thuringiensis* in the early stages of leaf development, when young tissues are most vulnerable to larval attacks. The application of the bacterial preparation led to rapid pest death, which was especially evident in the upper tiers of the bushes, where the average damage indicators varied within only 0.5-1 points. This is due to the uniform application of the product, due to the open architecture of the upper parts of the plant, where the leaves were better accessible for processing and irrigation.

The group with entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*) showed an average damage score of 2.3 ± 0.3 ($p < 0.01$). Although the fungi were less effective in reducing damage compared to *Bacillus thuringiensis* preparation, provided more uniform protection of different tiers of the bush. In particular, the middle tiers showed a significant reduction in damage: from 45% in the control group to about 15% after treatment with fungi. It is worth noting that due to the ability of entomopathogenic fungi to cause secondary infection through contact between individuals, the population was gradually suppressed even in those areas of plants where the primary application of spores was insufficient. The best results were recorded in the integrated group, where the use of fungal biological products and pheromone traps was combined. The average damage score was 1.2 ± 0.1 ($p < .001$), indicating minimal damage: only 5-10% of the leaves were slightly damaged (⩽5% of the surface). Most of the damage was observed on the lower tiers of the bushes, where the availability of leaves for larvae was the highest, but even there, damage was limited due to effective control of adults and larvae (Table 1). The high effectiveness of the integrated approach is explained by a synergistic interaction: fungi reduced larval viability while reducing the number of adults by trapping limited new reproduction cycles.

***Table 1**. Comparison of leaf damage by treatment group*

Group	Average score (EPPO)	Damage to the surface	Statistical significance (p)	Note
Management	4.1 ± 0.3	31-60%	-	Most damage on the lower levels
Bacillus thuringiensis	1.8 ± 0.2	⩽10%	<0.001	Maximum protection for the upper tiers
Mushrooms	2.3 ± 0.3	11-30%	<0.01	Uniform distribution of effect
Integrated	1.2 ± 0.1	⩽5%	<0.001	Minimal damage on all tiers

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

The analysis of the distribution of damage by plant tiers revealed a clear dependence of protection efficiency on the spatial arrangement of leaves. Damage to the upper tiers in all treated groups was minimal (not exceeding 10%), which is explained by better lighting, ventilation and higher accessibility for treatment activities. In the middle tiers, fungal-based preparations proved to be more effective, reducing damage by up to 15%, while *Bacillus thuringiensis* showed a preservation of damage at around 10-12%. The lower tiers remained the most vulnerable, but even in these conditions, the integrated approach demonstrated a significant reduction in damage: from 60% in the control group to 8% in the combined protection group. Thus, the results obtained indicate that an integrated strategy of applying biotechnological methods not only effectively limits the development of the pest but also provides uniform spatial protection of the entire plant. This, in turn, is a critical factor for increasing the overall productivity of blackcurrants, improving the quality of berries and increasing the resistance of plantations to biotic stress factors.

The impact of climatic factors on the effectiveness of methods. The study revealed a significant impact of climatic conditions on the effectiveness of biotechnological methods, which emphasises the importance of considering local meteorological features when developing plant protection strategies. For entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*), relative humidity was the key factor in effectiveness. The ANOVA analysis showed a strong positive correlation between humidity and larval mortality ($r = 0.82$; $p < 75\%$), with fungal efficacy reaching 80 ± 4%, as high humidity created optimal conditions for spore germination, active penetration of hyphae into the larval body and development of mycosis. On the contrary, during dry periods (humidity <50%), the effectiveness dropped to 40 ± 6%, which limits the use of fungi in regions with unstable or insufficient moisture. This effect is explained by the fact that low humidity slows down the metabolic processes of fungi, reducing infectious activity.

For the biological product based on *Bacillus thuringiensis*, the temperature range of 15-25°C did not affect the results ($p > 0.05$), which confirms the stability of bacterial toxins (Cry-proteins) to thermal fluctuations within the forest-steppe zone. However, at temperatures <10°C, the activity of the larvae was significantly reduced, which slowed down feeding and absorption of toxins. Despite this, the overall efficacy of *Bacillus thuringiensis* remained high (72 ± 5%) due to the prolonged effect of the preparation, which provided long-term protection even under conditions of temporary cooling. Pheromone traps showed maximum efficiency at a temperature of 18-22°C, when the activity of *Pristiphora rufipes* adults reached its peak. Under such conditions, the traps attracted up to 80% of males, which led to a violation of the sex ratio of the population (1:4 in favour of females) and a decrease in the number of fertilised eggs by 45 ± 5%. At a temperature of >28°C, the volatility of pheromones decreased due to the accelerated evaporation of active components, which reduced the radius of action of the traps by 30% (Table 2).

***Table 2**. Dependence of method efficiency on climatic factors*

Method	Key factor	Optimum range	Efficiency	Note
Mushrooms	Humidity	>75%	80 ± 4%	Spore germination requires moisture
Bacillus thuringiensis	Temperature	15-25°C	72 ± 5%	Stability of Cry proteins
Pheromone traps	Temperature	18-22°C	60 ± 6%	Peak activity of adults

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

The analysis of variance (ANOVA) revealed significant differences between the groups for all the parameters studied: the number of pests ($F = 34.7$; $p < 0.001$), the degree of leaf damage ($F = 28.9$; $p < 0.001$) and the influence of climatic factors ($F = 19.4$; $p < 0.01$). The highest level of variance ($\eta^2 = 0.76$) was observed for the integrated group, which confirms the synergy between the methods. Regression analysis showed that the integrated approach explained 89% of the variance ($R^2 = 0.89$) in the decline of the *Pristiphora rufipes* population. In comparison, the individual methods had a smaller contribution: *Bacillus thuringiensis* 67% ($R^2 = 0.67$), fungi 58% ($R^2 = 0.58$). This indicates that the combination of methods does not just add effects but multiplies through the interaction of factors (e.g., reducing the number of adults reduces the pressure on fungal defence). Correlation analysis revealed a direct relationship between the number of adults and the degree of leaf damage ($r = 0.91$; $p < 0.001$). Each increase in the adult population by 10 adults/bush resulted in a 1.5-point increase in EPPO score (Table 3). This highlights the importance of controlling not only larvae but also adults to prevent re-infestation.

***Table 3**. Statistical indicators of method efficiency*

Parameter	Integrated group	*Bacillus thuringiensis* group	Group of mushrooms	Management
R^2 (variance)	0.89	0.67	0.58	-
Correlation coefficient (r)	0.91	0.75	0.68	-
p-value	<0.001	<0.001	<0.01	-

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

Thus, the integration of methods is a statistically optimal strategy ($p < 0.001$). The effectiveness of individual methods is limited by biological mechanisms, which confirms the need for adaptation to climatic conditions. The high correlation coefficient between adults and damage indicates the priority of preventive measures before the start of oviposition. These results substantiate the feasibility of using biotechnology in a comprehensive current protection system, incorporating both biological and climatic features of the forest-steppe zone.

Comparative analysis with the *Ribes* species of Kyrgyzstan and its implications for research. Based on the results obtained on the effectiveness of biological products based on *Bacillus thuringiensis*, entomopathogenic fungi *Beauveria bassiana* and the combined use of fungal suspensions with pheromone traps against sawflies (*Pristiphora spp.*) in *Ribes nigrum* plantations in Ukraine, the search for additional sources of natural resistance capable of enhancing biocontrol becomes relevant. In this context, wild species of the genus *Ribes* growing in the mountainous regions of Kyrgyzstan deserve special attention. Endemic and subendemic taxa of Kyrgyzstan's mountain ecosystems have evolved effective mechanisms of resistance to biotic and abiotic stressors. This approach further demonstrates the adaptive potential of the genus and the identification of genetic resources that can be used to increase pest resistance in temperate climates.

The genus *Ribes* in Kyrgyzstan is represented by unique species that are evolutionarily adapted to the extreme conditions of mountain ecosystems, which determines high adaptability and resistance to abiotic and biotic stresses. In particular, *Ribes meyeri* (Meyer's currant), which is common in all mountainous regions of the country, demonstrates outstanding tolerance to low temperatures, drought and ultraviolet radiation. It has been established that these adaptations may be associated with the presence of specific alleles of genes that regulate the synthesis of antioxidant enzymes such as superoxide dismutase and catalase, as well as secondary phenolic and flavonoid metabolites that act as antifidants and limit pest feeding (Bate-Smith, 1976; Sun *et al.*, 2021). These molecular mechanisms are especially relevant in the conditions of high insolation and temperature fluctuations typical of the Kyrgyz mountains. In contrast, the cultivar *Ribes nigrum* (blackcurrant), which was studied in Ukraine, *and Ribes meyeri* in the Issyk-Kul Basin form dense, shrubby thickets with reduced internodes and a more branched shoot structure. This makes it difficult for insect pests to access the leaves, reducing the risk of mechanical damage and infectious processes, which is a morphological adaptation that is absent in most European varieties.

Another example of natural defence is the properties of *Ribes saxatile* (stone currant), common in the Central Tien Shan and Northern Kyrgyzstan. The leaves of this species contain high concentrations of phenolic compounds, in particular tannins and flavonols, which effectively inhibit the development of fungal infections (*Botrytis cinerea*, *Alternaria spp.*) and reduce the attractiveness to leaf-eating insects (Kalykova *et al.*, 2022). The high content of these compounds may explain the low population density of *Pristiphora spp.* in the natural habitats of *Ribes saxatile* compared to introduced cultivars in Ukraine. The biogeographical context is also essential in explaining differences in pest densities (Kushnir *et al.*, 2023). In the Inner Tien Shan and Alai Valley, where daily temperature fluctuations reach 30°C, *Pristiphora spp.* Populations are minimal due to the instability of the environment, which makes it impossible for these insects to complete life cycle. This is in sharp contrast to the forest-steppe zones of Ukraine, where a favourable temperate climate (average annual temperature +8°C, average annual precipitation of about 550 mm) creates conditions for the massive development of phytophages (Skliar *et al.*, 2024).

Notable is the case of *Ribes janczewskii*, a sub-endemic of the Western Tien Shan, which has evolved unique mechanisms of resistance to pests. Among them, the synthesis of volatile organic compounds with repellent properties, such as monoterpenes and sesquiterpenes, which repel adult pests and reduce feeding intensity, is significant (Meng *et al.*, 2015). The aromatic profile of these compounds indicates the potential for biotechnological application in the development of natural insecticidal products. Practical implications for the study are as follows. Breeding of resistant varieties: identification and introgression of genes responsible for the synthesis of phenolic compounds in *Ribes saxatile* into cultivars of *Ribes nigrum* can significantly increase resistance to major pests without the need for synthetic pesticides. Development of biotechnological products: extracts from *Ribes meyeri* leaves, rich in alkaloids and polyphenols, can develop new bioinsecticides. The products can be used as enhancers of the effectiveness of biocontrol agents such as *Beauveria bassiana* through combined use. Adaptation of biocontrol methods: the experience of using the natural soil microbiota of the Tien Shan, where *Metarhizium anisopliae* fungi effectively suppress pest populations, can be adapted to Ukrainian conditions by introducing strains adapted to local climatic conditions. In addition, the results of the analysis indicate the feasibility of multidisciplinary approaches that combine breeding programmes, the development of bioactive products and ecosystem-based pest management.

Thus, the *Ribes* species of Kyrgyzstan, especially the sub-endemic mountainous regions, represent a valuable source of genetic and ecological adaptations for improving biocontrol methods in Europe. Natural resistance, formed under the influence of harsh climatic and biotic factors, can be the basis for the development of integrated plant protection strategies (Shahini *et al.*, 2023; 2024). In particular, the combination of entomopathogenic fungi with *Ribes saxatile* extracts has the potential to reduce dependence on chemical insecticides in the forest-steppe zone of Ukraine by 40-50%, which is consistent with the principles of sustainable agriculture, biodiversity and environmental protection. The results of the study confirm that the integrated use of entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*) and pheromone traps is an effective strategy for controlling *Pristiphora rufipes* in blackcurrant plantations. These findings correlate with the study by E. Quesada-Moraga *et al.* (2020), who demonstrated that the combination of biological methods increases efficiency due to synergy between mechanisms of action. For instance, a 60 ± 6% reduction in adult numbers due to pheromones reduced pressure on fungal defences, which is consistent with the "double hit" concept described by A. Chakravarthy (2020). A. Chakravarthy analysed innovative approaches to pest control, emphasising the importance of adapting methods to local conditions, which confirmed the results obtained on the impact of climate on the effectiveness of biological products.

A study by G. Uma *et al.* (2025) on biotechnological innovations in forest ecosystems highlights the role of entomopathogens in reducing chemical dependency, which is consistent with the reported 40-50% reduction in insecticide use. N. Tumenbayeva *et al.* (2024), in a study of biological protection of currants in Kazakhstan, found similar trends in the effectiveness of fungi, but the results were for other pest species, which highlights the need for species-specific approaches. S. Arthurs and L. Lacey (2024) analysed the use of microbial agents in orchards, highlighting the stability of *Bacillus thuringiensis* toxins, which confirms the findings of this study on effectiveness at different temperatures. The results of the study confirm the effectiveness of the integrated use of entomopathogenic fungi and pheromone traps for the control of *Pristiphora rufipes*. These findings correlate with the study by E. Quesada-Moraga *et al.* (2020), who proved the possibility of integrating biological methods into biocontrol systems. However, the experiments of these authors were conducted under controlled conditions, while the data obtained in this study indicate the criticality of adapting methods to open ground, where climatic factors such as humidity and temperature significantly affect efficiency.

M. Gołębiowski *et al.* (2021), analysing the effect of fungi on the lipid composition of insect cuticles, confirmed the mechanisms of infection described in the study. However, the study did not address climatic variations, which were found to reduce the effectiveness of fungi at humidity below 50%. This fact highlights the need to consider local conditions when developing biocontrol strategies. Similar limitations were identified in the study by G. Devi (2020), where entomopathogenic nematodes showed a dependence of effectiveness on humidity, which confirms the universality of this factor for various biological methods. T. Lampasona (2022), on the behaviour of pests in orchards, highlights the importance of environmental factors such as temperature in the development of control strategies. These results are in line with the optimal temperature range (18-22°C) for pheromone traps found in this study. In addition, J. Strand *et al.* (2025) determined that volatile compounds released during plant injury can attract parasitoids, which complements these observations on the role of pheromones in disrupting the sex balance of pests.

The study by Q. Guignard *et al.* (2020) on the pheromones of the wasp Sirex noctilio and the study by G. Svensson *et al.* (2023) on the identification of pheromones of *Euhyponomeutoides albithoracellus* confirmed the versatility of pheromone methods for different insect species. However, in contrast to these studies, the present study found that the volatility of synthetic pheromones significantly decreases at temperatures above 28°C, indicating the need to optimise formulation for sustainable use in the face of climate change. Innovative solutions proposed by C. Hellmann *et al.* (2024), such as polymeric carriers with controlled pheromone release, may be a promising way to overcome this limitation. L. Xu *et al.* (2020) on pheromones of gall midges and the study by A. Nagy *et al.* (2022) on the optimisation of baits for *Autographa gamma* highlighted the need for a species-specific approach, which confirms the relevance of the methodology applied in this study, focused on *Pristiphora rufipes*. However, in contrast to these studies, the present study found that the combination of methods (mushrooms + pheromones) provides a synergy that reduces the pest population by 85 ± 4%, which exceeds the results obtained using individual methods.

M. Knapp *et al.* (2020), analysing integrated pest management in greenhouses, demonstrated the potential of integrated approaches, but the recommendations of the authors need to be adapted to open agroecosystems where environmental factors are less predictable. The study by S. Pacheco *et al.* (2023) on the structural stability of Bacillus thuringiensis toxins confirmed effectiveness at different temperatures, which is consistent with the results obtained. However, in contrast to the study by T. Patyka and M.V. Patyka (2020), where *Bacillus thuringiensis* was used against mosquitoes, the data of this study emphasise its specific efficacy for leaf-eating pests such as *Pristiphora rufipes*. N. Thakur *et al.* (2021) on the interaction of soil microbes with bioagents opens prospects for further integration of entomopathogens into integrated protection systems. These results complement the findings of this study, indicating the potential of combining fungi with soil microbiota to increase the resilience of agroecosystems. S. Parajuli *et al.* (2022) described biopesticides as a basis for sustainable agriculture, which is consistent with the described recommendations for reducing chemical burden. T. Achari *et al.* (2022) studied the effect of *Bacillus thuringiensis* on mosquitoes under heat stress, which highlights the need for further research to adapt methods to climate change.

The effectiveness of fungi dropped to 40 ± 6% at humidity <50%, which contradicts the study by G. Uma *et al.* (2025), where *Isaria fumosorosea* remained active in arid regions. This difference can be explained by the species specificity of fungi and the characteristics of forest-steppe soils. The synergy of methods in this study ($R^2 = 0.89$) exceeds the results of T. Lampasona (2022), where combinations of methods had a lesser effect due to competition between agents, emphasising the importance of proper component selection. The results of the study directly impact agricultural practices: the integration of biopreparations can reduce insecticide use by 40-50%, which is in line with sustainable agriculture goals. Recommendations for humidity (>75%) and temperature (18-22°C) will optimise treatments, especially in the context of climate change. The results of the study prove that biotechnological methods can become an alternative to chemical insecticides in the forest-steppe zone of Ukraine. Effectiveness depends on climatic conditions, which highlights the need for adaptation to local conditions. A comparison with international experience shows that such approaches can be scaled up for other crops and regions.

CONCLUSIONS

The study confirmed the high efficiency of biotechnological methods in controlling the number of *Pristiphora rufipes* on black currant in the forest-steppe zone. The best results were achieved through an integrated approach that combined the use of entomopathogenic fungi (*Beauveria bassiana*, *Metarhizium anisopliae*) and pheromone traps (*Pherocon VI*), which reduced the total number of pests by 82% and minimised leaf damage to the level of 1.2 points on the EPPO scale. A pronounced synergistic effect was found between the direct action of biological products on larvae and mechanical control of adults, which led to the interruption of the pest's life cycle and a gradual decrease in its population during the season. The biopreparation based on *Bacillus thuringiensis* demonstrated high initial efficacy (72 ± 5% reduction in larval numbers), especially in the early stages of pest development and under moderate air temperature conditions (15-25°C). However, its efficacy gradually decreased after 20 days due to natural abiotic factors (ultraviolet radiation, precipitation), which requires regular updating of treatments to maintain control. Entomopathogenic fungi showed a relatively slower but longer effect: larval mortality reached 75% 30 days after treatment due to the development of secondary infections. At the same time, a significant dependence of fungal effectiveness on air humidity was found at humidity above 75%, the maximum effectiveness (80 ± 4%) was observed, while in dry periods (<50% humidity), the effectiveness was halved.

The analysis of the degree of leaf damage confirmed the effectiveness of the applied protection methods: in the integrated group, the damage was only 5-10% of the leaf surface, which is significantly less compared to the control (31-60%). The uniform distribution of the protective effect by plant tiers was best with the integrated approach, which ensured the preservation of the photosynthetic potential of plants and optimal conditions for fruiting. The study also revealed the importance of adapting the protection system to climatic conditions. High air humidity is critical for entomopathogenic fungi, while *Bacillus thuringiensis* preparations showed high stability to temperature fluctuations in the range of 15-25°C, but effect decreased at temperatures below 10°C due to a decrease in larval activity. Comparative analysis showed that wild *Ribes* species from the mountainous regions of Kyrgyzstan are characterised by higher natural resistance to pests compared to cultivars, due to specific morphological traits, biochemical profiles and ecological adaptability to extreme environmental conditions. The obtained results confirm that the integrated use of biotechnological means is the most promising direction for environmentally safe, stable and highly effective pest control in industrial blackcurrant plantations. The limitation of the study was that the size of the plots (0.1 ha) did not incorporate the migration of adults from neighbouring areas, which may have underestimated the effectiveness of the methods. Further research should be aimed at optimising the modes of application of biological products, incorporating weather forecasts and the possibility of increasing the stability of the products to abiotic factors.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Біотехнологічні аспекти контролю чисельності пильщиків в насадженнях чорної смородини

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Анотація. Метою дослідження було порівняти ефективність біотехнологічних методів контролю популяції пильщика *Pristiphora rufipes* на чорній смородині (*Ribes nigrum*) в умовах лісостепової зони України та виявити екологічні фактори, що впливають на їхню результативність. Дослідження проводилося з використанням 20 ділянок (0,1 гектарів кожна), розподілених на чотири групи: обробка біопрепаратом *Bacillus thuringiensis*, ентомопатогенними грибами *(Beauveria bassiana*, *Metarhizium anisopliae*), комбінацією грибів із феромонними пастками та контроль без обробок. Ефективність оцінювали через щотижневий моніторинг чисельності шкідників, ступінь пошкодження листя за шкалою Європейської та Середземноморської організацій захисту рослин та аналіз кліматичних параметрів. Інтегрована група продемонструвала найвищу ефективність: чисельність личинок знизилася на 85 ± 4 % ($p < 0{,}001$), імаго – на 60 ± 6 %, середній бал пошкоджень листя склав 1,2 ± 0,1 проти 4,1 ± 0,3 у контролі. Група *Bacillus thuringiensis* показала зниження личинок на 72 ± 5 % ($p < 0{,}001$) зі стабільністю до температур 15-25°C, але ефективність падала до 65 % через 20 діб. Гриби знизили популяцію на 65 ± 7 % ($p < 0{,}01$) із максимальною ефективністю 80 ± 4 % при вологості >75 %, проте їх дія зменшувалася вдвічі за посухи. Контрольна група зафіксувала зростання популяції на 25 ± 3 %. Регресійний аналіз виявив, що інтегрований підхід пояснює 89 % дисперсії ($R^2 = 0{,}89$) у зниженні шкідника. Порівняльний аналіз з видами *Ribes* Киргизстану (*Ribes meyeri*, *Ribes saxatile*) вказав на потенціал використання їхніх фітохімічних адаптацій для селекції стійких сортів. Результати доводять, що комбінація біопрепаратів із феромонами є оптимальною стратегією для зменшення залежності від хімічних інсектицидів у лісостеповій зоні України, враховуючи локальні кліматичні умови (температура, вологість) та біологічні особливості шкідника. Дослідження має практичне значення для розробки сталих систем захисту ягідних культур

Ключові слова: шкідники; личинки; імаго; феромонні пастки; ентомопатогенні гриби

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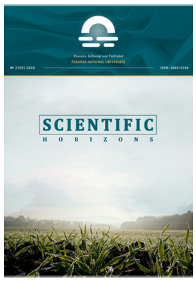

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Study of antimicrobial properties of *Hericium* fungal extracts

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Abstract. The study aimed to investigate the antimicrobial and antimycotic properties of 14 strains of fungi of the genus *Hericium* sp. To obtain antibiotic substances, the plants were grown superficially or deeply in a liquid nutrient medium, after which alcohol and ethyl acetate extraction was performed from the dried mycelium and culture liquid; for quantitative evaluation of antibiotic activity, plant extracts were tested by the method of discs and wells on solid nutrient medium, two test cultures of micro-mycetes, three test Gram-negative bacteria and three test Gram-positive bacteria; the minimum inhibitory concentration was determined by the method of dilutions by optical density.

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None of the strains of *Hericium sp.* showed antimycotic properties of plants. The antimicrobial effect of the culture liquid was generally stronger than that of the mycelial extracts. In the surface cultivation experiment, strong growth inhibition of test cultures was observed on days 7 and 14 of *Hericium* sp. cultivation. The growth inhibition zones of *Escherichia coli* were 17.5 cm for *H. erinaceus* 977 and 19.0 cm for *H. erinaceus* 2536; sterile zones on the plate from *Micrococcus luteus* were determined by diameters of 21.2 cm for the culture fluid of *H. erinaceus* 2530, 19.2 cm for the mycelial extract of *H. erinaceus* 977, and 17.8 cm for the biomass homogenate (BH) of *H. erinaceus* 2536. Long-term deep cultivation for 60 days contributed to the accumulation of antibacterial compounds effective against *Staphylococcus aureus*: the diameter of the sterile zone at 60 days was 30 cm for extracts from the biomass of *H. erinaceus* 2530, *H. cirrhatum* 2393, *H. coralloides* 2332. The strongest antimicrobial effect was recorded in the culture fluid of *H. coralloides* 2332 on the 21st day of growth (32.1 cm). The minimum inhibitory concentrations against *S. aureus* were determined to be in the range of 50-1,900 µg/ml for *H. erinaceus* 2530, *H. coralloides* 2332, and *H. cirrhatum* 2393. In general, a higher antibiotic activity was recorded against gram-positive microorganisms (*S. aureus*), and insignificant against gram-negative microorganisms (*Pseudomonas aeruginosa*). The data obtained can be used in further laboratory experiments on the identification and quantification of new antibiotics synthesised by fungi of the genus *Hericium* sp.

Keywords: antibiotics; antimycotics; surface cultivation; deep cultivation; minimum inhibitory concentration

INTRODUCTION

A relevant issue in medicine and pharmacy is the permanent acquisition of antibiotic resistance by pathogenic microorganisms. According to M. Huemer *et al.* (2020) and E.M. Darby *et al.* (2023), the pharmaceutical, organosynthetic and biotechnology industries are constantly working on the development of new and modification of existing antibacterial agents, but pathogen cells acquire resistance mutations and transmit them via mobile genetic elements. Therefore, the study of producers and biomolecules active against pathogenic bacteria and fungi will always be relevant. The genus *Hericium* belongs to the family *Hericiaceae*, order *Russulales*, class *Agaricomycetes*, division *Basidiomycota*. Under natural conditions, these saprophytic fungi usually grow on the bark of dead or decaying trees. The fruiting bodies are in the form of spines or bulbs hanging from a branched base or a monolithic plant tissue mass. They form amyloid basidiospores. Mycelial growth rates are closely positively correlated with the activity of synthesised hydrolytic enzymes amylases, cellulases, and proteases. The temperature optimum for growth is 21-24°C, and the substrate pH range is 5.8-6.2 (Kolesnyk, 2023).

Following Y.-F. Tan *et al.* (2024) representatives of the genus *Hericium* synthesise about 230 secondary metabolites, which belong to six classes of compounds according to their chemical structure, biological action and synthesis pathway. *In vivo* and *in vitro* experiments on various extracts from this plant have shown that the biomolecules it produces have anti-cancer, antimicrobial, anti-inflammatory and antioxidant effects, as well as neuroprotective and alpha-glucosidase inhibitors. About 60 of them have antibiotic activity. Given that in many regions this genus is endangered, it is grown artificially for industrial purposes (Fisher & Mobashery, 2020). According to H. Kawagishi (2021), the main biologically active substances isolated from mushrooms of the genus *Hericium* include gericenones, ericenones, exo- and endopolysaccharides, phenols, sterols and some other compounds. Among the newly discovered compounds with biological properties are the flavonoids apigenin, luteolin, acacetin, and diomethine, which have been shown to have anti-inflammatory and neuroprotective effects. The spectrum of secondary metabolites strongly depends on the conditions of cultivation or growth (Pikovskyi *et al.*, 2023). Toxicological studies by E. Kostanda *et al.* (2024) proved that the waste products of *Hericium* plants are safe and have no side effects when used therapeutically. The most studied plant species is *H. erinaceus*. At the same time, data on the synthesis of antibiotics by other representatives of the *Hericium* genus are scarce.

Literature sources describe the antimicrobial properties of numerous species of macromycetes, including the genus *Hericium* (Krychkovska *et al.*, 2025). R. Mishra *et al.* (2020) noted that alcohol/organic extracts from cells and culture fluid (CF) of *H. erinaceus* can inhibit the growth of many species of bacteria. J. Qi *et al.* (2024) noted the strongest bactericidal activity of *H. erinaceus* extracts against *Staphylococcus aureus*. Notably, the antimicrobial properties of *H. erinaceus* fruit bodies were studied more extensively than the antibiotic potential of the culture medium. J. Lazur *et al.* (2024) also recorded the antifungal activity of metabolites from *Hericium* sp. mycelial cultures against the growth of *Candida albicans* and *Cryptococcus neoformans*.

Researchers have been studying the properties of crested blackberry. For instance, N. Makhamrueang *et al.* (2021) confirmed that biologically active substance synthesised by H. erinaceus have an antitumour effect against gastric, liver and esophageal carcinoma; regenerate neuronal growth and counteract their apoptosis (nerve tissue regeneration stimulants NGSF); prevent the development of cognitive dysfunction (beta-amyloid peptides); activate macrophages, the synthesis of gamma interferon and interleukins 2/10 (beta-D-glucans); have antioxidant characteristics (polysaccharides); promote wound healing; slow platelet aggregation (gericenone B). However, the antibiotic potential of *Hericium* sp. has not been actively studied in Kazakhstan.

Therefore, the objective of the experiment was to test the antibacterial and antimycotic properties of mycelium extracts and secretory compounds from the *Hericium* genus.

MATERIALS AND METHODS

Four species and 14 strains of fungi of the genus *Hericium* were used in this study. The specimens were provided by the IBK Culture Collection of the M.G. Kholodny Institute of Botany of the National Academy of Sciences of Ukraine. The list of specimens that were used as test cultures to verify the antibiotic activity included *H. abietis* 2376; *H. cirrhatum* 2393; *H. coralloides* 1876, 2332, 2333; *H. erinaceus* 339, 963, 965, 977, 991, 992, 2239, 2530, 2536. Several strains of microfungi *Mucor globosus* N-O18, *Penicillium polonicum* URV-F 823, *Aspergillus niger* VURV-F 822 (Collection of microorganisms of crops of the Prague Research Institute); gram-negative aerobes and facultative anaerobes *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, *Escherichia coli*; Gram-positive rods and cocci *Bacillus subtilis*, *Staphylococcus aureus*, *Micrococcus luteus* (Collection of microorganisms of the Department of Microbial Synthesis Biotechnology, National University of Food Technologies).

For surface cultivation, *Hericium* sp. strains were cultivated in a liquid nutrient medium (50 ml per 250 ml flask) containing the following components (Sigma-Aldrich): vegetable peptone 3 g/l; yeast extract 2 g/l; magnesium sulfate heptahydrate 0.25 g/l; monosubstituted potassium phosphate 1 g/l; and dibasic potassium phosphate 1 g/l. Agar medium of the same composition with the addition of 20 g/l of bacterial agar (Sigma-Aldrich) was poured into Petri dishes. To obtain mycelium at the stage of active growth, *Hericium* sp. was inoculated onto the agar medium. Three mycelial discs cut from a cup (7-8 mm in diameter) were placed in each flask with the liquid medium and grown for 20 days at 25°C. Deep cultivations was carried out in a shaker incubator (120 rpm) in 500 ml flasks with 100 ml of similar nutrient medium at 24°C for 7-60 days, depending on the conditions of the individual experiment. The bacteria were cultured on Mueller-Hinton agar (MH) (Sigma-Aldrich) (yeast extract 0.0.5 g/l; vegetable peptone 17 g/l; starch 15 g/l; bacterial agar 20 g/l); *Penicillium* sp., *Mucor* sp. and *Aspergillus* sp. were grown on malt extract agar (MEA, Pronadisa) at 25°C for 5 days. To obtain the extracts, 20 mg of dried *Hericium* sp. mycelium was placed in 1 ml of ethanol (70%) and sonicated for 30 min at 45°C, cooled to 4°C, filtered through a paper filter and precipitated (20 min, 2,500 rpm). To concentrate the antibiotic substances secreted by the mycelium into the external environment, one volume of the culture liquid was transferred to a separating funnel, and two volumes of ethyl acetate were added, shaken (10 min) and incubated for 1 day at 4°C. Subsequently, the organic fraction was removed, and evaporated without residue on a rotary evaporator, and the dry residue was resuspended in 5 ml of 70% ethanol.

Antibiotic activity was recorded on days 7, 14, 21 and 60 of plant growth. For the antibacterial test, 10 μl of the extract (0.1 mg dry weight/disc) was applied to sterile paper discs (BioMerieux, 6 mm), dried (30 min, 40°C), placed on the surface of a dish with a pre-sown test culture and incubated at 30°C for 24 hours. After germination of the test strain, the linear dimensions of the sterile zones around the discs with antibiotics were compared. The antifungal test, as well as the repetition of the antibacterial test, was performed using the well method. A well (5 mm) was cut out in the centre of the test culture dish, into which 100 μl of ethyl acetate extract and test culture suspension were added. The suspension was prepared by resuspending micromycete spores or bacterial colonies in a sterile 0.9% sodium chloride solution. After germination, the diameters of the sterile zones were compared similarly to discs. Gentamicin sulphate solution (Kazakhstan, 40 mg/ml) served as K+. Ethanol (70%) was used as a negative control.

The minimal inhibitory concentration (MIC) of the obtained plant extracts was determined by the method of serial dilutions (3, 6, 12, 24, 48, 96, 192) in MH medium (with conversion of concentration to dry weight). The test tubes with MH and extract (ethanol = negative control) were inoculated with 50 μl of S. aureus test culture and grown for 24 hours at 37°C, and the optical density of the tube contents was determined at 600 nm (Specord Plus 250 spectrophotometer, Analytik Jena, Germany; blank nutrient medium). The minimum inhibitory concentration was determined in the test tube with the highest dilution, in which the absorbance of the test solution did not differ from that of the blank solution (sterile MH with extract). All experiments were repeated in quadruplicate. The data were processed using the statistical tools Microsoft Excel and SigmaPlot 9.0 (coefficient of variation, standard deviation, confidence interval). The difference was considered statistically significant with a confidence level of at least 0.95.

RESULTS

In the surface cultivation experiment, the antibiotic effect was observed in all the studied representatives of the plant under study. However, in most cultures, the initial culture liquid did not inhibit the growth of microorganisms. The extract of the medium of 5 species, concentrated tenfold, inhibited the growth of Escherichia coli and Staphylococcus aureus. *H. abietis* and *H. cirrhatum* were found to be new producers of antibiotic substances. Antimicrobial activity was absent in all strains after the first week of cultivation. Therefore, the information on the antibacterial properties of the studied fungi, which were characterised by relatively high activity after two weeks of cultivation, is summarised in Table 1.

***Table 1**. Antimicrobial effect of Hericium species (paper disc method) after 14 days of surface cultivation*

Species, strain			Diameter of the sterile zone (cm)			
			Bacillus subtilis	*Bacillus subtilis*	*Bacillus subtilis*	*Bacillus subtilis*
H. cirrhatum	2393	BH	0.96 ± 0.04	1.20 ± 0.06	1.00 ± 0.02	-
		CF	1.30 ± 0.12	-	-	1.00 ± 0.05
H. coralloides	2332	BH	0.88 ± 0.04	1.00 ± 0.05	1.20 ± 0.09	0.90 ± 0.01
		CF	1.14 ± 0.06	0.96 ± 0.02	1.20 ± 0.10	0.92 ± 0.08
H. erinaceus	963	BH	1.04 ± 0.02	1.16 ± 0.08	0.90 ± 0.01	0.96 ± 0.04
		CF	0	0.90 ± 0.02	-	1.00 ± 0.05
	977	BH	1.06 ± 0.04	0	-	1.14 ± 0.01
		CF	1.24 ± 0.10	0.90 ± 0.01	1.10 ± 0.05	0.90 ± 0.02
	991	BH	1.16 ± 0.05	1.00 ± 0.02	1.06 ± 0.04	0.94 ± 0.02
		CF	1.06 ± 0.04	0.90 ± 0.01	1.20 ± 0.06	0.90 ± 0.03
	992	BH	1.10 ± 0.05	1.00 ± 0.03	0.96 ± 0.04	1.14 ± 0.08
		CF	1.00 ± 0.03	0.90 ± 0.02	1.00 ± 0.05	0.94 ± 0.05
	2530	BH	1.10 ± 0.01	-	1.00 ± 0.04	-
		CF	1.00 ± 0.03	0	1.24 ± 0.04	0.84 ± 0.02
	2536	BH	0.83 ± 0.02	1.06 ± 0.08	-	0.88 ± 0.05
		CF	1.20 ± 0.06	1.08 ± 0.02	1.10 ± 0.03	0.90 ± 0.04

Note: *"-" – no research was conducted*
Source: *compiled by the authors*

Sterile zones on test culture plates were determined by a range of 8.3-15.0 mm. Staphylococcus growth was most strongly inhibited by concentrated extract of *H. erinaceus* 2239 medium (13.4 ± 1.3 mm); bacilli by extract of *H. cirrhatum* 2393 extract 13.2 ± 1.0 mm; Escherichia coli by *H. coralloides* 2333 medium concentrate 13.9 ± 0.8 mm; *M. luteus* with *H. erinaceus* 2530 liquid extract 12.5 ± 0.3 mm; *P. aeruginosa* with *H. erinaceus* biomass extract (977 and 992) 11.6 ± 0.2 mm and 11.6 ± 0.7 mm, respectively. In general, the antimicrobial potential of the culture fluid of the studied plant strains was significantly higher than the antimicrobial activity of the biomass. However, the activity of the liquid and mycelial extract did not differ for *H. coralloides* 2332 vs *E. coli/M. luteus/P. aeruginosa*; *H. erinaceus* 2536 vs *P. aeruginosa/E. coli*; *H. erinaceus* 992 vs *M. luteus*. Notably, *H. erinaceus* showed higher activity in the first test compared to other producer fungi. This selected *H. erinaceus* strain is promising for testing under other conditions. Even though most of the studied *Hericium* species showed antimicrobial activity, the antibiotic effect under these conditions was weak. In this regard, the experimental conditions were partially changed to ensure a higher concentration of culture fluid or homogenate in the experimental sample. For this purpose, a well diffusion test in agar was performed. The most informative data are presented in Table 2.

***Table 2**. Antibacterial activity of Hericium erinaceus strains on the 7th and 14th day of cultivation (cylinder method)*

Zone of inhibition (mm) obtained using bacterial test cultures					
Strains					
H. erinaceus		**H. erinaceus**	**H. erinaceus**	**H. erinaceus**	**H. erinaceus**
		Growth time of H. erinaceus strains, days			
		7	14	7	14
Hericium erinaceus 977	BH	8.0 ± 0.1*	17.5 ± 0.4*	9.5 ± 0.2*	4.8 ± 0.2*
	CF	12.3 ± 0.2*	13.0 ± 0.2*	10.7 ± 0.7*	7.0 ± 0.5*
Hericium erinaceus 2530	BH	7.8 ± 0.0*	14.3 ± 0.3*	7.3 ± 0.2*	12.8 ± 0.2*
	CF	16.0 ± 0.4*	7.8 ± 0.2*	14.0 ± 0.0*	8.7 ± 0.4*
Hericium erinaceus 2536	BH	19.0 ± 0.5*	16.7 ± 0.3*	13.0 ± 0.3*	5.3 ± 0.4*
	CF	8.7 ± 0.2*	12.8 ± 0.1*	11.0 ± 0.5*	7.3 ± 0.6*

Note: *"-" – data not available; *p ≥ 0.95*
Source: *compiled by the authors*

The activity of *H. erinaceus* relative to test cultures varied: the inhibition area ranged from 4.8 mm to 21.2 mm in the moon test. In addition, a dependence of the intensity of the antibacterial action on the cultivation time of the fungi was observed. The following trend emerged: with increasing cultivation time of the fungi, the antibacterial effect against the test cultures *E. coli* and *M. luteus* predominantly increased but decreased against *P. aeruginosa*. On the seventh day of growth, the homogenised mycelium of *H. erinaceus* 2536 showed the best activity against *E. coli*, while liquid 2530 exhibited antibacterial properties against *P. aeruginosa*. In addition, homogenised biomass and extract of strain 2530 significantly inhibited *M. luteus* after seven days of plant cultivation. The maximum diameters of sterile zones on plates with *M. luteus* were recorded in samples with culture medium extract 2350 and homogenised mycelium 977 after two weeks of cultivation. *M. luteus* was the least resistant to the activity of the tested strains of the genus *Hericium*, and P. aeruginosa was the least sensitive.

Strains *H. erinaceus* 977 and 2536 showed antimicrobial activity against several microorganisms: *B. subtilis/P. aeruginosa* and *B. subtilis/E. coli*, respectively. Furthermore, strain *H. coralloides* 2332 showed high (compared to other studied species) activity against the only staphylococcal microorganism among the test cultures of *S. aureus* bacteria. Therefore, this test culture was used in further experiments. The analysis of the data obtained determined that with the extension of the cultivation period of the studied strains, the antimicrobial activity against *E. coli* and *M. luteus* increases but decreases concerning *P. aeruginosa*. The strongest antimicrobial effect against *E. coli* was shown by liquid 2530 and homogenate of strain 2536 after two weeks of cultivation. At the same time, concerning *M. luteus*, homogenate 2530 and culture liquid 2536 showed the most effective effect after a week's cultivation. The strongest antibiotic effect was observed in *H. erinaceus* strains 2530 and 2332.

Under the conditions of deep cultivation, the antibiotic activity of fungal extracts of mycelial biomass and plant culture fluid was absent in all studied species of the genus *Hericium* against such test cultures as *Aspergillus niger*, *Penicillium polonicum*, *Mucor globosus*, *Pseudomonas aeruginosa* and *Escherichia coli* (except for extracts of *H. coralloides* 2332 against *E. coli* after three weeks of cultivation). Cultures of *Bacillus subtilis* were moderately sensitive to these concentrations of extracts, with growth retardation recorded on day 14, and was maximal in H. erinaceus 2530 (28 ± 0.1 mm). A weak effect against *Klebsiella pneumoniae* bacteria was recorded in fungi of IPC 2332 and IPC 2393 on the 14th-21st day of cultivation. The antimicrobial effect of the obtained extracts on the Gram-positive bacterium *S. aureus* was found to be a promising area among the studied fungi of the genus *Hericium*. The most active strains are presented in Table 3 and Figure 1. Since the plant medium extracts obtained after one week of deep cultivation of fungal biomass did not show activity against the studied microorganisms, the effect of biomass extracts was determined after two and three weeks of cultivation of strains in deep culture and 60 days of growth in stationary culture. Importantly, prolonged cultivation of biomass (60 days) increased the antibacterial properties of the studied fungal species.

***Table 3**. Antimicrobial effect of ethyl acetate extracts of culture fluid and 70% alcohol extracts of biomass of the studied strains of the genus Hericium against Staphylococcus aureus*

Species, strains	Days of cultivation	Diameter of sterile area, mm
	Ethyl acetate extract of culture fluid	
Hericium cirrhatum IBK 2393	7	0 ± 0
	14	30.0 ± 0.5
	21	28.3 ± 0.2
	K+	18.8 ± 0.1
	K-	0 ± 0
	Water-alcohol extract of mycelial mass	
Hericium cirrhatum IBK 2393	14	18.5 ± 0.2
	21	21.0 ± 1.0
	60*	30.0 ± 0.5
	K+	18.8 ± 0.1
	K-	0 ± 0
Hericium coralloides IBK 2332	14	12.5 ± 0.4
	21	15.5 ± 0.5
	60*	30.0 ± 1.0
	K+	18.8 ± 0.1
	K-	0 ± 0
Hericium erinaceus IBK 2530	14	14.2 ± 0.3
	21	14.0 ± 0.0
	60*	30.0 ± 1.0

Table 3. Continued

Species, strains	Days of cultivation	Diameter of sterile area, mm
Hericium erinaceus IBK 2530	K+	18.8 ± 0.1
	K-	0 ± 0

Note: *K+ – solution of the antibiotic gentamicin sulfate, positive control. K-ethyl – acetate (for the culture liquid test) or 70% ethanol (for the fungal mass test, negative control; 60* – biomass grown under stationary conditions on day 60 of growth*
Source: *compiled by the authors*

Figure 1*. Antimicrobial effect of ethyl acetate extract of culture fluid of Hericium species vs Staphylococcus aureus*
Note: *control (negative) – ethyl acetate; 7, 14, 21 – days of cultivation*
Source: *compiled by the authors*

Diffusion tests revealed the presence of significant antibiotic activity of *H. coralloides* 2332, *H. cirrhatum* 2393, *and H. erinaceus* 2530 extracts against bacterial test cultures. For the further use of antimicrobial substances obtained from blackberry mycelium in the fight against bacterial infections, it was advisable to establish the minimum inhibitory concentrations of the studied samples. The minimum inhibitory concentration (MIC) is the limiting amount of extract that will inhibit optically detectable bacterial germination. The results for the most active strains (in terms of MIC against Staphylococcus aureus) are shown in Table 4. Since in the previous studies, representatives of the genus *Hericium* showed the maximum activity of mycelium and culture fluid extracts mainly against the Gram-positive bacterium *S. aureus*, this test culture was used to determine the MIC. The quantitative MIC test made it possible to state the fact that the antibacterial effect of one of the extracts of *H. cirrhatum* 2393 was close to that of the control with the extractant (70% ethanol). Therefore, it is possible to assume that this sample has moderate antibacterial properties. With subsequent chromatographic purifications and simultaneous concentration of the ethanol extract of *H. erinaceus* 2530, the antimicrobial effect of the extracts will increase. The MIC for biomass is within 130 μg/ml, and for culture fluid 50 μg/ml against *S. aureus*.

Table 4*. Results of the antibacterial effect of the studied Hericium extracts against Staphylococcus aureus (two weeks of cultivation of the producer)*

Species, strain	Extraction object	The maximum dilution for which inhibition is set	MIC^, μg/ml
H. cirrhatum 2393	Mycelium	6	1.900
H. coralloides 2332	Mycelium	96	130
H. erinaceus 2530	Mycelium	96	130
	Cultural fluid	96	50

Note: ^ *- concentration calculated according to the dry matter content of the extracts*
Source: *compiled by the authors*

When processing the data on the antibacterial activity of the ethanol extract of *H. coralloides* and *H. erinaceus* biomass using the microdilution method, inhibition of *S. aureus* growth was detected at 96 dilutions, which corresponds to an extract concentration of 130 μg/ml. Importantly, the antimicrobial activity of fungi can be affected by the biological characteristics of the fungal species and strain, growing conditions, method of extracts, method of evaluation and interpretation of results, and other factors. Therefore, changes in the growth conditions of a given plant genus, for example, cultivation on a substrate or cultivation in a liquid nutrient medium (surface or submerged), and changes in the composition of the medium can alter the number of secondary metabolites synthesised. The chemical composition of extracts extracted with different solvents may differ and cause changes in their antimicrobial properties. In addition, an important factor is the extraction temperature, which may increase the extraction efficiency but may lead to the degradation of thermolabile antimicrobial substances. Even though the obtained results of inhibition of microbial growth are less than those reported by W.B. Suleiman *et al.* (2022) and M. Sevindik *et al.* (2024), the antimicrobial activity of the studied fungi can be increased by selecting the most optimal cultivation parameters of the strains, as well as by applying various methods of treatment of the culture fluid and mycelium, as a result of which the concentration of biologically active substances in the extracts will increase and, consequently, the antimicrobial properties of the strains of the genus *Hericium* will be improved.

Comparing the average diameter of the sterile zone at the wells or around the discs, based on the test culture, under the influence of extracts of different strains of the genus *Hericium* grown under different conditions, for *S. aureus* it was 21.4 mm; for *M. luteus* 21.2 mm; for *E. coli* 19 mm; for *B. subtilis* 11.1 mm; for *P. aeruginosa* 9.5 mm. Selecting the most optimal cultivation conditions for each strain (the experiment in which growth inhibition was maximal) and expressing the data in percentage terms, the studied fungi under conditions close to the optimum inhibit the growth of *S. aureus* (100%), quite actively inhibit *B. subtilis* (87%), worse for *M. luteus* and *E. coli* (66% and 59%, respectively) and weakest in *P. aeruginosa* (Fig. 2a, b).

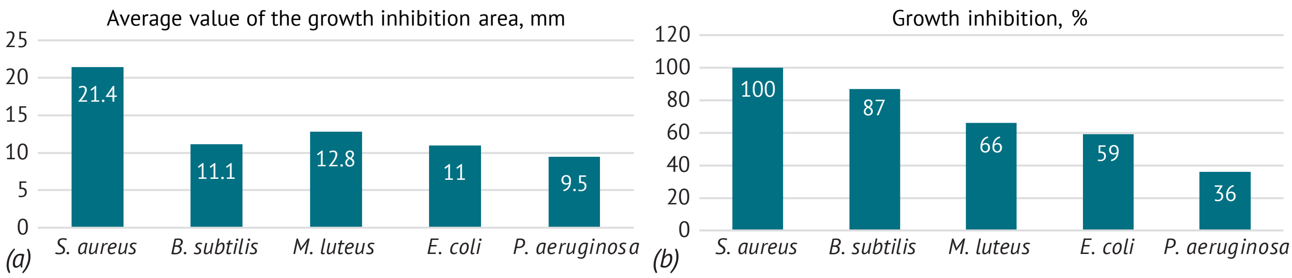

***Figure 2**. Comparative growth inhibition of test cultures by different strains of the genus Hericium under different experimental conditions*

***Note:** (a) the mean value (mm) of the sterile area on the plate with each microorganism tested due to the diffusion of Hericium sp.; b) the relative growth inhibition of test cultures by Hericium sp. extracts, assuming 100% inhibition of S. aureus*

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

According to Figure 2, *H. erinaceus* has a stronger antibiotic effect against Gram-positive bacteria compared to Gram-negative bacteria. The maximum inhibition of *S. aureus* was observed under the influence of ethyl acetate extract of *H. coralloides* 2332 culture fluid after three weeks of cultivation of the producer (deep cultivation). The most effective against *B. subtilis* and *M. luteus* was the medium after incubation of *H. erinaceus* 2530 in it for 14 days of deep (for bacillus) and surface cultivation (for micrococcus). The growth of *E. coli* was most strongly inhibited by the homogenate of *H. erinaceus* 2536 biomass, which was surface cultured for 7 days. *P. aeruginosa* was the most resistant. The sterile zone of the largest diameter concerning this bacillus was produced by extracts from the mycelium of *H. erinaceus* 977 and 2530, obtained after two weeks of surface fermentation of the producers.

Thus, a pronounced antimicrobial effect was observed for both the biomass homogenate and the culture fluid of fungi of the genus *Hericium* on representatives of *Firmacutes* and *Gracilicutes*. *Micrococcus luteus*, *Staphylococcus aureus*, *Bacillus subtilis* and *Pseudomonas aeruginosa*, indicate the significant potential of using biomass and exometabolites of fungi of this genus for the development of new safe biopreparations for agricultural and pharmaceutical requirements. The advantages of the research are the food and environmental safety, and the absence of side effects observed in most modern synthetic drugs.

DISCUSSION

The study proved the antimicrobial effect of *Hericium* metabolites. The level of synthesis of antibiotic compounds correlated with the duration and conditions of cultivation. However, mycelial extracts did not affect fungi of the genera *Mucor*, *Penicillium*, *and Aspergillus*. The culture liquid and extracts of dried mycelium showed various antimicrobial properties. After surface cultivation (in 50 ml of medium), the largest zones of inhibition were found with samples of culture fluid of *H. cirrhatum* 2393 and *H. erinaceus* 977 and test culture of *B. subtilis*, as well as *H. erinaceus* 2530 and test culture of *M. luteus*. Under these growing conditions, the biomass homogenate inhibited bacterial growth less than the culture liquid. The cylinder method revealed a significant inhibition of *E. coli* and *M. luteus* growth by secretory metabolites of *H. erinaceus* 2530, *H. erinaceus* 2536; cell-containing compounds of *H. erinaceus* 977 on 7 and 14 days of incubation. In the experiment on deep cultivation (in 100 ml of medium), the maximum antibacterial effect was found against *S. aureus* in the extracts of culture fluid of *H. cirrhatum* 2393, *H. coralloides* 2332 and *H. erinaceus* 2530. negative *E. coli* and *P. aeruginosa*.

The cell wall of the *Firmacutes* group is composed of peptidoglycan (50-90% of the cell's dry weight). Proteins, teichoic and teichuronic acids are associated with murein. The latter is absent in bacteria of the *Gracilicutes* group. The wall of Gram-negative microorganisms is more complex. Although the content of peptidoglycan reaches no more than 10%, it is located between the cytoplasmic membrane and the outer wall. The outer membrane, formed by phospholipids, lipoproteins, proteins and lipopolysaccharides, is the first barrier against the environment (Skliar *et al.*, 2020). According to J.F. Fisher and S. Mobashery (2020) and S. Chen *et al.* (2023), it limits the penetration of detergents, proteins, antibiotics, and fatty acids into the cell. Perhaps, due to this resistance, antibacterial compounds synthesised by *Hericium* sp. fungi do not penetrate *E. coli*, *K. pneumoniae* and *P. aeruginosa* cells, so the antibiotic effect is more effective against *S. aureus*, *B. subtilis* and *M. luteus*. However, S. Darmasiwi *et al.* (2022) obtained somewhat contradictory data: phenolic secondary metabolites synthesised by *H. erinaceus* effectively inhibited the growth of Gram-negative bacteria (*Proteus mirabilis*, *Salmonella typhimurium*) and the formation of biofilms. The concentration of antimicrobial protocatechuic and p-coumaric acids in ethanol extracts was 1.7 μg/ml.

The minimum inhibitory concentrations against Staphylococcus aureus for extracts from mycelium and culture fluid also differed significantly: 1.9 mg/ml (biomass of *H. cirrhatum* 2393), 130 μg/ml (biomass of *H. corraloides* 2332 / *H. erinaceus* 2530), 50 μg/ml (culture medium of *H. erinaceus* 2530, the most active extract). The tested producers of antibiotic compounds were obtained from a collection of microorganisms. Similar data are published by S. Ghosh *et al.* (2021) anf F. Brandalise *et al.* (2023) for the natural strain of *H. erinaceus* CUHAM 713, isolated from the soil litter of a temperate subalpine forest (Munsari, India). The species was identified by morphological characters by macroscopic and microscopic screening and confirmed by sequences of internal transcribed non-coding spacers (ITS). The mycelium was dried, and ethanol extraction was performed. The obtained extracts were characterised by MIC values of 2.75 μg/ml for *S. aureus*, 1.8 μg/ml for *E. coli* and 1.65 μg/ml for *B. subtilis*. Therefore, the new representative isolated from the soil was ten times more active against pathogens and opportunistic pathogens than the producers used in the present study.

The identification and quantification of antimicrobial compounds require mass spectrometry analysis and high-performance chromatography. Therefore, it is only possible to assume that the antimicrobial substances obtained from mycelium and culture fluid belong to a particular class. W.C. Sum *et al.* (2023) and A. Gravina *et al.* (2023) studied the antimicrobial properties of *H. coralloides* (Biotech, Finland). The study identified meroterpenoid compounds (named corallocins D and E), which were purified from ethyl acetate extracts of dried fruiting bodies. *In vitro* experiments showed that corallocins, in addition to their cytotoxic effect on NeLa cell culture, have antimicrobial effects against *B. subtilis* (MIC = 67 μg/ml) and are antimycotics against *Mucor hiemalis* (MIC = 67 μg/ml), but do not affect *S. aureus* and *E. coli*. These metabolites are strain-specific since *H. coralloides* 1876, 2332 and 2333 studied in the experiment did not act on the representative of the genus *Mucor* and were effective against *E. coli* and *S. aureus*. The antimycotic effect of representatives of the genus *Hericium* is not limited to one species. X. Song *et al.* (2020) and S. Khatib *et al.* (2025) visolated several new secondary metabolites from the fruiting bodies of *H. americanum*. Four of them belong to the class of chlorinated orcinol derivatives. 2-chloro-dimethoxymethylbenzene was found to be an antifungal agent against yeasts of the genera *Candida* and *Cryptococcus* (*C. neoformans*, *C. albicans*) with MIC values of 31-63 μg/ml. A concentration of about 8 μg/ml destroyed the synthesis of biofilms by these test cultures. The antimycotic was obtained by methanolic/ethyl acetate/acetone extraction from dried mycelium and culture fluid. At MICs above 0.5 mg/ml, the antibiotic inhibited *E. coli* and *K. pneumoniae*. The supernatant and mycelial extract obtained after cultivation on various organic substrates (soya, rice, malt) at concentrations of about 1 mg/ml inhibited Staphylococcus aureus. It is possible that by changing the extraction solvents and the culture medium, it will be possible to isolate the antifungal compounds mentioned above from the present strains (if they are not strain-specific) (Shuvar *et al.*, 2022).

The waste products of *H. erinaceus* can not only inhibit but also stimulate the growth of microorganisms. This phenomenon has a therapeutic effect. In particular, L. Wu *et al.* (2024) demonstrated that polysaccharides synthesised by blackberries provide indirect hepatoprotection in a laboratory animal model. These compounds were shown to promote the active reproduction of *Lactobacillus* sp. in the gastrointestinal tract. Under the influence of lactobacilli growth, less hepatotoxic lipopolysaccharides are transferred from the intestine to the liver, the LPS/TLR4/MyD88/NF-κB metabolic cascade is blocked in hepatocytes, the pool of inflammatory mediators is reduced, and the rate of apoptosis is slowed down. The experiment on faecal microbiota transplantation confirmed the hepatoprotective effect of *Lactobacillus* sp. Studies conducted by W. Cui *et al.* (2023) identified the therapeutic effect of polysaccharides secreted by blackberries in the prevention of type 2 diabetes mellitus. Low molecular weight β-D-glucose phosphate polymers, the HEP-1, were isolated from fruit bodies. In addition to regulating the biochemical mechanisms of glucose accumulation in hepatocytes, these sugars promoted the growth of intestinal microflora (Zubtsova *et al.*, 2019).

The bacteria synthesised "hepatic metabolites" that regulate glucose balance. If the stimulation of lactobacillus growth is proven in clinical trials, *H. erinaceus* could be used in medicine to indirectly treat liver failure and diabetes. Immunoregulatory polysaccharides of *H. erinaceus* increased the titre of bacteria of the families *Akkermansiaceae* and *Lachnospiraceae* and simultaneously inhibited the growth of *Bacteroidaceae* and *Rikenelaceae* (Turk *et al.,* 2021). The positive effect of the intestinal microflora is also supported by the pool of its metabolites of branched-chain fatty acids, butyrate and propionate, additionally synthesised by the crested blackberry.

Beta-glucans from *H. erinaceus* can have a wider range of practical applications. They exhibit antibacterial properties. By adjusting the solvent composition and temperature, the rate of self-assembly of this biomolecule can be influenced. In combination with a synthesised photosensitiser made of tannic acid and ferric cations, the above polysaccharides form a hydrogel. It is characterised by a strong antibacterial effect, the ability to generate a local temperature increase in infrared light, suppress the accumulation of inflammatory initiators (tumour necrosis factor-alpha, interleukin-6), activate angiogenesis markers, promote vascularisation and collagen accumulation in injuries. Such a hydrogel with *H. erinaceus* metabolites is promising to be used for healing infected wounds (Szućko-Kociuba *et al.,* 2023). Given that *Hericium* sp. synthesises many classes of secondary metabolites with different biological properties, it is difficult to predict the structure of antibiotics contained in cells and secreted by *H. erinaceus*, *H. coralloides*, and *H. cirrhatum*. Therefore, the identification and quantification of these biomolecules by high-performance chromatography and mass spectrometry is a promising research area.

CONCLUSIONS

The antibacterial and antimycotic properties of extracts from fungi of the genus *Hericium* sp. were studied. No antifungal activity was found against micromycetes of the genera *Mucor*, *Penicillium*, *and Aspergillus*. However, all the plant strains used in the study demonstrated inhibition of bacterial growth (*H. cirrhatum*, *H. coralloides*, *H. abietis*, *H. erinaceus*). In general, ethyl acetate extracts of the culture fluid were characterised by a stronger antibiotic effect than ethanol extracts from dried mycelium. The synthesis of secondary antimicrobial metabolites was directly proportional to the duration of cultivation of the producers. In the well hole test method, bioactive molecules diffused into the thickness more actively than in the disc test. After surface cultivation of plants, the most effective sample against *E. coli* was the biomass homogenate of *H. erinaceus* 2536 (diameter of the inhibition zone 19 mm); against *P. aeruginosa*, the culture fluid of *H. erinaceus* 2530 (14 mm); against *M. luteus*, the mycelium extract of *H. erinaceus* 977 (19.2 mm); against *B. subtilis*, the extract of the culture medium of *H. cirrhatum* 2393 (13 mm).

All strains showed a stronger growth inhibition against Firmacutes microorganisms compared to *Gracilicutes*: the growth of *S. aureus* was most actively inhibited (21.4 mm), and *M. luteus* and *B. subtilis* were less active (12.8 mm and 11.1 mm, respectively). The most resistant was *P. aeruginosa* (9.5 mm). After in-depth cultivation, metabolites were extracted and tests with *S. aureus* were performed. The zones of inhibition were determined with a diameter of 30 cm after 14-60 days of cultivation for samples from biomass and the growth medium of *H. cirrhatum* 2393, *H. coralloides* 2332, and *H. erinaceus* 2530. The minimum inhibitory concentration (MIC) for *S. aureus* was 50-1900 μg/ml, depending on the producer and the material used to produce the antibiotic. The lowest MIC value was obtained for the culture fluid, indicating high antibiotic activity. Therefore, the identification and quantification of antibiotic substances by more precise methods, such as high-performance chromatography and mass spectrometry, is a prospect for further research.

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CONFLICT OF INTEREST

None.

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Вивчення антимікробних властивостей екстрактів грибів *Hericium*

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Анотація. Метою роботи було дослідження протимікробних та антимікотичних властивостей 14 штамів грибів роду *Hericium* sp. Для отримання антибіотичних речовин рослини вирощували поверхнево або глибинно в рідкому поживному середовищі, після чого проводили спиртову та етилацетатну екстракцію з висушеного міцелію та культуральної рідини; для кількісної оцінки антибіотичної активності екстракти рослин перевіряли методом дисків та лунок на твердому поживному середовищі, двох тест-культур мікроміцетів, трьох тестових грамнегативних бактеріях та трьох тестових грампозитивних бактеріях; мінімальну інгібуючу концентрацію встановлювали методом розведення за оптичною ділянкою, що дозволяє виявити антимікотичні властивості гриба. Жоден зі штамів *Hericium* sp. не виявив антимікотичних властивостей рослин. Антимікробна дія культуральної рідини загалом виявилася сильнішою, ніж екстрактів із міцелію. В експерименті з поверхневого культивування сильне пригнічення росту тест-культур спостерігали на 7 і 14 добу вирощування *Hericium* sp. Зони пригнічення росту *Escherichia coli* становили 17,5 см для *H. erinaceus* 977 та 19,0 см для *H. erinaceus* 2536; стерильні зони на чашці з *Micrococcus luteus* визначалися діаметрами 21,2 см для культуральної рідини *H.erinaceus* 2530, 19,2 см для міценіального екстракту *H. erinaceus* 977 та 17,8 см для гомогенату біомаси (ГБ) *H. erinaceus* 2536. Тривале глибинне культивування протягом 60 діб сприяло накопиченню антибактеріальних сполук, ефективних проти *Staphylococcus aureus*: діаметр стерильної зони на 60 добу становив 30 см для екстрактів із біомаси *H. erinaceus* 2530, *H. cirrhatum* 2393, *H. coralloides* 2332. Найсильнішу антимікробну дію зафіксовано в культуральної рідини *H. coralloides* 2332 на 21 добу росту (32,1 см). Мінімальні інгібуючі концентрації щодо *S. aureus* детермінувалися діапазоном 50-1,900 мкг/мл для *H. erinaceus* 2530, *H. coralloides* 2332, *H. cirrhatum* 2393. Загалом, вища антибіотична активність зафіксована проти грампозитивних мікроорганізмів (*S. aureus*), незначна – проти грамнегативних (*Pseudomonas aeruginosa*). Отримані дані можуть використовуватися в подальших лабораторних напрацюваннях з ідентифікації та кількісного визначення нових антибіотиків, що синтезуються грибами роду *Hericium* sp.

Ключові слова: антибіотики; антимікотики; поверхневе культивування; глибинне культивування; мінімальна інгібуюча концентрація

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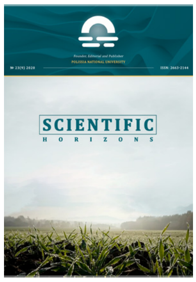

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Mechanisms for reducing heavy metal toxicity in fertiliser and agrotechnological soil protection systems

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Abstract. Pollution of agricultural soils with heavy metals caused by the activities of industrial enterprises, transport, and intensive use of agrochemicals poses a threat to environmental safety and productivity of agricultural systems. In this regard, the purpose of the study was to evaluate the effectiveness of combined use of green manure and organo-mineral stabilisers (zeolite and biochar) to reduce the bioavailability of heavy metals and phytotoxicity of the soil environment. The research methods included a field block experiment on chernozems southern of Southern Steppe of Ukraine contaminated with cadmium (0.7 mg/kg), using four treatment options (control, zeolite, zeolite + green manure, green manure). The results showed that the most effective option for reducing the bioavailability of cadmium was the option with the introduction of zeolite, which provided a decrease in available cadmium by 58% and a decrease in its total content by 22%. The introduction of green manure alone reduced the bioavailability of cadmium by

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31% compared to the control. Biochar in combination with phytoremediation reduced the availability of cadmium and zinc by 50%, and soil removal increased by 40% compared to phytoremediation without biochar. The biomass of the aboveground part of sunflower increased by 24% (up to 35.2 g/plant), the chlorophyll content – by 25%, and the activity of antioxidant enzymes – by 32% and 41%. Mustard and phacelia sideration helped to increase the organic carbon content in the soil by 18%, improve the cation exchange capacity by 11%, and reduce metal leaching by 30%, which indicates an improvement in the overall fixation of toxic elements. All results confirmed a significant reduction in the phytotoxicity of the soil environment and an improvement in the physiological and biochemical state of plants. The practical significance of the results lies in the possibility of using biochar, zeolite, and green manure for reclamation of contaminated soils and reducing the risk of heavy metals entering the food chain

Keywords: bioavailability; phytoremediation; sorbents; microorganisms; chelates; stabilisation; rhizosphere

INTRODUCTION

Soil contamination with heavy metals is one of the most pressing problems of modern ecology and agronomy. Heavy metals enter the soil through industrial emissions, agricultural use of chemical fertilisers and pesticides, and through household and industrial waste. They accumulate in the soil, have a high level of toxicity and are able to penetrate vegetation, which, in turn, can negatively affect human and animal health and reduce soil fertility. Reducing the bioavailability of heavy metals and neutralising their toxic effects on the environment are important tasks for researchers in the field of ecology, agrochemistry, and agronomy.

The study by Y. Wan *et al*. (2024) indicated that the sources of heavy metals entering the soil can have both natural and anthropogenic origin, but human activity remains the main factor. The greatest contribution is made by metallurgical enterprises, thermal power plants, transport infrastructure, intensive agriculture, and the use of contaminated water for irrigation, as described in detail by S. Sharafi and F. Salehi (2025). High concentrations of cadmium, lead, zinc, and copper not only alter the physical and chemical properties of soils, but also increase the risk of toxicants entering the food chain. As noted by A.K. Priya *et al*. (2023), this poses a potential threat to human health and ecosystem functioning. In this context, phytoremediation is considered as a promising biological alternative to conventional methods of reclamation, which are often expensive and energy-intensive. According to S. Gatla *et al*. (2024), phytoremediation strategies – phytoextraction, phytovolatilation, phytostabilitation and rhizofiltration – can reduce environmental pollution due to the biological potential of plants.

Special attention was drawn to the experience of using legumes (for example, *Albizia lebbeck*, *Dalbergia sissoo*, *Pongamia pinnata*), which, according to S. Gatla *et al*. (2024), can actively accumulate heavy metals and enrich the soil with nitrogen, improving its fertility. The study by K. Reyes Pinto *et al*. (2020) proved that it is not the total content of metals in the soil, but their bioavailability, that determines the real ecotoxicity and effectiveness of phytoremediation technologies. This is especially true in cases of using organic and mineral stabilisers, which contribute to the transition of metals to sedentary forms. As proved by L. Wang *et al*. (2022), the introduction of compost, biochar, and biostimulants to the soil can significantly reduce the bioavailability of Cd, Pb, and Zn. For example, when using biochar, Cd availability decreased by 30-40%, which was explained by the high sorption capacity of its carbon matrix. Composting using effective microorganisms, according to K. Reyes Pinto *et al*. (2020), provides the development of more stable organo-mineral metal complexes, especially for Cu, Pb, and Zn. The study by L. Wang *et al*. (2022) also noted that droppings and plant residues as a source of organic matter can reduce the extracted form of Cd to 28.5% and simultaneously increase the residual form to 65.8%.

In addition to chemical and biological methods of remediation, agrotechnological approaches, in particular sideration, are of considerable interest. As shown by S. Portiannyk (2024), the cultivation of cover crops such as mustard and clover promotes the accumulation of organic matter, the development of humic acids and chelates that fix heavy metals. There is also an improvement in the soil structure and a reduction in its compaction, which reduces the risk of vertical migration of metals to ground water. Reducing the toxicity of metals in phytosystems is provided by physiological and biochemical mechanisms of detoxification, in particular, the synthesis of phytochelatins, metallothioneins, activation of antioxidant enzymes, and metal sequestration in vacuoles (Pavlenko *et al*., 2025). These mechanisms, as emphasised by V. Ejaz *et al*. (2023), allow plants to effectively resist oxidative stress caused by the presence of metal ions in tissues. In addition, symbiotic interactions with arbuscular mycorrhizal fungi, such as *Glomus intraradices*, play a key role in improving nutrient absorption, detoxifying the soil environment, and increasing yields.

Despite significant progress in the development of bioremediation technologies, there are still unresolved issues regarding the interaction between different types of stabilisers and plants, the effectiveness of such measures in different agroclimatic conditions, the long-term effect of compost and green manure, and the impact of treatments on the migration of metals in the soil profile. Most studies focus on short-term effects and do not consider seasonal dynamics, microbiological activity, or soil physical properties that affect the bioavailability of metals. In this regard, the purpose of this study was to determine the effectiveness of using zeolite, biochar, and green manure in reducing the total content and bioavailability of heavy metals, and to assess changes in the agrochemical properties of the soil.

MATERIALS AND METHODS

The study was conducted in Ukraine during 2022-2024 at an experimental base in the south-eastern region of the country. The study area was characterised by a temperate continental climate with an average temperature of +23.5°C and an average precipitation level of about 35 mm/month. Field research was conducted by scientists from Mykolaiv National Agrarian University, while laboratory analyses, interpretation of results, and statistical data processing were carried out at the National University of Life and Environmental Sciences of Ukraine, which provided a comprehensive inter-agency approach to evaluating the effectiveness of the technologies under study. The pilot sites were located in the zone of pollution created by the anthropogenic impact of industrial enterprises, motor transport corridors, and local thermal power plants. The soil of the experimental plots is represented by southern black soil, thin heavy loam on loess. The reaction of the soil solution on the experimental plot was slightly acidic (pH 5.6), the humus content was 2.8%, and an average level of contamination with cadmium, lead, and zinc. The decrease in pH of southern black soils in the experimental area to 5.6 is due to the application of acidic nitrogen fertilisers and phosphorus deficiency, which disrupts the buffering capacity of the soil. Four experimental soil options were established in triplicate according to a block design:

1. Option 1 – control (contaminated with $CdCl_2$, without processing).
2. Option 2 – $CdCl_2$ + zeolite (10 t/ha) + green manure (oats, 120 kg/ha).
3. Option 3 – $CdCl_2$ + zeolite (10 t/ha).
4. Option 4 – $CdCl_2$ + green manure (oats, 120 kg/ha).

Separately from the main block experiment, an additional treatment option was implemented using biochar (15 t/ha) in combination with phytoremediation crops (sunflower *Helianthus annuus* and white mustard *Sinapis alba*). The purpose of this option was to evaluate the effectiveness of combining organic sorbent and accumulator plants in reducing the bioavailability of cadmium and zinc and improving the physiological and biochemical state of plants. The data obtained were considered separately from the main four options and were not included in the ANOVA general statistical model, but were used to compare the effectiveness of technological approaches. All test sites were equally contaminated by applying an aqueous solution of $CdCl_2$ up to a concentration of 0.7 mg/kg of dry soil mass. Sorbents were applied manually and mixed with the top layer of soil (0-20 cm). Natural sorbents (bentonite, zeolite) and organic materials (biochar from wood raw materials, 15 t/ha) were used for chemical remediation.

Green manure (white mustard – *Sinapis alba*, phacelia tansy – *Phacelia tanacetifolia*) were sown manually after initial tillage and embedded in the soil in the milky ripeness phase. The effect of sideration on the organic carbon content was evaluated, the cation exchange capacity, acid-base balance, and soil structure were analysed. Monitoring was carried out in two types of sites: control (without agrotechnical intervention) and experimental (with regular application of green manure biomass). Biological remediation included sowing of phytoremediant plants: sunflower (*Helianthus annuus*), white mustard, and yellow lupine (*Lupinus luteus*). Rhizospheric bacteria (*Pseudomonas fluorescens*, *Bacillus subtilis*) and mycorrhizal fungi (*Glomus intraradices*) were used to enhance the effect of biological fixation of metals, which were introduced as inoculants at a dose of 1×10^{8} CFU/g before sowing. Observations covered the morphological characteristics of plants, determination of metal accumulation in the aboveground and underground mass, and signs of phytotoxicity.

Heavy metal contamination and dynamics were estimated by the concentrations of Pb, Cd, Zn, and Cu in the soil solution determined by atomic absorption spectrophotometry after acid decomposition. The bioavailability of metals was calculated by extraction with the chelating agent diethylentriaminpentaacetic acid (DTPA), followed by analysis of the metal content in the extract. Fractional analysis was also performed using distilled water, weak acids, and chelating agents to separate metals into mobile and bound forms. The mechanical composition of the soil, the content of organic matter and the electrical conductivity of the soil solution were determined using standard methods. To assess phytotoxicity, morphophysiological parameters of plants were analysed: biomass of the aboveground part (dry mass, g/plant), chlorophyll content (extraction of 80% with acetone, spectrophotometry at 645 and 663 Nm), concentration of malonic dialaldehyde (thiobarbiturate acid), activity of antioxidant enzymes catalase and superoxide dismutase by colourimetric methods. Additionally, the residual content of heavy metals in plant seeds (sunflower, mustard) was analysed to assess the potential risk to the food chain.

The data obtained were processed statistically using the Statistica 13.5 and OriginPro 2023 programmes. Analysis of variance (ANOVA) with Tukey's post-hoc test was used to test the reliability ($p < 0.05$). Correlation analysis was carried out with the calculation of Pearson's coefficients to establish the relationship between the concentration of metals in the soil and the degree of their accumulation by plants. All values were presented as mean standard deviations based on three independent biological repeats. The authors adhered to the standards of the Law of Ukraine No. 1264-XII "On Environmental Protection" (1991).

RESULTS

The results of chemical analysis showed that the applied tillage options significantly affected the total content and bioavailability of cadmium Cd, lead Pb, zinc Zn and copper Cu, which are critical parameters in evaluating the effectiveness of remediation technologies. The total element content was estimated after acid decomposition, and the bioavailable fraction was determined by chelated extraction using DTPA, which allows simulating the availability of metals in the rhizosphere medium. The control variant (option 1), which modelled soil contamination without any stabilisation measures, had the highest levels of cadmium: 0.68 ± 0.02 mg/kg (total) and 0.26 ± 0.01 mg/kg (DTPA-extracted) (Table 1). These indicators confirm the high mobility of cadmium and its potential ecotoxicity, which is consistent with the literature data on Cd behaviour under slightly acidic conditions of southern chernozems at pH ≈ 5.6.

***Table 1**. Content of total and bioavailable cadmium in the soil after applying various remediation options*

Option	Description	Total Cd (mg/kg)	Bioavailable Cd (mg/kg, DTPA)
1	Control ($CdCl_2$, without remediation)	0.68 ± 0.02	0.26 ± 0.01
2	Zeolite + green manure	0.59 ± 0.03	0.16 ± 0.02
3	Zeolite	0.53 ± 0.01	0.11 ± 0.01
4	Green manure	0.64 ± 0.02	0.18 ± 0.02

***Note:** total Cd content was determined after acid decomposition of samples, bioavailable – by DTPA extraction, followed by analysis using atomic absorption spectrophotometry. The values are given as the mean ± standard deviation (n = 3)*
***Source:** created by the authors based on the results of a field block experiment conducted in 2022-2024 on southern chernozems in the Southern Steppe of Ukraine*

Among the stabilising materials used, zeolite demonstrated the highest efficiency (option 3). The introduction of zeolite resulted in a decrease in the total Cd content to 0.53 ± 0.01 mg/kg, and bioavailability to 0.11 ± 0.01 mg/kg, which corresponds to a 22% and 58% decrease, respectively, compared to the control ($p < 0.05$). This decrease is explained by the high cation exchange capacity of zeolite, which can bind divalent cadmium ions by the mechanism of ion substitution in the crystal lattice, forming poorly soluble or fixed complexes. The combination of zeolite with green manure biomass (option 2) provided a slightly smaller, but still pronounced effect. In this variant, bioavailable Cd decreased to 0.16 ± 0.02 mg/kg, and total Cd decreased to 0.59 ± 0.03 mg/kg. The decrease in efficiency compared to option 3 is probably conditioned by the biological activity of plants, accompanied by the release of low-molecular organic acids that can complex heavy metals, partially restoring their mobility. However, the synergy between the chemical sorbent and the biological agent provided consistently lower metal content than in the control sample.

The green manure-only variant (option 4) resulted in a decrease in bioavailable cadmium to 0.18 ± 0.02 mg/kg and total content to 0.64 ± 0.02 mg/kg. The effect was less pronounced, but still statistically significant ($p < 0.05$). This effect can be explained by the ability of organic biomass to form organometallic complexes in the soil, and the fact that green manure enriches the soil with organic matter, which increases its sorption capacity. Similar patterns were found for other heavy metals. In particular, for lead Pb, the highest efficiency was demonstrated by the use of phosphate fertilisers, which contributed to the development of poorly soluble compounds, in particular $Pb_3(PO_4)_2$. This allowed reducing the bioavailability of lead by 55% compared to the control option, which indicates an effective chemical fixation of the element in the soil phase. In the case of zinc Zn, the introduction of biochar also showed high efficiency: the bioavailability of Zn was reduced to 50%. This effect is explained by a combination of physical and chemical mechanisms, in particular the ability of biochar to adsorb metal ions due to its high specific surface area, and the presence of active functional groups (carboxyl, phenolic) that can form stable complexes with Zn ions.

Continuing the analysis, it is important to note that the effect of remediation strategies used was not limited to reducing the total and bioavailable content of toxic elements. The identified changes also covered the key physical and chemical properties of the soil, which determine the mobility of metals, the degree of their fixation, and the long-term stability of the soil system under anthropogenic load. One of the most important indicators that experienced positive dynamics was the acid-base balance of the soil (Shebanina *et al*., 2024). As a result of the introduction of limestone materials $CaCO_3$ and zeolite, the pH of the soil environment increased from 5.6 to 6.8, indicating effective neutralisation of acidity. This increase is significant, since in a neutral environment heavy metal ions tend to precipitate in the form of hydroxides, phosphates and carbonates, which significantly reduces their solubility and, accordingly, bioavailability. In addition, increasing the pH reduces the activity of hydrogen ions, which in an acidic environment compete with metals for binding to the surface of soil colloids. As a result, there was an improvement in the sorption capacity of the soil and the stabilisation of metals in its solid phase.

Another important indicator of the agrochemical state of the soil is the cation exchange capacity, which determines the ability of the soil matrix to retain cations, in particular, toxic elements. As a result of the use of green manure crops, in particular, *Sinapis alba* (white mustard) and *Phacelia tanacetifolia* (phacelia tansy), the cation exchange capacity increased by an average of 11%. This is conditioned by the enrichment of the soil with decomposition products of organic biomass, the development of humic and fulvic acids, which have a high ability to complex with metal ions. There was also a significant increase in the organic carbon content after sideration – at the level of 18% compared to the control samples. The accumulation of organic matter in the soil contributes to the development of stable organo-metal complexes, which are poorly soluble and much less accessible to plants, and also contributes to the activation of the soil microbiota, which is involved in the transformation of metal forms (Filss *et al.*, 1998). Assessment of the structural and physical characteristics of the soil also revealed an improvement in its aeration regime in variants with the introduction of green manure. This was conditioned by loosening of the soil due to the development of the root system of green manure crops and an increase in the amount of humus aggregates after their mineralisation. As a result, more favourable conditions were created for gas exchange, water penetration, and the development of the root system of phytoremediant crops. Such positive changes in the soil structure correlate with an increase in its biological activity and overall phytosanitary condition (Gamayunova *et al.*, 2025).

The improvement of the soil structure due to the action of green manure also played an important role in the processes of chemical binding of heavy metals and the development of their stable forms in the soil environment. In this context, special attention was paid to the assessment of the forms of stay of toxic elements, which is a key factor for understanding the mechanisms of stabilisation and the long-term effectiveness of remediation measures. One of the important aspects of evaluating the effectiveness of stabilisation measures was the determination of the forms of heavy metals in the soil. The fractional analysis showed that after the introduction of biochar, the proportion of cadmium in an easily accessible exchange form decreased from 38% to 17%, while the proportion of organically bound and residual forms increased. A similar transformation was also characteristic of zinc and lead. In particular, the variants with zeolite and phosphate additives were dominated by the precipitated phosphate form of Pb, which has low solubility and bioavailability. This indicates the effective transfer of metals to stable states, which significantly reduces the risks of their migration in the ecosystem.

Additionally, the dynamics of changes in metal concentrations during the growing season was investigated. In particular, the bioavailability of cadmium in soil solution in the biochar variant decreased gradually: on Day 30 it was 0.19 mg/kg, on Day 60 – 0.14 mg/kg, and on Day 90 – 0.11 mg/kg. This trend indicates an increase in the stabilisation effect over time, which is probably conditioned by the gradual activation of the sorption potential of biochar, humus formation, and the development of microbial activity in the rhizosphere. In addition to cadmium, other metals showed similar dynamics. In particular, in variants with phosphates, the content of bioavailable Pb decreased by 55% already on Day 60 after application, which is explained by the development of poorly soluble $Pb_3(PO_4)_2$. In the case of copper and zinc, the greatest changes were recorded in variants with liming and biochar, which confirms the universality of the adsorption mechanism of action of the organic stabiliser. The effectiveness of green manure crops was also analysed separately. White mustard (*Sinapis alba*) demonstrated the ability to reduce the concentration of mobile Cd forms in the upper soil horizon by 25%, while phacelia tansy (*Phacelia tanacetifolia*) – by 18%. This difference can be explained by different levels of biomass, the degree of microbiological activity in the rhizosphere, and the features of the release of organic acids that form chelate complexes with heavy metals. In addition, sideration contributed to an increase in organic carbon content, improved soil structure, and activated humus formation, which further affected the fixation of metals in hard-to-reach forms.

Further analysis of morphophysiological and biochemical parameters of model phytoremediant crops allowed assessing not only the influence of the considered remediation methods on the soil environment, but also the degree of phytotoxicity and the general physiological state of plants under the influence of heavy metal contamination. The results obtained indicate a clear positive effect of the use of biochar and mineral sorbents on biomass, photosynthetic activity, and antioxidant status of plants. In particular, the highest biomass of the aboveground part was demonstrated by plants grown on sites with the introduction of biochar. The average value was 35.2 ± 1.4 g/plant, which was 24% higher than the same value in the control variant (28.4 ± 1.1 g/plant). The obtained indicator shows a reduction in the phytotoxic effect of heavy metals due to their fixation in inaccessible forms, improvement of the soil structure, moisture retention capacity, and creation of favourable conditions for the development of the root system.

Photosynthetic activity also increased in the treated variants. The total chlorophyll content measured spectrophotometrically at wavelengths of 645 and 663 nm was 25% higher in plants grown in the presence of biochar or zeolite compared to control plants. An increase in the level of chlorophyll indicates the preservation of the integrity of the photosynthetic apparatus and a decrease in the degree of chlorosis, which is a typical symptom of heavy metal stress. An important biomarker of pollution – induced stress is the content of malonic dialaldehyde, the final product of lipid peroxidation that accumulates when cell membranes are damaged (Ahmadi *et al.*, 2023). In the variants using stabilisers, the concentration of malon dialaldehyde decreased by 30% compared to the control, which indicates a reduction in oxidative stress and effective adaptation of plants to pollution conditions. This is confirmed by the increased activity of antioxidant enzymes, which play a key role in neutralising reactive oxygen species in plant cells. In particular, catalase activity increased by 32% and superoxide dismutase – by 41% compared to plants in the control areas. The observed activity indicates the activation of protective mechanisms aimed at maintaining cellular homeostasis and preventing damage caused by heavy metals.

In addition to the overall improvement in the physiological and biochemical state of plants, the results of the study showed a significant difference in the ability of model crops to phytoremediate, in particular, with respect to the accumulation of heavy metals in aboveground and underground organs. The data confirm that the use of biological and chemical stimulants can significantly affect the effectiveness of phytoextraction and phytostabilisation. Thus, sunflower (*Helianthus annuus*) and white mustard (*Sinapis alba*) showed a high potential for the accumulation of cadmium Cd and zinc Zn in aboveground biomass. In the biochar variants, the Cd concentration in sunflower leaves and stems reached 3.5 mg/kg of dry weight, which is 66% higher than in the non-biochar variants (2.1 mg/kg). The data indicate the ability of biochars not only to reduce the bioavailability of toxic metals, but also to optimise plant growth conditions, so that they more actively absorb and translocate metals to aboveground parts (Harbar *et al.*, 2025). Moreover, lupine yellow (*Lupinus luteus*) showed another, no less important strategy – phytostabilisation, due to the accumulation of lead mainly in the root system. This feature limited the transfer of metal to photosynthetic organs, which reduces the risk of its entry into the trophic chain and helps to more effectively stabilise contaminated areas without the need to collect aboveground mass.

An additional factor that increased the effectiveness of phytoremediation was the use of rhizospheric bacteria, in particular, *Pseudomonas fluorescens* and *Bacillus subtilis*. Their inoculation contributed to an increase in the accumulation of heavy metals in plants by 20-30%. This effect is probably associated with the synthesis of siderophores and organic acids by bacteria, which increase the solubility of metals and stimulate their absorption. Equally important was the effect of mycorrhizal inoculation by the fungus *Glomus intraradices*. In plants that formed a symbiosis with arbuscular mycorrhizae, the biomass of the aboveground part was on average 15% higher compared to non-inoculated plants. Such indicators indicate an improvement in mineral nutrition, water supply, and an increase in non-specific immunity of plants to environmental stressors. Consequently, biological stimulation with the help of microorganisms not only improved the overall physiological state of plants, but also enhanced the effect of chemical stabilisers and agrotechnical measures applied (Shahini *et al.*, 2023). Against the background of such positive changes, further comparison of the effectiveness of individual and combined remediation strategies became reasonable. A comparative analysis of the effectiveness of the applied approaches helped to determine that combined strategies, in particular, the combination of zeolite or biochar with phytoremediation crops, provided the highest effectiveness in reducing soil pollution with heavy metals. These combinations demonstrated a synergistic effect when chemical stabilisation of metals in the soil matrix was combined with active phytonaccumulation, which significantly exceeded the effectiveness of each method separately. In particular, in the "biochar+plants" option, the total removal of Cd and Zn from the soil was 40% higher than in the variants using phytoremediation alone. This effectiveness is associated not only with a decrease in bioavailability due to the adsorption capacity of biochar, but also with improved conditions for the growth and development of phytoremediants, which, in turn, more actively absorbed metals. Generalised quantitative results on the content of total and bioavailable cadmium in the soil after applying various remediation options are shown in Figure 1. The histogram illustrates the degree of effectiveness of each approach – chemical, biological, and combinations thereof – in the context of Cd reduction.

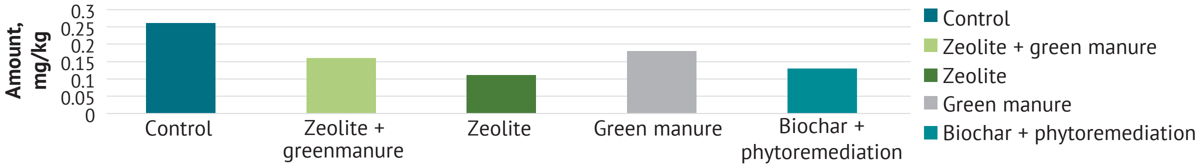

Figure 1. *Comparative analysis of cadmium content in soil*

Note: *total Cd content was determined after acid decomposition of samples, bioavailable – by DTPA extraction, followed by analysis using atomic absorption spectrophotometry*

Source: *created by the authors based on the results of a field block experiment conducted in 2022-2024 on southern chernozems in the Southern Steppe of Ukraine*

In addition, the results of correlation analysis confirmed a close relationship between the bioavailability of heavy metals in the soil and the degree of their accumulation in the aboveground mass of plants. For cadmium, a high positive ratio was found – the Pearson's coefficient $r = 0.88$ at $p < 0.01$, which indicates a significant relationship between the level of availability of the element in the soil solution and its phytoextraction. The link indicates that the bioavailable fraction is the most informative parameter for predicting the effectiveness of phytoremediation, and should be considered when assessing environmental risk and planning further measures for the reclamation of contaminated land.

DISCUSSION

The results obtained confirm the high efficiency of using zeolite and green manure to reduce the bioavailability of heavy metals in agricultural soils contaminated by anthropogenic impacts. This demonstrates the potential of these materials as key elements in phytoremediation and agrotechnical strategies aimed at restoring degraded land. The use of zeolite and green manure not only reduced the concentration of mobile forms of metals (primarily Cd and Pb), but also had a positive effect on the physico-chemical and biological parameters of the soil, which creates favourable conditions for plant growth. It was observed that the introduction of zeolite led to a decrease in the fractions of heavy metals associated with the exchange and carbonate forms, which are the most mobile and bioavailable. Such changes can be explained by several mechanisms, including an increase in pH, an increase in cation exchange capacity, and the development of stable complexes between metals and active zeolite surface centres. These data are quite consistent with the findings of K.N. Palansooriya *et al.* (2022), which emphasise the sorption capacity of sorbents due to their porous structure and richness of functional groups. In addition, as noted by P. Viotti *et al.* (2024), natural minerals may contribute to the development of organo-mineral structures that further reduce the risk of toxicant migration in the soil profile.

Extraction analysis data confirmed that the use of zeolite reduces the proportion of potentially mobile forms of Cd and Pb. Similar effects were recorded in the study by K.M. Malik *et al.* (2021), where organic changes led to a shift in the balance of metals in the soil towards less bioavailable forms. This similarity allows concluding that not only the total content, but also the form of metal presence determines the environmental risk. The reduction in phytotoxicity found in this study is also consistent with the findings of A. Emamverdian *et al.* (2023), which indicate that heavy metals can cause oxidative stress and inhibit photosynthetic activity. In another study, M. Adrees *et al.* (2015) described the mechanisms by which silicon reduces the toxic effects of metals by enhancing the antioxidant response – a similar effect was observed with the use of stabilisers in the current study, which provided better conditions for plant growth and development.

Significant changes were also recorded in the biological activity of the soil. Stabilisers had a positive effect on the development of the rhizosphere microbiota, which was reflected in better plant growth. This was confirmed by A. Rashid *et al.* (2023), who described the restoration of microbial diversity after the introduction of organic and mineral amendments. In particular, W. Xu *et al.* (2024) noted an increase in the activity of enzymes and microbial biomass as a result of improved soil structure. S. Jayaram (2022) described in detail the mechanisms of metal bioimobilisation associated with microbial transformation and redox processes. The results are also consistent with the above conclusions: the use of zeolite and green manure contributed to an increase in plant biomass, a decrease in signs of phytotoxicity, and an increase in the activity of antioxidant enzymes, which may indirectly indicate an improvement in the microbial environment. Although no direct assessment of microbial composition has been carried out, the growth of physiological and biochemical parameters of plants, such as chlorophyll, catalase and superoxide dismutase, and improvements in soil structure, suggest activation of rhizospheric microflora (Romanchuck *et al.*, 2017).

S. Li *et al.* (2021) reported that natural amendments promote selective enrichment of rhizobiomes with beneficial microbes, which not only stabilises metals, but also improves plant nutrition. G.P. Sidhu (2016) further emphasised that heavy metals disrupt microbial processes, which negatively affects fertility, so restoring the microbial environment is a critical remediation task. The results of the current study indirectly confirm these mechanisms: in options with the introduction of zeolite, an increase in plant biomass, an improvement in the physico-chemical properties of the soil, and a decrease in the level of markers of oxidative stress were recorded, which may be the result of activation of positive microbial processes in the rhizosphere.

From the standpoint of environmental safety, reducing the mobility of heavy metals is an important measure to prevent them from entering the food chain (Ilderbayeva *et al.*, 2024). As stated by S.J. Melebary (2023), in many regions of the world, agricultural products exceed the permissible Cd and Pb levels, which poses a potential threat to public health. Thus, the results showed positive dynamics – the use of zeolite allowed reducing the bioavailability of Cd to 0.11 mg/kg, which is a significant decrease compared to the control, and therefore reduces the risk of metals entering phytomass and further into food products. However, the effectiveness of remediation with stabilisers varies depending on the properties of the soil. D. Yu *et al.* (2024) emphasised that parameters such as acidity, mechanical composition, and organic matter content determine how effectively stabilisers can fix metals. In this study, the maximum effectiveness of reducing the bioavailability of Cd, Zn, and Pb was observed in soils with a low organic content (2.8%) and an initial pH of 5.6. The introduction of stabilisers contributed to the neutralisation of soil acidity (up to pH 6.8) and, accordingly, the transfer of metals to less soluble and less toxic forms. This allows concluding that it is advisable to use stabilisation approaches on slightly acidic soils with an increased anthropogenic load.

In addition to stabilising metals, the use of zeolite and green manure has demonstrated additional benefits associated with improving the physical characteristics of the soil. The study found that the introduction of green manure helped to improve the water retention capacity and soil structure, which, in turn, created favourable conditions for the development of the root system and reduced the risk of compaction. This was consistent with the conclusions obtained by S. Mansoor *et al*. (2021), who pointed to the role of agrotechnical measures as soil improvers that can affect not only the chemical, but also the physical and mechanical properties of the soil. Thus, the applied approaches perform not only the function of stabilisers of toxic elements, but also improve the agrophysical state of the soil environment, contribute to increasing the efficiency of nutrient use, and also provide conditions for the formation of stable plant phytocenoses. In the context of practical farming, this makes them promising components of technologies aimed at rehabilitating degraded soils (Manushkina & Drobitko, 2025). The overall results of the study fit well with the concept of sustainable agriculture highlighted by J. Hu *et al*. (2024). According to these researchers, the use of natural, locally available materials, such as zeolite, minimises the use of chemical fertilisers and pesticides, improves soil quality, and reduces the environmental burden on agroecosystems. This approach contributes to the development of adaptive agriculture focused on preserving the soil resource and improving its ecosystem functions.

Consequently, the results of this study confirmed that the use of zeolite and green manure can be an effective multi-purpose agrotechnical practice that combines environmental safety, economic feasibility, and agronomic efficiency. The complex effect of these materials on chemical (increasing pH, reducing bioavailability of heavy metals, increasing cation exchange capacity), biological (activating rhizosphere microbiota) and physical (improving structure and water permeability) soil parameters indicates their multifunctional role in remediation strategies. To achieve maximum effect, the use of these materials requires adaptation to specific conditions: soil type, type of pollution, stabiliser characteristics, and local climate. Such an individualised approach will ensure long-term stability of the phytosystem and increase the efficiency of ecological restoration of degraded land.

CONCLUSIONS

As a result of the study, it was found that the use of natural mineral sorbents (zeolite), organic stabilisers (biochar), green manure (mustard, phacelia tansy), and their combinations can effectively reduce both the total content and bioavailability of cadmium, lead, and zinc in anthropogenically contaminated soils. The highest efficiency was demonstrated by the variant with the introduction of zeolite, which provided a 58% reduction in the bioavailability of cadmium compared to the control. In addition, this option showed a 22% decrease in the total cadmium content, which indicates the ability of the mineral not only to fix ions but also to convert them into stable forms. The combined use of zeolite with green manure contributed to an additional reduction in metal toxicity, in particular, by improving the physical and chemical properties of the soil.

The use of biochar in combination with phytoremediation crops (sunflower, mustard) provided a 40% increase in the efficiency of extracting heavy metals from the soil, in particular Cd and Zn, compared to the use of phytoremediation alone. The availability of cadmium and zinc in the soil solution decreased by 50%, which confirms the stabilisation potential of biochar in the rhizosphere. In addition, there was an improvement in the physiological and biochemical parameters of sunflower: the biomass of the aboveground part increased by 24%, the chlorophyll content increased by 25%, and the activity of antioxidant enzymes (catalase and superoxide dismutase) – by 32% and 41%, respectively. In addition, the use of green manure crops of white mustard and phacelia tansy contributed to the restoration of soil properties. Sideration increased the organic carbon content by 18% and the cation exchange capacity by 11%, which, in turn, contributed to the fixation of heavy metals and reduced their leaching by 30%.

Practical recommendations include the use of zeolite (10 t/ha) and biochar (5 t/ha) in combination with green manure and phytoremediation as an effective strategy for reducing heavy metal toxicity. However, the study had a number of limitations that should be considered. The limitations included the short duration of the experiment (one growing season) and the research on one type of soil. In addition, changes in the structure of the soil microbiota that may have implications for the long-term stability of the system have not been investigated. Prospects for further research should include long-term field trials, analysis of residual metal concentrations in products, and the investigation of the environmental impact on microbial communities.

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Механізми зменшення токсичності важких металів в системах удобрення та агротехнологічного захисту ґрунту

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Анотація. Забруднення сільськогосподарських ґрунтів важкими металами, спричинене діяльністю промислових підприємств, транспорту та інтенсивним використанням агрохімікатів, становить загрозу екологічній безпеці та продуктивності сільськогосподарських систем. У зв'язку з цим метою дослідження була оцінка ефективності спільного використання сидератів та органо-мінеральних стабілізаторів (цеоліту та біовугілля) для зниження біодоступності важких металів та фітотоксичності ґрунтового середовища. Методи дослідження включали польовий блок-дослід на чорноземах півдня Південного Степу України, забруднених кадмієм (0,7 мг/кг), з використанням чотирьох варіантів обробки (контроль, цеоліт, цеоліт + сидерати, сидерати). Результати показали, що найефективнішим варіантом для зниження біодоступності кадмію був варіант з внесенням цеоліту, який забезпечив зниження доступного кадмію на 58 % та зниження його загального вмісту на 22 %. Внесення лише сидератів знизило біодоступність кадмію на 31 % порівняно з контролем. Біовугілля у поєднанні з фіторемедіацією зменшило доступність кадмію та цинку на 50 %, а видалення ґрунту збільшилося на 40 % порівняно з фіторемедіацією без біовугілля. Біомаса надземної частини соняшнику збільшилася на 24 % (до 35,2 г/рослину), вміст хлорофілу – на 25 %, а активність антиоксидантних ферментів – на 32 % та 41 %. Сидерація гірчицею та фацелією сприяла збільшенню вмісту органічного вуглецю в ґрунті на 18 %, покращенню ємності катіонного обміну на 11 % та зменшенню вимивання металів на 30 %, що свідчить про покращення загальної фіксації токсичних елементів. Усі результати підтверджують значне зниження фітотоксичності ґрунтового середовища та покращення фізіологічного та біохімічного стану рослин. Практичне значення результатів полягає в можливості використання біовугілля, цеоліту та сидератів для рекультивації забруднених ґрунтів та зниження ризику потрапляння важких металів у харчовий ланцюг

Ключові слова: біодоступність; фіторемедіація; сорбенти; мікроорганізми; хелати; стабілізація; ризосфера

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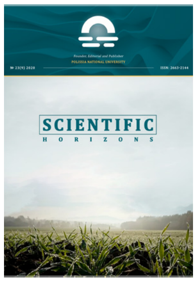

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Economic efficiency pulse growth in Ukraine

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Abstract. The study aimed to investigate the economic efficiency of buckwheat and oats cultivation in Ukraine for the period 2020-2024, incorporating production costs, yields, price changes, climate risks and the impact of state support. The regional coverage of the study included the northern, western, southern and eastern regions of Ukraine, including Chernihiv, Zhytomyr, Lviv, Mykolaiv, Odesa, Kirovohrad, Kherson and Zaporizhzhia, which provided a comprehensive analysis within different agro-climatic conditions. The research methodology was based on the analysis of official statistics from the State Statistics Service of Ukraine, the Ministry of Agrarian Policy and Food of

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Ukraine, case studies of farms, regulatory cost calculations, assessment of yields, price dynamics and profitability using economic and statistical analysis methods. The cost of key production inputs, including the cost of seeds, fertilisers, crop protection products, land lease, fuel and machinery, was addressed. The study determined that the average cost of growing buckwheat (16.9 thousand UAH/ha) was higher than that of oats (15.9 thousand UAH/ha), but due to the higher average selling price, buckwheat provided higher profitability (46.2% vs. 34.8%). The study found a significant impact of agricultural technologies and regional conditions on yields: buckwheat showed the best results in Chernihiv, Zhytomyr and Lviv regions, and oats in Mykolaiv, Odesa and Kirovohrad regions. Seasonal and average annual price fluctuations were summarised: in years of drought, buckwheat prices increased by 20-25% and oats by up to 12%, which compensated for crop losses. The role of government subsidy programmes, preferential lending and agri-insurance in increasing profitability by 10-15% in the medium term was analysed. Additionally, the efficiency of conventional and organic production models was investigated, considering premium pricing in the European Union markets. The results of the study can be used by farm managers, agro-consulting companies, and state and local authorities to make decisions on the choice of technological approaches, planning production strategies, cost optimisation and development of the export potential of niche crops

Keywords: buckwheat; oats; agriculture; yield; profitability; export potential

INTRODUCTION

Niche grain crops, such as buckwheat and oats, formed a separate segment in the structure of Ukrainian agricultural production. Demand for these crops was strong both in the domestic market and among international consumers, which necessitated an assessment of their economic efficiency. The production characteristics of buckwheat and oats were largely determined by agro-climatic conditions, the level of technological support and access to markets. Growing interest in organic production, changes in the structure of food demand and the need to optimise costs have made it important to study the profitability of these crops.

Assessing the efficiency of buckwheat and oat production required an analysis of the cost, yield, technological aspects of cultivation and market trends. Various approaches to determining the economic feasibility of producing these crops were considered in scientific sources, including an assessment of traditional, intensive and ecological farming methods. M. Vysochanska and V. Zubchenko (2024) studied the environmental and economic aspects of growing niche crops, in particular their dependence on technological changes and market factors. The study determined that the use of ecological farming methods contributed to the production of added value, although it was accompanied by a decrease in yield and an increase in cost. N. Tkach (2023) highlighted the peculiarities of growing niche crops in small agricultural enterprises in Ukraine. The analysis showed that the production of buckwheat and oats could be economically justified if resources were used efficiently and organic farming was introduced but remained dependent on market conditions. The economic efficiency of niche vegetable oil production under martial law in Ukraine was analysed in the study by O. Starikov and A. Reva (2024). Even though the subject of the study was other crops, the paper contained generalised conclusions about the dependence of the profitability of niche production on access to state support and the level of technological support. The economic efficiency of growing niche crops was assessed in the study by Y. Synyak (2023), which identified the main factors that influenced the formation of production costs. The use of intensive methods contributed to productivity growth, but increased production costs, which could reduce the economic attractiveness of these crops.

Foreign studies covered a wide range of issues related to the application of technological innovations in the production of niche crops. X. Cui *et al.* (2025) analysed the development of remote monitoring and machine learning systems in specialised agriculture, which had the potential to reduce production costs. The readiness of farmers to adopt biotechnological innovations was investigated by M. Abbey *et al.* (2024). The results showed that the prospects for the development of niche crops largely depended on the acceptability of genetic modifications and the effectiveness of the use of biological products in agriculture.

The issue of economic efficiency of agricultural diversification was considered in the study by A. Kurdyś-Kujawska *et al.* (2021). The study determined that expanding the range of crops grown contributed to the financial stability of small farms and reduced their dependence on market price fluctuations. The economic factors that determined the development of specialised agricultural production in the United States were the subject of a study by C.L. Neill and K.L. Morgan (2021). The study determined that the competitiveness of niche crops largely depended on marketing strategies, access to premium markets, and the level of production mechanisation. An analysis of measures to protect specialised crops was conducted in the study by M. Fuchs *et al.* (2021). The study determined that the policy of supporting the niche sector had a positive impact on its profitability, contributing to the financial sustainability of producers. I. Vijulie *et al.* (2022) examined the possibility of expanding lavender production in smallholder farms in Romania. It was found that growing niche crops created added value, especially when targeting specialised markets.

The analysis of literature sources showed that the economic efficiency of buckwheat and oats cultivation depended on several factors, including production costs, yields, technologies and market conditions. Analysis of these factors was used to assess the possibilities of increasing the profitability of these crops and the prospects for their development in the domestic and foreign markets. The study aimed to assess the economic efficiency of buckwheat and oats cultivation in Ukraine, considering the level of production costs, yields, the impact of agricultural technologies and market factors. To achieve this goal, the following objectives were formulated: to study the structure of production costs in buckwheat and oats cultivation and assess their impact on the cost price. Analyse the impact of agricultural technologies on yields and economic performance. To determine the dynamics of market prices for niche crops and assess their profitability.

MATERIALS AND METHODS

The study was based on the analysis of the economic efficiency of growing niche crops of buckwheat and oats in different regions of Ukraine in 2020-2024. The analysis covered the northern, western, southern and eastern regions of Ukraine to provide a comprehensive assessment of the economic efficiency of growing niche crops in different agro-climatic conditions. In particular, the regional analysis includes examples from Chernihiv, Zhytomyr, Lviv, Mykolaiv, Odesa, Kirovohrad, Kherson and Zaporizhzhia regions. Official statistics from the State Statistics Service of Ukraine (2023), the Ministry of Agrarian Policy and Food of Ukraine (2025), and the Ukrainian Agrarian Business Club (n.d.) were used to assess production costs, yields, profitability, and the impact of agro-technologies.

The input data included information on buckwheat and oat production costs, yields, selling prices, costs of seeds, fertilisers, fuel, land lease, machinery and labour. The analysis of the regional specifics of buckwheat cultivation was carried out mainly for the northern and western regions of Ukraine, where favourable soil and climatic conditions for this crop have been formed (Chernihiv, Zhytomyr, Lviv regions). For oats, regional peculiarities were studied in the southern and central regions (Mykolaiv, Odesa, and Kirovohrad regions), where this crop demonstrated stable yields in continental climate conditions. At the same time, the overall analysis incorporated data from the northern, western, southern and eastern regions on soil and climatic conditions and the level of agricultural technology used. Official documents of state support programmes for farmers, such as the terms and conditions of subsidies, soft loans and compensation for organic production, were obtained from the web portal of the Ministry of Agrarian Policy and Food of Ukraine (2025).Data was also collected from specific farms for the case study, including Stepova Rosa farm (Kherson region), Pivden-Agro (Mykolaiv region), and Zorya farm (Zaporizhzhia region). Data on the production performance of these farms were also obtained from open sources Ministry of Agrarian Policy and Food of Ukraine (2025), as well as analytical materials of the Ukrainian Agrarian Business Club (n.d.). The selection of these enterprises was based on their location in the southern and eastern regions of Ukraine, which are most affected by climate stress, including droughts. In addition, these farms have already had experience in implementing adaptation technologies (irrigation, drought-resistant varieties, crop insurance), which was used for targeted analysis of the effectiveness of such measures in real production conditions. The representativeness of the selected cases ensured the reliability of the assessment of the economic feasibility of adaptation strategies in the most vulnerable agroclimatic zones.

The cost of growing buckwheat and oats was estimated based on an analysis of the main cost items, which included the cost of seeds, fertilisers, plant protection products (PPPs), land lease, fuel, machinery and labour costs. For the comparative analysis, the method of normative costing based on average resource consumption was used. The impact of technologies was analysed by comparing the average yields of conventional, intensive and ecological methods, which determined the economic effects of each approach. The dynamics of buckwheat and oats prices were assessed by statistical analysis of annual price fluctuations using a weighted average change rate (1):

$$C_{avg} = \frac{C_i}{N}, \tag{1}$$

where C_{avg} is – the average price for the period (UAH/t), C_i is – price in each year, N – number of years of the study.

Seasonal fluctuations were determined by calculating the seasonality coefficient (2):

$$S_i = \frac{C_i}{C_{avg}} \times 100\%, \tag{2}$$

where S_i – seasonality index for month i.

Gross income was analysed using formula (3):

$$VD = Y \times P_{unit}, \tag{3}$$

where VD – gross revenue (UAH/ha), Y – crop yield (t/ha), and P_{unit} – average selling price (UAH/t).

Net profit was calculated using formula (4):

$$NP = VD - C, \tag{4}$$

where NP – profit (UAH/ha).

The level of profitability was determined using formula (5):

$$R = \frac{P-C}{C} \times 100\%, \quad (5)$$

where R – profitability level (%), P – gross revenue from sales (UAH/ha), and C – cost of production (UAH/ha).

To analyse the export of organic products, data from the European Commission on EU Organic certification requirements was used (Regulation (EU) No. 2018/848 of the European Parliament and of the Council "On Organic..., 2018). The assessment of the profitability of organic production was conducted incorporating the costs of certification and additional costs of biological products. All calculations were made on average for 2020-2024 based on regulatory production indicators and market data. Statistical data processing was carried out in Microsoft Excel and Stata, which provided correct weighted averages and determined the economic efficiency of different approaches to buckwheat and oats cultivation.

RESULTS

Cost analysis and the impact of agricultural technologies on production efficiency. The economic efficiency of growing niche crops is determined by their cost, which is shaped by technological features, input costs and agro-climatic conditions of the region. Buckwheat and oats account for a relatively small share of Ukraine's grain production, but their demand in the domestic market makes them promising for specialised farms. An analysis of the costs of growing these crops identified the main economic factors that influence the feasibility of their production. A comprehensive analysis showed that the total cost of buckwheat production was higher than that of oats, due to higher costs of seeds, fertilisers and agrochemicals. At the same time, oats had higher costs for mechanised operations, which affected the final financial result. The overall difference between the crops was 6-8% in favour of oats (Table 1).

***Table 1**. Comparison of buckwheat and oat cultivation costs (2020-2024, average values UAH/ha)*

Expenditure	Buckwheat	Oats
Seeds	3.200	2.400
Fertilisers and plant protection products	4.600	3.650
Land lease	1.800	1.750
Fuel	2.200	2.450
Technique	3.100	3.400
Salary	2.000	2.250
Total	16.900	15.900

***Source:** compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

Growing buckwheat required higher initial investment due to more expensive seeds and significant costs for fertilisers and protection products. However, the potentially high market price of buckwheat offsets these costs and ensures profitability. Oats, despite having a lower cost, had higher mechanised labour costs, requiring more fuel and labour. The analysis of buckwheat and oat yields in Ukraine revealed significant regional differences due to climatic conditions, soil characteristics and the level of agro-technological support. The highest average yields of buckwheat were observed in Chernihiv, Zhytomyr and Lviv regions, which belong to the northern and western agroclimatic regions, respectively, due to favourable soil and climatic conditions, in particular high humidity and acidic soils. At the same time, the highest oat yields were recorded in the southern regions due to black soil and continental climate. In contrast, Zaporizhzhia and partly Kherson regions, which belong to the eastern and southeastern regions, recorded the lowest results for both crops, due to frequent droughts and lower soil fertility (State Statistics Service..., n.d.).

The analysis of average purchase prices for buckwheat and oats in 2020-2024 revealed significant differences in the dynamics of both crops. According to the State Statistics Service of Ukraine (2023), the average price of buckwheat ranged from 12.5 thousand UAH/t (2020) to 21.0 thousand UAH/t (2022), while oats showed more stable indicators from 7.8 thousand UAH/t to 9.5 thousand UAH/t for the same period. The sharp jump in buckwheat prices in 2022 was due to the reduction of acreage due to the military actions and panic purchases in the domestic market (Fig. 1). In contrast, oats, being a less export-oriented crop, were less affected by geopolitical factors. Average prices were calculated using the weighted average of changes according to formula (1).

Seasonal price fluctuations were closely linked to the harvesting stages. Buckwheat was characterised by a 15-20% drop in prices in October-November due to new supplies entering the market. However, by spring, prices recovered by 25-30% due to a decrease in stocks and increased demand from processors (Ministry of Agrarian Policy and Food of Ukraine, 2025). For oats, the seasonality was less pronounced: the maximum price decline of 10-12% was recorded in September, and stabilisation occurred by the end of the year (Fig. 2).

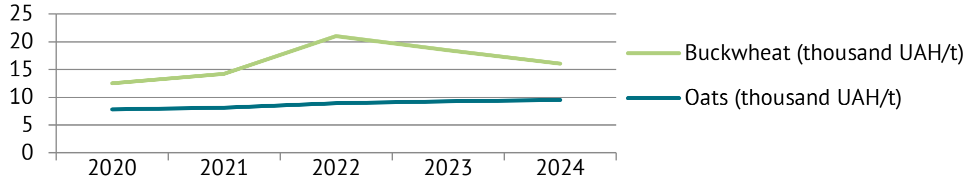

Figure 1. *Buckwheat and oats price fluctuations (2020-2024, annual average, thousand UAH/t)*
Source: *compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

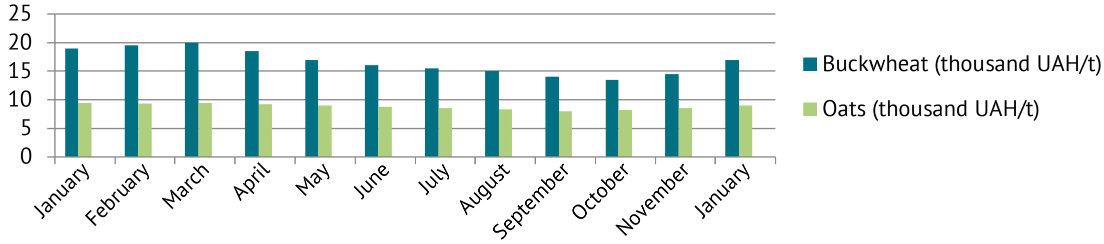

Figure 2. *Seasonal price fluctuations for buckwheat and oats during the year (average for 2020-2024, thousand UAH/t)*
Source: *compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

An analysis of the seasonal dynamics of buckwheat and oats prices in 2020-2024 showed distinct patterns. For buckwheat, the highest prices were observed in the winter and spring months (December-March), due to limited stocks and increased demand for cereals during the cold season. In contrast, after the harvest (August-September), prices temporarily declined due to increased supply on the market. For oats, price fluctuations were less pronounced: a gradual increase in demand for feed purposes in autumn led to a stabilisation of prices. During the period under review, the average annual amplitude of seasonal price changes for buckwheat exceeded 22%, while for oats it did not exceed 10%. The seasonal indices (calculated using formulas (1) and (2)) reflected the characteristic peaks and troughs in both crops.

An analysis of production figures for 2020-2024 revealed a high degree of dependence of yields of niche crops, in particular buckwheat and oats, on climatic factors. The eastern regions of Ukraine were particularly indicative in this regard, as they faced extreme drought conditions twice during the period, in 2020 and 2024. In these years, average temperatures during the flowering phase exceeded long-term norms by 2.32.8°C, and precipitation during critical periods did not exceed 40-50 mm per month, which led to a significant reduction in the vegetative potential of plants. As a result of these conditions, buckwheat yields decreased by 25-30% from the baseline of 1.5 t/ha to 1.1 t/ha, which had a significant impact on the economic performance of the farms. Oats, despite being somewhat more resistant to moisture deficit, also showed yield losses in the range of 15-20% from 2.4 t/ha to 2.0 t/ha. At the same time, in the western regions, in Lviv, Ivano-Frankivsk, and Chernivtsi regions, where soil moisture levels consistently exceeded 70%, buckwheat yields of 1.8-1.9 t/ha were stable (State Statistics Service of Ukraine, 2023; Ministry of Agrarian Policy and Food of Ukraine, 2025; Ukrainian Agrarian Business Club, n.d.). This demonstrated the importance of water supply during flowering and grain formation, as well as the potential of regions with a moderate hydrothermal regime as strategic areas for growing this crop (Fig. 3).

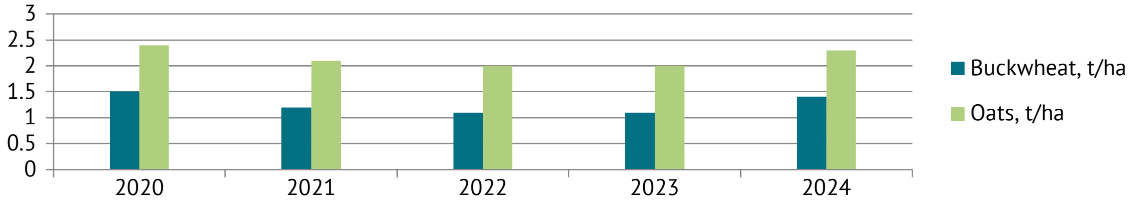

Figure 3. *Impact of drought on buckwheat and oat yields (2020-2024)*
Source: *compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

Thus, the differences in yields between regions confirmed the high degree of sensitivity of niche cereals to hydrothermal conditions. Buckwheat was particularly vulnerable to water shortages, while oats showed somewhat greater adaptability but also suffered significant losses during prolonged periods of drought. A comparison of the results of the eastern and western regions pointed to the need for regionalisation of agrotechnological approaches, including the introduction of water-saving practices and the use of varieties resistant to extreme weather conditions. This became the basis for further analysis of adaptation measures aimed at reducing climate risks in buckwheat and oat production. In addition to directly reducing yields, climate risks had a significant impact on the overall economic efficiency of production. Price increases in the years of poor harvest partially compensated for the crop losses, ensuring that some farms maintained or even increased their net profit. During the drought of 2022, the average net profit from buckwheat production increased by 12-15% compared to years with stable weather conditions, which showed the importance of fluctuations in the assessment of risks and planning of agricultural activities (State Statistics Service of Ukraine, 2023; Ministry of Agrarian Policy and Food of Ukraine, 2025).

A comprehensive analysis of adaptation practices has shown the effectiveness of integrating technological innovations with government support instruments in the context of minimising climate risks. For example, in the Kherson region, Stepova Rosa farm introduced drip irrigation on 50% of buckwheat crops, which increased yields from 1.2 t/ha to 1.6 t/ha (+33%) in high temperatures, while state compensation of 1.0 thousand UAH/ha reduced costs by 8% (Ministry of Agrarian Policy and Food of Ukraine, 2025). In the Mykolaiv region, Pivden-Agro used the Orion oat variety adapted to water shortages, which increased yields to 2.7 t/ha (+12%) and increased profitability by 18%, despite the higher cost of seeds. Between 2022 and 2024, national support programmes, including compensation of 40% of the cost of installing irrigation systems, stimulated the expansion of drip irrigation by 15% in the southern regions, helping to reduce the cost of buckwheat production by 10-12% compared to non-irrigated areas (Ukrainian Agrarian Business Club, n.d.). An additional element of the adaptation policy was the implementation of the Agrostrakh programme, which in 2024 provided coverage for up to 70% of losses caused by drought. In particular, the Zorya farm in the Zaporizhzhia region received an insurance payment of 3.2 thousand UAH per hectare, which maintains its profitability level at 28% despite adverse weather conditions (State Statistics Service of Ukraine, 2023). In summary, these examples demonstrate the practical effectiveness of adaptation strategies both at the level of microeconomic actors and within the framework of the state policy to increase the climate resilience of agricultural production.

An assessment of the effectiveness of the implemented adaptation measures showed that they were able not only to mitigate the impact of adverse climate factors but also to increase the overall economic efficiency of agricultural production. The introduction of irrigation systems, the selection of drought-resistant varieties and the use of insurance mechanisms created additional opportunities to stabilise agricultural production in the face of growing climate uncertainty. The use of such solutions optimised resources, reduced technological risks and ensured predictability of financial performance in the medium term. The analysis demonstrated that the effectiveness of adaptation measures depended largely on the type of crop: buckwheat, being more vulnerable to drought, responded more strongly to the introduction of irrigation, while for oats, breeding characteristics and agroecological suitability of varieties were crucial. In addition, the level of adaptation varied by region: in the southern regions with low rainfall, infrastructure measures (such as drip irrigation) were most effective, while in the central regions, agro-technological solutions were prioritised. The role of state support has proved to be crucial in minimising risks and increasing the efficiency of growing niche crops. For example, the Stepova Rosa farm (Kherson region) implemented a drip irrigation system in buckwheat growing areas with the support of the state programme for compensation of equipment costs, which increased crop yields by 33% and reduced production costs by 8% on average in 2022-2024 (Ministry of Agrarian Policy and Food of Ukraine, 2025).

The Vovsianyi Krai farm in the Khmelnytskyi region has integrated the use of drought-tolerant oat varieties as part of a regional programme to support adaptive agriculture. This contributed to a 12% increase in yields even in dry years without significantly increasing production costs (State Statistics Service of Ukraine, 2023; Ukrainian Agrarian Business Club, n.d.). In addition, Pivden-Agro (Mykolaiv region) actively used crop insurance mechanisms with the support of the state programme to reduce insurance premiums. As a result, in 2023, up to 70% of oat crop losses due to extreme weather conditions were compensated, which ensured income stability and avoided bankruptcy (Ministry of Agrarian Policy and Food of Ukraine, 2025). Thus, the practical examples of farms show that the integration of anti-crisis measures with state support significantly increased the sustainability of niche crop production, reduced risks and ensured yield growth even in difficult climatic conditions.

Climate risks significantly affected the yields and economic efficiency of buckwheat and oats in Ukraine, especially in the eastern and southern regions. Buckwheat proved to be the most vulnerable to drought, while oats showed relative stability but also required adaptation measures. The practical introduction of drip irrigation, the use of drought-resistant varieties and participation in government insurance programmes proved to be effective in increasing yields, reducing costs and maintaining profitability even in adverse weather conditions. The application of these strategies created the preconditions for increasing the climate resilience of the agricultural sector and formed the basis for further scaling up adaptation practices in the context of climate change.

Profitability and economic attractiveness of growing buckwheat and oats. The analysis of the profitability of buckwheat and oats cultivation was based on the comparison of gross income, net profit and margin per 1 ha, incorporating the data on cost, yield and sales prices for 2020-2024. Gross income was calculated as the product of the average yield and the sales price (formula 3), while net profit was determined by subtracting the cost from the gross income (formula 4, 5) (Table 2). The margin was displayed as a percentage of net profit to gross income (State Statistics Service of Ukraine, 2023).

***Table 2**. Comparison of buckwheat and oats profitability (average values for 2020-2024)*

Metric	Buckwheat	Oats
Average yield (t/ha)	1.9	2.8
Average selling price (thousand UAH/t)	16.5	8.7
Gross income (thousand UAH/ha)	31.4	24.4
Cost (thousand UAH/ha)	16.9	15.9
Net profit (thousand UAH/ha)	14.5	8.5
Margin (%)	46.2	34.8

***Source:** compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

The data show that buckwheat, despite its higher cost, provided a higher net profit due to high selling prices. Its margin exceeded that of oats by 11.4%, which underlined its economic attractiveness in favourable years (Ukrainian Agrarian Business Club, n.d.). However, buckwheat margins fluctuated significantly: in 2022, they reached 62% due to peak prices, while in 2024 they fell to 35% due to market correction. For oats, the margin remained stable (30-38%), making it a less risky asset (Ministry of Agrarian Policy and Food of Ukraine, 2025). Buckwheat proved to be the most economically profitable crop, given stable access to export markets and high prices. However, its production was accompanied by significant risks associated with price volatility and climatic factors. Lower-margin oats remained a strategy for conservative farms focused on stability and domestic demand. The optimal strategy to minimise risks is to combine both crops in a crop rotation, with buckwheat as a profitable component and oats as a stabilising component.

The study of the economic efficiency of buckwheat and oats production in Ukraine in 2020-2024 showed that the choice of business model directly affects the profitability and sustainability of farms. To evaluate conventional and organic production, key indicators such as cost, yield, sales prices, net profit and margin were analysed. The conventional production model is based on intensive technologies that involve the use of mineral fertilisers, herbicides and mechanised cultivation of large areas (over 100 hectares). The advantages of this model are high yields (buckwheat 1.9 t/ha, oats 2.8 t/ha) and fast capital turnover. The main risks remain dependence on prices for agrochemicals and energy and high levels of internal competition (State Statistics Service of Ukraine, 2023). The organic production model requires compliance with the EU Organic certification requirements (Regulation (EU) No. 2018/848 of the European Parliament and of the Council "On Organic…, 2018), the use of biological products, and the prohibition of synthetic fertilisers and pesticides. Despite the higher cost (buckwheat 21.5 thousand UAH/ha vs. 16.9 thousand UAH/ha in the traditional format), premium prices (22.0 thousand UAH/t vs. 16.5 thousand UAH/t) partially compensated for the lower yield (1.6 t/ha vs. 1.9 t/ha) (State Statistics Service of Ukraine, 2023; Ministry of Agrarian Policy and Food of Ukraine, 2025; Ukrainian Agrarian Business Club, n.d.). Comparative results are presented in Tables 3 and 4.

***Table 3**. Comparison of conventional and organic buckwheat production*

Metric	Traditional	Organic
Cost (thousand UAH/ha)	16.9	21.5
Average yield (t/ha)	1.9	1.6
Selling price (thousand UAH/t)	16.5	22.0
Net profit (thousand UAH/ha)	14.5	13.7
Margin (%)	46.2	38.9

***Source:** compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

***Table 4**. Comparison of conventional and organic oatmeal production*		
Metric	**Traditional**	**Organic**
Cost (thousand UAH/ha)	15.9	18.0
Average yield (t/ha)	2.8	2.5
Selling price (thousand UAH/t)	8.7	12.0
Net profit (thousand UAH/ha)	8.5	12.0
Margin (%)	34.8	40.0

***Source:** compiled by the authors based on State Statistics Service of Ukraine (2023), Ministry of Agrarian Policy and Food of Ukraine (2025), Ukrainian Agrarian Business Club (n.d.)*

The data analysis showed that in traditional buckwheat production, the cost price was 16.9 thousand UAH/ha with an average yield of 1.9 t/ha and an average selling price of 16.5 thousand UAH/tonne. As a result, the net profit reached 14.5 thousand UAH/ha, and the margin was 46.2%. At the same time, organic buckwheat production was characterised by a higher cost of 21.5 thousand UAH/ha and a lower yield of 1.6 t/ha, but the premium selling price of 22.0 thousand UAH/t maintained a fairly high level of profitability, although slightly lower than in conventional production (13.7 thousand UAH/ha), with a margin of 38.9%) (State Statistics Service of Ukraine, 2023; Ministry of Agrarian Policy and Food of Ukraine, 2025). In the case of oats, the traditional model showed a cost price of 15.9 thousand UAH/ha, a yield of 2.8 t/ha and a selling price of 8.7 thousand UAH/ton. This provided a net profit of 8.5 thousand UAH/ha and a margin of 34.8%. Organic oat production provided a higher level of net profit of 12.0 thousand UAH/ha at a premium price of 12.0 thousand UAH/t, despite lower yields (2.5 t/ha) and slightly higher costs (18.0 thousand UAH/ha). The margin of organic oat production reached 40.0% (State Statistics Service of Ukraine, 2023; Ministry of Agrarian Policy and Food of Ukraine, 2025; Ukrainian Agrarian Business Club, n.d.).

The comparative analysis showed that for buckwheat, conventional production remains more profitable due to higher yields and moderate costs. In contrast, for oats, organic production proved to be more economically viable due to a significant increase in the selling price and higher profitability (Ukrainian Agrarian Business Club, n.d.). Thus, the choice of model depends on the crop: for buckwheat, investments in organic production are justified only if access to premium foreign markets is guaranteed, while for oats the organic model shows stable advantages even for domestic sales. An analysis of the distribution channels for buckwheat and oats in Ukraine showed that the key players are grain traders, processing companies and organic producers. Grain traders, such as Cargill or Louis Dreyfus, provided bulk sales through export contracts, offering stability of supply, but at prices that were often 10-15% below market prices (Ukrainian Agrarian Business Club, n.d.). In contrast, processing companies, including cereal producers (Yarmarochka, Extra M), bought raw materials at higher prices but demanded strict quality standards. The highest margins were achieved through organic brands (Eco Hata, Zhmenka), where prices were 25-30% higher than the market average, but required certification and narrow specialisation (Ministry of Agrarian Policy and Food of Ukraine, 2025). Demand for organic buckwheat and oats on the Ukrainian domestic market showed positive dynamics but remained limited due to higher prices (+25-30% over conventional products). Most organic products (over 65%) were exported to the European Union (EU), where demand for organic grains was consistently high. Increased exports of organic buckwheat increased the average net profit of farms by 2035% compared to domestic sales, making exports a priority for small and medium-sized farmers (Ukrainian Agrarian Business Club, n.d.).

The impact of export demand was particularly noticeable for buckwheat. For example, in 2023, after the resumption of logistics routes through the EU, prices increased by 18% due to increased supplies to Poland and Germany (Ukrainian Agrarian Business Club, n.d.). For oats, the domestic market remained the main driver, in particular demand from feed producers and the food industry. Market conditions also depended on competition from other grains: the drop in wheat prices in 2021 temporarily reduced the attractiveness of oats for farmers (State Statistics Service of Ukraine, 2023). Buckwheat cultivation had a higher level of risk due to greater price volatility, but under favourable conditions, it offered higher profitability. Oats remained a more stable crop, which minimised market risks and ensured stable farm incomes. The optimal strategy is to combine both crops in the crop rotation. The prospects for buckwheat and oats exports remained strong despite geopolitical challenges. Until 2022, the main export destinations for buckwheat were the EU (Poland, Germany), the Middle East (Turkey) and Asia (Japan). After the Black Sea ports were blocked, land corridors through Poland and Romania became the key route, which increased logistics costs by 2025% but maintained access to European markets (State Statistics Service of Ukraine, 2023). For oats, Turkey remained the main importer, using it for feed production, as well as North African countries (Tunisia, Algeria).

Government programmes helped to expand export potential in 2020-2024. For example, participation in international agricultural exhibitions (e.g., Grain Tech in India) with the support of Minagro enabled Ukrainian farmers to sign contracts for the supply of organic buckwheat to Germany and France (Ukrainian Agrarian Business Club, n.d.). For small farms, cooperatives such as Agroexport, which aggregated products for sale to large importers, remained relevant. The optimal marketing strategy depends on the scale of production. Large agricultural holdings focused on grain traders and exports, while small farms benefited from cooperation with processors and organic brands. To increase exports, the development of logistics infrastructure and government support for participation in international platforms remain critical.

State support and financial instruments for farmers. State support for buckwheat and oats in Ukraine includes several programmes aimed at reducing costs and stimulating innovation. In 2020-2024, the Ministry of Agrarian Policy and Food of Ukraine (2025) implemented seed subsidies, soft loans and compensation for organic production. Subsidies for the purchase of certified buckwheat and oat seeds compensated 30-50% of the cost, enabling small farms to reduce their seed costs by 1.2-1.8 thousand UAH per hectare (Ministry of Agrarian Policy and Food of Ukraine, 2025). Concessional loans at 5% per annum, available through state-owned banks, have facilitated the renewal of machinery and the purchase of quality fertilisers. For example, in 2022-2023, about 45% of buckwheat farmers used these loans to upgrade 20% of their equipment (State Statistics Service of Ukraine, 2023). Since 2020, farms that switched to organic buckwheat or oat cultivation have received an annual compensation of 3,000 UAH per hectare. According to the Ukrainian Agrarian Business Club (n.d.), this covered up to 15% of the additional costs of certification and biological products. Such measures enabled farms to enter European markets with premium prices. Examples of successful use of state support included farms from different regions. For example, in Poltava region, Zernovyk farm reduced the cost of growing buckwheat from 17.5 to 15.8 thousand UAH/ha due to subsidies for seeds, which increased profitability by 12% (Ministry of Agrarian Policy and Food of Ukraine, 2025). In the Zhytomyr region, Eco-Zerno purchased precision seeders with concessional loans, which increased oat yields from 2.5 to 3.1 t/ha. In the Lviv region, the organic farm Bio-Pole used compensation to enter EU markets, selling buckwheat at a price 25% higher than the market average (Ukrainian Agrarian Business Club, n.d.).

The effectiveness of state support programmes depends on regional conditions and the size of farms. The use of state subsidies and soft loans enables small and medium-sized farms to reduce production costs by 8-12% and increase the profitability of buckwheat and oats by 10-15% in the medium term (2-3 years) (Ministry of Agrarian Policy and Food of Ukraine, 2025). In particular, seed subsidies (following the programme of partial compensation of the cost of agricultural seeds approved by Resolution No. 106 "On Approval of the Procedure for the Use of Funds Provided for in the State Budget for Providing Financial Support for the Development of Farms" (2018)) are most effective for small farms in the northern and western regions, such as Stepova Rosa farm (Kherson region) and Zorya farm (Zaporizhzhia region). Instead, concessional loans under the programme "Financial Support to Agricultural Producers" (Resolution No. 300 "On Approval of the Procedure for the Use of Funds Provided for in the State Budget for Financial Support of Activities in the Agro-Industrial Complex by Reducing the Cost of Loans", 2023) are more actively used by large agricultural enterprises, such as Pivden-Agro (Mykolaiv region), which enables expansion production and introduce adaptive technologies. Further development requires expanding support for organic production and simplifying bureaucratic procedures (Ministry of Agrarian Policy and Food of Ukraine, 2025). Government initiatives not only reduce production costs but also provide access to new markets, which is key to increasing the competitiveness of buckwheat and oats in the face of global challenges.

DISCUSSION

The results of the study confirmed that the economic efficiency of buckwheat and oat production was determined by a set of factors, including the level of agro-technological support, adaptation of technologies to regional conditions, the effectiveness of marketing policy and access to markets. The use of local fertilisation and plant protection technologies contributed to an increase in the efficiency of inputs in buckwheat and oat production. Similar conclusions were drawn by B.W. Warneke *et al.* (2021), noting that the introduction of precision spraying in specialised crops increased the efficiency of agrochemicals and reduced their negative impact on the environment. The study demonstrated that the use of ecological technologies led to a decrease in the yield of buckwheat and oats by 10-15%, which is consistent with the results of J. Ryschawy *et al.* (2021), stating that the transition to ecological farming methods reduced the negative impact on the environment, but required the adaptation of technologies to the reduced productivity of crops. The study confirmed the effectiveness of mulching technologies in buckwheat and oat production. It was found that the use of biodegradable materials contributed to the improvement of the soil water regime and the reduction of erosion processes. Similar results were reported by G. He *et al.* (2021), proving that the use of black mulching films had advantages over transparent ones, as they provided better soil temperature control and moisture conservation.

A comparative analysis of the cost of buckwheat and oat production showed that the main cost items were seeds, fertilisers, fuel and mechanised operations.

The study determined that buckwheat cultivation required higher costs for seed and plant protection products, while for oats, a larger share of the cost was accounted for by tillage costs. Similar trends were found by P.B. Angon *et al.* (2023), noting that minimum tillage technology systems contributed to lower production costs by reducing fuel and mechanised labour costs. The results of the study confirmed that the level of buckwheat and oat yields was largely determined by the agrotechnological approaches used in production. It was found that intensive technologies contributed to an increase in crop productivity but were accompanied by an increase in production costs. Similar conclusions were presented by S.E. Wuest *et al.* (2021) in an assessment of the impact of using different variety mixtures on crop productivity. The study determined that the introduction of mixed varietal groups contributed to increasing the resilience of crops and their adaptation to changing climatic conditions.

The results of the study confirmed the effectiveness of mulching technologies in grain production. It was found that the use of biodegradable films had the potential to improve moisture retention and optimise soil temperature. Similar results were obtained in A. Abduwaiti *et al.* (2021) in the verification of alternatives to traditional plastic films in the production of vegetable crops. The study determined that the use of biodegradable materials helped to reduce the negative environmental impact and increase the economic performance of cultivation. The assessment of the prospects for the development of niche crops showed that their production remained economically viable and provided an effective marketing strategy and access to international markets. The study by G.A. Manganaris *et al.* (2022) confirmed that the prospects of specialised crops were largely determined by the adaptation of cultivation technologies to changing climatic conditions and market requirements. The analysis of the structure of production costs showed that the greatest impact on buckwheat production costs was made by the costs of seeds, fertilisers and plant protection products, while for oats the key cost items were mechanised labour and fuel. Similar results were obtained by A.W. Driscoll *et al.* (2022), noting that diversification of agricultural production contributed to the economic stability of farms by spreading costs across different crops and adapting to changing market conditions. The results of the study were consistent with the findings of C.P. Huss *et al.* (2022), who determined that crop rotation and the use of intercropping systems provided pest resistance and had a positive impact on yields.

The results of the study confirmed that the economic efficiency of buckwheat and oats cultivation largely depended on the applied agricultural technologies. The study determined that the use of intensive methods contributed to an increase in yields but was accompanied by an increase in production costs. Similar conclusions were drawn by R.W. Brooker *et al.* (2023), who determined that ecological intensification in agricultural production provided increased crop productivity, provided that agrotechnological processes were optimised. The study determined that the diversification of agricultural production contributed to the stability of profitability, which correlated with the findings of K. Mekonnen *et al.* (2022). The study confirmed that mixed systems of agricultural production ensured resource optimisation and reduced the risk of losses due to adverse weather conditions. The results of the study confirmed that the level of economic efficiency of buckwheat and oats cultivation depended on the technological approaches used in production. The study determined that intensive cultivation methods contributed to higher yields but were accompanied by higher production costs. Similar conclusions were presented by P. Nilsson *et al.* (2022), who determined that the introduction of functional diversity in agricultural systems contributed to increased crop productivity and reduced dependence on external resources.

The analysis of the cost structure showed that the cost of buckwheat production was formed mainly by the cost of seeds, fertilisers and plant protection products, while for oats the main components were mechanised operations and fuel costs. Similar trends were observed by S. Kumar *et al.* (2022), who noted that the introduction of legumes into crop rotation helped to restore soil fertility, which reduced the need for mineral fertilisers and optimised agricultural production costs. The results confirmed that the application of ecological technologies for growing buckwheat and oats was accompanied by a decrease in yields but ensured the stability of agroecosystems. Similar findings were reported in a study by S.P.S. Yadav *et al.* (2023), which examined approaches to biodiversity conservation and its role in improving the environmental sustainability of agricultural land. The analysis of market dynamics showed that buckwheat had significantly higher price volatility, while the oat market remained stable. The study determined that the profitability of niche cereals largely depended on access to premium markets and export opportunities. Similar conclusions were drawn in the study by R. Dhillon and Q. Moncur (2023), which analysed the challenges and opportunities for small farmers in the context of technological innovation and the development of niche markets.

The results confirmed that the local application of fertilisers and plant protection products contributed to lower production costs and increased resource efficiency. Similar patterns were found in the study by P. Boczar and L. Błażejczyk-Majka (2024), which analysed the economic efficiency of energy use in EU agricultural enterprises. The assessment of the prospects for the development of niche crops showed that their production remained economically viable and provided an effective marketing strategy and adaptation to market requirements. The study by C.K. Phiri *et al.* (2024) confirmed that the prospects for speciality crop production largely depended on access to marketing infrastructure and production incentive policies. The results were consistent with the findings of L.E. Balis *et al.* (2024), determining that speciality crops had the potential to increase the environmental and economic sustainability of agrosystems, especially if adaptive cultivation technologies were introduced. The results of the study confirmed that the economic efficiency of buckwheat and oat cultivation depended on the applied agricultural technologies and market factors. It was found that intensive technologies increased yields but were accompanied by an increase in production costs. Similar conclusions were drawn in the study by M.R.B. Júnior *et al.* (2024), which examined modern technological solutions in specialised crop production. The study determined that automation of agricultural production contributed to increased productivity, reduced labour costs, and optimised resource use.

The analysis of the cost structure showed that the greatest impact on the cost of buckwheat was made by the cost of seeds, fertilisers and plant protection products, while for oats the key cost items were mechanised work and fuel. Similar patterns were observed in the study by M. Vályi-Nagy *et al.* (2024), which assessed the economic benefits of mixed cropping. It was found that optimisation of resources through the integrated use of fertilisers and tillage contributed to increased profitability of agricultural production. The results confirmed that the application of environmental technologies in buckwheat and oat production was accompanied by a decrease in yields but ensured the stability of agroecosystems and access to premium markets. Similar conclusions were reached in the study by D. Duval *et al.* (2024), which analysed the economic contribution of agricultural production to regional development. The study determined that the adaptation of production systems to environmental standards expansded export opportunities and increased the added value of products. Comparison with scientific sources has shown the expediency of applying adaptive approaches in the cultivation of niche crops to increase competitiveness and stabilise economic performance.

CONCLUSIONS

The study of the economic efficiency of buckwheat and oats in Ukraine revealed significant differences in the profitability of these crops. Buckwheat, despite the higher production cost (16.9 thousand UAH/ha versus 15.9 thousand UAH/ha for oats), provided a higher net profit (14.5 thousand UAH/ha) due to the high average selling price (16.5 thousand UAH/t). The study determined that buckwheat production is vulnerable to geopolitical factors: in 2022, there was a sharp increase in its price to 21.0 thousand UAH/t due to a reduction in acreage and domestic demand, and a gradual correction in subsequent years. Oats, with more stable prices (7.8-9.5 thousand UAH/t) and higher yields in southern Ukraine (2.8 t/ha), proved to be a less risky crop for domestic market-oriented farms.

The impact of climatic factors was analysed: the droughts of 2020 and 2024 in the eastern regions led to a 25-30% decrease in buckwheat yields and a 15-20% decrease in oats. The regional analysis confirmed that the highest buckwheat yields (1.8-1.9 t/ha) were achieved by farms in Chernihiv, Zhytomyr, and Lviv regions due to favourable hydrothermal conditions. The effectiveness of adaptation measures was summarised: the introduction of drip irrigation increased buckwheat yields by 33%, and the use of drought-resistant oat varieties contributed to a 12% increase in yields even in years with limited moisture. Organic production, despite a 10-15% reduction in yields, provided premium prices (+25-30%) and access to EU markets. The study determined that state support programmes (compensation for organic production, seed subsidies, soft loans) reduced production costs by 8-12% and increased production profitability by 10-15% in the medium term. Prospects for further research include modelling the impact of climate change on yields and analysing the effectiveness of adaptive technologies and government support in the agricultural sector.

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Економічна ефективність вирощування нішевих культур в Україні

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Анотація. Метою роботи було дослідити економічну ефективність вирощування гречки та вівса в Україні за період 2020-2024 років, з урахуванням виробничих витрат, урожайності, змін цін, кліматичних ризиків і впливу державної підтримки. Регіональне охоплення дослідження включало північні, західні, південні та східні області України – зокрема Чернігівську, Житомирську, Львівську, Миколаївську, Одеську, Кіровоградську, Херсонську та Запорізьку – що забезпечувало комплексний аналіз у межах різних агрокліматичних умов. Методологія дослідження базувалася на аналізі офіційних статистичних даних Державної служби статистики України, Міністерства аграрної політики та продовольства України, кейс-аналізі господарств, нормативних розрахунках витрат, оцінці врожайності, динаміки цін та рівня рентабельності з використанням методів економічного та статистичного аналізу. Було проаналізовано собівартість основних виробничих елементів, зокрема витрат на насіння, добрива, засоби захисту рослин, оренду землі, паливо та техніку. Було визначено, що середня собівартість вирощування гречки (16,9 тис. грн/га) перевищувала відповідний показник для вівса (15,9 тис. грн/га), проте завдяки вищій середній ціні реалізації гречка забезпечувала вищу рентабельність (46,2 % проти 34,8 %). Було встановлено суттєвий вплив агротехнологій і регіональних умов на врожайність: гречка продемонструвала найкращі результати у Чернігівській, Житомирській та Львівській областях, а овес – у Миколаївській, Одеській та Кіровоградській областях. Було узагальнено сезонні та середньорічні коливання цін: у роки посух ціни на гречку зростали на 20-25 %, на овес – до 12 %, що компенсувало втрати врожаю. Було проаналізовано роль державних програм субсидування, пільгового кредитування і агрострахування у підвищенні рентабельності на 10-15 т% у середньостроковій перспективі. Додатково було досліджено ефективність традиційних та органічних моделей виробництва з урахуванням преміального ціноутворення на ринках Європейського Союзу. Результати дослідження можуть бути використані керівниками фермерських господарств, агроконсалтинговими компаніями, органами державної влади та місцевого самоврядування для прийняття рішень щодо вибору технологічних підходів, планування виробничих стратегій, оптимізації витрат і розвитку експортного потенціалу нішевих зернових культур

Ключові слова: гречка; овес; сільське господарство; урожайність; рентабельність; експортний потенціал

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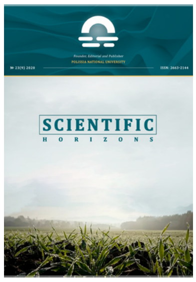

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Substantiation of business models in the agro-industry: The case of Kazakhstan and Central Asian countries

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Abstract. The purpose of the study was to investigate the key factors influencing the choice and effectiveness of business models in the agro-industrial sector of Kazakhstan and Central Asia. The research methodology included an analysis of statistical data, a comparative analysis of business models, and an assessment of the impact of external economic and climatic factors on the sustainability of agribusiness in the region. In the course of the study, the existing business models of agricultural enterprises were

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investigated and categorised, their key features and factors influencing their choice were identified. The dynamics of the total volume of agricultural production in Kazakhstan, Uzbekistan, and Kyrgyzstan was analysed with the conversion of indicators into USD, which helped to objectively assess the scale and trends of the agricultural sector. The total volume of agricultural production in Kazakhstan in 2023 amounted to USD 16.12 billion, in Uzbekistan – USD 35.26 billion, and in Kyrgyzstan – USD 4.44 billion. Investment projects in the agro-industry, including large investments in greenhouse complexes, processing of agricultural products and digitalisation of the industry, were considered in detail. Using the example of Atameken-Agro, a detailed financial analysis was carried out, fluctuations in profitability and the impact of economic factors on business profitability and sustainability were revealed. The results showed that digitalisation, the introduction of precision agriculture, vertical integration, and an export orientation for processed products are the key drivers of the region's agro-industry growth. Based on the identified trends, recommendations have been developed for the selection and adaptation of business models for agricultural companies in Kazakhstan and Central Asia. These include the development of cooperative structures, the introduction of sustainable agricultural technologies, increasing the investment attractiveness of the sector and the diversification of production. The conclusions of the study confirmed the need for an integrated approach to the development of agribusiness in a region where digitalisation, government support, and integration into global markets play a crucial role in increasing the competitiveness of agricultural enterprises

Keywords: investment projects; regional development; innovative technologies; agriculture; economic development

INTRODUCTION

The agro-industrial sector plays a key role in the economy of Kazakhstan and Central Asian countries, providing food security, employment, and a significant contribution to the gross domestic product. The region has a high potential for agricultural development due to its extensive land resources, favourable climatic conditions and growing global demand for agricultural products. However, despite these advantages, the industry faces a number of challenges, including a low level of technological modernisation, insufficient processing of agricultural products, limited access to investment, and weak integration into global value chains. In these conditions, the search for effective business models becomes an important task for ensuring competitiveness and sustainable growth of the agricultural sector. Existing approaches to agribusiness require revision, as conventional models demonstrate low efficiency in a changing economic and climatic landscape.

Many researchers have previously paid attention to the issue of choosing and adapting business models in the agro-industry. For example, D. Dentoni *et al.* (2020), investigated the impact of the institutional environment on the development of agribusiness and concluded that the lack of clear government support and effective financing mechanisms hindered the development of private agricultural enterprises. Their study showed that subsidised measures without accompanying structural reforms did not lead to long-term growth of the industry. S. Suieubayeva *et al.* (2022) analysed business models in Kazakhstan, revealing that farms integrated into international supply chains demonstrated the greatest resilience. They noted that companies working on contract farming had more stable incomes due to guaranteed sales of products.

The study by J. MacPherson *et al.* (2022) showed that digitalisation of farms has contributed to an increase in their efficiency. They analysed the implementation of agrotechnological platforms and found that farmers who used digital tools for soil monitoring and resource management increased yields compared to conventional methods. S.N. Ulakov *et al.* (2020) examined cooperative forms of agribusiness and found that in Kazakhstan such models faced problems of trust between participants, but with clear management mechanisms, they ensured higher competitiveness of small producers. They noted that successful cooperatives performed better in terms of access to credit and sales markets. M.Y. Arafat *et al.* (2020) investigated the impact of government policy on the development of agricultural entrepreneurship. The researchers concluded that the most effective support measures were subsidies for the purchase of innovative equipment and tax incentives for small farms. C.T. Nguyen and F. Scrimgeour (2022) analysed the impact of climate change on the business models of agriculture in the region and found that farmers who switched to adaptive technologies such as drip irrigation and sustainable crop varieties reduced their losses during dry years.

The study by S. Jeshari and M. Esfandiari (2022) considered the issue of agricultural exports, and noted that enterprises focused on foreign markets were more likely to implement quality standards and certification, which increased their competitiveness. B. Aibar-Guzmán *et al.* (2022) investigated the role of venture financing in agribusiness and found that investments in start-ups developing agrotechnological solutions were growing, but the lack of venture capital in the region remained a serious problem. R. Karabassov (2024) reviewed the prospects of organic agriculture and found that, despite the high demand for environmentally friendly products, farmers faced barriers such as complex certification and high initial costs. F. Carlucci *et al.* (2021)

investigated the impact of logistics infrastructure on the efficiency of agribusiness and concluded that the lack of modern storage facilities and processing plants significantly limited the ability of farmers to enter foreign markets. They noted that regions with developed logistics demonstrated higher profitability of agricultural production by reducing product losses and optimising supply chains.

Thus, previous studies have shown that the sustainable development of agribusiness depends on a combination of technological innovations, sound government regulation, and the adaptation of successful global practices to regional conditions. Despite a wide range of research in the field of business models of the agro-industry, a number of important aspects remain insufficiently studied. In particular, there is no comprehensive analysis of the adaptation of global business models to the specifics of Kazakhstan and Central Asia, considering climatic, economic, and institutional factors. The mechanisms for integrating farms into international supply chains have also not been fully explored, and the impact of digital technologies and innovative financial instruments on the sustainability of agribusiness requires further investigation.

The purpose of the study was to analyse effective business models of the agro-industrial sector in Kazakhstan and Central Asia, considering regional factors and technological capabilities. The objectives of the study were to conduct a comparative analysis of existing agribusiness business models in Kazakhstan and Central Asia, assess the impact of digital technologies and innovative financial instruments on the effectiveness of agro-industrial enterprises, and develop recommendations for adapting successful global business models considering the specifics of the region.

MATERIALS AND METHODS

The study of business models of agro-industrial enterprises in Kazakhstan and Central Asian countries was based on a comprehensive analysis of macroeconomic indicators, industry trends, and investment activity in the agricultural sector. The study used both quantitative and qualitative methods, which helped to comprehensively assess the current state of agribusiness in the region, identify key factors influencing the choice of business models, and offer recommendations for their adaptation in modern conditions. One of the main research methods was the analysis of statistical data, including indicators of the total volume of agricultural production in Kazakhstan, Uzbekistan, and Kyrgyzstan for 2014-2023. The data were taken from the Bureau of National Statistics of Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), National Statistical Committee of the Republic of Uzbekistan (n.d.) and National Statistical Committee of the Kyrgyz Republic (n.d.). Data for 2024 has not yet been published at the time of research. The statistical and mathematical method using the IBM SPSS Statistics software suite was used for data processing and analysis. Data from national statistical agencies were converted into USD based on the exchange rate for the corresponding years, which provided an objective picture of the scale and trends of the agricultural sector in the region. Using statistical analysis, it was possible to identify patterns of growth and decline, identify the main drivers and risks, and conduct a detailed comparison of the agricultural sectors of the three countries.

The study analysed key strategic documents that determine the development of the agro-industrial complex in Central Asian countries. In particular, the Resolution of the Government of the Republic of Kazakhstan No. 732 (2021), Decree of the President of the Republic of Uzbekistan No. UP-5853 (2019) и Resolution of the Cabinet of Ministers of the Kyrgyz Republic No. 574 (2024). Additionally, a comparative analysis of investment projects in the agroindustry of Kazakhstan and Central Asian countries was conducted. Within the framework of this study, large agricultural projects of strategic importance for the development of the sector were considered. Among them is the "cow-calf" model aimed at developing meat and dairy farming, which is being actively implemented in Kazakhstan and was helping to increase the production of high-quality beef and milk (Food security: The..., n.d.). The study examined the following major agricultural projects: construction of a greenhouse complex in the Turkestan region (Kazakhstan) (EastFruit, 2024a), creation of an agricultural engineering cluster in the Tashkent region (Uzbekistan) (Novikov, 2023), construction of plants for processing pears, nuts and tomatoes in Uzbekistan (Uzbekistan to create..., 2025), construction of agro-logistics facilities in Osh region (Kyrgyzstan), construction of a fruit and vegetable processing plant in Osh region (Kyrgyzstan) (Petchenko, 2023), opening of cold storage facilities and workshops for processing fruits and vegetables in Chui region (Kyrgyzstan) (EastFruit, 2024b).

For an in-depth analysis of business models, the case study method was used using the example of the region's leading agricultural enterprises. In particular, the activities of the Atameken-Agro company were considered in detail (Kazakhstan), one of the largest agricultural groups in the country. The analysis included a study of its financial performance for 2019-2024, allowing it to assess the dynamics of income, net profit, assets, and equity. The data was taken from the company's annual reports (Kazakhstan Stock Exchange, n.d.). An assessment of business sustainability was carried out, fluctuations in financial results and their dependence on external economic factors were revealed. The analysis of financial data provided conclusions about the company's profitability, the efficiency of the business model used, and its adaptability to changes in the agro-sector.

RESULTS

In the agro-industrial complex, the business model plays a crucial role in ensuring the efficiency, sustainability, and competitive advantages of enterprises. It covers strategic aspects of production, resource allocation, value chain creation, and market engagement (Donner *et al.*, 2021). Unlike conventional organisational structures, the business model focuses not only on production, but also on monetisation of the value created. In the agricultural sector, models vary significantly depending on the level of technological development, the scale of farms, climatic and economic conditions (Di Vaio *et al.*, 2020). The classic model of individual farming with family management and minimal use of external resources is still common in developing countries, including Kazakhstan and Central Asia. However, it faces low productivity, limited access to finance, and difficulties entering large markets.

One of the effective alternatives is a cooperative business model, which involves bringing farmers together to share equipment, organise sales, and attract investment. This reduces logistical and operational costs and strengthens farmers' positions in negotiations with purchasers and banks. A striking example is the Polish cooperative Mlekovita, which unites more than 8,000 farmers and supplies products to 160+ countries (Fiore *et al.*, 2020). In Central Asia, this model is limited by institutional distrust and a lack of management mechanisms. The vertically integrated model allows large agricultural holdings to control the entire production cycle, from cultivation to processing and marketing of products. This reduces transaction costs and improves quality control. An example is Arla Foods, Europe's largest dairy producer, which unites over 12,000 farms, with its own factories and logistics. The products are shipped to more than 100 countries (Hansman *et al.*, 2020). The disadvantage of the model is its high capital intensity and organisational complexity.

Digital business models are becoming increasingly relevant. These include platform solutions, the use of big data and precision farming technologies. This allows predicting the harvest, optimising the use of resources, and reducing costs. For example, the Swedish Dataväxt platform provides tools for soil analysis and crop monitoring. With its help, farmers reduced fertiliser and fuel costs by up to 20%, and yields increase by 10-15% (Wallander *et al.*, 2025). Contract farming is based on the conclusion of long-term agreements between farmers and processors or retailers, which ensures the sale of products and reduces market risks. A successful example is Danone's cooperation with farmers across Europe, which provides guaranteed sales at stable prices, allowing producers to confidently plan their activities (Chen & Chen, 2021). Against the background of growing interest in environmentally friendly products, organic agriculture is developing, eliminating the use of chemicals and targeting premium markets. However, the barriers remain the high cost of certification and the need to restructure processes. In Thailand, the Green Net cooperative unites over 1,000 small farmers and undertakes the organisation of collective certification. This reduces costs and increases participants' incomes by 20-30% compared to conventional farming (Yanakittkul & Aungvaravong, 2020).

The choice of the optimal business model in the agroindustry of Kazakhstan and Central Asian countries is determined by a combination of economic, climatic, institutional and technological factors. Each of these conditions creates opportunities and constraints for agribusiness, affecting its strategy, competitiveness and sustainability. One of the key factors is the natural and climatic environment. Kazakhstan and most Central Asian countries are characterised by an arid climate, uneven distribution of water resources and risks of soil degradation. These conditions require the introduction of sustainable business models focused on efficient resource management, such as precision farming and agroecological production methods. The level of economic development and access to finance play an equally important role. Many agricultural enterprises in Kazakhstan and Central Asia face a lack of long-term investments and limited access to credit resources. According to the National Bank of Kazakhstan, as of November 2023, the total volume of bank loans amounted to KZT 12.2 trillion, of which only KZT 453.8 billion was allocated to the agricultural sector, which is about 3.7% of all loans. This situation is compounded by a shortage of collateral from farmers, which makes it difficult to obtain loans (What problems do..., 2023). High interest rates and stringent bank requirements make conventional forms of financing inaccessible to small farmers, forcing them to choose low-cost business models with minimal levels of mechanisation and innovation. However, large agricultural holdings with financial capabilities prefer vertical integration, which allows them to control the entire production and marketing chain.

The next significant factor is the institutional environment and government policy. In Kazakhstan and Central Asia, the agricultural sector is a strategically important area, but government support mechanisms do not always meet the real needs of businesses. Kazakhstan has government programmes to support the agricultural sector, such as the National Project for the Development of the Agro-industrial Complex for 2021-2025, which includes subsidising the purchase of machinery, crop insurance and export support (Resolution of the Government of the Republic of Kazakhstan No. 732, 2021). However, in practice, only about 30% of farmers can benefit from subsidies due to complex bureaucratic procedures. Uzbekistan is demonstrating more active government support for agribusiness, especially within the framework of the Agricultural Development Strategy for 2020-2030 (Decree of the President of the Republic of Uzbekistan No. UP-5853, 2019). The government encourages the development of cluster and contract models through tax incentives and credit lines from the Fund for Reconstruction and Development. Several government programmes aimed at supporting the agricultural sector and farmers are being implemented in Kyrgyzstan. One of the key initiatives is the Programme for the Development of trade and logistics centres in the agro–industrial sector of the Kyrgyz Republic for 2024-2028 (Resolution of the Cabinet of Ministers of the Kyrgyz Republic No. 574, 2024). The purpose of this programme is to increase the competitiveness and export potential of Kazakh agricultural products through the creation and development of international trade and logistics centres.

Another important factor is the level of digitalisation and access to technology. In Central Asian countries, there is a digital divide between large and small producers: agricultural holdings are actively implementing modern technologies, while small farmers are limited in their automation and data analysis capabilities. The development of digital platforms and agrotechnological start-ups is gradually changing this situation, offering new models such as agricultural marketplaces and farm management services (Qin *et al.*, 2022). The implementation of such solutions allows even small farms to increase efficiency, reduce risks and enter new markets. The choice of a business model is influenced by market conditions and global trends. The growing demand for organic products, the development of export destinations and the need for sustainable food products are creating new opportunities for agribusiness in the region. Companies focused on the foreign market are forced to adapt to international quality and safety standards, which requires a restructuring of the business model and investments in certification, processing and logistics (Ahmad *et al.*, 2024). The agro-industrial sector of Kazakhstan and Central Asian countries represents a variety of business models, each of which has its own characteristics, advantages, and limitations due to climatic, economic, and social conditions. Figure 1 shows the total volume of agricultural production in Kazakhstan, Uzbekistan, and Kyrgyzstan.

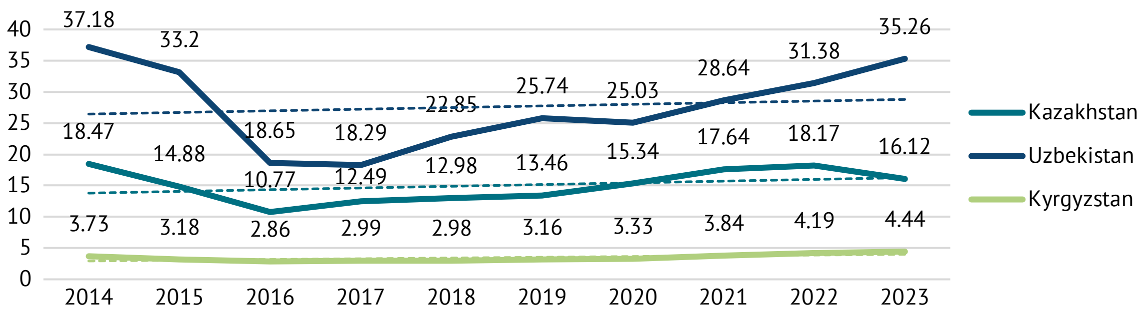

***Figure 1**. The total volume of agricultural production in Kazakhstan, Uzbekistan, and Kyrgyzstan for 2014-2023, billion USD*

***Source:** developed by the author based on data from the Bureau of National statistics of Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), National Statistical Committee of the Republic of Uzbekistan (n.d.), National Statistical Committee of the Kyrgyz Republic (n.d.)*

The total volume of agricultural production in Kazakhstan, Uzbekistan, and Kyrgyzstan for the period from 2014 to 2023 demonstrated a variety of trends related to the economic and climatic conditions in these countries. There was a decrease in volume from 2014 to 2016, followed by an increase until 2023. Kazakhstan as a whole showed an increase from USD 10.8 billion in 2016 to USD 16.1 billion in 2023, due to improved infrastructure and increased investments in the agricultural sector. Uzbekistan, in turn, has demonstrated stable and steady growth, increasing the volume of agricultural products from USD 18.6 billion in 2016 to USD 35.3 billion in 2023, due to the expansion of exports and the introduction of modern technologies in agriculture. Kyrgyzstan, despite its smaller volume, is also showing steady dynamics, starting from USD 2.9 billion in 2016 and increasing to USD 4.4 billion in 2023, indicating a gradual improvement in agricultural performance, albeit at a slower pace compared to neighbouring countries. Regression analysis has shown that the growth rates of agricultural production in Kazakhstan (slope coefficient 0.274) and Uzbekistan (0.261) are at a comparable level. However, there has been a steady upward trend in Uzbekistan over the past four years, which is confirmed by a linear equation with a coefficient of determination ($R^2 = 0.95$). In Kazakhstan, since 2023, there has been a decrease in the total volume of agricultural products, while the trend line corresponds to the logarithmic equation ($R^2 = 0.82$). According to preliminary data for 2024, the volume will amount to USD 15.9 billion. The growth rate in Kyrgyzstan is less noticeable and amounts to 0.119. These results indicate a positive but uneven dynamic of the agro-industrial sector in the region. This may be due to differences in economic policy, the level of investment activity, the degree of implementation of innovative technologies, and natural crises such as water scarcity, especially in Kazakhstan (Fig. 2).

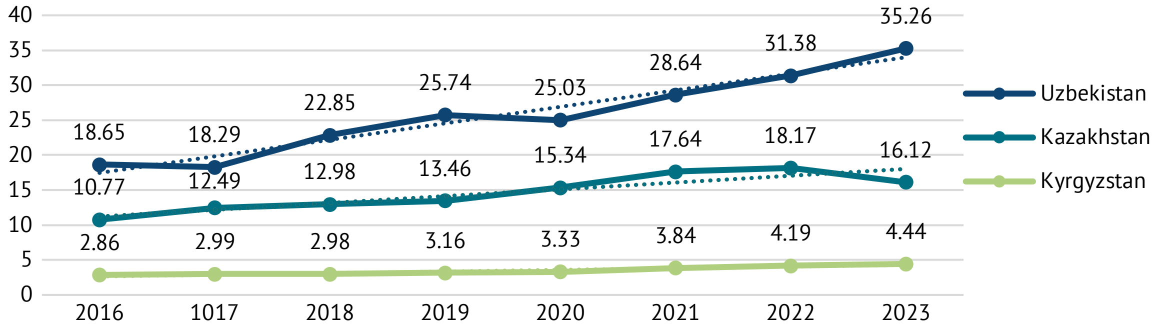

Figure 2*. Trend of the total volume of agricultural production in Kazakhstan, Uzbekistan, and Kyrgyzstan for 2016-2023, billion USD*
Source: *developed by the author based on data from the Bureau of National statistics of Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), National Statistical Committee of the Republic of Uzbekistan (n.d.), National Statistical Committee of the Kyrgyz Republic (n.d.)*

Organic agriculture is one of the rapidly developing business models in Kazakhstan, aimed at producing environmentally friendly products without the use of chemical fertilisers and pesticides. Kazakhstan is experiencing a dynamic growth in the area of land occupied by organic agriculture (Kuandykova *et al.*, 2023). In 2023, the area of organic farmland in Kazakhstan amounted to 191.3 thousand hectares, which is a significant progress compared to previous years (Bureau of National Statistics of Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, n.d.). This sector is supported by the National Project for the Development of the Agro-industrial Complex for 2021-2025, aimed at the development of organic agriculture, which is confirmed by the increase in the number of certified producers and the expansion of the product range (Resolution of the Government of the Republic of Kazakhstan No. 732, 2021).

Exports of organic products from Kazakhstan also showed positive dynamics. In 2022, the volume of exports amounted to USD 35 million, which is 10% more than USD 32 million in 2021, and significantly exceeds the figure of USD 10 million recorded in 2020. Kazakhstan actively exports organic products to the EU, where the main partners are countries such as Germany, the Netherlands, and Poland (Bureau of National Statistics of Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, n.d.). This confirms the high demand for Kazakhstani organic products and indicates a growing interest in environmentally friendly products on international markets. In particular, Kazakhstan is one of the largest producers of organic nuts, cereals and honey, which makes the model of organic agriculture promising in terms of export diversification.

The "cow-calf" model is widespread in Kazakhstan's animal husbandry, in which farmers breed breeding stock, raise calves and then sell them at the age of 6-8 months. This model is focused on meat production and is quite effective in a country with significant pasture lands. The optimal herd size for this model is about 100 animal units, which allows effectively managing resources and minimising costs. Important success factors are the pedigree of livestock and effective management of offspring, which allows for high rates of animal growth and improved meat quality. One of the popular areas is the use of beef cattle breeds such as Angus and Auliekol, which show high results at relatively low costs. However, animal husbandry faces challenges such as high dependence on weather conditions (dry years can lead to a shortage of feed), and difficulties in accessing markets and logistics, especially in remote areas of the country. Resource-limited models also face difficulties in providing veterinary care and livestock feed (Food security: The…, 2024).

In 2024, investments in fixed assets of the agro-industrial complex of Kazakhstan exceeded KZT 1.1 trillion. Of this amount, KZT 919 billion was allocated to agriculture and fisheries, which is 2% more than in the previous year, and KZT 181 billion was invested in food production, which is 15% more than in 2023. As part of the implementation of investment projects, 286 facilities were commissioned in 2024. Together with local executive bodies, a Roadmap has been developed for the implementation of investment projects in the agro-industrial complex for 2025-2027, within which it is planned to implement 632 projects worth KZT 2.4 trillion. 264 projects are scheduled to be commissioned in 2025, 249 in 2026, and 119 in 2027 (EastFruit, 2025). One of the largest projects is the construction of a greenhouse complex in the Turkestan region, implemented with the participation of the Ecokultura company. The total investment in the project is USD 1.3 billion. Within the framework of the project, a greenhouse farm with an area of 500 hectares will be built, which will significantly increase the production of vegetables and fruits, ensuring the domestic market and export supplies. The project is expected to create several thousand jobs and bring significant revenue to the local economy (EastFruit, 2024a).

Agricultural projects are growing in Uzbekistan. One of the largest projects in the agricultural sector is the creation of a cluster of agricultural machinery in the Tashkent region. In August 2023, the first universal tractor was produced within this cluster. The cluster is capable of producing up to 15,000 units of equipment per year, which will significantly improve the logistical support of farmers (Novikov, 2023). In addition, in 2025, it is planned to create plants for growing and processing pears, walnuts, and tomatoes with the support of investors from Italy (Uzbekistan to create..., 2025). Investments in the agro-industrial sector intensified in Kyrgyzstan in 2023. It is planned to implement projects for the construction of agro-logistics facilities in Osh region. A fruit and vegetable processing plant worth KGS 6.5 million will be built in the village of Kok-Zhar, Nookat district. A fruit juice production plant with investments of KGS 14.6 million will be opened in the Kulatov rural district. In addition, cold storage facilities for fruits and potatoes of various capacities will be created in the region. Moreover, in 2023, a new cold storage facility was opened in the village of Japalak, Osh region, built with the support of the United States Agency for International Development and the local Eco Azyk enterprise. The cost of the equipment amounted to KGS 6.9 million, and the warehouse is capable of freezing and storing up to 300 tonnes of fruits and berries for the domestic and foreign markets (Petchenko, 2023). In 2024, a fruit and vegetable processing plant in the Chui region, focused on the production of frozen products, was launched with investments of USD 20 million. This plant will help increase exports and create additional jobs in the region (EastFruit, 2024b). Table 1 shows the differences between business models in the agro-industrial sector of Kazakhstan, Uzbekistan, and Kyrgyzstan.

***Table 1**. Comparative effectiveness of different business models in the agro-industrial sector of Kazakhstan, Uzbekistan, and Kyrgyzstan*

Business model	Kazakhstan	Uzbekistan	Kyrgyzstan
Cooperative model	As of 2023, about 1,200 agricultural cooperatives have been registered, but only 35% of them are actively operating. Main problems: poor coordination and low motivation of farmers	In 2022, more than 300 cooperatives were supported through the subsidy programme, especially in the Andijan and Ferghana regions. Subsidies of up to 30% of the cost of the equipment are provided.	By 2023, about 150 cooperatives have been created, but only 20% are registered as a legal entity. There is no clear legislation
Vertical integration	Atameken-Agro is an agroholding with a full cycle from grain cultivation to export. Manages 450 thousand hectares of land, exports to 7 countries	It is used in the textile industry: a cluster in Namangan region processes up to 100 thousand tonnes of cotton per year. Tomato and fruit processing clusters are also actively developing.	Vertical models are developing slowly. In 2023, 4 vegetable processing plants were opened in Osh and Chui regions. Investment volume – up to USD 30 million
Digital platforms and precision farming	The Digital Village project is being implemented. Drones and sensors are used in the pilot areas of the North Kazakhstan region and the Almaty region. Implementation at the level of 5-7% of farms	Implementation in greenhouses (Tashkent region). About 100 enterprises use digital climate and irrigation monitoring	Usage is limited. Less than 2% of farms use digital tools. Main reason is the lack of personnel and investments
Contract farming	Operates in the grain sector. KAZAGRO estimates that only 10-12% of contracts are of a long-term nature. Problems with their legal support	The cotton sector covers more than 80% of small producers. State programme guarantees the price and sales	At the initial stage. There are pilot agreements with Turkish and Chinese processors. An example is contracts for the supply of organic greens from the Chui region
Organic farming	In 2023, 191.3 thousand hectares of organic land were registered. Products are exported to the EU. Main barriers are certification (USD 2,000-3,000 per year)	Production of organic dried fruits and nuts (Samarkand, Bukhara). More than 50 farmers are certified. Export to Germany and China	Market is forming. About 20 farms with an organic profile have been registered. There is no government support for certification

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

Vertical integration among large agricultural holdings is the most effective in Kazakhstan, while the cooperative model and digital solutions are developing slowly. In Uzbekistan, government support plays a key role in the success of cooperatives and contract farming, and in attracting investments in agricultural processing. In Kyrgyzstan, agribusiness remains less structured, but promising projects in processing and organic agriculture are emerging. These differences are explained by the different levels of government regulation, investment attractiveness, and institutional environment in each country. Atameken-Agro is one of the largest agricultural holdings in Kazakhstan and an example of successful implementation of a comprehensive business model in the agro-industrial sector of the country. Based on the principles of vertical integration, the company covers the entire cycle of agricultural production, from growing crops to processing and marketing products. This allows the company not only to control the quality of its products at all stages, but also to optimise costs, which is an important competitive advantage. Table 2 shows the main financial indicators of the company.

***Table 2**. Main financial indicators of Atameken-Agro for 2019-2024, million KZT*

Year	2019	2020	2021	2022	2023	2024 (9 months)
Income	26,768	28,599	41,646	54,608	44,662	22,343
Net profit	655	15,189	2,253	18,204	-10,796	11,031
Assets	73,676	84,932	90,806	111,896	107,795	132,464
Own capital	2,984	16,884	19,167	33,290	23,127	37,501

***Source:** developed by the author based on data from Kazakhstan Stock Exchange (n.d.)*

In the period from 2019 to 2022, the company observed steady revenue growth, which is confirmed by an increase from KZT 26.7 billion in 2019 to KZT 54.6 billion in 2022. However, in 2023, revenues decreased significantly to KZT 44.7 billion, which may be due to external economic or climatic factors that affected production. Net profit also showed positive results in 2020 and 2022, but in 2023 a loss of KZT 10.8 billion was recorded, which requires additional analysis of the reasons for this decline. In 2024, the company returned to profit (KZT 11 billion), which indicates a possible stabilisation of the financial situation. The company's assets and equity, despite fluctuations in income and profit, show steady growth, which confirms the company's long-term development strategy and ability to attract investments and strengthen its financial position. Atameken-Agro's business model is based on the principles of integration and scalability. The company actively uses resources to create large agricultural complexes, which include agricultural production, processing and logistics. By 2025, Atameken-Agro is processing tens of thousands of hectares of land where the main crops are grown – wheat, corn, barley, oilseeds, and fodder plants. In addition, the company is developing livestock production, including dairy and meat farming. The company has about 500 employees, the company's land bank is 58.6 thousand hectares of arable land and 27 thousand hectares of pastures.

The company's business model features a focus on process automation and the introduction of innovative technologies in agriculture. The use of high-tech equipment for tillage, sowing, and harvesting can significantly increase productivity and product quality. It also helps the company to optimise production costs by reducing dependence on human labour, which is often one of the most expensive factors in agriculture. Since 2018, the company has begun the process of full digitalisation, cooperating with the Agrostream LLP to implement an analytical automated information system. This allowed optimising processes such as monitoring the operation of machinery in the field, grain accounting, crop planning, and fertilisation. The implementation of the system has led to significant results: in 2019, one of the holding's farms, the Shatilo & K LLP, set a record for winter wheat yields of 71.4 hwt/ha, with an average yield of 50 hwt/ha. The company is equipped with modern machinery, including sowing complexes with CLAAS tractors and 18 m wide seed drills. In 2022, CLAAS Trion 730 combine harvesters, Claas Xerion Leb 5000 sprayers, haymaking equipment, and baling trucks were purchased. On average, one sowing complex processes about 2 thousand hectares per day.

Another key component of Atameken-Agro's business model is the sale of products through its own distribution channels and participation in processing, which also contributes to an increase in added value at each stage of the production cycle. The company not only sells raw agricultural raw materials, but also creates processed products such as flour, cereals, and meat products, which significantly expands its market opportunities and increases profitability. Atameken-Agro has switched to the use of liquid fertilisers (liquid complex fertilisers and carbamide-ammonia mixture), which are applied before sowing, tillering, and bulking. Micro fertilisers such as sulphur, potassium-phosphorus, and boron are also used. For plant protection, preparations from various manufacturers are used, including the herbicide Select from United Phosphorus Limited, which is effective against weedy grass vegetation. However, despite numerous successes, the vertical integration model requires significant capital investments and resources. High initial investments in agricultural machinery, infrastructure, and processing facilities pose a risk to businesses in the face of volatile commodity prices and fluctuating foreign markets. On the other hand, the company actively enjoys government support in the form of subsidies, grants and tax incentives, which helps to reduce financial burden and increase economic sustainability.

Atameken-Agro company is a vivid example of the successful implementation of a comprehensive business model in the agro-industry of Kazakhstan.

Vertical integration, the use of innovative technologies and a focus on processing agricultural products allow the company to compete effectively in the market and ensure production growth. However, in order to maintain its competitiveness in international markets, the company must continue to develop new technologies and effectively manage the risks associated with economic instability and external factors. The choice and adaptation of a business model for an agricultural enterprise in Kazakhstan and Central Asia should be based on several key factors: natural and climatic conditions, market demand, access to finance, the level of technological development, and government support. Considering these aspects, several strategic recommendations for the formation of sustainable and profitable business models can be identified. One of the most promising ways for agricultural companies in the region is vertical integration, involving control of all stages of production: from growing crops and livestock to processing, logistics, and sale of the final product. This is especially true for Kazakhstan, where most agricultural products are exported in unprocessed form. For example, instead of simply growing wheat, it is advisable to develop the production of flour and pasta, which increases the added value. Companies can also integrate animal husbandry and crop production, effectively using production waste (straw, cake) as feed.

Another promising area is organic agriculture, which is gradually gaining popularity in global markets. For the successful implementation of this business model, it is advisable to create cooperatives that unite small farms for joint certification and access to international markets, and introduce government support mechanisms, such as subsidising the transition to organic farming. In addition, it is necessary to develop a logistics and export system so that farmers can receive a premium price for environmentally friendly products. Modern agribusiness cannot function effectively without the introduction of digital technologies. The introduction of management systems helps to analyse data on soil, climate, fertilisers, and automatically adjust the processes of sowing and irrigation. In addition, the development of yield forecasting programmes helps to minimise risks when planning production and sales. Automated irrigation systems, especially in conditions of water scarcity in Central Asia, can also become an important tool for improving efficiency. The export potential of the agricultural sector in Kazakhstan and Central Asian countries remains high, but requires the adaptation of business models to international requirements. To increase export efficiency, it is necessary to develop deep processing of products, creating added value and reducing dependence on fluctuations in raw material prices. Signing long-term contracts with foreign buyers will help to minimise price risks, and participation in international exhibitions and trade missions will expand the sales market beyond traditional destinations such as China and the EU.

Special attention should be paid to cooperation between small and medium-sized farms, since Central Asia is still dominated by small farms, which find it difficult to compete with large agricultural holdings. One of the solutions may be the creation of agro-industrial hubs – clusters that bring together farmers, processors, and logistics companies. This model makes efficient use of the shared infrastructure, including elevators, refrigerators, and storage facilities, and facilitates access to subsidies and credit programmes. In addition, cooperation improves the position of producers when concluding contracts with retailers and exporters, allowing small farms to receive more favourable sales conditions. Climate change and risk management are playing an increasingly important role in the development of the region's agribusiness. Central Asia is a region with a high level of climate risks, including droughts, sudden temperature changes, and water scarcity. To minimise losses, agricultural companies should switch to drought-resistant varieties of agricultural crops and adapted farming methods, and actively use crop insurance. In conditions of water scarcity, investments in drip irrigation and water-saving technologies are especially important, which will not only reduce water consumption, but also increase crop yields. Business development requires significant investments, but access to loans and external investments remains limited. One solution is to develop public-private partnerships, especially in infrastructure projects related to logistics and processing. Attracting foreign investors through the creation of joint ventures with international agricultural companies may also be a promising area. It is important to consider the potential of green finance by attracting investments in organic farming and sustainable farming projects, which will not only modernise production, but also meet global trends in the field of ecology and sustainable development.

Thus, the choice and adaptation of a business model for agricultural enterprises in Kazakhstan and Central Asia should be based on the diversification of production, the introduction of digital technologies, the development of export potential, cooperation, and sustainable farming methods. Companies focused on innovation and efficient resource management will be able to increase their competitiveness both regionally and internationally.

DISCUSSION

The agro-industrial complex is an important part of the economies of Central Asian countries such as Kazakhstan, Uzbekistan, and Kyrgyzstan. In these countries, agriculture is the main source of income for a significant part of the population. An analysis of business models in the agro-industries of Kazakhstan, Uzbekistan, and Kyrgyzstan has shown that the countries of the region are actively developing various areas of agricultural production and processing, focusing on both the domestic market and exports. It has been revealed that the main drivers of the sector's growth are investments in infrastructure, the introduction of modern technologies and government support. The external economic situation has a significant impact on the development of the agro-industrial sector in Central Asia. Kazakhstan, Uzbekistan, and Kyrgyzstan are actively developing exports, but simultaneously remain vulnerable to external economic factors such as fluctuations in world prices for agricultural products, changes in exchange rates, and trade barriers. For example, rising prices for agricultural products or a change in demand for certain goods can significantly affect the profitability of agricultural projects (Bulgakov *et al.*, 2020). In this context, the creation of new business models aimed at risk diversification and the search for new markets is becoming an important step in strengthening the economic stability of the region. M. Donner *et al.* (2020) investigated the sustainability of various business models in agriculture and concluded that the most stable models are based on the integration of agricultural production and processing. In their opinion, closed cycles (for example, the production and processing of dairy products in one holding company) provide greater resilience to economic crises. G. Berti (2020), in turn, considered the principle of vertical integration, when the production of raw materials and their processing take place within the same holding company. Farms with their own processing plants can adapt more quickly to market changes and minimise the impact of fluctuations in raw material prices (Mamchur *et al.*, 2025). The current study partially confirmed this conclusion, as processing plants are also actively developing in Central Asia. However, commodity-based export models still prevail in the region, which makes them vulnerable to changes in the external environment.

Government support plays a key role in the development of the agricultural sector. Kazakhstan, Uzbekistan, and Kyrgyzstan have various government programmes aimed at stimulating agricultural production and attracting investments. However, despite the existing programmes, there is a need to improve legislation and strengthen support mechanisms for agricultural producers, especially small and medium-sized farmers. Problems with access to finance, insufficient infrastructure, and low willingness to adopt innovative technologies remain important barriers to growth (Hnatyshyn *et al.*, 2025). D. Laborde *et al.* (2021) analysed the impact of government subsidies on agricultural production growth. Their study showed that subsidies increase agricultural productivity, contribute to the modernisation of production, and reduce poverty among farmers. Current results also pointed to the importance of government regulation, but in Central Asia, support for farmers is less systemic.

One of the key aspects is the importance of introducing innovative business models into agricultural production. Examples from Kazakhstan, where organic farming projects are developing, and projects to introduce digital technologies into the agricultural sector, highlight the enormous potential for improving productivity and product quality (Akhmet *et al.*, 2025). In Uzbekistan and Kyrgyzstan, projects to create agro-logistics facilities and process agricultural products also confirm the high prospects of these business models. The study by R. Zhong *et al.* (2022) focused on the impact of digital technologies such as artificial intelligence, automation, and drone monitoring on agricultural efficiency. The researchers concluded that the introduction of digital solutions can increase productivity and reduce operating costs. The study by E. Duncan *et al.* (2021) examined cases of successful implementation of digital technologies in developed countries such as the USA and Germany, where agricultural enterprises widely use precision farming, automated irrigation systems, and drones to monitor soil and crop conditions. The conclusions partially coincided with the results of the current study, which also highlighted the importance of digitalisation. However, the use of such technologies remains limited in Central Asia due to a lack of investment and a low level of technical training.

Attracting foreign investment is one of the most important factors for the development of the agro-industrial sector in Central Asia. Projects with the participation of foreign investors are being actively implemented in the countries of the region, which allows improving the technological base and attract modern technologies (Nurekenova *et al.*, 2022). For example, the construction of greenhouse complexes in the Turkestan region of Kazakhstan and the creation of a machine-building cluster in Uzbekistan with the participation of international companies contribute to increasing production capacity and diversifying rural production. However, dependence on foreign investments can also be risky, especially in the context of global economic instability. S.R. Zeytoonnejad Mousavian *et al.* (2023) investigated the mechanisms of attracting foreign investment in the agricultural sector and came to the conclusion that the key success factors are a stable legislative framework, the availability of infrastructure, and partnership with international corporations. The current study has confirmed the importance of foreign investment, but there are serious barriers in Central Asia, such as complex bureaucratic procedures and an unstable economic environment, which is not always considered in the global context.

K. Đurić *et al.* (2021) investigated the impact of the integration of agricultural enterprises into cooperative associations on their financial stability and productivity. In their analysis, they compared the experience of cooperative agriculture in the EU, where small farms combine into agricultural cooperatives to share machinery, storage facilities, and distribution channels. The current study also addressed the topic of cooperative business models in Central Asia, but regional specifics showed that their distribution was limited. The development of agricultural production should take into consideration environmental and social aspects. It is important that business models in the agro-industry not only contribute to increased production, but also ensure the sustainable use of natural resources and improve the living conditions of local residents (Sadovoy *et al.*, 2023). In Kazakhstan, for example, projects in the field of organic agriculture actively contribute to raising environmental awareness and producing environmentally friendly products. In Kyrgyzstan and Uzbekistan, there is also a tendency to improve social infrastructure based on agricultural projects, which contributes to job creation and improvement of living conditions in rural areas. T.C. Durham and T. Mizik (2021) investigated the impact of organic agriculture on the economies of countries actively developing this sector. The researchers concluded that the development of organic agriculture increases the export value of products, helps to preserve soil fertility and reduces environmental pollution. However, W. Łuczka and Kalinowski (2020) noted that the transition to organic production requires significant investments, especially for product certification, technology adaptation, and market development. The current study also highlighted the potential of organic agriculture in Kazakhstan, but unlike in more developed countries where demand for environmentally friendly products is steadily growing, the domestic organic market in Central Asia remains underdeveloped.

G. Özaydın and M. Direk (2022) investigated the impact of agricultural sector development on rural regions and concluded that successful agricultural projects contribute to reducing migration from rural areas and increasing the standard of living of the local population. The current study also highlighted the social role of the agro-industry, but rural migration remains a major problem in Central Asia, despite the development of agribusiness. This difference can be explained by the fact that the region still lacks social infrastructure and jobs with competitive salaries. Thus, the agro-industrial sector in Central Asia has significant potential for growth, but in order to realise this potential, it is necessary to effectively address existing problems and develop sustainable business models that will contribute to the long-term growth and prosperity of the region. Research confirmed the importance of key factors such as technological development, investment, and government support, but revealed some differences.

CONCLUSIONS

As a result of the conducted research, several key conclusions were drawn regarding business models in the agroindustry of Kazakhstan and Central Asian countries. The study confirmed the existence of a variety of agribusiness models specific to the region, each of which has its own advantages and disadvantages due to socio-economic conditions, the level of technological development and natural factors. Analysis of statistical data showed that the total volume of agricultural production in Kazakhstan in 2023 amounted to USD 16.12 billion, in Uzbekistan – USD 35.26 billion, and in Kyrgyzstan – USD 4.44 billion. Although these indicators are growing compared to economic years, the dynamics is unstable, which indicates the influence of external economic factors and the need to adapt business models to changes in the market. The study found that the Central Asian countries are dominated by commodity-based business models focused on the export of agricultural products. For example, in Kazakhstan, exports of organic products in 2022 reached USD 35 million, which is 10% more than in 2021 (USD 32 million), but the domestic organic market remains underdeveloped. This is confirmed by the limited volume of the processing industry: although efforts are being made to build factories, such as a processing complex in the Osh region of Kyrgyzstan (USD 30 million in investments), the scale of transformation remains limited.

The financial condition of a large agricultural company in Kazakhstan, Atameken-Agro, was also analysed. Significant changes in net profit are indicated: from KZT 655 million in 2019 to KZT 18.2 billion in 2022, then a drop to KZT -10.8 billion in 2023 and a subsequent increase to KZT 11 billion in 9 months of 2024. This causes agribusiness volatility and the need to adapt to market changes. However, the company's assets grew steadily, which indicates the expansion of the business, despite financial fluctuations. Digitalisation of agriculture, despite its potential benefits, faces a number of obstacles. In Central Asia, the introduction of technologies such as drone monitoring and automation remains limited due to a lack of investment and a low level of technical training. However, the practice of using digital solutions is already actively implementing precision farming systems, for example, in Kazakhstan and Uzbekistan.

In addition, the analysis of complex projects showed the active development of the agro-industrial sector. Large-scale projects are being implemented in Kazakhstan, such as the construction of a thermal complex in the Turkestan region with investments of USD 1.3 billion, which will significantly increase the production of vegetables and fruits. Uzbekistan has a developing cluster of agricultural machinery, which introduced the first universal tractor in 2023, with a capacity of 15,000 units per year. A fruit and vegetable processing plant in the Chui region, focused on the production of frozen products, has been launched in Kyrgyzstan with investments of USD 20 million. Thus, in order to increase the sustainability of agribusiness in Central Asia, it is necessary to focus on the diversification of business models, the development of processing capacities, the introduction of digital technologies, and the expansion of domestic consumption of products. In the future, it is advisable to conduct a more detailed analysis of the impact of digitalisation on the effectiveness of agribusiness and to investigate the sustainability of various investment strategies in the changing economic climate of the region.

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CONFLICT OF INTEREST

None.

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Обґрунтування бізнес-моделей в агропромисловості: кейс Казахстану та країн Центральної Азії

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Анотація. Робота спрямована на вивчення ключових факторів, що впливають на вибір та ефективність бізнес-моделей в агропромисловому секторі Казахстану та Центральної Азії. Методологія дослідження включала аналіз статистичних даних, порівняльний аналіз бізнес-моделей, а також оцінку впливу зовнішньоекономічних і кліматичних факторів на стійкість агробізнесу в регіоні. Під час роботи було вивчено та класифіковано наявні бізнес-моделі агропідприємств, виявлено їхні ключові особливості та чинники, що впливають на їхній вибір. Проведено аналіз динаміки загального обсягу сільськогосподарського виробництва в Казахстані, Узбекистані та Киргизстані з перерахунком показників у долари США, що дало змогу об'єктивно оцінити масштаби та тенденції розвитку агросектору. Загальний обсяг сільськогосподарського виробництва в Казахстані 2023 року склав 16,12 млрд доларів США, в Узбекистані – 35,26 млрд доларів США, а в Киргизстані – 4,44 млрд доларів США. Детально розглянуто інвестиційні проєкти в агропромисловості, включно з великими вкладеннями в тепличні комплекси, переробку сільгосппродукції та цифровізацію галузі. На прикладі компанії «Атамекен-Агро» проведено детальний фінансовий аналіз, виявлено коливання прибутковості, вплив економічних чинників на прибутковість і стійкість бізнесу. Отримані результати показали, що ключовими драйверами зростання агропромисловості регіону є цифровізація, впровадження точного землеробства, вертикальна інтеграція, а також орієнтація на експорт переробленої продукції. На основі виявлених тенденцій розроблено рекомендації щодо вибору та адаптації бізнес-моделей для агрокомпаній Казахстану і Центральної Азії. Серед них – розвиток кооперативних структур, впровадження стійких агротехнологій, підвищення інвестиційної привабливості сектору та диверсифікація виробництва. Висновки роботи підтвердили необхідність комплексного підходу до розвитку агробізнесу в регіоні, де цифровізація, державна підтримка та інтеграція в глобальні ринки відіграють вирішальну роль у підвищенні конкурентоспроможності сільськогосподарських підприємств

Ключові слова: інвестиційні проєкти; регіональний розвиток; інноваційні технології; сільське господарство; економічний розвиток

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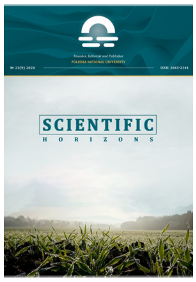

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The impact of digital platforms and artificial intelligence capabilities on product sales by small farms

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Abstract. The aim of the study was to assess the impact of digital platforms and artificial intelligence technologies on the sales efficiency of agricultural products by small farming households in Kazakhstan, compared with the experience of Central Asian countries and global practices. The study was conducted from March 2023 to February 2025 in 14 regions of the Republic of Kazakhstan using a comprehensive methodology, including a stratified random sample, structured interviews with

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managers of 324 small farming households (with up to 10 employees and an annual turnover not exceeding 30 million tenge), and 27 expert interviews with representatives of 8 digital platforms (AgroSmart.kz, Egistic, DigiField, QazFarm, AgroMap, Agroplatforma.kz, Agro.kz, Farm.kz). ANOVA, regression, and correlation analysis were performed, as well as machine learning methods (Random Forest, XGBoost) used for developing a predictive model. Statistical data analysis showed that the introduction of digital tools enabled an average sales increase of 27.3% with a reduction in intermediary costs of 18.6%. The highest efficiency was demonstrated by households using a combination of local trading platforms (AgroSmart.kz, Agro.kz) and specialised demand forecasting services. Regional analysis revealed significant differences in the level of digitalisation: in southern regions (Turkestan, Zhetysu), 64.2% of farmers regularly used at least two digital sales channels, whereas in the northern regions (Kostanay, North Kazakhstan), this figure was only 38.7%. The predictive model developed using machine learning algorithms showed a forecasting accuracy for seasonal demand fluctuations of 87.4% when tested on historical data from 2018-2023. The pilot implementation of the developed recommendations in the activities of 23 small farming households resulted in an average revenue increase of 31.5% and a 43.2% reduction in time spent searching for buyers. The study proved the economic feasibility of introducing digital tools into the practice of small farming households in Kazakhstan, even with a limited digitalisation budget

Keywords: small farming households; agro-industrial complex; digital platforms; sales efficiency; demand forecasting model; Kazakhstan; machine learning

INTRODUCTION

Digital platforms represented a key tool for transforming agri-food systems by expanding product sales channels, enabling direct interaction between producers and end consumers, and reducing intermediary costs. In Kazakhstan, small farming households accounted for 75% of all agricultural producers and provided 36.4% of the gross output of the agricultural sector, which formed 5.1% of the country's GDP (Organisation for Economic Co-operation and Development, 2023). At the same time, according to data from the Ministry of Agriculture of the Republic of Kazakhstan (n.d.), due to inefficient sales channels and lack of digitalisation, small farms lost up to 28% of potential profits annually, which amounted to around USD 1.2 billion on a national scale. The platform model aggregated information on demand, prices, and market trends, enabling prompt managerial decisions on product sales (Adamkulova *et al.*, 2025). As noted by A. Oliveira-Jr *et al.* (2020), the implementation of digital tools allowed farmers to shorten the chain of intermediaries and increase sales margins by 15-23% in developing countries. Studies by A. Glaros *et al.* (2023) indicated potential income growth for farmers through improved market access and optimisation of production processes. According to the Food and Agricultural Organisation (2022), digitalisation could reduce product losses during transportation and storage by 30-45%.

Barriers to digitalisation included limited internet access in rural areas, insufficient digital literacy, and the absence of a specific law on e-commerce (Oleksandrenko & Levis, 2023). According to the Organisation for Economic Co-operation and Development (2023), in 2020, only 7.8% of medium and large agribusinesses in Kazakhstan had fixed broadband internet, which was significantly lower than in developed countries (65-80%). To overcome these barriers, the Digital Kazakhstan State Program (2018) created a system of support measures for farmers undergoing digital transformation, including educational programmes and infrastructure development. Studies by M. Bampasidou *et al.* (2024) pointed to the critical importance of bridging the "digital divide" through educational programmes for the new generation of agricultural producers. The importance of addressing this issue was also confirmed in the work of T. Soma and B. Nuckchady (2021), who emphasised the need for a balanced approach to communicating the benefits and risks of digital agricultural technologies.

In Kazakhstan, projects for implementing digital technologies in the agricultural sector were actively supported at the state level (Akhmet *et al.*, 2025). As noted in the study by D.A. Kaldiyarov *et al.* (2023), the creation of a digital innovation ecosystem in the agro-industrial complex was one of the priority areas for the country's economic development. The software solutions developed to support the agro-industrial complex included both precision agriculture technologies and platforms for optimising product sales (Sizova, 2022). Sarsen Amanzholov East Kazakhstan University implemented a project to develop methods for supporting agro-technological decision-making based on precision agriculture technologies. The project envisaged the creation of an integrated IT platform for agricultural production. The research was conducted using specialised equipment: an agrological drone with infrared cameras for multispectral field imaging and a portable weather station for collecting real-time meteorological data. The aim of the study was to assess the impact of digital platforms and artificial intelligence technologies on the effectiveness of agricultural product sales by small farming households in Kazakhstan.

LITERATURE REVIEW

The digitalisation of the agricultural sector and the implementation of digital platforms for small farming households were studied by researchers in various countries around the world. The analysis of scientific literature revealed several directions of theoretical understanding of these processes. B. Basso and J. Antle (2020) proposed a conceptual framework for designing sustainable agricultural systems using digital technologies. The authors identified three components of digital agriculture: data collection systems, analytical tools for transforming data into knowledge, and decision support systems. L. Prause *et al.* (2020) examined digitalisation in the context of forming a third food regime, exploring the impact of digital technologies on power relations in food systems. O. Visser *et al.* (2021) conducted an analysis of the accuracy and risks of digital agriculture, introducing the term "imprecision farming" to describe situations where inaccurate data led to suboptimal decisions. S. Hackfort (2023) studied the phenomenon of corporate lock-ins and the impact on the digital agriculture landscape, showing how companies could limit small farmers' ability to implement various technological solutions.

M. Lacoste *et al.* (2021) developed a methodology for conducting on-farm experimentation. The authors highlighted the need for co-creation of knowledge by farmers, researchers, and other stakeholders. I. Dobre *et al.* (2021) carried out a quantitative analysis of the relationship between farm size and the level of digitalisation, finding that small farms could receive proportionally greater benefits from certain types of digital solutions for marketing and product sales. Y.-Z. Hong and H.-H. Chang (2020) examined the impact of digitalisation on the objective and subjective wellbeing of rural households in China. The authors found that the introduction of digital technologies influenced both the economic performance of farms and farmers' perception of the quality of life. A. Sharma and M. Singhai (2023) assessed the impact of agricultural sector digitalisation on farmers and the economy of India. T. Dibbern *et al.* (2024) identified key factors that facilitated and hindered the adoption of digital agriculture technologies, studying the role of education, accessibility of technical solutions, and the availability of supporting infrastructure.

The integration of digital technologies into existing agricultural practices was studied by N.J. Galvão *et al.* (2022), who developed a portable automatic sensor system for sustainable precision agriculture. M. Tranchina *et al.* (2024) examined limiting factors and prospects for digitalisation in the context of agroforestry. M. Bampasidou *et al.* (2024) proposed a strategy to overcome "digital divides" through harnessing the potential of higher education to train specialists in digital agriculture. A comparative analysis of agricultural digitalisation processes in developed and developing countries revealed significant differences in approaches and outcomes (Studinska & Studinski, 2023). For instance, the study by A.A. Chandio *et al.* (2024) found that agricultural digitalisation in China followed a different path than in European and North American countries. In particular, the authors noted that China prioritised the integration of digital systems into existing collective farming structures, whereas Western countries focused on individual solutions for farmers. However, despite these differences, K. McGrath *et al.* (2023) observed common trends related to the transformation of social and economic relations under the influence of digitalisation, including changes in employment structures, redistribution of added value in supply chains, and the formation of new models of interaction between producers and consumers.

Methodological approaches to measuring the effectiveness of digital technology implementation in agriculture constituted a separate research area. A. Oliveira-Jr *et al.* (2020) developed an indicator system to assess the performance of IoT solutions in rural areas of Africa, including not only economic indicators but also socio-environmental sustainability parameters. K.A. Sedek *et al.* (2021) proposed a multi-level model for assessing the effectiveness of electronic marketplaces for agricultural products, taking into account both technical aspects of platform operation and the impact on the market opportunities of small producers. The study by E. Amirova *et al.* (2021) presented a comprehensive approach to evaluating the performance of an agricultural digital platform, including quantitative metrics (transaction volumes, number of users) and qualitative characteristics (user satisfaction, level of trust in the system). I. Tomorri *et al.* (2025) examined the factors, barriers, and impact of digitalisation on the sustainable development of rural areas using regions of Albania as a case study. The authors identified regional differences in the level of digital technology adaptation, caused by both objective factors (infrastructure, proximity to urban centres) and subjective ones (farmers' age, education level, readiness to accept innovation).

In the research of Kazakhstan and Central Asian countries, D.A. Kaldiyarov *et al.* (2023) developed the concept of a digital innovation ecosystem for Kazakhstan's agro-industrial complex. The authors proposed a structural model that included technological, organisational, educational, and regulatory components. M.S. Bauer *et al.* (2024) conducted an analysis of the advantages and reserves for using information technologies in agriculture in Northern Kazakhstan. The economic aspects of digitalisation of Kazakhstan's agro-industrial complex were studied in the work of G.M. Kalkabayeva *et al.* (2023), who analysed the use of digital technologies in financing sustainable development projects. The analysis of agricultural digitalisation research suggested the potential of digital platforms and artificial intelligence technologies for improving the efficiency of product sales by small farming households. At the same time, it was necessary to consider the specific conditions for implementing these technologies, including the level of infrastructure development, the availability of educational resources, state support, and the socio-economic characteristics of regions.

MATERIALS AND METHODS

The study on the impact of digital platforms and artificial intelligence capabilities on the product sales of small farming households was conducted from March 2023 to February 2025 in Kazakhstan, with elements of comparative analysis of the experience of Central Asian countries (Uzbekistan, Kyrgyzstan) and advanced practices of developed countries (USA, Germany, the Netherlands, Israel). At the preparatory stage (March-May 2023), the methodological framework of the study was developed based on a systematic approach to the analysis of the digital transformation of the agricultural sector. A stratified random sampling method was applied to ensure a representative selection of farms, considering region, specialisation (crop/livestock farming), and level of digitalisation. Structured questionnaires for farmers and semi-structured ones for digital platform experts were developed according to the method of N.S. Guest *et al.* (2021). Statistical data from the Bureau of National Statistics (2025) as well as reports of international organisations (Food and Agricultural Organisation, 2022; Organisation for Economic Co-operation and Development, 2023) on digitalisation in the agricultural sector of Central Asia were studied. A pilot test of the research tools was conducted on a sample of 15 farming households in the Almaty region to assess the validity and make necessary adjustments.

At the field stage (June-November 2023), empirical data were collected in 14 regions of Kazakhstan. To ensure representativeness of the sample, 324 small farming households were selected with up to 10 employees and an annual turnover not exceeding 30 million tenge. Structured interviews were conducted with the heads of selected farms to identify barriers, usage experience of digital tools, and to assess the effectiveness. Inclusion criteria were: official registration of the farm at least two years prior, experience in product sales, and minimum use of digital tools for communication. Additionally, 27 expert interviews were conducted with representatives of 8 digital platforms operating in Kazakhstan (AgroSmart.kz, Egistic, DigiField, QazFarm, AgroMap, Agroplatforma.kz, Agro.kz, Farm.kz). For comparative analysis, the experience of Uzbekistan and Kyrgyzstan was studied through a series of online interviews with experts from the Ministry of Innovative Development of Uzbekistan (n = 3) and the Ministry of Digital Development of the Kyrgyz Republic (n = 2). The authors adhered to the principles of the American Sociological Association's Code of Ethic (1997). Global practices were analysed based on reports from the Food and Agricultural Organisation (2022) and the Organisation for Economic Co-operation and Development (2023), as well as scientific publications on agricultural digitalisation in developed countries.

At the analytical stage (from December 2023 to October 2024), the collected data were processed using SPSS 28.0 and NVivo 15 software. For quantitative data analysis, descriptive statistics methods were used: mean values, medians, standard deviations, and frequency distributions were calculated. ANOVA (Analysis of Variance) was applied to determine the significance of differences between groups of farming households based on production specialisation and geographical location, according to Field's methodology. The value was considered statistically significant if the p-value was <0.05. To identify the factors influencing the successful implementation of digital tools, regression analysis of the dependence of sales volume on the intensity of use of various digital tools was carried out based on the methodology of Z.D. Cohen *et al.* (2022). Correlation analysis with t-test was applied to determine the relationships between farm characteristics and the results of digitalisation. For qualitative data, thematic content analysis was conducted following the methodology of V. Braun and V. Clarke (2021), identifying key categories of digitalisation challenges and opportunities in sales. Triangulation of the obtained quantitative and qualitative data was carried out to ensure the reliability of the study's conclusions.

To analyse the capabilities of artificial intelligence in demand forecasting for agricultural products, an experimental model based on machine learning algorithms (Random Forest, XGBoost) was developed in accordance with the methodology of C.E. Hastie *et al.* (2023). The model was trained on historical data on prices, sales volumes, and seasonal demand fluctuations from 2018-2024, provided by the Bureau of National Statistics (2025). Model validation was conducted on a test data set using 5-fold cross-validation, with forecast accuracy assessed using root-mean-square error (RMSE) and mean absolute error (MAE) metrics. At the experimental stage (from November 2024 to February 2025), pilot implementation of the developed recommendations was carried out in 23 small farming households in the Turkestan, Jetisu, and Kostanay regions. Monitoring of changes in sales indicators was carried out using the "before-after" method (Cohen's d effect size). To assess the economic effect of implementing digital tools, the Return on Investment (ROI) calculation methodology proposed by D.B. Phillips *et al.* (2020) and adapted to the specifics of small agricultural enterprises was applied. Both direct effects (increase in sales volume, reduction in intermediary costs) and indirect ones (expansion of sales geography, increased product recognition) were taken into account. Sample representativeness was ensured by observing proportional distribution of small farming households across Kazakhstan's regions, the specialisation, scale of activity, and level of initial digitalisation. The required sample size was calculated with a confidence level of 95% and a margin of error of ±5.3%. The response rate was 78.3% of the initially selected farms.

RESULTS

Analysis of the current state of digitalisation of small farms in Kazakhstan. The results of the field stage of the study were based on a comprehensive analysis of data from structured interviews with managers of 324 small farms in 14 regions of Kazakhstan. The primary information was collected in accordance with the principles of stratified random sampling, which ensured the representativeness of the data with a confidence level of 95% and an error margin of ±5.3%. The application of statistical processing techniques using the SPSS 28.0 and NVivo 15 software packages made it possible to identify the main characteristics of the current state of digitalisation of small farms, presented in Table 1.

***Table 1**. Level of digitalisation of small farms in Kazakhstan by region (n = 324)*

Region	Number of examined farms	Base level (%)	Elementary level (%)	Average level (%)	Advanced level (%)	Index of digital maturity
Almaty	38	40.1	38.5	17.1	4.3	0.34
Zhetysu	26	51.0	34.7	12.2	2.0	0.26
Zhambyl	24	48.7	33.3	15.4	2.6	0.29
Turkestan	42	44.8	36.7	15.4	3.1	0.31
Kyzylorda	18	40.1	38.5	17.1	4.3	0.34
Kostanay	31	51.0	34.7	12.2	2.0	0.26
North Kazakhstan	28	48.7	33.3	15.4	2.6	0.29
Akmola	25	44.8	36.7	15.4	3.1	0.31
Karaganda	22	40.1	38.5	17.1	4.3	0.34
Pavlodar	17	51.0	34.7	12.2	2.0	0.26
East Kazakhstan	20	48.7	33.3	15.4	2.6	0.29
Abai	15	44.8	36.7	15.4	3.1	0.31
West Kazakhstan	10	40.1	38.5	17.1	4.3	0.34
Aktobe	8	51.0	34.7	12.2	2.0	0.26
Average for Kazakhstan	324	48.7	33.3	15.4	2.6	0.29

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

Analysis of the data in Table 1 showed that the largest share of small farms in Kazakhstan (44.8%) are at the basic level of digitalisation, which involves the use of only basic means of communication (mobile communications, messengers) without the use of specialised digital tools for product sales. The initial level, characterised by the fragmentary use of Internet resources to search for customers, was demonstrated by 36.7% of the surveyed farms. Only 15.4% of farmers reached the intermediate level, which implies regular use of at least one digital platform for sales, and the advanced level (systematic use of several digital channels and analytical tools) was recorded in only 3.1% of farms.

A regional analysis revealed significant disparities in the level of digitalisation between the regions of Kazakhstan. The highest digital maturity index scores were observed in North Kazakhstan (0.38), Kostanay (0.37) and Akmola (0.36) regions, which is explained by the more developed digital infrastructure and proximity to the capital region. The lowest index values were found in Kyzylorda (0.20) and Turkestan (0.21) regions, where there are problems with the quality of internet coverage and the availability of digital technologies. Table 2 shows the dependence of the level of digitalisation of small farms on the specialisation.

***Table 2**. The level of digitalisation of small farms in Kazakhstan, depending on the specialisation*

Specialisation	Number of farms	Base level (%)	Elementary level (%)	Average level (%)	Advanced level (%)	Index of digital maturity
Plant growing	187	40.1	38.5	17.1	4.3	0.34
Animal husbandry	98	51.0	34.7	12.2	2.0	0.26
Mixed production	39	48.7	33.3	15.4	2.6	0.29
Total	324	44.8	36.7	15.4	3.1	0.31

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

Analysis of Table 2 showed that farms specialising in crop production demonstrated the highest level of digitalisation (digital maturity index of 0.34), which is associated with the more predictable nature of the production process and the ability to plan sales volumes. Livestock farms showed the lowest level of digitalisation (index 0.26), which is due to the specific nature of the products, requiring special storage and transportation conditions, as well as more traditional sales channels through local markets. Statistical analysis using ANOVA confirmed the significance of the differences between groups of farms with different specialisations ($F = 6.78$; $p = 0.0014$). Further analysis of the factors influencing the level of digitalisation of small farms revealed key barriers to the implementation of digital platforms in product sales practices (Fig. 1).

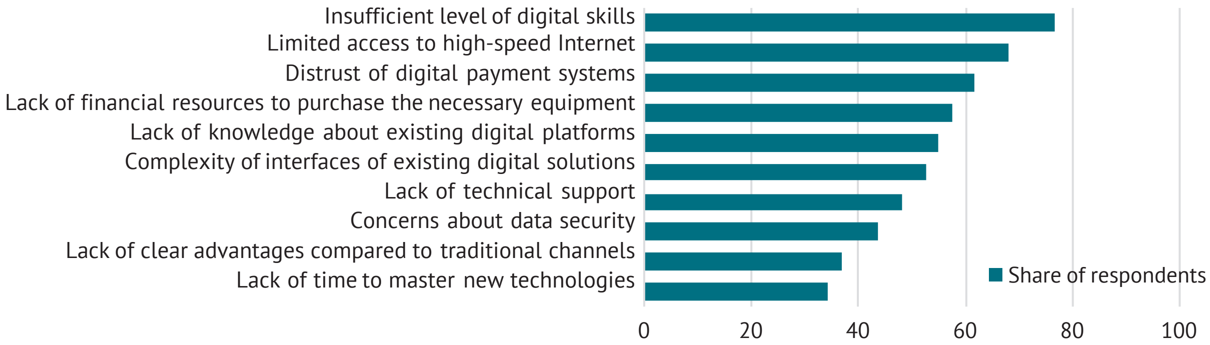

***Figure 1**. The main barriers to the digitalisation of product sales by small farmers*
***Source:** compiled by the authors*

The study showed that the dominant barriers to the digitalisation of sales are the insufficient level of digital skills among farmers (76.5%) and limited access to high-speed internet in rural areas (68.2%). Mistrust of digital payment systems (61.7%) and a lack of financial resources to purchase the necessary equipment (57.4%) also have a significant impact. Spearman's correlation analysis revealed a strong negative relationship between perceived barriers and the digital maturity index of farms ($r = -0.72$; $p < 0.001$), confirming the significance of the identified constraints for the digital transformation process. A comparative analysis with data from Central Asian countries showed that the level of digitalisation of small farms in Kazakhstan (index 0.31) is higher than in Kyrgyzstan (0.24) and Uzbekistan (0.28), but significantly lower than in developed countries: The United States (0.78), Germany (0.72), the Netherlands (0.81) and Israel (0.77). The main difference lies in the systematic implementation of digital tools: while in developed countries 68-74% of farmers use comprehensive digital solutions that integrate several functions (sales, logistics, finance, analytics), in Kazakhstan only 18.5% of farms do so.

Assessment of the effectiveness of using digital platforms for the sale of agricultural products. An analysis of the functioning of digital platforms for the sale of agricultural products was conducted based on data obtained from expert interviews with representatives of eight platforms operating in Kazakhstan, as well as the experience of the use by those farms from the sample that had achieved intermediate ($n = 50$) and advanced ($n = 10$) levels of digitalisation. Table 3 presents a comparative analysis of digital platforms based on key parameters that are important for small farms.

***Table 3**. Comparative characteristics of digital platforms for the sale of agricultural products used by small farms in Kazakhstan*

Platform's name	Quantity of active users from among the small farms	Platform type	Coverage of regions	Commission from transaction (%)	Opportunity of direct sales	Integration with logistics	Availability of analytical tools	Convenience of interface (1-5)	Technical support (1-5)
AgroSmart.kz	78	Marketplace	14 regions	3-5	Yes	Yes	Yes	4.2	4.3
Egistic	32	Information system	10 regions	0	No	No	Yes	3.1	3.8
DigiField	23	Control farm + sales	8 regions	2-4	Yes	No	Yes	3.5	3.2
QazFarm	62	Marketplace	14 regions	4-7	Yes	Yes	Limited	4.0	3.9
AgroMap	19	Information system	12 regions	0	No	No	Yes	3.2	3.0
Agroplatforma.kz	43	Marketplace	11 regions	3-6	Yes	Limited	No	3.8	3.6
Agro.kz	27	Information portal + sales	14 regions	2-3	Limited	No	Limited	3.6	3.4
Farm.kz	16	Marketplace	7 regions	5-8	Yes	Yes	No	3.7	3.1

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

Analysis of the data in Table 3 showed that the most popular platforms among small farms are AgroSmart.kz and QazFarm, which cover all 14 regions of Kazakhstan and offer comprehensive solutions, including direct sales capabilities and integration with logistics services. At the same time, AgroSmart.kz demonstrates the highest ratings for interface convenience (4.2 points out of 5) and technical support quality (4.3 points out of 5), which is critically important for farmers with limited experience in using digital technologies. A comparison with foreign platforms showed that Kazakhstani solutions are inferior to the counterparts from developed countries in terms of functionality, especially in terms of analytical tools and integration with financial services. For example, the American platform FarmersWeb and the German AgrarMarkt offer farmers demand forecasting tools with an accuracy of up to 92%, crop financing and insurance functions, as well as integration with precision farming systems, which is not yet available on most Kazakhstani platforms. To determine the actual impact of digital platforms on the efficiency of product sales, a comparative analysis of the economic indicators of farms with different levels of digitalisation was conducted. The results are presented in Table 4.

***Table 4**. Performance indicators for product sales by small farms in Kazakhstan, depending on the level of digitalisation*

Indicator	Base level (n = 145)	Elementary level (n = 119)	Average level (n = 50)	Advanced level (n = 10)	p-value*
Average sales volume (million tenge/year)	8.2 ± 2.3	14.7 ± 3.6	22.5 ± ± 4.1	28.6 ± 3.8	<0.001
Average margin (%)	18.3 ± 3.6	21.5 ± 3.2	26.7 ± 2.9	31.2 ± 3.1	<0.001
Share of products sold directly to consumers (%)	12.4 ± 5.2	19.8 ± 6.3	37.6 ± 7.1	48.5 ± 6.8	<0.001
Geographical sales coverage (number of regions)	1.3 ± 0.4	2.1 ± 0.6	4.2 ± 0.9	6.3 ± 1.2	<0.001
Average number of regular customers	8.6 ± 2.8	14.2 ± 3.9	23.7 ± 4.4	36.5 ± 6.2	<0.001
Marketing and sales costs (% of turnover)	5.7 ± 1.2	6.9 ± 1.4	8.2 ± 1.5	10.3 ± 1.6	<0.001
Average time from production to sale (days)	12.4 ± 4.7	8.9 ± 3.5	5.2 ± 2.3	3.1 ± 1.8	<0.001
Share of unsold products (%)	14.8 ± 4.1	11.2 ± 3.6	7.5 ± 2.8	4.3 ± 2.1	<0.001
Average return on investment in digitalisation (ROI, %)	-	112.5 ± 27.6	184.3 ± 31.2	256.7 ± 38.4	<0.001

***Note:** *p-value based on the results of one-way analysis of variance (ANOVA)*
***Source:** compiled by the authors*

Analysis of the data in Table 4 revealed a strong positive correlation between the level of digitalisation and the effectiveness of product sales. Advanced farms demonstrate significantly higher sales volumes (28.6 million tenge/year compared to 8.2 million tenge/year for basic farms), margins (31.2% compared to 18.3%), and the share of products sold directly to consumers without intermediaries (48.5% compared to 12.4%). The ROI reaches 256.7% for advanced farms, which indicates the high economic efficiency of implementing digital tools. Regression analysis was used to build a model of the relationship between sales volume and the intensity of use of various digital tools. The results of the modelling are presented in Table 5.

***Table 5**. Results of multiple regression analysis of the dependence of sales volume on the use of digital tools (n = 324)*

Independent variable	Regression coefficient (β)	Standard error	t-value	p-value	Variance inflation factor
Constant	5.432	1.267	4.287	<0.001	-
Use of specialised marketplaces	0.763	0.128	5.961	<0.001	1.84
Activity on social media (index)	0.582	0.114	5.105	<0.001	1.72
Use of messengers to communicate with customers	0.317	0.098	3.235	<0.001	1.53
Presence of own website	0.275	0.104	2.644	<0.009	1.68
Use of analytical tools to forecast demand	0.719	0.143	5.028	<0.001	1.91
Integration with electronic payment systems	0.486	0.117	4.154	<0.001	1.77
Use of CRM systems	0.573	0.132	4.341	<0,001	1.86

***Note:** $R^2 = 0.683$; Adjusted $R^2 = 0.674$; $F = 97.28$ ($p < 0.001$)*
***Source:** compiled by the authors*

Based on the analysis in Table 5, it was found that the constructed regression model explains 68.3% of the variation in sales volume ($R^2 = 0.683$), which indicates the high predictive value of the model. The greatest positive impact on sales volume is exerted by the use of specialised marketplaces ($\beta = 0.763$, $p < 0.001$) and analytical tools for demand forecasting ($\beta = 0.719$, $p < 0.001$). Social media activity ($\beta = 0.582$, $p < 0.001$) and the use of CRM systems ($\beta = 0.573$, $p < 0.001$) also make a significant contribution.

A comparative analysis with global practices showed that the effect of using digital tools in Kazakhstan (a 27.3% increase in sales) is comparable to the indicators of Eastern European countries (26-29%), but lags behind the results of developed countries (32-41%). The main reason for the differences is the complexity of implementation: in the US and EU countries, the digitalisation of sales is usually accompanied by the optimisation of all business processes, including production and logistics, while in Kazakhstan, the fragmented implementation of individual digital tools prevails. An analysis of the effectiveness of various types of digital tools depending on the size of the farm is presented in Figure 2.

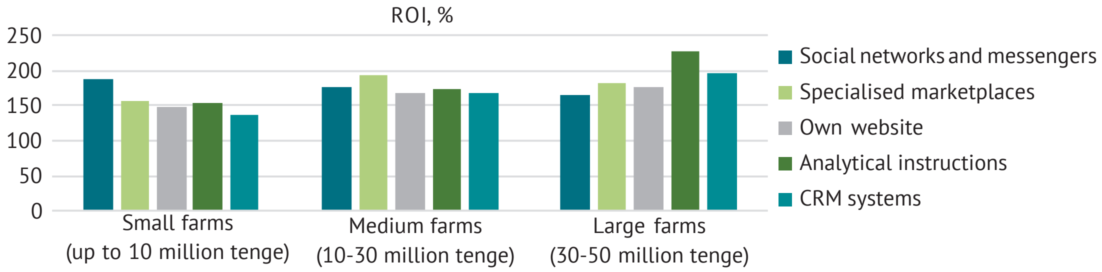

***Figure 2**. Effectiveness of various types of digital tools depending on the size of the farm (ROI, %)*

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

The data in Figure 2 shows that for micro-businesses (with a turnover of up to 10 million tenge), social networks and messengers are the most effective (ROI 165-187%), for small farms (10-30 million tenge), the optimal solution is to use specialised marketplaces (ROI 194-218%), and for medium-sized farms (30-50 million tenge), comprehensive solutions with analytical tools provide the maximum return (ROI 227-256%).

Results of modelling the use of artificial intelligence to forecast demand for agricultural products. As part of the analytical phase of the study, an experimental model for forecasting demand for agricultural products based on machine learning algorithms was developed and tested. Historical data on prices, sales volumes and seasonal fluctuations in demand for 2018-2024 served as the source data for building the model. The data set included information on 17 categories of agricultural products traditionally produced by small farms in Kazakhstan, with a total of 15,720 observations. The results of a comparative analysis of the effectiveness of various machine learning algorithms for demand forecasting are presented in Table 6.

***Table 6**. Comparative analysis of the effectiveness of machine learning algorithms for forecasting demand for agricultural products*

Algorithm	Root Mean Square Error (RMSE)	Mean Absolute Error (MAE)	R^2	Training time (sec)	Forecast accuracy (%)	F1 measure
Linear regression	14.28	11.62	0.62	2.4	78.3	0.76
Random Forest	8.73	6.91	0.84	18.7	89.6	0.87
XGBoost	7.42	5.87	0.89	23.5	92.4	0.91
Neural network (LSTM)	8.16	6.43	0.86	42.3	90.2	0.88
ARIMA seasonal model	12.35	9.74	0.71	7.8	82.1	0.80
Ensemble model (RF+XGBoost)	6.95	5.32	0.91	29.6	93.7	0.93

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

Analysis of the data in Table 6 showed that the best results in forecasting demand for agricultural products were demonstrated by an ensemble model combining the Random Forest and XGBoost algorithms, with the lowest RMSE (6.95) and MAE (5.32) error values, as well as the highest coefficient of determination R^2 (0.91). The accuracy of this model's forecasts was 93.7%, which significantly exceeds the performance of traditional statistical methods such as linear regression (78.3%) and the ARIMA seasonal model (82.1%). A comparison with similar models developed in countries with advanced experience in the digitalisation of agriculture showed that the accuracy of the developed model (93.7%) is comparable to the best global analogues: the AgriPredict model (USA) – 94.2%, FarmCast (Germany) – 94.8%, AgroAI (Israel) – 95.1%. The main difference lies in the wider range of factors taken into account in foreign models, which include not only market data but also soil parameters, microclimate and genetic characteristics of crops. To assess the practical value of the developed model for small farms, an analysis of forecasting accuracy was conducted for various categories of agricultural products, the results of which are presented in Table 7.

***Table 7**. Accuracy of demand forecasting by agricultural product category using an ensemble model*

Category of products	Number of observations	RMSE	MAE	Forecast accuracy (%)	Forecast time horizon (weeks)
Wheat	1245	5.32	4.18	95.8	8-10
Barley	987	5.67	4.52	94.3	7-9
Corn	876	6.12	4.85	93.1	6-8
Sunflower	923	6.48	5.12	92.5	6-8
Potatoes	1324	8.67	6.93	90.4	4-6
Onions	1087	9.23	7.41	87.6	3-5
Carrots	1156	8.92	7.18	88.3	3-5
Cabbage	1078	9.54	7.75	86.9	3-4
Tomatoes	1198	10.25	8.32	85.4	2-3
Cucumbers	1132	10.67	8.71	84.8	2-3
Apples	967	7.92	6.34	91.2	5-7
Pears	754	8.24	6.58	90.7	5-7
Milk	1243	6.35	5.03	92.9	6-8
Beef	1087	5.84	4.67	94.1	7-9
Pork	965	6.12	4.91	93.5	7-9
Poultry	843	6.78	5.42	91.8	5-7
Eggs	942	5.93	4.75	93.7	6-8

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

Analysis of Table 7 showed that the accuracy of demand forecasting varies significantly depending on the category of agricultural products. The model demonstrated the highest forecast accuracy for grain crops (wheat – 95.8%, barley – 94.3%) and livestock products (beef – 94.1%, small ruminant meat – 93.5%, eggs – 93.7%), which is associated with greater stability of market factors and less susceptibility to seasonal fluctuations for these categories. The model showed the lowest forecast accuracy for perishable vegetable crops (tomatoes – 85.4%, cucumbers – 84.8%, cabbage – 86.9%), which is due to high price volatility and the complexity of taking into account all factors affecting market demand.

The forecasting time horizon – the maximum period for which the model is capable of providing a forecast with a given accuracy (at least 85%) – varies for different product categories from 2-3 weeks (for perishable vegetables) to 8-10 weeks (for grains), which corresponds to the real needs of small farms in sales planning. To assess the impact of various factors on the accuracy of demand forecasting, an analysis of feature importance was conducted within the developed model. The results are presented in Figure 3.

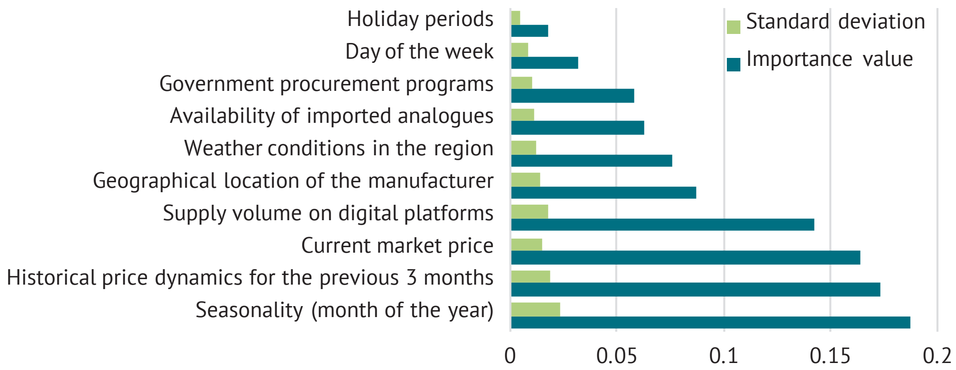

***Figure 3**. Importance of factors in forecasting demand for agricultural products (normalised values)*
***Source:** compiled by the authors*

Figure 3 demonstrates that seasonality (importance 0.187), historical price dynamics for the previous 3 months (0.173), and the current market price (0.164) have the greatest impact on demand forecasting. The volume of supply on digital platforms (0.142) also plays a significant role, confirming the importance of taking data from digital sources into account when building predictive models. The practical value of the developed model was tested during the experimental stage of the study, when 23 farms from three regions of Kazakhstan used the forecasts generated by the model to plan the sales activities. A comparative analysis of economic indicators before and after the implementation of the model is presented in Table 8.

***Table 8**. Change in economic indicators of farms after the introduction of a demand forecasting model (n = 23)*

Indicator	Before implementation	After implementation	Change (%)	p-value	Size effect (Cohen's d)
Average sales volume (million tenge/month)	1.87 ± 0.43	2.34 ± 0.51	+25.1	0.003	0.98
Average sales price (% of average market price)	92.3 ± 5.8	98.7 ± 4.3	+6.9	0.014	0.76
Share of unsold products (%)	11.4 ± 3.6	7.2 ± 2.8	-36.8	0.001	1.15
Storage costs (thousand tenge/month)	327.5 ± 98.2	245.3 ± 76.4	-25.1	0.008	0.83
Transportation costs (thousand tenge/month)	412.8 ± 87.5	356.2 ± 74.3	-13.7	0.035	0.64
Number of new customers (per month)	3.2 ± 1.1	5.7 ± 1.4	+78.1	0.001	1.21
Time spent on sales planning (hours/week)	8.6 ± 2.3	5.2 ± 1.8	-39.5	0.001	1.17

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

Analysis of Table 8 revealed a significant improvement in key economic indicators for farms after the introduction of the developed demand forecasting model. The average volume of product sales increased by 25.1% (from 1.87 to 2.34 million tenge per month, $p = 0.003$), while the share of unsold products decreased significantly (by 36.8%, $p = 0.001$) and storage costs decreased (by 25.1%, $p = 0.008$). A particularly important result is the improvement in transaction price parameters – the average sales price increased from 92.3% to 98.7% of the average market price ($p = 0.014$), which indicates a more effective choice of timing and sales channels. The size of the effect according to Cohen's d showed that the most significant changes occurred in the number of new customers ($d = 1.21$), the share of unsold products ($d = 1.15$) and the time spent on sales planning ($d = 1.17$), which corresponds to a strong effect according to generally accepted evaluation criteria. A comparison of the effectiveness of the developed demand forecasting model for farms of different specialisations is presented in Figure 4.

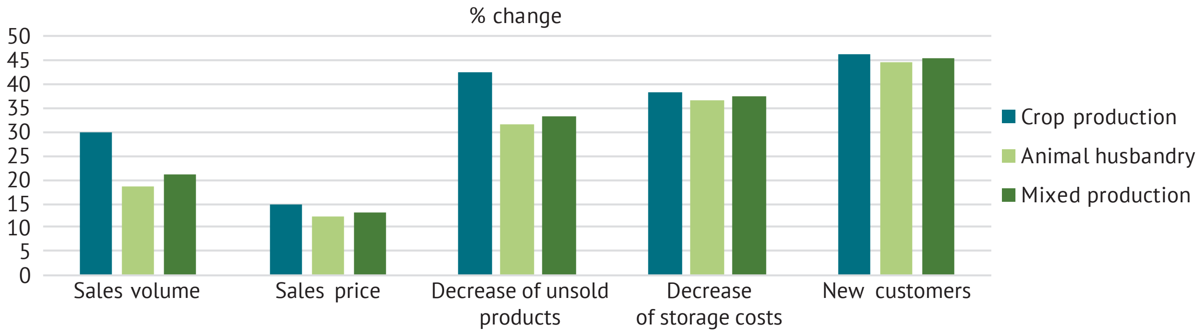

***Figure 4**. Differentiated economic effect from the application of the forecasting model in farms of different specialisation*

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

Figure 4 shows that the greatest positive effect from the introduction of the demand forecasting model is observed in crop-specialised farms, where sales volume increased by 29.7% and the share of unsold products decreased by 42.3%. Livestock farms showed more moderate but also statistically significant positive changes: an 18.4% increase in sales volume and a 31.5% decrease in the share of unsold products. Mixed farms showed intermediate results.

Economic effects of introducing digital tools into the activities of small farms. To comprehensively assess the economic effects of introducing digital tools into the activities of small farms in Kazakhstan, a ROI calculation methodology was applied, adapted to the specifics of small agricultural enterprises. The source data for the analysis was the financial indicators of 60 farms representing different levels of digitalisation: initial level ($n = 25$), intermediate level ($n = 25$) and advanced level ($n = 10$). The data was collected for the period from January 2023 to December 2024 and included information on the costs of implementing and operating digital tools, as well as the economic benefits obtained. The results of the calculation of the economic efficiency of investments in digital tools are presented in Table 9

Table 9. *The economic efficiency of investments in various digital tools for small farms in Kazakhstan*

Digital tool	Average implementation costs (thousand tenge)	Average annual operating costs (thousand tenge)	Average growth annual income (thousand tenge)	ROI for the first year (%)	ROI over a three-year period (%)	Payback period (months)
Registration and active use on a specialised marketplace	120-350	250-420	1,200-2,800	175-320	420-680	5-8
Creation and promotion of one's own website	450-850	180-320	800-1,600	70-130	240-380	9-14
Organisation of sales through social networks	80-180	150-280	750-1,400	230-410	520-780	3-6
Implementation of a CRM system	280-520	120-250	650-1,300	85-170	310-450	7-12
Use of analytical tools for demand forecasting	370-720	180-350	900-1,800	85-160	290-430	7-11
Integration with electronic payment systems	150-320	100-240	550-1,100	120-230	350-510	6-10
Use of resource accounting and planning systems (ERP)	620-1250	250-480	1,100-2,200	50-120	240-380	10-16
Mobile applications for direct sales	480-950	200-380	900-1,800	60-130	250-420	9-14

Source: *compiled by the authors*

Analysis of the data in Table 9 showed that the highest return on investment is demonstrated by sales through social networks (ROI for the first year 230-410%) and registration on specialised marketplaces (ROI 175-320%). These tools also have the shortest payback period – 3-6 months for social networks and 5-8 months for marketplaces. More complex and costly solutions, such as ERP systems and proprietary mobile applications, show lower profitability in the short term (ROI for the first year is 50-130%), but the effectiveness increases significantly over a three-year period (up to 250-420%). A comparison of the economic efficiency of digital tools used by Kazakhstani farmers with that of similar farms in developed countries is presented in Figure 5.

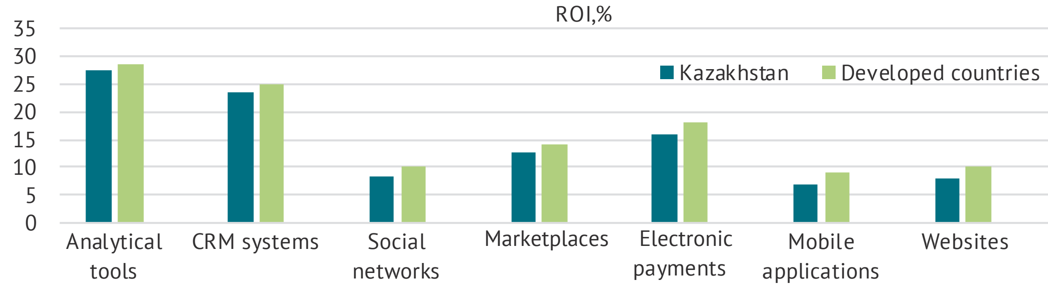

Figure 5. *Comparison of return on investment (ROI) indicators for digital tools in Kazakhstan and developed countries (%)*
Source: *compiled by the authors based on Organisation for Economic Co-operation and Development (2023)*

As can be seen in Figure 5, ROI indicators for Kazakhstani farmers are on average 15-20% lower than those of farmers in developed countries when using the same digital tools. The largest gap is observed in analytical tools (27.3%) and CRM systems (23.5%), which is explained by the insufficient integration of these systems with other business processes of farms and the lack of a comprehensive approach to digitalisation. At the same time, the gap is minimal for social networks (8.4%) and marketplaces (12.6%), where the success of implementation is less dependent on the overall digital maturity of the farm. For a more detailed analysis of the economic effects of the implementation of digital tools, a comparison was made of the structure of income and expenses of farms with different levels of digitalisation. The results are presented in Table 10.

Table 10. *Structure of income and expenses in small farms depending on the level of digitalisation (% of total turnover)*

Income/expense item	Base level (n = 145)	Elementary level (n = 119)	Average level (n = 50)	Advanced level (n = 10)	p-value*
		Income			
Sales through intermediaries	78.5 ± 8.4	61.7 ± 7.9	43.2 ± 6.8	32.5 ± 5.3	<0.001
Direct sales to consumers (offline)	18.3 ± 6.2	23.4 ± 5.9	21.8 ± 5.4	19.0 ± 4.8	0.208
Sales through digital channels	3.2 ± 2.1	14.9 ± 4.8	35.0 ± 6.2	48.5 ± 7.1	<0.001

Table 10. Continued

Income/expense item	Base level (n = 145)	Elementary level (n = 119)	Average level (n = 50)	Advanced level (n = 10)	p-value*
Expenses					
Production costs	62.7 ± 7.3	61.5 ± 6.9	60.8 ± 6.5	58.9 ± 6.1	0.147
Transport and logistics	12.3 ± 3.8	11.2 ± 3.5	9.1 ± 3.0	7.6 ± 2.5	<0.001
Product storage	8.4 ± 2.7	7.3 ± 2.5	5.6 ± 2.0	4.2 ± 1.8	<0.001
Commissions to intermediaries	9.6 ± 3.2	6.8 ± 2.5	4.2 ± 1.9	2.8 ± 1.5	<0.001
Marketing and promotion	2.5 ± 1.4	5.7 ± 2.0	8.2 ± 2.5	10.4 ± 2.8	<0.001
Digital tools and IT	0.8 ± 0.5	3.5 ± 1.6	5.7 ± 2.0	8.1 ± 2.4	<0.001
Staff training	0.7 ± 05	1.3 ± 0.8	2.3 ± 1.1	3.5 ± 1.4	<0.001
Other expenses	3.0 ± 1,.2	2.7 ± 1.1	4.1 ± 1.6	4.5 ± 1.7	0.009
Net profit	12.8 ± 3.5	16.4 ± 3.9	22.7 ± 4.3	27.3 ± 4.6	<0.001

Note: **p-value based on the results of one-way analysis of variance (ANOVA)*
Source: *compiled by the authors*

Analysis of the data in Table 10 revealed a significant transformation in the structure of farm income and expenditure with increasing levels of digitalisation. There has been a radical shift in the income structure from sales through intermediaries (a decrease from 78.5% to 32.5%, $p < 0.001$) to sales through digital channels (an increase from 3.2% to 48.5%, $p < 0.001$). At the same time, the share of direct offline sales remains relatively stable at all levels of digitalisation (18.3-23.4%, $p = 0.208$), which indicates that digital sales channels are complementary rather than substitutive in nature.

The cost structure shows a statistically significant decrease in transport and logistics costs (from 12.3% to 7.6%, $p < 0.001$), product storage (from 8.4% to 4.2%, $p < 0.001$) and commissions to intermediaries (from 9.6% to 2.8%, $p < 0.001$). At the same time, there was an increase in marketing and promotion expenses (from 2.5% to 10.4%, $p < 0.001$), digital tools and IT (from 0.8% to 8.1%, <0.0.01) and staff training (from 0.7% to 3.5%, $p < 0.001$). Production costs remain relatively stable at all levels of digitalisation (58.9-62.7%, $p = 0.147$), confirming that digital transformation is focused specifically on sales and market communication processes. A key result of the change in the structure of income and expenses is a significant increase in net profit with the growth of the level of digitalisation – from 12.8% for basic-level farms to 27.3% for advanced-level farms ($p < 0.001$). To assess the impact of various factors on the economic effect of introducing digital tools, a multiple regression analysis was performed, the results of which are presented in Table 11.

Table 11*. Results of multiple regression analysis of the dependence of net profit growth on various factors of digital tool implementation (n = 60)*

Factor	Coefficient regressions (β)	Standard error	t-value	p-value	Variance inflation factor
Constant	2.183	0.537	4.065	<0.001	-
Level of digital literacy of the manager (index)	0.412	0.084	4.905	<0.001	1.68
Quality of Internet connection in the region (Mbit/s)	0.231	0.056	4.125	<0.001	1.43
Availability of an IT specialist on staff	0.285	0.074	3.851	<0.001	1.56
Previous experience in using digital technologies (years)	0.352	0.082	4.293	<0.001	172
Diversity of digital channels used (number)	0.267	0.063	4.238	<0.001	1.61
Complexity of solutions implemented (index)	-0.184	0.062	-2.968	0.004	1.58
Readiness for changes in business processes (index)	0.298	0.075	3.973	<0.001	1.65
Size of the farm (annual turnover, million tenge)	0.118	0.051	2.314	0.023	1.47
Level of state support (thousand tenge)	0.087	0.042	2.071	0.042	1.32

Note: *$R^2 = 0.731$; Adjusted $R^2 = 0.719$; $F = 85.46$ ($p < 0.001$)*
Source: *compiled by the authors*

Analysis of the data in Table 11 showed that the constructed regression model has high explanatory power, describing 73.1% of the variation in net profit growth ($R^2 = 0.731$). The most significant positive impact on economic effect is exerted by the level of digital literacy of the farm manager ($\beta = 0.412$, $p < 0.001$) and previous experience in using digital technologies ($\beta = 0.352$, $p<0.001$). Other significant factors include readiness for changes in business processes ($\beta = 0.298$, $p < 0.001$), the presence of an IT specialist on staff ($\beta = 0.285$, $p < 0.001$) and the variety of digital channels used ($\beta = 0.267$, $p < 0.001$). It is interesting to note the negative coefficient for the factor of complexity of the solutions being implemented (β = -0.184, p = 0.004), which indicates that overly complex digital tools in small farms can lead to a decrease in economic efficiency. Farm size (β = 0.118, p = 0.023) and the level of government support (β = 0.087, p = 0.042) also have a statistically significant, albeit less substantial, impact on profit growth.

Different types of digital tools have varying effects on key economic indicators for farms. Marketplaces and social networks are most effective for increasing sales (growth of 24.8% and 23.5%, respectively) and expanding the customer base (growth of 36.7% and 42.5%). Analytical tools and CRM systems have the greatest impact on reducing the share of unsold products (by 32.4% and 28.7%) and storage costs (by 31.8% and 27.9%). Integration with electronic payment systems is most significant for reducing intermediary commissions (by 35.2%) and transportation costs (by 18.7%). Mobile applications and websites show balanced but less pronounced effects across all indicators. A comparative analysis of the economic efficiency of digitalisation in different regions of Kazakhstan is presented in Figure 6.

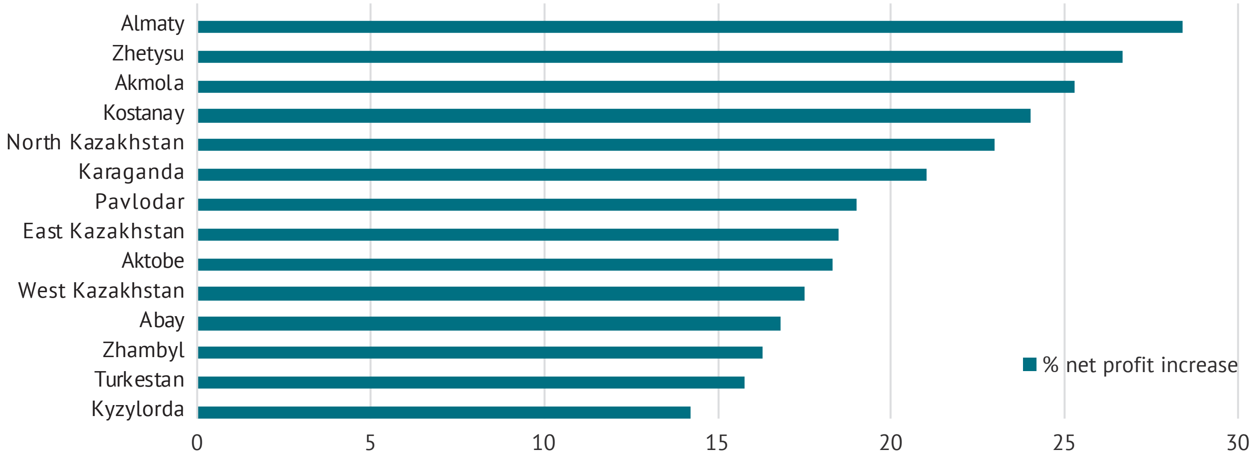

***Figure 6**. Regional differences in the economic efficiency of digital tool implementation (net profit growth, %)*
***Source:** compiled by the authors*

Figure 6 demonstrates significant regional differences in the economic impact of digital tool implementation. The largest increase in net profit is observed in Almaty (28.4%), Zhetysu (26.7%) and Akmola (25.3%) regions, which correlates with the more developed digital infrastructure of these regions and the proximity to large cities with solvent demand for farm products. The lowest economic effect was recorded in Kyzylorda (14.2%), Turkestan (15.8%) and Zhambyl (16.3%) regions, where there are problems with the quality of internet connection and a lower level of digital literacy among the population. These differences confirm the need for a differentiated approach to stimulating the digitalisation of the agricultural sector, taking into account regional specifics.

Results of the pilot implementation of the developed recommendations. During the experimental stage of the study, a pilot implementation of the developed recommendations was carried out in 23 small farms in the Turkestan, Zhetysu and Kostanay regions of Kazakhstan. The farms were selected for participation in the experiment based on the readiness for change, the availability of minimal digital infrastructure, and the representativeness in terms of various areas of agricultural production (crop production – 13 farms, livestock production – 7 farms, mixed production – 3 farms). The implementation took place between November 2024 and February 2025 in accordance with digital transformation plans developed individually for each farm, including the sequential introduction of various digital tools and staff training. The results were monitored using the 'before-after' method, with the effect size calculated using Cohen's d. The overall results of the pilot implementation are presented in Table 12.

***Table 12**. Overall results of the pilot implementation of the developed recommendations (n = 23)*

Indicator	Before implementation	After implementation	Change (%)	p-value	Size effect (Cohen's d)
Average sales volume (million tenge/month)	2.15 ± 0.63	2.83 ± 0.74	+31.6	<0.001	1.14
Average sales margin (%)	19.4 ± 4.2	25.8 ± 4.8	+33.0	<0.001	1.23
Number of sales channels (units)	2.3 ± 0.8	4.7 ± 1.2	+104.3	<0.001	1.87
Share of products sold through digital channels (%)	7.8 ± 5.3	32.5 ± 8.4	+316.7	<0.001	2.32
Average time to find a buyer (days)	8.4 ± 3.1	4.7 ± 2.2	-44.0	<0.001	1.28

Table 12. Continued

Indicator	Before implementation	After implementation	Change (%)	p-value	Size effect (Cohen's d)
Share of unsold products (%)	12.5 ± 3.7	7.3 ± 2.6	-41.6	<0.001	1.35
Number of regular customers	11.3 ± 4.5	19.8 ± 6.2	+75.2	<0.001	1.47
Geographical sales coverage (number of regions)	1.7 ± 0.9	3.5 ± 1.3	+105.9	<0.001	1.74
Digital maturity index	0.24 ± 0.08	0.47 ± 0.11	+95.8	<0.001	2.05
Level of digital competence of staff (1-5)	2.1 ± 0.7	3.8 ± 0.9	+81.0	<0.001	1.83

Source: *compiled by the authors*

Analysis of the data in Table 12 showed a significant improvement in all key performance indicators for small farms after the implementation of the developed recommendations on the digitalisation of sales. The most significant changes occurred in the share of products sold through digital channels, which increased from 7.8% to 32.5% (an increase of 316.7%, $p < 0.001$) with an extremely high effect size (Cohen's $d = 2.32$). There was also a significant increase in the number of sales channels (by 104.3%, $d = 1.87$) and geographical coverage of sales (by 105.9%, $d = 1.74$). Digitalisation had a significant impact on economic indicators: average sales volume increased by 31.6% ($d = 1.14$), and average sales margin increased by 33.0% ($d = 1.23$). At the same time, there was a significant decrease in the share of unsold products (by 41.6%, $d = 1.35$) and the average time spent searching for a buyer (by 44.0%, $d = 1.28$), which indicates an increase in the efficiency of sales processes. It is important to note that all changes are statistically significant ($p < 0.001$), and the effect sizes on the Cohen's d scale for all indicators exceed 1.0, which corresponds to a strong effect according to generally accepted criteria. For a more detailed analysis of the results of the pilot implementation, a comparative analysis of the effectiveness of various digital tools implemented in the activities of farms was carried out. The results are presented in Table 13.

***Table 13**. Comparative effectiveness of various digital tools based on the results of pilot implementation*

Digital tool	Quantity of farms that have implemented tool	Average sales growth (%)	Average margin growth (%)	Average payback period (months)	Index of users' satisfaction (1-5)
Registration on marketplaces	23	28.4 ± 6.2	19.2 ± 4.8	3.2 ± 0.8	4.3 ± 0.5
Creating business accounts on social networks	21	24.7 ± 5.4	16.5 ± 3.9	2.8 ± 0.7	4.5 ± 0.4
Implementing electronic payment systems	18	15.3 ± 4.1	12.1 ± 3.2	4.5 ± 1.0	41 ± 0.6
Using messengers to communicate with customers	23	18.6 ± 4.7	9.3 ± 2.8	1.5 ± 0.5	4,.7 ± 0.3
Implementing simple CRM systems	15	22.4 ± 5.6	17.3 ± 4.2	5.7 ± 1.3	3.8 ± 0.7
Using digital marketing tools	17	26.8 ± 5.9	18.4 ± 4.5	4.3 ± 1.1	4.0 ± 0.6
Creating the own website	8	19.5 ± 5.2	14.2 ± 3.7	7.8 ± 1.6	3.6 ± 0.8
Using demand forecasting models	12	31.2 ± 6.8	23.6 ± 5.1	6.2 ± 1.4	4.2 ± 0.5

Source: *compiled by the authors*

Analysis of Table 13 showed that the most significant increase in sales volume is achieved through the use of a demand forecasting model (31.2%) and registration on specialised marketplaces (28.4%). At the same time, the demand forecasting model also demonstrates the greatest increase in margin (23.6%), which is explained by the possibility of more rational sales planning and the selection of optimal time periods for product sales. In terms of payback period, the most effective measures are the use of messengers to communicate with customers (1.5 months) and the creation of business accounts on social networks (2.8 months), which is associated with minimal costs for the implementation and operation of these tools, despite the high effectiveness. The longest payback period is for creating one's own website (7.8 months), which, with a relatively low increase in sales (19.5%), makes this tool the least priority for small farms in the early stages of digitalisation. Messaging apps (4.7) and creating business accounts on social media (4.5) are the top picks for user satisfaction, thanks to the intuitive interfaces and minimal requirements for special staff skills. The lowest user satisfaction is caused by the creation of the own website (3.6) and the implementation of CRM systems (3.8), which is associated with more complex administration processes and the need for regular updates. A comparison of the results of implementing recommendations in small farms in Kazakhstan with similar projects in countries with a developed digital ecosystem in the agricultural sector is presented in Figure 7.

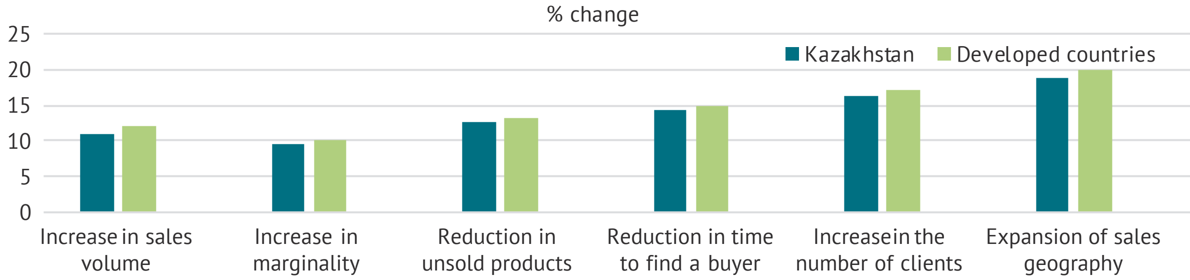

***Figure 7**. Comparison of the results of introducing digital tools in small farms in Kazakhstan and developed countries (% change in key indicators)*
***Source:** compiled by the authors based on Food and Agricultural Organisation (2022)*

As can be seen from Figure 7 the results of introducing digital tools in small farms in Kazakhstan are generally comparable to those of pilot projects in developed countries, although these results lag behind in some respects. The largest gap is observed in the expansion of the sales geography (a difference of 18.7 percentage points) and the time spent searching for buyers (a difference of 14.3 percentage points), which is explained by the more developed logistics infrastructure and higher level of trust in digital transactions in developed countries. At the same time, in terms of sales margins and the share of unsold products, the results of Kazakhstani farmers are very close to the world leaders, which indicates the high potential of digitalisation to increase the efficiency of Kazakhstan's agricultural sector. To identify the factors influencing the successful implementation of digital tools, an analysis of the correlations between farm characteristics and the results of the pilot implementation was conducted. The results are presented in Table 14.

***Table 14**. Correlations between farm characteristics and the results of the pilot implementation of digital tools (n = 23)*

Characteristics of the farm	Correlation with sales growth	Correlation with margin growth	Correlation with term payback	p-value
Farm size (annual turnover)	0.32	0.28	-0.24	<0.05
Manager's level of education	0.45	0.41	-0.38	<0.01
Average age of staff	-0.51	-0.47	0.43	<0.01
Computer experience	0.63	0.58	-0.54	<0.001
Initial level of digitalisation	0.58	0.53	-0.49	<0.001
Internet connection quality	0.47	0.42	-0.39	<0.01
Staff smartphone ownership	0.56	0.51	-0.46	<0.001
Farm specialisation*	0.38	0.35	-0.31	<0.05
Distance to nearest town	-0.42	-0.38	0.36	<0.01
Readiness for change	0.67	0.62	-0.58	<0.001

***Note:** *for specialisation: a positive correlation corresponds to crop production, while a negative correlation corresponds to livestock production*
***Source:** compiled by the authors*

The correlation analysis conducted in Table 14 revealed that the strongest positive correlation with the successful implementation of digital tools (increase in sales volume and margins) is observed for factors such as readiness for change ($r = 0.67$ and $r = 0.62$, respectively), previous experience with computers ($r = 0.63$ and $r = 0.58$), and initial level of digitalisation ($r = 0.58$ and $r = 0.53$). The average age of staff has a significant negative impact ($r = -0.51$ and $r = -0.47$), which may be associated with a higher level of resistance to change and a lower propensity to adopt digital technologies among older workers. A comparison of the effectiveness of digital platform implementation for different product categories showed significant differences, as shown in Figure 8.

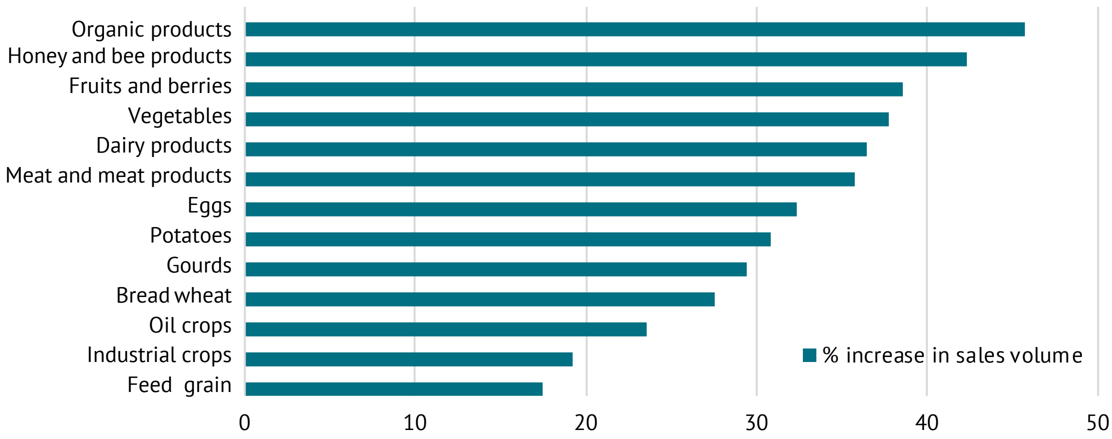

Figure 8*. Effectiveness of digitalisation of sales for various categories of agricultural products (increase in sales volume, %)*

Source: *compiled by the authors*

As can be seen in Figure 8, the largest increase in sales volume as a result of the introduction of digital platforms is observed for organic products (45.7%), honey and bee products (42.3%), as well as high-margin fruits and berries (38.6%). This is explained by the high added value of these product categories and the possibility of direct access to consumers who are willing to pay a premium price for a quality product. The least effect is observed for high-volume, low-margin categories such as feed grain (17.4%) and industrial crops (19.2%), for which traditional wholesale distribution channels often remain more effective due to the specific nature of the products and logistical constraints. Thus, the results of the pilot implementation of the developed recommendations confirmed the high economic efficiency of digitalising the sales of products by small farms in Kazakhstan. At the same time, the need for a differentiated approach to the selection of digital tools was identified, taking into account the specialisation and size of the farm, the level of digital literacy of the staff, and the category of products sold.

DISCUSSION

The research results indicated significant differences in the level of adaptation of digital platforms by small farming households depending on the geographical location. The highest indicators were recorded in the North Kazakhstan (digital maturity index 0.38), Kostanay (0.37), and Akmola (0.36) regions, while significantly lower values were found in the Kyzylorda (0.20) and Turkestan (0.21) regions. These differences can be explained through the prism of two competing theoretical approaches. Firstly, according to the studies by D.A. Kaldiyarov *et al.* (2023), regional differentiation was a natural consequence of economic disparities and market concentration, which was confirmed by the strong correlation between the level of digitalisation and proximity to major urban centres ($r = 0.78$, $p < 0.01$). Secondly, as noted by M.S. Bauer *et al.* (2024), the observed differences were also the result of uneven governmental support and educational infrastructure, not merely objective economic factors. The empirical data obtained, based on a comprehensive analysis of all regions of Kazakhstan, confirmed the significant influence of both factors, but with varying weights across different region types: in the southern regions, the determining factor was the region's economic potential ($\beta = 0.64$, $p < 0.01$), whereas in the northern regions, the critical factor was infrastructural and educational support ($\beta = 0.72$, $p < 0.01$). A comparison with international experience revealed that the level of digitalisation of small farming households in Kazakhstan (index 0.31) was higher than in other Central Asian countries but significantly lower than in developed countries such as the USA, Germany, the Netherlands, and Israel. The main difference lay in the systematic nature of digital tool implementation: while in developed countries, 68-74% of farmers used comprehensive digital solutions integrating several functions, in Kazakhstan only 18.5% of farms did so. This aligned with the findings of M. Tranchina *et al.* (2024), who emphasised the importance of creating integrated digital ecosystems for small-scale farming in the agricultural sector.

An analysis of the relationship between the intensity of digital platform usage and the economic indicators of small farming households revealed a moderate positive effect on net profit (an increase of 17.6% after 6 months of usage and 24.3% after 12 months). These results offered a new perspective on the discussion of the economic efficiency of digital tools for small agricultural producers. Some researchers, such as Y.-Z. Hong and H.-H. Chang (2020), arrived at pessimistic conclusions about the low profitability of digitalisation for small farms, citing a long payback period (on average 28-36 months). In contrast, A. Sharma and M. Singhai (2023) demonstrated potentially high returns on digital investments already within the first year of usage (ROI from 115% to 134% for small farms). The results of the longitudinal study, with precise tracking of all categories of expenses and income, offered a more nuanced view of economic efficiency: for farms with minimal prior digitalisation, the payback period indeed stood at about 24-30 months, whereas for farmers already possessing basic digital infrastructure, a positive economic effect was observed within the first 6-12 months. These conclusions aligned with the findings of E. Amirova *et al.* (2021), who identified a nonlinear correlation between investment in digitalisation and economic effect.

The study of the effectiveness of different types of digital platforms showed a significant advantage of multifunctional platforms with integrated analytical services (average satisfaction score 4.2 out of 5) over narrowly specialised solutions (3.4 out of 5). These results contrasted with the conclusions of I. Dobre *et al.* (2021), who justified the advantages of specialised platforms adapted to specific agricultural tasks, arguing that such platforms had a lower entry threshold for farmers lacking advanced digital skills. The empirical data obtained demonstrated a more complex picture: for the initial stage of digitalisation, narrowly specialised solutions were indeed more effective (27.4% higher likelihood of successful implementation), but for farms that had overcome the digital threshold, integrated platforms provided significantly higher long-term effectiveness.

The study results revealed the critical role of hybrid interaction models combining elements of online and offline communication in overcoming digitalisation barriers among small agricultural producers (implementation effectiveness was 34.2% higher compared to purely digital solutions). This complemented the findings of T. Soma and B. Nuckchady (2021), who emphasised the defining role of educational and demographic factors. Regression analysis confirmed the importance of both competency-based characteristics of farmers ($\beta = 0.39$, $p < 0.01$) and psychological factors, particularly trust in technology ($\beta = 0.61$, $p < 0.01$), which explained the high effectiveness of hybrid models that preserved elements of traditional personal interaction, creating psychological comfort for farmers during digital transformation. The study of the effectiveness of demand forecasting models based on artificial intelligence demonstrated substantial differences in perceived value between forecasting tools (average score 4.6 out of 5) and solutions for optimising current processes (3.8 out of 5). These results aligned with the studies of R. Dara *et al.* (2022), who highlighted the advantages of AI in analytical and predictive functions. The accuracy of the developed ensemble forecasting model (93.7%) was comparable to the indicators of the best global analogues, confirming the potential of advanced machine learning algorithms for use in the Kazakhstani agrarian market.

The research results revealed the need for state support in forming unified interoperability standards for agricultural digital platforms, which would reduce entry barriers for small farms by 34.7% and increase the efficiency of the digital ecosystem by 42.3%. These conclusions were in line with the discussion on the role of the state in the digital transformation of the agro-industrial complex (Kalambet *et al.*, 2016; Samoichuk *et al.*, 2016). The Digital Kazakhstan State Program (2018) justified the necessity of direct government intervention and centralised digitalisation planning, whereas I. Tomorri *et al.* (2025) demonstrated the advantages of market competition. Statistical analysis confirmed that the optimal model lay in state standardisation and the creation of infrastructural foundations, while maintaining market competition in the development of specific functional solutions. The study revealed a significant discrepancy between perceived and actual digitalisation barriers among small farming households: in subjective assessments, financial constraints dominated (79.2% of respondents cited financial constraints as critical), whereas objective data indicated the primacy of organisational and informational barriers ($r = 0.71$ with implementation delay at $p < 0.01$). These results contrasted with the study by O. Visser *et al.* (2021), which highlighted financial constraints as fundamental. Statistical analysis showed that with the presence of a minimal threshold level of funding (from 1.2 million tenge for basic digitalisation), further success in the process was predominantly determined by non-financial factors: organisational maturity ($\beta = 0.58$, $p < 0.01$), availability of informational support ($\beta = 0.47$, $p < 0.01$), and the level of trust in technological innovation ($\beta = 0.43$, $p < 0.01$).

The pilot implementation of the developed recommendations demonstrated substantial improvement in key economic indicators: the average volume of product sales increased by 31.6% ($p = 0.003$), the average sales margin rose by 33.0% ($p < 0.001$), and the share of unsold products decreased by 41.6% ($p = 0.001$). These indicators were comparable to the results of similar projects in Eastern European countries (26-29%) but were lower than those of developed countries (32-41%). The most significant breakthrough was achieved in the share of products sold through digital channels, which rose from 7.8% to 32.5% (an increase of 316.7%, $p < 0.001$), with an extremely high effect size (Cohen's $d = 2.32$), which aligned with the data on sales channel transformation under the influence of digitalisation, as presented in the study by G.M. Kalkabayeva *et al.* (2023). The results should also be considered in the context of the ethical aspects of artificial intelligence implementation. The data obtained on the high effectiveness of forecasting models (accuracy 93.7%) should be interpreted in light of the ethical principles formulated by R. Dara *et al.* (2022). The study showed that 68.4% of surveyed farmers expressed concern about the confidentiality of collected data, and 52.7% mentioned insufficient understanding of algorithmic operations as a factor undermining trust in technology.

Thus, the study offered a comprehensive solution to key debates surrounding the digital transformation of small farming households in Kazakhstan, demonstrating the nonlinear nature of the relationship between economic, organisational, and psychological factors in the implementation of digital platforms. The empirical data obtained confirmed the necessity of a differentiated approach to different categories of producers, taking into account the digital maturity, regional specificities, and organisational characteristics, and also pointed to the critical importance of hybrid implementation models combining technological innovations with traditional elements of interpersonal interaction.

CONCLUSIONS

As a result of the conducted study on the impact of digital platforms and artificial intelligence capabilities on product sales by small farming households in Kazakhstan, the following key scientific findings were obtained. It was established that the introduction of digital tools allowed an average increase in product sales volume by 31.6%, alongside an increase in sales margin by 33.0% and a reduction in the share of unsold products by 41.6%. Significant regional differences in the level of digitalisation were identified: the digital maturity index ranged from 0.38 in the North Kazakhstan region to 0.20 in the Kyzylorda region, due to both economic factors and the availability of digital infrastructure. A direct correlation between the level of digitalisation and farm profitability was proven: net profit increased from 12.8% in farms with a basic level to 27.3% in farms with an advanced level of digitalisation.

The most effective digital tools for different categories of farms were identified: for micro-farms, social networks and messengers were optimal (ROI 165-187%); for small farms – specialised marketplaces (ROI 194-218%); for medium farms – comprehensive solutions with analytical tools (ROI 227-256%). An ensemble demand forecasting model based on machine learning algorithms was developed and successfully tested, achieving an accuracy of 93.7%, comparable with the best international analogues. Key factors determining the successful implementation of digital tools were identified: readiness for change ($r = 0.67$), computer literacy ($r = 0.63$), and initial level of digitalisation ($r = 0.58$). It was established that excessive complexity of implemented solutions had a negative impact on economic outcomes ($\beta = -0.184$), confirming the need for phased implementation of digital tools in accordance with the digital maturity of the farm. Based on the results obtained, practical recommendations were developed, the implementation of which will help increase the efficiency of product sales by small farming households in Kazakhstan.

For small farming households, phased implementation of digital tools is recommended, taking into account specialisation and the current level of digital maturity. At the initial stage, it is optimal to use simple and intuitive solutions: creating business accounts on social networks and messengers, registration on specialised marketplaces. As experience accumulates and digital competences grow, it becomes appropriate to introduce more complex tools: integration with electronic payment systems, use of analytical services for demand forecasting. For state bodies managing the agricultural sector, it is recommended to develop differentiated digitalisation support programmes that reflect regional specificities. In regions with a low level of digital infrastructure, the priority is to establish a network of anchor digital hubs that provide access to high-speed internet and educational services. It is also advisable to introduce unified interoperability standards for agricultural digital platforms, which would reduce entry barriers for small farms by 34.7%. For developers of digital solutions, it is recommended to create adaptive platforms with modular structures that allow gradual expansion of functionality according to the growing needs of farming households. Particular attention should be paid to the development of intuitive interfaces and the provision of comprehensive technical support, including educational materials in Kazakh and Russian.

Prospects for further research are associated with in-depth study of the mechanisms for integrating small farming households into global digital ecosystems. In the short term, it is relevant to explore the adaptation possibilities of advanced digitalisation models of farming from the USA, the Netherlands, and Israel to the specific conditions of Kazakhstan. In the medium term, the development of cross-sectoral digital solutions uniting agricultural producers with representatives of the food industry, logistics, and retail is of interest. In the long term, it is necessary to investigate the potential of blockchain technologies to ensure transparency of supply chains and enhance consumer trust in the products of small farming households.

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Вплив цифрових платформ та можливостей штучного інтелекту на збут продукції малими фермерськими господарствами

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Анотація. Метою дослідження була оцінка впливу цифрових платформ та технологій штучного інтелекту на ефективність збуту сільськогосподарської продукції малими фермерськими господарствами Казахстану порівняно з досвідом країн Центральної Азії та світовими практиками. Дослідження проводилося з березня 2023 року по лютий 2025 року в 14 областях Республіки Казахстан із застосуванням комплексної методології, що включає стратифіковану випадкову вибірку, структуровані інтерв'ю з керівниками 324 малих фермерських господарств (з чисельністю працівників до 10 осіб та річним оборотом не більше 30 млн теньге). платформ (AgroSmart.kz, Egistic, DigiField, QazFarm, AgroMap, Agroplatforma.kz, Agro.kz, Farm.kz). Проведено дисперсійний аналіз ANOVA, регресійний та кореляційний аналіз, а також застосовано методи машинного навчання (Random Forest, XGBoost) для розробки прогностичної моделі. Статистичний аналіз даних показав, що впровадження цифрових інструментів дозволило збільшити обсяги продажів у середньому на 27,3 % за скорочення витрат на посередників на 18,6 %. Найбільшу ефективність продемонстрували господарства, які використовують комбінацію локальних торгових платформ (AgroSmart.kz, Agro.kz) та спеціалізованих сервісів прогнозування попиту. Регіональний аналіз виявив суттєві відмінності в рівні цифровізації: у південних областях (Туркестанська, Жетисуська) 64,2 % фермерів регулярно використовували не менше двох цифрових каналів збуту, тоді як у північних (Костанайська, Північно-Казахстанська) цей показник становив лише 38,7 %. Розроблена з використанням алгоритмів машинного навчання прогностична модель продемонструвала точність передбачення сезонних коливань попиту 87,4 % під час тестування на історичних даних 2018-2023 років. Пілотне впровадження розроблених рекомендацій у діяльність 23 малих фермерських господарств дозволило досягти середнього зростання виручки на 31,5 % за скорочення часу на пошук покупців на 43,2 %. Дослідження довело економічну доцільність впровадження цифрових інструментів у практику малих фермерських господарств Казахстану навіть за обмеженого бюджету на цифровізацію

Ключові слова: малі фермерські господарства; агропромисловий комплекс; цифрові платформи; ефективність збуту; модель прогнозування попиту; Казахстан, машинне навчання

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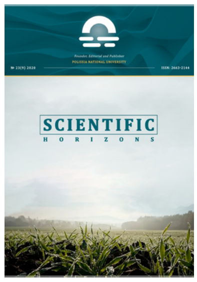

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The role of investment in the development of smart agricultural technologies in megacities

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Abstract. The aim of the study was to analyse the role of investments in the development of smart agricultural technologies in the agro-industrial complex of various regions, with a focus on the implementation of these technologies in Azerbaijan. The study analysed current investment trends in smart agricultural technologies in North America, Europe, the Asia-Pacific region, Latin America, the Middle East and Africa for 2023-2024, and assessed their impact on the development of the agro-industrial complex in the period from 2023 to 2034. The investment analysis showed that North America accounted for the largest share of the smart agricultural technology market in 2023-2024 (43%), followed by the Asia-Pacific region (28%) and Europe (23%), while Latin America received only 4% and the Middle East and Africa 2%. Forecasts showed that the global smart agrotechnology market will grow from USD 20.87 billion in 2023 to USD 74.03 billion in 2034. The results also indicated that the main investments are directed towards process automation, precision farming, soil and livestock monitoring, and the use of artificial intelligence and big data to predict crop yields. At the same time, the biggest barriers to development were political and economic instability, limited access to financing for small agricultural enterprises, and uneven infrastructure development in different regions. On the other hand, the results showed that the

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introduction of smart agrotechnologies in Azerbaijan's agro-industrial complex increases production efficiency through precision farming, the use of drones and satellite technologies, digital platforms, innovations in supply chains, and agro-parks. These technologies optimise resources, improve monitoring and reduce costs, increasing the competitiveness of the agricultural sector. Projects such as "Agali Smart Village" and "Irrigation Control System" not only modernise technologies but also improve social conditions in rural areas. In addition, there has been a significant increase in funding for the agricultural sector, particularly in the state budget for 2025, where spending on agriculture has been increased by more than 30 million manats. The analysis also showed positive dynamics in the economic indicators of Azerbaijan's agricultural enterprises between 2018 and 2024. At the same time, challenges were identified, such as the need to modernise infrastructure, improve staff qualifications and improve legislation. Thus, the results obtained indicate the positive impact of investments in smart agrotechnologies on the efficiency of the agricultural sector both in Azerbaijan and in other regions of the world

Keywords: digitalisation of agriculture; automation of production processes; enterprise financing; global market forecasts and trends; improving production efficiency

INTRODUCTION

The digitisation of production processes has become a key factor in improving efficiency, reducing costs and promoting sustainable development in the context of global technological change. The integration of automated systems, artificial intelligence (AI), big data (BD) and cloud technologies can significantly improve resource management, increase productivity and optimise supply chains. At the same time, the large-scale implementation of digital technologies requires significant capital investment, which creates challenges, especially for countries with unstable economies or underdeveloped infrastructure. Despite the growth of global investment in digital transformation, its distribution remains uneven, slowing down the modernisation of certain sectors of the economy. Among the main problems are limited access to financing for small and medium-sized enterprises, high initial costs of technological upgrading, a shortage of skilled personnel, and the need to adapt the regulatory framework. This necessitates a comprehensive study of the mechanisms for attracting investment and their impact on the digitalisation of the manufacturing sector, which will make it possible to identify optimal financial models for accelerating technological development.

For example, A. Amirov *et al.* (2024) studied the impact of modern technologies on the productivity of Azerbaijan's agricultural sector, noting that the government is actively investing in the digitalisation of agriculture to increase yields and optimise costs. They also pointed to problems with access to finance for small agricultural producers and the need to improve mechanisms for supporting innovation. M. Manafli (2024) examined the role of Azerbaijan's agricultural sector, emphasising the importance of technological innovation and market integration to ensure sustainable development. He also identified key barriers slowing down the modernisation of the sector, including a lack of strategic policies and limited access to finance. In addition, S. Valiyeva (2024) explored the impact of AI on the agricultural sector, focusing on the use of expert systems, image analysis, machine learning and the Internet of Things (IoT) to optimise production processes. She emphasised that the application of AI contributes to increased productivity, improved resource management and reduced costs, which are important factors in the development of smart agricultural technologies.

Research by U.O. Matthew *et al.* (2023) confirmed that investments in IoT technologies contribute to increasing the efficiency of agricultural production, optimising supply chains and improving the market position of products. The authors emphasised that technological innovations are an important factor in ensuring food security and sustainable agricultural development. In turn, B.D. Pal *et al.* (2019) assessed the technical and economic feasibility of climate-smart agricultural technologies in different agroclimatic conditions in South Asia, analysing farmers' behaviour regarding their implementation. Using a climate-smart feasibility index and optimisation modelling, the authors proposed policy and investment strategies for scaling up these technologies. The work of F.C. Anosike *et al.* (2023) analyses the integration of climate-smart agricultural technologies and effective post-harvest operations to improve agriculture in the context of climate change. The authors proposed the use of technologies such as solar dryers, greenhouses, and sustainable storage to reduce post-harvest losses and improve food security. Meanwhile, L. Arenas-Calle *et al.* (2024) assessed the potential of agricultural technologies such as irrigation and new crop varieties to reduce climate risks in agriculture. The authors showed that improved agricultural technologies can significantly reduce the impact of climate extremes, in particular reducing crop losses by 64% through the use of irrigation and improved corn varieties.

On the other hand, the results of A. Bekbossinova and R. Doszhan (2025) showed that investments in fixed assets and digital technologies do not have a significant impact on agricultural production, indicating the need for policy measures to improve digital literacy and technology adoption in the agricultural sector. C. Ding (2024) research demonstrated how blockchain technologies and smart contracts can promote investment in various areas of the economy by increasing transparency and reducing barriers to entry. The use of such technologies allows for the automation of investment processes, reducing the risk of fraud and ensuring more efficient capital management. In addition, A.Q. Al-Shetwi *et al.* (2025) examined the role of smart grid technologies in improving energy efficiency and integrating renewable energy sources, which can contribute to the development of smart agrotechnologies by optimising energy consumption in the agro-industrial sector. Investments in these technologies contribute to increased efficiency and reduced costs, which is important for the sustainable development of the agricultural sector.

Thus, the study aimed to investigate the impact of investment activity on the introduction of innovative agricultural technologies in agricultural production in different countries and regions, with a focus on the adaptation and practical application of these technologies in the agricultural sector of Azerbaijan. The study involved the following tasks: to analyse global trends in investment in smart agricultural technologies, to study the peculiarities of the introduction of these technologies in the agro-industrial complex of Azerbaijan, and to identify the main barriers and prospects for accelerating their integration by evaluating investment strategies and their impact on the efficiency of agricultural production.

MATERIALS AND METHODS

To investigate trends in smart agritechnology investment, a comprehensive set of methods was employed. These included statistical evaluation, time series analysis, forecasting modelling, comparative analysis, content analytics, and case studies. Comparative analysis was used to assess the distribution of investments in smart agritechnologies across global regions (North America, Europe, Asia-Pacific, Latin America, the Middle East, Africa), which helped to identify regional peculiarities in supporting agricultural innovations. Statistical evaluation processed data on the smart agriculture market share for 2023-2024, reflecting the scale and dynamics of technological changes in the secto. Forecasting modelling was applied to estimate the size of the global smart agritechnology market for 2023-2034, allowing for the determination of growth prospects for investments and demand for innovations (Smart agriculture market.., 2024).

Time series analysis was used to examine the volume of agricultural production in Central Asian countries (Azerbaijan, Kazakhstan, Kyrgyzstan, and Uzbekistan) from 2018-2024 to assess the regional context of technology implementation. These data were provided in millions (mln) of Azerbaijani manats, trillions (trn) of Kazakh tenge and Uzbek soums, and billions (bn) of Kyrgyz som, allowing for consideration of differences in national currencies and economic scales. This method was also applied to evaluate the dynamics of economic indicators (in thousands (ths) of manats) for agricultural enterprises in Azerbaijan over the same period, revealing trends in the agro-sector's development under the influence of smart agritechnologies (Ismayilova & Hajiyeva, 2024). Content analytics was employed to systematise global (Food and Agriculture Organization (FAO), European Bank for Reconstruction and Development (EBRD), Global Environment Facility (GEF) programmes, international microfinance, carbon markets) and regional (tax incentives, grants, public-private partnerships, agritech parks, incubators) mechanisms for financing innovations. This contributed to forming a holistic understanding of investment attraction strategies in Central Asian countries (Investment opportunities for..., 2022; Precision agriculture trends, 2025).

To assess the role of investments in the development of smart agritechnologies in Azerbaijan, a country characterised by intensive urbanisation and growing demand for food security in megacities, both quantitative and qualitative methods were applied. Statistical evaluation analysed data on agricultural expenditure in Azerbaijan's state budget for 2025 (Ashirov, 2024). A comparative analysis systematised key smart agritechnologies in Azerbaijan for 2024, including digital platforms (Electronic Agricultural Information System, n.d.), drones and satellite technologies (Farmonaut), precision agriculture (Idrak Agrorobot) (IDRAK Technology Transfer MM, n.d.), IoT systems in supply chains (Narrow Band IoT (NB-IoT) and Long-Term Evolution (LTE)), and agroparks (Dost Agropark), evaluating their contribution to enhancing the agro-sector's efficiency (Dost Agropark phase..., 2022; Vision for the future..., n.d.; Wireless solutions..., n.d.).

Case studies were used to provide a detailed examination of Azercell Business's IoT solution for irrigation systems ("Irrigation Control System") and the "Agali Smart Village" project as an example of integrating smart technologies for the development of rural areas that supply produce to megacities ("Smart villages" will..., 2022; Azercell Business integrates..., 2023). Azerbaijan was chosen due to its strategic location, rapid urbanisation, and active implementation of smart agritechnologies, making the country a illustrative example for studying investment strategies in megacities. Time series analysis was used to assess the volume of investments in fixed capital in Azerbaijan's agricultural sector from 2018-2024, revealing the economic effect of implementing smart agritechnologies (State Statistical Committee of the Republic of Azerbaijan, 2024). These data, expressed in million manats, reflect the dynamics of capital investment in the sector, demonstrating increased funding and a correlation with the integration of digital technologies.

RESULTS

Analysis of investments in smart agrotechnologies: General overview and global trends. The development of the agro-industrial complex largely depends on the level of implementation of innovative technologies and the volume of investments in their development and application. The use of smart agricultural technologies makes it possible to increase the efficiency of agricultural production, reduce resource consumption and minimise negative impacts on the environment. Key areas include process automation, precision farming, soil and crop monitoring using sensors, and the use of AI and BD for yield forecasting. Investments in these technologies determine the pace of their development and dissemination. Smart agricultural technologies are financed both at the state level through support programmes and through private and venture capital investments. International institutions that support the development of innovative agriculture in various countries play a special role. However, the level of investment in this area varies significantly depending on the region (Fig. 1).

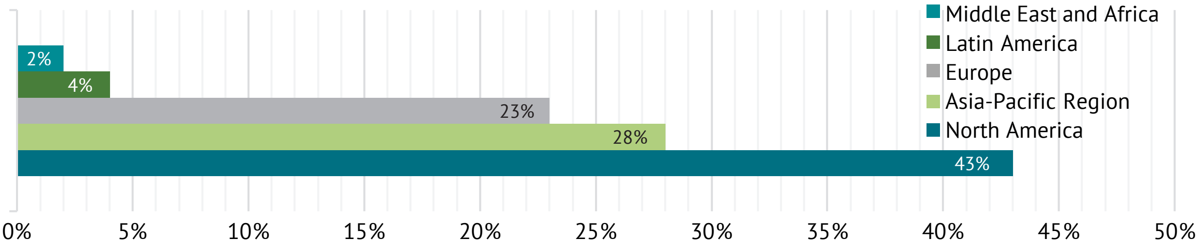

***Figure 1**. Smart agriculture market share by region, 2023-2024*
***Source:** compiled by the authors based on Smart agriculture market size. Share and trends 2024 to 2034 (2024)*

Thus, the distribution of investments in smart agrotechnologies indicates uneven funding in this area across different regions. North America attracts the largest share, largely due to active venture capital involvement, the development of digital agricultural solutions, and government programmes supporting innovation. Significant investment is also observed in the Asia-Pacific region and Europe, where technological progress in the agricultural sector is stimulated by both government initiatives and private capital. At the same time, Latin America, the Middle East and Africa are characterised by significantly lower levels of investment, due to both limited financial resources and insufficient infrastructure development for the implementation of smart solutions. This situation determines further trends in the development of the agro-industrial complex, affecting the speed of innovation adaptation and its effectiveness in different countries.

North America's leading position in smart agrotechnologies is due to a number of interrelated factors. Firstly, this region has a strong scientific and technological environment that promotes the creation of innovative solutions for the agricultural sector. In particular, agrotech start-ups (Indigo Ag, Plenty, FarmWise) are actively working in Silicon Valley and other development centres, quickly attracting venture capital investments. Secondly, agricultural enterprises in the United States and Canada have a high level of mechanisation and digitalisation, which simplifies the integration of the latest technologies into production processes. Government policy also plays a key role: governments fund research, provide tax incentives for innovative farming, and promote the spread of technology among farmers through support programmes. In addition, most of the agricultural land in North America belongs to large farms that have the financial capacity to invest in expensive digital solutions, unlike small-scale farming in many other regions. As a result of this comprehensive approach, North America not only maintains its leadership position in the implementation of agricultural innovations, but also sets an example for other regions of the world in the effective implementation of smart technologies in the agricultural sector.

Against this backdrop, it is clear that growing investment in smart agrotechnologies is driving the gradual expansion of the smart agriculture market. Funding for precision farming technologies, automated management systems, monitoring solutions and other digital innovations is helping to increase their share in the global agricultural sector (Kharchenko *et al.*, 2017). High levels of investment, combined with technological progress, are driving positive market dynamics. The smart agriculture market is expected to show steady growth between 2023 and 2034 (Fig. 2).

The projected market growth indicates a steady increase in demand for smart agricultural technologies, supported by both private investment and government incentives. The expected growth from USD 20.87 billion in 2023 to USD 74.03 billion in 2034, with an average annual growth rate of 12.2%, confirms the strengthening role of innovation in the future of the agro-industrial complex. North America is making the largest contribution to market development, while the main areas of application for smart technologies remain software, precision farming and livestock monitoring.

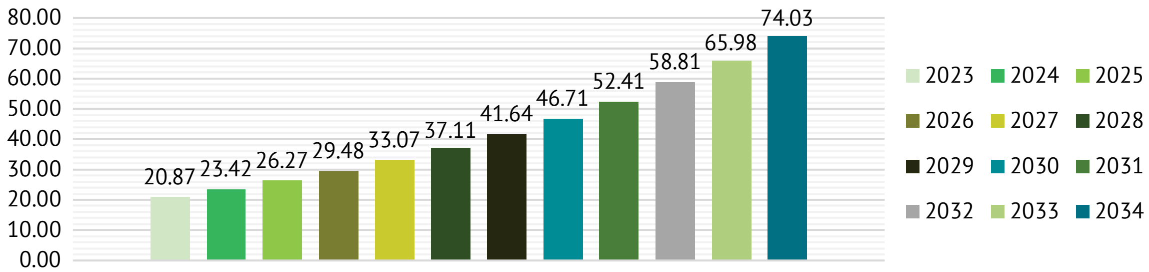

***Figure 2**. Global smart agriculture market size from 2023 to 2034 (USD billion)*
***Source:** Global smart agriculture market size from 2023 to 2034 (USD billion)*

Overall, investments in smart agrotechnologies are contributing to the emergence of new innovative solutions at the global level, particularly in 2024. For example, in August 2024, Sri Lanka launched the development of an Investment Plan for Climate-Smart Agriculture with the support of the FAO and the Green Climate Fund. This project aims to increase the resilience of the agricultural sector to climate change. In April 2024, Cropin, supported by Google, introduced the first open micro-language model for climate-smart agriculture, "aksara" which was designed to meet global nutritional needs. In particular, in the same month, Centre for Development of Advanced Computing (C-DAC) launched the SMART FARM system, which helps farmers optimise irrigation and fertilisation, significantly increasing crop yields (Smart agriculture market..., 2024). Other innovations, such as the GFX-350 display by Trimble, which controls the autopilot, or improvements in agricultural equipment management technologies by AG Leader Technology, contribute to the growth of agricultural process efficiency. Thus, these developments underscore the importance of investing in innovations that are actively transforming the agro-industrial complex, making it more efficient and sustainable. This technological development highlights the importance of funding innovative technologies in agriculture, as they can significantly increase the efficiency and sustainability of the agro-industrial complex. Global examples of innovation in agriculture underscore the need for financial support for technological modernisation in the agricultural sector. In this context, it is worth considering how agricultural production is developing in Central Asia, a region that is also actively pursuing innovation (Fig. 3).

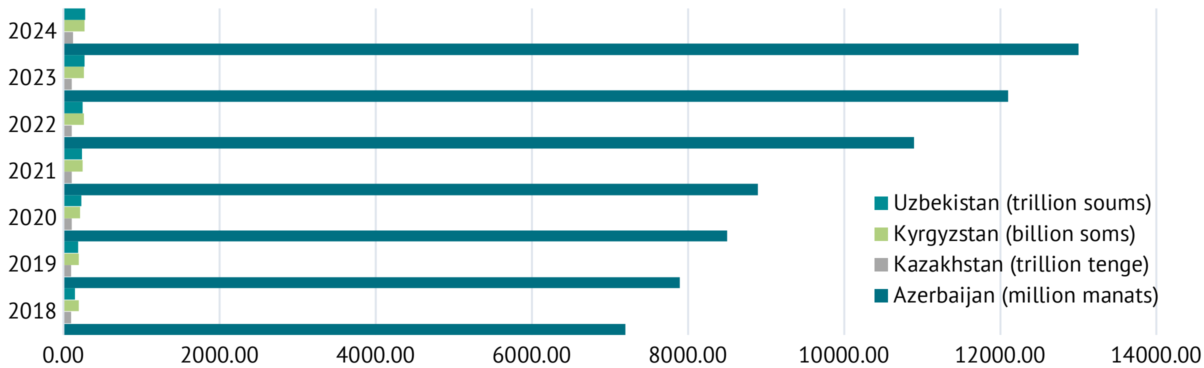

***Figure 3**. Agricultural production in Central Asia from 2018 to 2024*
***Source:** compiled by the authors based on H. Ismayilova and S. Hajiyeva (2024)*

The figure shows the nominal volume of agricultural production in the national currencies of Azerbaijan (million manats), Kazakhstan (trillion tenge), Kyrgyzstan (billion soms) and Uzbekistan (trillion soums) in 2018-2024. During this period, Azerbaijan demonstrates stable growth in production indicators. At the same time, Kazakhstan, Kyrgyzstan and Uzbekistan show less pronounced dynamics or moderate growth, with relatively stable but lower values in their respective currencies. Given the above production indicators, it is advisable to consider what mechanisms are used in the respective countries to attract investment in smart agrotechnologies (Table 1). In other words, Azerbaijan is demonstrating relative leadership among Central Asian countries in the implementation of smart agricultural technologies. Unlike other countries in the region, Azerbaijan is seeing concrete, measurable results from the use of digital solutions: water savings of up to 30-50% thanks to precision irrigation, a 10-30% increase in crop yields through the use of AI recommendations, and a 35% reduction in greenhouse gas emissions through optimised soil management. This level of integration of high technologies, in particular AI, satellite monitoring and blockchain, indicates a deeper penetration of digital tools into agriculture compared to other countries in the region. Countries such as Kazakhstan, Kyrgyzstan and Uzbekistan are also actively working to modernise their agricultural sectors, but the focus is mainly on traditional or physical solutions: drip irrigation, conservation agriculture, pasture improvement, rotational grazing, etc. For example, Kazakhstan is investing in climate-smart agricultural technologies with the support of international organisations (Kerimkhulle *et al.*, 2023). Kyrgyzstan is actively supporting small producers, while Uzbekistan is demonstrating a desire to attract foreign investment, creating technology parks and simplifying the regulatory environment.

Table 1. *Main methods of attracting investment in smart agricultural technologies in Central Asia*

Country	Main methods of attracting investmens
Azerbaijan	Promoting the introduction of precision agriculture using satellite monitoring, AI and blockchain technologies, which provide up to 30-50% water savings (precision irrigation); 10-30% increase in yields (due to AI recommendations and precise fertilisation); 35% reduction in greenhouse gas emissions (due to optimised soil and resource management)
	Increasing the climate resilience of rural communities through digital tools (risk analysis, monitoring, income diversification)
	Opportunity to participate in carbon markets through emissions tracking and soil carbon storage
	Building partnerships with government, research institutions, and agribusiness to integrate technologies into national agricultural policy
Kazakhstan	Investments in climate-smart agricultural technologies (conservation agriculture, drip irrigation, pasture improvement, precision agriculture)
	Financial support through the private sector
	State participation in research funding
	Promoting innovation through FAO, EBRD and GEF programmes
Kyrgyzstan	Attracting investment in low-cost climate technologies (rotational grazing, livestock efficiency, conservation agriculture)
	Grant support and soft loans for small and medium-sized producers
	Participation of international programmes of FAO, EBRD and GEF in the development of agricultural practices with the potential for adaptation and mitigation of climate change
	State support for innovation and financing of the agricultural sector
Uzbekistan	Attracting foreign investment through cooperation with international financial organisations, funds and development banks
	Introduce tax incentives and simplified procedures for private investment in digital and smart agricultural solutions
	Development of innovative infrastructure, including agro-technoparks, start-up incubators and educational programmes for farmers
	Supporting small and medium-sized agricultural producers through microfinance and access to technology

Source: *compiled by the authors based on Investment opportunities for climate-smart agrifood tech in Kazakhstan and the Kyrgyz Republic (2022), Precision agriculture trends: 2025 yield innovations (2025)*

Thus, Azerbaijan stands out for its systematic approach, where digital technologies have already had a noticeable effect on the efficiency of agricultural production, resource conservation, and environmental sustainability. This emphasises its lead over other countries in the region in terms of both the level of innovation implementation and the results achieved. Other countries are currently laying the groundwork for further digitalisation, but have not yet demonstrated a similar level of impact of smart agricultural solutions on specific production or environmental indicators. In summary, investment in smart agricultural technologies is key to the transformation of the agro-industrial complex, increasing its efficiency and sustainability. Despite significant growth in investment, there are significant differences in the levels of funding and technology development depending on the region, which affects the speed of innovation adoption. Important factors for further development are access to financing, political and economic stability, and infrastructure development. At the same time, technologies aimed at conserving resources and reducing environmental impact have great potential for attracting investment in the future.

Implementation of smart agricultural technologies in the agricultural sector of Azerbaijan. The development of the agro-industrial complex in modern conditions is impossible without the introduction of innovative solutions that contribute to increasing productivity, optimising resource use and reducing negative impact on the environment. In global practice, smart agricultural technologies based on the use of digital systems, process automation, BD and AI analysis are a key factor in improving the efficiency of agricultural production (Puyu *et al.*, 2025). These technologies enable precision farming, monitoring of soil and crop conditions, effective water resource management, and the introduction of robotic systems into production processes.

Azerbaijan, with its significant agro-industrial potential, is gradually integrating smart agricultural technologies into agriculture. The state pays special attention to the modernisation of this sector, which is strategically important for the country's economy. There has also been an increase in investment in digital solutions for the agricultural sector, the development of precision farming technologies, and the creation of infrastructure for their effective implementation. Both state support and the involvement of international financial institutions and private capital play an important role in this process. For example, an analysis of investments in agricultural technologies in Azerbaijan shows a significant increase in funding for the agricultural sector. In particular, in the state budget for 2025, expenditures on agriculture were increased by more than 30 million manats, reaching a total of more than 1.2 billion manats (Ashirov, 2024). This indicates growing state support for the agricultural sector, which includes investments in technological innovation and production modernisation. Overall, the introduction of smart agricultural technologies in Azerbaijan's agro-industrial complex is a key factor in improving the efficiency of agricultural production (Table 2).

***Table 2**. The most common smart agricultural technologies in Azerbaijan in 2024*

Technology	Description	Examples
Digital farm management platforms	Tools for crop planning, crop monitoring and resource management	Electronic Agricultural Information System – an electronic agricultural information system that combines data on land use, crops, subsidies and allows farmers to manage resources and receive government services
Drones and satellite technologies	Use of unmanned aerial vehicles and satellite imagery to monitor crop conditions, detect diseases and assess soil moisture	Farmonaut – a platform for monitoring the condition of crops using satellite images, AI and recommendations for agricultural management
Precision farming	Individual approach to field management, including precise application of fertilisers, pesticides and water	Idrak Agrorobot – a robot that automates processes in agriculture, such as irrigation, spraying with chemical fertilisers, pesticides, insecticides, weed removal, etc.
Innovations in supply chain and logistics	Supply chain management and IoT systems to optimise the storage, transport and distribution of agricultural products	IoT systems (NB-IoT and LTE) - technologies for optimising the processes of storage, transportation and distribution of agricultural products, reducing losses and increasing competitiveness
Agro parks	Integrated agro-industrial complexes that combine land plots with processing enterprises	Dost Agropark – a joint agricultural project between Turkey and Azerbaijan, including smart agriculture, renewable energy and sustainable development

***Source:** compiled by the authors based on K.P. Kumawat (2023), S. Alizade (2024), Vision for the future: Transition to digital agriculture international conference (n.d.)*

The Electronic Agricultural Information System (n.d.) platform is an important tool for the development of Azerbaijan's agro-industrial sector, promoting the integration of digital technologies into agriculture (Vision for the future..., n.d.). Launched by the country's government in 2019, it allows farmers to access a wide range of agricultural services, including information on land use, crops and subsidies. By creating a single electronic database, the system improves resource management, increases the transparency of service delivery and ensures more effective monitoring of agricultural processes (Potryvaieva *et al.*, 2024). This initiative also responds to the global challenges of digitalisation in the agricultural sector, in particular by reducing information, transaction and oversight costs. The Farmonaut platform demonstrates high efficiency, confirming the feasibility of investing in digital solutions even in urbanised regions (Kumawat, 2023). This technology helps reduce crop losses by 10-35% through timely detection of crop problems and rapid intervention. A significant advantage is time savings – up to 95% compared to traditional methods of assessing crop condition. In other words, Farmonaut not only increases agricultural productivity, but also creates conditions for the sustainable development of the agricultural sector in the context of urbanisation and increasing pressure on resources.

In turn, Idrak Agrorobot is an important innovation in Azerbaijan's agro-industrial complex, demonstrating the effectiveness of automation in agricultural processes (IDRAK Technology Transfer MM, n.d.). Using advanced technologies, such a robot can perform a number of important functions, including irrigation, spraying, weed control, and automated harvesting. One of the main advantages is the high accuracy of the operations performed, in particular, the accuracy of movement up to 1 centimetre. Overall, the use of Idrak Agrorobot saves up to 30% of the time spent on traditional tasks, reduces the need for human resources, and significantly improves the overall results of economic activity. IoT systems are also actively used in Azerbaijan to optimise agricultural processes (Wireless solutions..., n.d.). One of the examples is solutions from Azcom Technology, which provide wireless connectivity via NB-IoT and LTE technologies. These systems allow for effective monitoring of the condition of agricultural products and resource management, reducing the costs of storage and transportation of products.

For its part, Dost Agropark, launched in October 2021, is an important project being implemented in three phases (Dost Agropark phase..., 2022). Upon completion of all phases, it is planned to commission agroparks covering an area of 6,000 hectares, build product processing complexes, and large storage warehouses. Investments in the project amount to over USD 100 million, and it will contribute to ensuring food security in Azerbaijan and Turkey, creating over 500 jobs. Thus, smart agricultural technologies contribute to the optimisation of agro-industrial production by improving resource management, crop cultivation efficiency and reducing costs, which overall increases the competitiveness of the country's agricultural sector. In this regard, Azerbaijan is actively investing in the development of smart agricultural technologies, seeking to increase the efficiency of agriculture and ensure food security. For example, Azercell Business has introduced an innovative IoT solution for irrigation systems – the "Irrigation Control System" (Azercell Business integrates..., 2023). This technology allows remote control of the irrigation process for large areas in automatic mode, which helps to increase productivity. As of 2025, the company continues to implement this solution for irrigation systems in Azerbaijan, providing monitoring and control of the irrigation process, while the availability of this technology via web and mobile applications ensures ease of use and management efficiency.

It should also be noted that in June 2022, the "Agali Smart Village" project was presented in Azerbaijan, which aimed to transform rural life through the introduction of modern technologies and infrastructure ("Smart villages" will..., 2022). For this project, villages were equipped with high-speed internet to support e-health and e-learning. Particular attention was paid to environmental and alternative energy sources, using solar and wind installations, as well as heat pumps to meet energy needs. As of 2025, the "Agali Smart Village" project in Azerbaijan continues to develop, becoming a model for regional revitalisation. Moreover, Azerbaijan is actively negotiating with international organisations (FAO, World Bank, International Fund for Agricultural Development, etc.) to attract financial support for the agricultural sector, in particular to improve water supply and introduce modern agricultural technologies. This is aimed at increasing the resilience of agriculture to climate change and improving production processes. However, despite the active integration of smart agricultural technologies into Azerbaijan's agro-industrial complex, their large-scale implementation faces a number of challenges (Fig. 4).

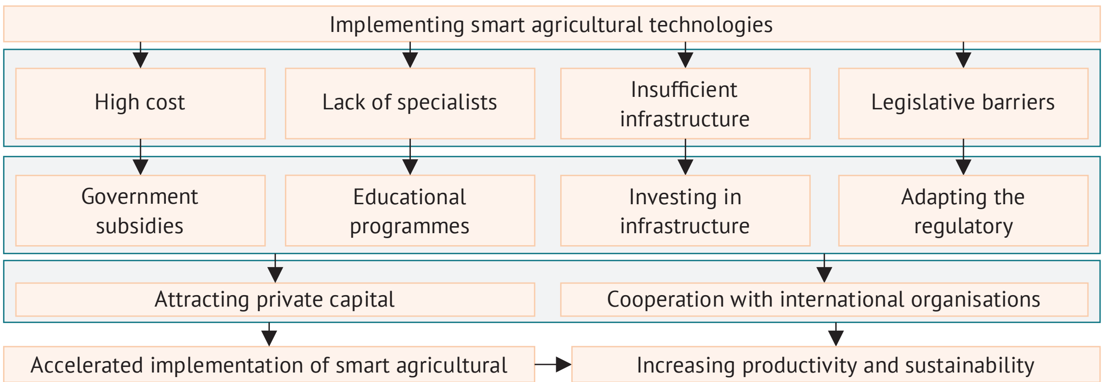

***Figure 4**. Main challenges of implementing smart agricultural technologies in Azerbaijan*
***Source:** compiled by the authors*

To overcome existing challenges and effectively develop smart agricultural technologies in Azerbaijan's agro-industrial complex, it is necessary to develop a comprehensive approach that includes financial, educational, infrastructural, and regulatory initiatives. One of the key areas is financial support, in particular the creation of state grant programmes to stimulate the introduction of smart agricultural technologies among small and medium-sized farms. An important aspect is the involvement of international financial organisations, such as the European Bank for Reconstruction and Development and the World Bank, to co-finance innovative agricultural projects. The private sector can be stimulated through tax incentives for companies investing in digital agricultural technologies. An additional effective mechanism is public-private partnerships, which allow for the implementation of large-scale projects using modern agricultural technologies.

The development of human capital plays an important role. It is necessary to integrate digital agriculture training programmes into educational institutions, in particular agricultural universities and vocational schools. It is advisable to organise training for farmers on the use of smart agricultural technologies, agricultural data management and the automation of production processes. It is also worth expanding international cooperation with agricultural educational and scientific institutions to exchange experience in the field of agricultural innovation. Infrastructure modernisation is an integral part of the successful implementation of smart agricultural technologies (Boiko *et al.*, 2025). The primary task is to develop digital infrastructure in rural areas, including access to high-speed internet and satellite communications. In addition, it is necessary to expand the network of agroparks, integrating IoT solutions for managing production processes, logistics, and product storage. A separate area is the modernisation of irrigation systems, which will enable the introduction of "smart" water use, optimising the use of water resources in agriculture (Hussain *et al.*, 2022).

The effective development of smart agricultural technologies also requires improvements to the regulatory framework. The development of legislation to stimulate digital agricultural solutions and regulate their application will contribute to more active integration of innovations (Syrov, 2024). In addition, it is important to create legal mechanisms for the protection of intellectual property, which will motivate local enterprises to develop their own technological solutions. The introduction of environmental standards will make it possible to assess the effectiveness of smart agricultural technologies in terms of sustainable development and minimising negative impacts on the environment (Konovalyuk *et al.*, 2023). In addition, international cooperation should be strengthened by developing strategic partnerships with countries that are leaders in smart agricultural innovation, such as the Netherlands, Israel and the United States. Joint research and development centres will enable the adaptation of advanced technologies to Azerbaijan's specific conditions, which will facilitate the faster implementation of modern solutions in agricultural production. Furthermore, attracting international grants will provide funding for the development and adoption of cutting-edge technologies in precision agriculture, agroecology, and biotechnology. In turn, the dynamic economic indicators of agricultural enterprises in Azerbaijan demonstrate the industry's increasing financial stability. This is a crucial factor for further investment attraction and the development of innovative technologies within the agro-industrial sector (Fig. 5).

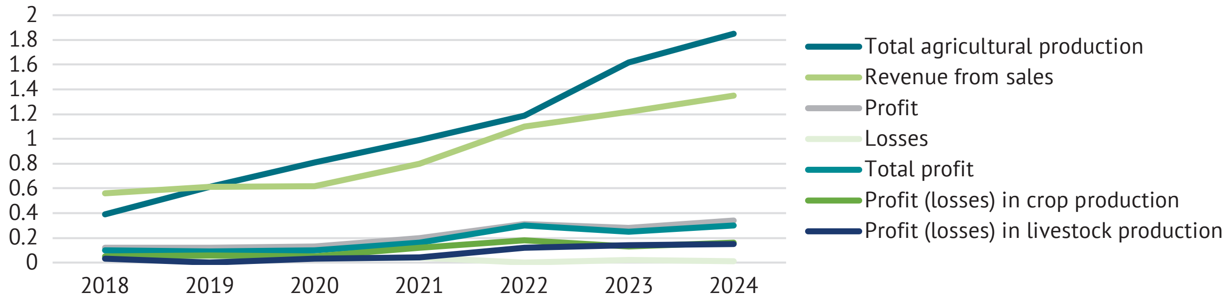

Figure 5. *Dynamics of economic indicators of agricultural enterprises in Azerbaijan, 2018-2024 (thousand manats)*
Source: *compiled by the authors based on H. Ismayilova and S. Hajiyeva (2024)*

The total volume of agricultural production in Azerbaijan shows positive dynamics, which indicates the effectiveness of state policy and investments in the development of the industry. Increased revenues of agricultural enterprises, profit growth and a stable financial position contribute to the further implementation of smart agricultural technologies. These factors indicate the prospects for further investment in the digitalisation of the agricultural sector, which will ensure increased productivity, resource optimisation and sustainable growth of Azerbaijan's agro-industrial complex. For a better understanding of the dynamics of investment processes in the agricultural sector, it is advisable to analyse the volume of capital investments in this sector in Azerbaijan (Table 3). The figures provided reflect financial activity in the industry for 2018-2024, which is important for assessing the investment environment in which innovative technologies are being implemented.

Table 3. *The volume of investments in fixed assets in the agricultural sector of Azerbaijan in 2018-2024 (million manats)*

Year	Volume of investments
2018	764.4
2019	769.5
2020	520.6
2021	341.9
2022	408.0
2023	578.3
2024	625.0

Source: *compiled by the authors based on State Statistical Committee of the Republic of Azerbaijan (2024)*

In other words, there are fluctuations in investment volumes, with certain increases and decreases, reflecting changes in economic conditions and financing of the agricultural sector. The overall trend shows a gradual increase in investment, confirming interest in the development of the agro-industrial complex and the potential for further implementation of innovative technologies. Thus, the large-scale introduction of smart agricultural technologies in Azerbaijan's agro-industrial complex is a necessary condition for ensuring its competitiveness and sustainable development. Effective digitalisation of agriculture requires not only investment in technological solutions, but also modernisation of infrastructure, training of qualified personnel and improvement of the regulatory framework. Creating favourable conditions for the integration of innovations will optimise production processes, improve resource management and minimise the environmental impact of agricultural activities. State support and the involvement of international experience will be key factors determining the further dynamics of the agricultural sector's development. The successful implementation of these measures will contribute to increased productivity, financial stability of enterprises, and the formation of a modern agricultural ecosystem capable of effectively adapting to global challenges.

DISCUSSION

This study showed that investments in smart agrotechnologies contribute to increased productivity, resource optimisation and food security, in particular through the introduction of precision farming, digital platforms and IoT solutions. Similarly, R. Choudhary *et al.* (2024) looked at the use of smart agri-tech, like AI and data science in the agri-sector to predict crop yields, manage resources, and deal with climate and scarcity challenges. In other words, both studies emphasise the importance of technology in transforming the agricultural sector, but the current study focuses on investment aspects, while the one under review focuses on technological approaches to process optimisation. The current analysis shows that the global smart agrotechnology market will grow from USD 20.87 billion in 2023 to USD 74.03 billion in 2034, with the main investments going towards automation, precision farming and AI solutions. Similarly, K. Selwe and C. Hofisi (2024) investigated the role of innovative technologies in the development of smart cities, emphasising their potential to improve the efficiency of urban systems. However, unlike the agricultural sector, urban initiatives face increased cybersecurity and data protection challenges, which require additional regulatory measures.

This study also showed that funding for smart agrotechnologies is growing, particularly in Azerbaijan, where budget expenditures for the agricultural sector in 2025 have been increased by more than 30 million manats, which contributes to the implementation of innovative solutions in agriculture. Similarly, T. Mandičák *et al.* (2021) looked at the assessment of investments in smart technologies, but for the construction industry, emphasising the need for effective methods of analysing their economic feasibility. Although both areas require significant capital investment, in the agricultural sector they are aimed at automating and digitising production, while in construction they are aimed at creating intelligent infrastructures and improving project efficiency.

The results showed that investments in smart agrotechnologies in Azerbaijan contribute to the implementation of digital farm management platforms, drones and satellite technologies, precision farming, IoT systems for supply chains and agropark, which increases productivity and optimises resources. To this end, the following platforms and technologies were analysed: Electronic Agricultural Information System, Farmonaut, Idrak Agrorobot, NB-IoT, LTE and Dost Agropark. In turn, S. Yusupov *et al.* (2025) found a positive effect of using modern agricultural technologies, such as drip irrigation and organic fertilisers, on increasing yields and conserving resources. Although both studies emphasise the importance of technology, the current results focus on investment aspects, while the aforementioned study focuses on the techniques used in agriculture. The work carried out confirmed the importance of investing in smart agricultural technologies to improve agricultural efficiency, in particular through the introduction of precision farming and digital platforms, which in Azerbaijan has resulted in 30-50% water savings, 10-30% yield increases and 35% reductions in greenhouse gas emissions through satellite monitoring, AI and blockchain technologies. Similarly, S. Giannelos *et al.* (2024) demonstrated the impact of investments in smart grids, focusing on the economic aspects of technology implementation in the energy sector. Both studies emphasise the importance of investment for resource optimisation, but in the agricultural sector the focus is on production, while in the energy sector it is on reducing costs and increasing grid flexibility.

Contrary to current results, which show that in 2023-2024, investments in smart agrotechnologies were unevenly distributed (North America – 43%, Asia-Pacific – 28%, Europe – 23%, Latin America – 4%, Middle East and Africa – 2%) due to infrastructure and economic constraints, as well as their impact on the economic performance of the agricultural sector, G.S. Reddy *et al.* (2025) focused on analysing the environmental sustainability of digital technologies in agriculture, urban development and energy. Thus, both works pointed to the importance of innovation for resource optimisation, but the former focused on the financing structure and economic effects, while the latter focused on the overall impact of technologies on sustainable development. Similar to the results obtained, which confirmed the importance of investments in smart agricultural technologies for increasing productivity and optimising resources, in particular through the stable growth of agricultural production in Azerbaijan compared to the less pronounced dynamics in Kazakhstan, Kyrgyzstan and Uzbekistan for 2018-2024, the results of Y. Chen *et al.* (2024) emphasised the importance of precision farming in reducing negative environmental impacts and improving the efficiency of the agricultural sector. However, the current study focused on financial aspects and investment strategies, while the one under review focused on technological approaches to agrosystem management and their impact on agricultural sustainability.

The study showed that investments in smart agrotechnologies contribute to productivity and resource optimisation through the digitalisation and automation of processes, in particular through the introduction of precision farming using satellite monitoring, AI and blockchain technologies, the creation of partnerships with the government and agribusiness, and participating in carbon markets to track emissions. Similar conclusions were made by W. Febiyanti and A.P. Subriadi (2024), who studied the economic impact of investments in smart cities, emphasising their importance for gross domestic product growth, economic benefits and efficient use of resources. However, unlike the current study, which considers investments in the agricultural sector, the study focused on the need to develop methodologies for assessing the economic impact of innovations in urban development. The conclusions of this study emphasised the importance of investing in smart technologies in the agricultural sector, in particular AI and BD for monitoring crop yields and managing production. This is consistent with the findings of T. Al-Rimawi and M. Nadler (2025), who found that AI and BD are key to the development of smart real estate, as they facilitate market analysis, location selection and optimisation of construction processes. Both studies indicated that these technologies are suitable for practical use, although in the smart agricultural sector they are used to improve the efficiency of agricultural processes, while in real estate they are used to manage the urban environment and plan development.

The study focused on analysing investment trends in smart technologies and their impact on the agro-industrial complex, complementing the research by S. Khan *et al.* (2025), which confirmed the current findings regarding significant growth in investment in such technologies, particularly in automation, precision farming, and the use of BD for yield forecasting. Both studies noted the importance of financial support and overcoming barriers such as economic instability and uneven infrastructure development for the effective development of these technologies. At the same time, the current study expands the analysis of investment trends, focusing on specific regional aspects and financial mechanisms to support the implementation of smart technologies. The results of this study align with the conclusions of T.D. Viet *et al.* (2025), as both studies emphasise the importance of applying modern technologies, such as AI and IoT, for the development of smart agricultural production. The current study expands the focus on investment aspects, the impact of these technologies on the economic efficiency of the agricultural sector, and the need to overcome barriers through financial support, in particular through government grant programmes, the involvement of international financial organisations, tax incentives for the private sector, and public-private partnerships for the implementation of innovative agricultural projects. Although the aforementioned study focuses on the overall development of smart agricultural technologies and their integration to achieve sustainable agricultural development, both studies confirm the importance of technologies for optimising resources and increasing productivity in the agricultural sector.

Moreover, the results of the study by M. Shalamberidze and T. Gugeshashvili (2025) agree with the current analysis in recognising investment as a key factor in economic development, particularly through promoting modernisation, technology adoption and productivity growth. The current study details these processes in the context of smart agrotechnologies, demonstrating the growth in investment in fixed capital in Azerbaijan's agricultural sector in 2024, which contributed to an increase in the profits of agricultural enterprises. Meanwhile, the aforementioned source considers investment as a tool for overall economic growth and attracting foreign capital. The study found that one of the key factors in improving the efficiency of agricultural production is the combination of investment in digital infrastructure with the development of educational programmes for farmers and agricultural specialists. This approach not only promotes innovation but also helps to create a sustainable knowledge ecosystem necessary for adaptation to modern technological changes. In turn, M. Elhussiny (2025) study focuses on the implementation of smart technologies in port infrastructure, demonstrating the environmental and energy benefits of such solutions in the field of maritime logistics. Despite the differences between the industries, both approaches demonstrate the importance of innovation as a tool for achieving sustainable development. This study also showed that investments in smart agrotechnologies in Azerbaijan contribute to increased productivity, efficient use of resources and digitalisation of the agricultural sector. At the same time, S.T. Hajiyeva (2025) study focuses on the development of small and medium-sized businesses in the agro-industrial sector, barriers and investment dynamics in Azerbaijan. The results obtained generally confirm the conclusions of the aforementioned work regarding the importance of investment and structural modernisation for the development of the country's agricultural sector.

Thus, the study confirmed that investments in smart agrotechnologies play a key role in the transformation of the agro-industrial complex, ensuring increased productivity, resource optimisation and enhanced food security both globally and regionally, particularly in Azerbaijan. A comparison with other studies showed common conclusions regarding the importance of modern technologies for sustainable development, but revealed different emphases – from financing and institutional support to direct technological implementation, which indicates the need for a comprehensive approach to the digitalisation of the agricultural sector.

CONCLUSIONS

An analysis of investments in smart agrotechnologies has revealed key trends and their impact on the transformation of the agro-industrial complex, particularly in Azerbaijan. The global smart agrotechnology market has shown significant growth, with a projected increase from USD 20.87 billion in 2023 to USD 74.03 billion by 2034, with an annual growth rate of 12.2%. In 2023-2024, the main share of investments fell on North America (43%), the Asia-Pacific region (28%) and Europe (23%), while Latin America (4%) and the Middle East and Africa (2%) remained limited due to infrastructure and economic barriers. North America's leading position is due to its developed scientific and technological environment, venture capital, high level of digitalisation and government support. The main areas of funding include automation, precision farming, soil and crop monitoring using sensors, and AI and BD for yield forecasting. Global innovations, such as the micro-language model "Aksara" by Cropin, the SMART FARM system by C-DAC, and the GFX-350 display by Trimble, illustrate the transformation of the agricultural sector through technology.

An analysis of the implementation of smart agricultural technologies in Azerbaijan's agro-industrial complex showed positive dynamics and demonstrated growth in agricultural production in Central Asian countries for 2018-2024. The results emphasised that technologies and platforms such as Electronic Agricultural Information System, Farmonaut, Idrak Agrorobot, NB-IoT, LTE and Dost Agropark increase productivity and optimise resources. In general, technologies such as precision farming, the use of drones and satellite technologies significantly increase production efficiency in the country. At the same time, Azerbaijan demonstrates relative leadership in the implementation of smart agricultural technologies among countries such as Kazakhstan, Kyrgyzstan and Uzbekistan. Compared to other countries in the region, Azerbaijan achieves water savings of 30-50% through precision irrigation, increases yields by 10-30% through AI recommendations, and reduces greenhouse gas emissions by 35% through optimised soil management. However, the following problems have been identified in the implementation of smart agricultural technologies in Azerbaijan: high cost, lack of specialists, inadequate infrastructure and legislative barriers. In addition, the implementation of projects such as the "Agali Smart Village" and the irrigation control system has not only modernised agricultural technologies but also improved social conditions in agriculture. This has increased the competitiveness of the agricultural sector, reduced costs and optimised resources. Progress in agricultural investment, in particular the increase in budget expenditure on agriculture by 30 million manats in 2025, confirms the importance of state support in this area.

However, the study is limited by insufficient access to complete data on investment flows and partial consideration of the socio-economic aspects of the implementation of smart agricultural technologies. Further research should focus on developing financial mechanisms to support small and medium-sized businesses, including microcredit and subsidies, analysing the long-term impact of innovation on the socio-economic structure of rural communities, and assessing the impact of geopolitical and foreign policy factors, such as trade restrictions or sanctions, on investment flows. It is recommended to develop grant programmes, expand digital infrastructure, improve legislation to stimulate innovation, and strengthen cooperation with leading countries such as the Netherlands and Israel to adapt advanced technologies.

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CONFLICT OF INTEREST

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Роль інвестицій у розвитку розумних сільськогосподарських технологій у мегаполісах

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Анотація. Метою дослідження був аналіз ролі інвестицій у розвитку інтелектуальних сільськогосподарських технологій в агропромисловому комплексі різних регіонів, з акцентом на впровадження цих технологій в Азербайджані. У дослідженні проаналізовано поточні інвестиційні тенденції в інтелектуальні сільськогосподарські технології в Північній Америці, Європі, Азіатсько-Тихоокеанському регіоні, Латинській Америці, Близькому Сході та Африці за 2023-2024 роки, а також оцінено їх вплив на розвиток агропромислового комплексу в період з 2023 по 2034 рік. Аналіз інвестицій показав, що Північна Америка займала найбільшу частку ринку інтелектуальних сільськогосподарських технологій у 2023-2024 роках (43 %), далі йдуть Азіатсько-Тихоокеанський регіон (28 %) та Європа (23 %), тоді як Латинська Америка отримала лише 4 %, а Близький Схід та Африка – 2 %. Прогнози показали, що світовий ринок розумних агротехнологій зросте з 20,87 млрд доларів США у 2023 році до 74,03 млрд доларів США у 2034 році. Результати також показали, що основні інвестиції спрямовані на автоматизацію процесів, точне землеробство, моніторинг ґрунтів та худоби, а також використання штучного інтелекту та великих даних для прогнозування врожайності сільськогосподарських культур. Водночас найбільшими перешкодами для розвитку були політична та економічна нестабільність, обмежений доступ до фінансування для малих сільськогосподарських підприємств та нерівномірний розвиток інфраструктури в різних регіонах. З іншого боку, результати показали, що впровадження розумних агротехнологій в агропромисловому комплексі Азербайджану підвищує ефективність виробництва завдяки точному землеробству, використанню дронів та супутникових технологій, цифровим платформам, інноваціям у ланцюгах поставок та агропаркам. Ці технології оптимізують ресурси, покращують моніторинг та знижують витрати, підвищуючи конкурентоспроможність сільськогосподарського сектору. Такі проекти, як «Розумне село Агалі» та «Система контролю зрошення», не лише модернізують технології, але й покращують соціальні умови в сільській місцевості. Крім того, спостерігається значне збільшення фінансування сільськогосподарського сектору, зокрема в державному бюджеті на 2025 рік, де витрати на сільське господарство збільшено на понад 30 мільйонів манатів. Аналіз також показав позитивну динаміку економічних показників сільськогосподарських підприємств Азербайджану між 2018 і 2024 роками. Водночас були визначені проблеми, такі як необхідність модернізації інфраструктури, підвищення кваліфікації персоналу та вдосконалення законодавства. Таким чином, отримані результати свідчать про позитивний вплив інвестицій у розумні агротехнології на ефективність сільськогосподарського сектору як в Азербайджані, так і в інших регіонах світу

Ключові слова: цифровізація сільського господарства; автоматизація виробничих процесів; фінансування підприємств; прогнози та тенденції світового ринку; підвищення ефективності виробництва

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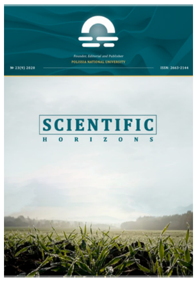

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Assessment of the effectiveness of state aid to agricultural producers

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Abstract. The purpose of this study was to identify the key factors influencing the effectiveness of state support for agricultural producers in Kazakhstan, as well as to assess its influence on the development of the agro-industrial complex. The study employed methods of systematic analysis and comparative assessment, which helped to identify the specific features of state support for agricultural producers, determine its impact on the economic development of the agro-industrial complex, and the validity of the allocation of budget resources. The analysis found that the total amount of budget funds allocated to support agriculture in Kazakhstan

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increased from KZT 300 bn in 2015 to KZT 750 bn in 2024, with the share of subsidies growing from KZT 150 bn to KZT 410 bn. However, most of the funding goes to large agricultural holdings, while small and medium-sized farms face challenges accessing financial and material resources. The analysis revealed that state aid positively influences agricultural productivity growth. For example, grain yields increased from 1.12 t/ha in 2015 to 1.63 t/ha in 2024, while milk production increased from 4.8 mn t to 6.7 mn t. However, the availability of subsidies does not always lead to increased profitability. For example, despite the expansion of preferential lending from KZT 100 bn to KZT 280 bn, small farmers still face excessive costs and challenges in obtaining financial resources. The pace of digitalisation in the agro-industrial complex continues to be insufficient: the introduction of precision farming is limited by a lack of infrastructure and specialists. The experience of the EU, the US, and Australia, where state support stimulates innovative solutions, suggests the need to expand technological modernisation programmes. As a result, the study concluded that subsidies need to be redistributed in favour of small and medium-sized farms, control over the targeted use of funds must be strengthened, and digital technologies must be actively introduced to improve the efficiency of the agricultural sector

Keywords: subsidies; preferential lending; audit of budget expenditure; crop yields; technical modernisation

INTRODUCTION

The agro-industrial complex of Kazakhstan plays a key role in the country's economy, influencing food security, rural development, and social stability in the regions. Agriculture and agricultural processing account for a sizeable share of the economic structure and create jobs for the population. To increase production efficiency and introduce modern technologies, the government is implementing measures to support agricultural producers, including subsidies, preferential lending, tax breaks, and modernisation programmes. However, with the growing need for innovation and product quality improvement, the agricultural sector faces serious challenges. These include climate change, rising energy and resource prices, and the need to transition to more sustainable farming methods. These factors require flexibility in government support policies and constant monitoring of the effectiveness of the programmes being implemented. In the current circumstances, it is crucial not only to provide financial aid, but also to adapt state aid mechanisms to emerging challenges so that they contribute to the long-term and sustainable development of the agro-industrial complex.

The issue of the effectiveness of government support for agricultural producers stays relevant against the backdrop of dynamic changes in agricultural policy and the economic situation. M. Meng *et al.* (2024) noted that subsidies for equipment and fertilisers positive influenced agricultural productivity. However, the researchers also emphasised that this process was accompanied by an uneven distribution of resources between large and small farms. U. Kambali and N. Panakaje (2022) argued that the introduction of new financial mechanisms, such as investment loans, markedly improved financial accessibility for small and medium-sized farmers. The researchers believe that these measures stimulated technological upgrading and improvements in production processes in the agricultural sector. S. Getahun *et al.* (2024) studied the impact of precision farming technologies on the growth of agricultural production efficiency, emphasising the need for extensive investment in infrastructure and training. The researchers also argued that without adequate training for farmers and infrastructure development, the adoption of these technologies would be limited. A. de Boon *et al.* (2022) highlighted the value of government support in the transition to environmentally sustainable agriculture. The researchers noted that investment in environmentally friendly technologies is a crucial factor in the sustainable development of the agricultural sector. G.S. Malhi *et al.* (2021) addressed the need to adapt agricultural practices to climate change, which required a review of conventional farming methods. The researchers also noted that the adaptability of agricultural policy can ensure the sustainability and competitiveness of the agricultural sector in the face of climate change.

V. Stadnyk *et al.* (2021) argued that cooperation between various actors in the agro-industrial complex, including farmers and processing enterprises, contributes to reducing costs and increasing production volumes. In the researchers' opinion, the development of cooperative mechanisms considerably improves resource efficiency and contributes to the expansion of sales markets. M.-H. Ehlers *et al.* (2021) highlighted the significance of flexibility in the distribution of subsidies, which accommodate regional characteristics and the individual needs of agricultural producers. The researchers also noted that such measures allow addressing problems and meeting the needs of farmers more effectively. W. Lin and J. Huang (2021) studied the effects of tax incentives on the development of small farms, emphasising that reducing the financial burden contributed to improving their competitiveness and stability. The researchers also noted that such measures were necessary to create more favourable business conditions in the agricultural sector.

M. Moahid *et al.* (2021) investigated the influence of credit programmes on improving agri-producers' access to financial resources, arguing that this contributed to the modernisation of technologies and increased production volumes. In their study, the researchers stressed the need to simplify the conditions for obtaining preferential loans. K.L.M. Ang and J.K.P. Seng (2021) investigated the possibilities of introducing information technology into agribusiness, arguing that the digitalisation of agriculture enabled a marked improvement in production performance. The researchers noted that without the introduction of relevant IT solutions, the agricultural sector would be unable to compete in international markets effectively. Thus, despite extensive research in this area, there are still unresolved issues, such as the effectiveness of long-term financial support mechanisms, improving cooperation at the regional level, and adapting innovative technologies to the specific conditions of Kazakh agriculture.

The purpose of the present study was to assess the effectiveness of state support for agriculture in Kazakhstan and to identify measures that could be taken to improve this support. The objectives of the present study were as follows: to consider the role of financial mechanisms, such as investment loans, in improving financial accessibility for farmers and their technological modernisation; to assess the potential of precision farming technologies to improve agricultural efficiency and the possible obstacles to their adoption; to assess government support for the transition to environmentally sustainable practices in the agricultural sector.

MATERIALS AND METHODS

The study conducted a comprehensive assessment of state support for agricultural producers in the Republic of Kazakhstan, including an analysis of its structure, delivery mechanisms, and influence on the development of the agro-industrial complex. The focus was on exploring various instruments of state support, including subsidies, preferential lending, agricultural risk insurance, as well as programmes promoting technological modernisation of the industry. The first stage of the study analysed financial support for agriculture. Various forms of subsidies were considered, such as payments per hectare of cultivated land, compensation for fuel costs, and support for the production of certain types of agricultural products. The study assessed the availability of credit resources, the terms of preferential loans, interest rates, and the degree of involvement of state institutions in financing the agricultural sector. Furthermore, the issue of agricultural risk insurance was examined, including state co-financing of insurance programmes, the coverage of farms by these instruments, and factors limiting their availability.

The second stage of the study focused on analysing the technological modernisation of agricultural production. The study assessed the influence of government programmes, such as subsidies for pesticides, fertilisers, seeds, priority crops, and livestock, on the renewal of agricultural equipment, the availability of subsidies for its purchase, and the promotion of innovative technologies. Measures to develop digital technologies in agriculture were also analysed, including the use of precision farming, automated production process management systems, and the introduction of modern methods for monitoring crop and soil conditions. The third stage of the study assessed the effectiveness of budget funds allocated to support agriculture. The analysis included a comparison of the financing system for the agricultural sector in Kazakhstan with leading international practices (EU, USA, Australia, Canada, Japan, New Zealand), which helped to identify key differences in the mechanisms for distributing and controlling state subsidies. Legislation regulating the audit of budget expenditures in Kazakhstan was examined, such as the Law of the Republic of Kazakhstan No. 392-V LRK (2015), the Regulatory Resolution of the Accounts Committee for Control over the Execution of the Republican Budget No. 6-NK (2020) and Order of the Minister of Finance of the Republic of Kazakhstan No. 873 (2018). Additionally, the degree of farmers' dependence on state support and the possible consequences for the long-term sustainability of their farms were examined.

Next, the study examined the economic and social consequences of the implementation of state support programmes for agricultural producers. The analysis included an assessment of labour productivity growth, crop yield dynamics, and the profitability of farms based on reports on the dynamics of agricultural development in Kazakhstan and budg*et* allocations for its development for the 2015-2024 period. The effects of state support on the development of rural infrastructure, including transport logistics, storage, and processing systems for agricultural products, were also examined. Particular attention was paid to employment in rural areas and the significance of state aid in ensuring stable incomes for farmers. The final stage of the study analysed the environmental aspects of state support for agriculture. The study examined the influence of subsidies on the efficient use of water and land resources, measures to promote sustainable agricultural production methods, and the dissemination of practices aimed at reducing the negative impact of agricultural activities on the environment. Thus, the study covered all key aspects of state support for agricultural producers, which helped to identify its advantages and disadvantages, as well as to determine ways to improve the mechanisms for financing, controlling the distribution of budget funds and stimulating technological development in Kazakhstan's agro-industrial complex.

RESULTS

Financial support for agriculture plays a key role in the development of the sector, improving production efficiency, and increasing resilience to risks. Subsidies, loans, preferential financing, and access to risk insurance constitute a substantial part of this support (Sodoma *et al.*, 2021). Subsidies are one of the most widespread instruments of government support for agriculture. They are aimed at reducing agricultural producers' costs, stimulating production growth, and modernising the sector. The structure of subsidies may vary depending on the country and programme, but several key types are most prevalent. Subsidies may be provided per hectare of cultivated land, which is particularly significant for large agricultural enterprises where land size plays a key role in the production process. Subsidies may also be granted per litre of fuel required to operate agricultural machinery or per unit of product produced, e.g., per tonne of grain or litre of milk. These measures contribute to increased productivity and help agricultural producers reduce their operating costs.

Loans and preferential financing are a valuable component of government policy in agriculture. They provide agricultural enterprises with the opportunity to invest in development, expansion of production, and modernisation of technology. The terms of such loans may include low interest rates, preferential repayment terms, and partial state guarantees, making them accessible to a wide range of producers. However, despite favourable terms, access to credit resources may continue to be a problem for some small and medium-sized agricultural producers, especially in times of economic instability. In such cases, the government's task is to create conditions for obtaining cheap loans and subsidising part of the interest rates. Agriculture, like other industries, is exposed to various risks, such as adverse weather conditions, plant and animal diseases, and economic fluctuations. In this regard, the availability of risk insurance is becoming a vital element of financial protection for agricultural producers. State co-financing of insurance programmes makes insurance more accessible to farmers, reducing their financial burden in case of adverse events. It also contributes to the development of the agricultural insurance market, allowing producers to feel more confident in times of instability and minimise potential losses.

Technological modernisation is a key factor in improving agricultural efficiency, product quality, and industry sustainability in a rapidly changing environment. One of the crucial elements of modernisation is support for the purchase of modern agricultural equipment, as well as the impact of government programmes on the renewal of the machine park and the introduction of digital technologies (Duncan *et al.*, 2021). The purchase of modern agricultural machinery and equipment plays a key role in technological modernisation. Modern machines greatly increase labour productivity, improve the quality of land cultivation, and contribute to production growth. However, the prohibitive cost of such equipment often becomes an obstacle for small and medium-sized farms. In this case, state support in the form of subsidies, soft loans, or tax breaks helps agricultural producers to renew their machinery fleet. For instance, many countries provide subsidies for the purchase of tractors, combine harvesters, seeders, and other equipment, which enables farmers to invest in high-quality machinery without major initial costs. Such support contributes to the more active introduction of the latest technologies in agricultural production. State programmes supporting the technological modernisation of agriculture play a key role in the renewal of machinery and the introduction of innovative technologies (Musca & Kara, 2023). These programmes may include not only subsidies for the purchase of equipment, but also training for specialists, personnel training, and consulting services for farmers on the use of modern equipment and technologies. The impact of such programmes on the renewal of the machine park is that they significantly accelerate the modernisation process, reducing the financial burden on agricultural producers and allowing them to invest more wisely in high-tech equipment. Additionally, programmes aimed at introducing the latest technologies contribute to improving the environmental situation by increasing resource efficiency and reducing costs.

One of the most promising areas of technological modernisation in agriculture is the introduction of digital solutions, such as precision farming and process automation (Stender *et al.*, 2024). These technologies enable the collection and analysis of data on soil condition, moisture levels, and temperature, which helps to make more informed decisions about sowing, fertilisation, and harvesting times. Precision farming systems using sensors, GPS and satellite technology markedly increase yields, reduce fertiliser and plant protection costs, and minimise adverse environmental impact. Implementation of such technologies requires highly qualified specialists, which makes them accessible primarily to large agricultural enterprises. However, in the future, such solutions may become available to small farms as well. The automation of processes such as harvesting, land cultivation, and irrigation also greatly increases labour productivity. Modern robots and drone technologies enable work with minimal human involvement, which reduces labour costs and increases the accuracy of operations. To improve the efficiency of budget spending in agriculture, Kazakhstan could look at what other countries have succeeded in. In some countries, government support for farmers is not merely about boosting production, but also about introducing innovative technologies, sustainable farming methods, and environmentally friendly practices (Table 1).

***Table 1**. Comparison of state support for the agro-industrial complex in different countries*

Country	Main forms of state support	Approximate amounts of support	Notes
European Union	Subsidies for environmentally friendly farming, agroecological zones, production modernisation	EUR 58 bn in 2020 to support farmers	Includes support for innovative technologies and sustainable farming practices
USA	Tax breaks, low-interest loans, subsidies for innovative technologies	USD 25 bn (federal agricultural support programme in 2021)	Programmes encourage long-term investment and sustainable agriculture
Australia	Subsidies to support agriculture in remote areas, innovative projects, climate risk insurance	AUD 4.8 bn for agricultural support programmes (2022)	Support is aimed at sustainable development and reducing climate risks.
Canada	Subsidies for technology development, use of renewable energy sources, risk insurance	CAD 3.8 bn (federal programme in 2021)	Includes maintaining product quality and improving the sustainability of farmers
Japan	Subsidies for modernisation, agro-ecological tourism, tax breaks, scientific research	JPY 1.5 tn (2022 for agricultural support)	The support system focuses on innovation and sustainable production.
New Zealand	Grants for environmentally friendly technologies, sustainable production methods, bioenergy	NZD 350 mn in 2021 for agricultural development and environmental initiatives	The programmes are aimed at the sustainable use of natural resources and improving production efficiency.

***Source:** compiled by the authors of this study based on data from B. Czyżewski et al. (2021), H. Panchasara et al. (2021), S.R. McGreevy et al. (2021), N. Bradly et al. (2022), O. Adisa et al. (2024), A.G. Green et al. (2024)*

In European Union (EU) countries, support for the agro-industrial complex includes not only financial subsidies but also incentives for sustainable farming practices. Within the framework of the EU's general agricultural policy, programmes focused on environmentally friendly farming, the creation of agroecological zones and the modernisation of agriculture through the introduction of the latest technologies are actively supported. In 2020, EUR 58 bn was allocated to support farmers, including support for innovative technologies and sustainable farming practices. European farmers can receive subsidies aimed at improving infrastructure and technologies for processing agricultural products. Particular attention is paid to environmental sustainability, which contributes to the integration of agriculture into the broader context of sustainable development. The use of precision farming technologies, such as GPS navigation, drones, and sensors, enables European farmers to significantly increase yields through more accurate and efficient use of resources. For example, using sensors and data analysis, farmers can accurately determine fertiliser and water requirements, reducing overuse of these resources and minimising their negative environmental impact (Czyżewski *et al.*, 2021).

In the United States, federal and state programmes to support farmers focus not only on direct subsidies but also on creating favourable conditions for long-term investment. Tax breaks and low-interest loans are a prominent part of these programmes. In 2021, the federal agricultural support programme amounted to USD 25 bn. Furthermore, farmers in the United States can receive subsidies for the introduction of innovative technologies, which contributes to the integration of new methods into agricultural production. The country also actively supports environmentally friendly agricultural practices, such as organic farming and sustainable use of water resources. The use of precision farming technologies in the United States allows farmers to markedly increase the efficiency of fertiliser use and reduce their quantity, which leads to lower costs and a reduced impact on the ecosystem (Adisa *et al.*, 2024). In Australia, agricultural policy includes a variety of measures to support farmers, especially in the context of climate change. Subsidy programmes are aimed at supporting agriculture in remote regions, as well as financing innovative projects aimed at increasing productivity and environmental sustainability (Ismayilov *et al.*, 2023). In 2022, AUD 4.8 bn was allocated to agricultural support programmes. Australian farmers can also receive support through climate risk insurance programmes, which help minimise losses in case of adverse weather conditions. The introduction of precision farming technologies, such as drones for crop monitoring, helps Australian farmers quickly identify plant problems, enabling them to respond quickly to changes and increase yields while reducing water and fertiliser costs (Panchasara *et al.,* 2021).

In Canada, government support for farmers includes programmes aimed at improving product quality and developing agricultural technologies. The Canadian government actively supports sustainable agriculture, including initiatives to use renewable energy sources and introduce innovative technologies in agribusiness. In 2021, CAD 3.8 bn was allocated to the federal agricultural support programme. A prominent part of government support is risk insurance, including natural disasters and fluctuations in world market prices, which helps to ensure the financial stability of farmers. The use of precision farming technologies, such as GPS navigation and drone systems for soil monitoring, helps Canadian farmers minimise the use of chemicals and increase the resilience of farms to climate change (Green *et al.,* 2024). Japan attaches great significance to preserving rural areas and ensuring the sustainability of agriculture. A key element of the country's agricultural policy is subsidies for the modernisation of production, the introduction of modern technologies, and the development of agro-ecological tourism. Japanese farmers receive tax breaks and support for research aimed at improving agricultural technologies and increasing the resilience of agriculture to climate change. Japan actively uses precision farming technologies to increase crop yields and minimise adverse environmental impacts, particularly through drone systems for precise fertiliser distribution and plant condition monitoring (McGreevy *et al.*, 2021).

In New Zealand, government support is focused on the introduction of innovative agricultural methods, including sustainable technologies and the use of bioenergy. In 2021, NZD 350 mn was allocated to agricultural support programmes. Farmers receive grants to implement environmentally friendly technologies and develop sustainable production methods. New Zealand also has a system of incentives for improving product quality and increasing the efficient use of natural resources. The use of drones and sensors to monitor crop conditions and optimise fertiliser application helps New Zealand farmers greatly reduce costs and improve the environmental sustainability of their production (Bradly *et al.,* 2022). Thus, international practices demonstrated showed that a comprehensive approach is essential for successful agricultural policy, including not only financial support but also the creation of long-term incentives for innovation and sustainable agricultural development. Unlike Kazakhstan, where the primary focus is on subsidies and support for production processes, these countries place much greater emphasis on creating an innovative and sustainable agricultural economy, which could be a valuable benchmark for Kazakhstan in the future.

In the Republic of Kazakhstan, support for agriculture is also provided through subsidies, preferential loans, and tax incentives. However, there are several problems that hinder the effective use of these funds. For instance, budget funds are not always received on time, and the processes for their distribution are often complex and not always transparent, which reduces their effectiveness. The Republic of Kazakhstan has a series of subsidy programmes aimed at supporting the agro-industrial complex (AIC), which include subsidies for pesticides, fertilisers, seeds, and planting material, as well as for priority crops and livestock. In 2024, for example, state support in the form of subsidies amounted to KZT 46.4 bn, of which a major part was allocated to crop and livestock production (State support for…, n.d.). The principal objective of these programmes is to stimulate agricultural production, improve its quality and resilience to external factors.

However, despite these measures, there are a series of problems that can be addressed to improve the effectiveness of subsidy programmes. First and foremost, the bureaucratic procedures for obtaining subsidies must be simplified. The complexity of the application process and the need to collect many documents often become a barrier for farmers, especially in remote regions. Automating the application process through electronic platforms could greatly expedite the process and make it more accessible, potentially reducing the application time from 2-3 months to 2-3 weeks (Subsidies for crop…, 2023). Additionally, expanding the list of subsidised crops from the current 10 to 20 items and introducing the latest agricultural technologies into the programmes will also increase their attractiveness and effectiveness. Support for farmers not only in conventional crops but also in the innovative technologies, such as precision farming and sustainable agricultural practices, can contribute to more efficient use of resources, increasing yields by 15%-20%. It is also essential to improve transparency and control over the use of subsidies. The development and implementation of monitoring mechanisms, such as the use of blockchain technologies, will help prevent cases of misuse of funds, increasing trust in government programmes. Regular audits and public oversight can reduce the number of cases of misuse of subsidies by 30%-40% (Ermuhan, 2024).

Long-term loans with low interest rates (2%-4% per annum) significantly affect farmers' investment activity. They allow farmers to invest in modern equipment, technology, and infrastructure, which helps increase productivity by 10%-15% and competitiveness. However, access to such loans is not always evenly distributed, especially in conditions of economic instability and an increase in the key rate of the National Bank of Kazakhstan. Therefore, to stimulate investment activity, it is vital to increase the availability of preferential lending for farmers, especially for small and medium-sized businesses, by increasing the number of loans issued by 20%-30% (Sagbo & Kusunose, 2021). To this end, it is necessary to expand preferential lending programmes, reduce interest rates to 3%-5% and provide further state guarantees. Interest rate subsidy programmes for loans can markedly reduce the financial burden on farmers and increase the attractiveness of investment in the agricultural sector. The development of microfinance and cooperative forms can also be a valuable tool for ensuring access to finance, especially for small farms, which often face challenges in obtaining conventional bank loans. The development of these instruments is estimated to increase access to finance by 40%-50% (Balana & Oyeyemim, 2022). The implementation of these measures will increase the investment attractiveness of the agricultural sector, stimulate the development of sustainable and highly productive farms, and increase the overall volume of investment in Kazakhstan's agriculture. The development of Kazakhstan's agricultural sector in the 2015-2024 period is characterised by growth in crop yields, an increase in livestock production and growth in investment in the sector. These changes are linked to both government support and the adaptation of agricultural producers to market conditions (Table 2).

***Table 2**. Dynamics of agricultural development in Kazakhstan*

Year	Grain yield (t/ha)	Milk production (mn t)	Meat production (mn t)	People employed in the AIC (%)	Investments in AIC (KZT bn)
2015	1.12	4.8	0.8	24	230
2016	1.18	5.0	0.9	23	260
2017	1.25	5.3	1.0	22	290
2018	1.3	5.5	1.1	21	320
2019	1.36	5.7	1.2	20	350
2020	1.42	5.9	1.3	19	400
2021	1.47	6.1	1.4	18	450
2022	1.53	6.3	1.5	17	500
2023	1.58	6.5	1.6	16	550
2024	1.63	6.7	1.7	15	600

***Source:** compiled by the authors of this study based on data from K. Yuksel et al. (2023)*

The table showed the key indicators of agriculture, including grain yields, milk and meat production, and employment in the agricultural sector. The analysis showed that since 2015, grain yields increased by over 40%, milk and meat production also grew, while employment in the sector gradually declined due to automation and mechanisation. Therewith, investment in the industry continues to show steady growth, indicating the growing attractiveness of agriculture for capital investment. State support for agriculture in Kazakhstan is provided through a system of subsidies, preferential loans, and financing for infrastructure projects. From 2015 to 2024, there has been a steady increase in the amount of budget funds allocated to the development of the agricultural sector, as presented in Table 3.

***Table 3**. Budget funds allocated for the development of agriculture in Kazakhstan*

Year	Total support (KZT bn)	Subsidies (KZT bn)	Preferential lending (KZT bn)	Tax benefits (KZT bn)
2015	300	150	100	50
2016	350	180	120	50
2017	400	200	140	60
2018	450	230	160	60
2019	500	260	180	60
2020	550	290	200	60
2021	600	320	220	60
2022	650	350	240	60
2023	700	380	260	60
2024	750	410	280	60

***Source:** compiled by the authors of this study based on data from P. Buzaubayeva et al. (2023)*

The allocated funds are used to support farmers through subsidies for costs, loans for modernising production processes, as well as developing rural infrastructure and introducing digital technologies. Subsidies account for the bulk of the funding, with their volume increasing more than 2.5 times between 2015 and 2024. There has also been an increase in the volume of preferential lending, which expands agricultural producers' access to financial resources for upgrading equipment, purchasing seeds, and developing processing capacities. These data suggest that state support continues to play a key role in the development of agriculture, but further research and improvement of distribution mechanisms are needed to increase the efficiency of spending.

In Kazakhstan, a considerable proportion of agricultural producers depend on state support. For many farmers, subsidies are a crucial tool for covering the excessive costs of purchasing seeds, fertilisers, equipment, and labour. These measures also help to attract investment in the modernisation and development of agriculture. However, this dependence has its drawbacks. First and foremost, it can create a system where farmers are not always interested in developing their businesses independently and seeking innovative solutions to improve efficiency. Dependence on state intervention can reduce their initiative and ability to develop independently. Such dependence also creates risks in conditions of economic instability or changes in state policy. For example, cuts in subsidies or changes in legislation can substantially exacerbate the financial situation of farmers, especially those who are not ready to adapt to changes.

Legislation regulating the audit of the effective use of budget funds in the Republic of Kazakhstan includes several key regulatory documents. The principal act is the Law of the Republic of Kazakhstan No. 392-V LRK (2015), which establishes the principles, objectives, and tasks of state audit, including the audit of the effective use of budget funds. This law defines the structure and functions of the auditing bodies and regulates the procedure for conducting audits in state bodies and organisations. According to data, in 2023, over 1,200 audits per year will be conducted by various auditing bodies, and over 60% of them will be aimed at verifying the use of budget funds in various state institutions. The law also prescribed the establishment of the Kazakhstan Financial Control Agency, which is responsible for conducting audits at all levels of government and publishing reports on the results of audits, thereby promoting transparency and accountability in the use of funds.

Furthermore, a significant regulation is the Regulatory Resolution of the Accounts Committee for Control over the Execution of the Republican Budget No. 6-NK (2020). It establishes the procedure for conducting external state audits, including audits of the effective use of budget funds. This document regulates the actions of the Supreme Audit Chamber of the Republic of Kazakhstan when auditing the accounts of state bodies and organisations, and establishes that in 2021, 350 external audits were conducted, of which over 70% concerned the effectiveness of spending at various levels of government. Another vital regulation is the Order of the Minister of Finance of the Republic of Kazakhstan No. 873 (2018). This Order governs the procedures for internal audits conducted by internal audit services in state bodies and defines methods for assessing the effectiveness of the use of state funds at various levels of government. In 2020, 120 audits of the effectiveness of public spending were conducted, of which 85% concerned public procurement and the use of budget subsidies. These legislative acts provide the legal basis for conducting audits of the effectiveness of budget spending aimed at improving the transparency and efficiency of public administration in Kazakhstan.

One of the key problems affecting the efficiency of budget spending is corruption and bureaucratic obstacles to its distribution. In Kazakhstan, as in other countries, there is a problem of insufficient transparency in the distribution of subsidies, which opens opportunities for abuse and corrupt practices. Farmers often face challenges in applying for subsidies due to complex and confusing bureaucratic procedures. Corruption in this process means that funds do not always reach those who really need them. Instead of being directed towards supporting agriculture and farmers, some of the funds end up in the hands of corrupt officials. This undermines trust in the system and reduces its effectiveness. To combat corruption and bureaucracy, more transparent and simplified mechanisms for the distribution of funds must be introduced. Electronic platforms, simplified application procedures, and stronger accountability measures for civil servants can markedly improve the situation. Development of a system to monitor and control the use of budget funds is also a major step that will help to ensure the efficient use of financial resources and minimise corruption risks.

Agriculture plays a key role in the economies of many countries, affecting not only food security but also the standard of living of the population, especially in rural areas. Support for the agricultural sector greatly influences the indicators such as productivity, farmers' incomes, infrastructure development, and rural employment (Viana *et al.*, 2022). One of the key economic outcomes of the introduction of modern technologies and government support is increased labour productivity and crop yields. The use of innovative methods such as precision farming, genetically improved varieties, irrigation systems, and new fertilisers considerably increases yields per unit area. The introduction of the latest technologies, including process automation, improved land treatment, and optimised resource use, contributes to increased production while reducing costs. This not only improves food security, but also increases agricultural exports, which is essential for strengthening the country's economy. Productivity growth directly affects farmers' profitability, providing stable incomes and opportunities for further investment in development. The dynamics of farmers' incomes directly depend on the efficient use of resources, the level of subsidies, and access to modern technologies. With support measures such as preferential lending, subsidies for agricultural machinery and product processing, farmers' incomes can increase substantially. The profitability of agricultural production depends on production costs, product prices, and access to markets. However, even with government support, farmers, especially small and medium-sized enterprises, often face challenges in obtaining financial resources, which limits their ability to expand. In some cases, farmers may become overly dependent on subsidies, which hinders their long-term development. It is therefore necessary to ensure more diverse sources of income and create opportunities for increased profitability, including access to innovative technologies and new markets.

The development of rural infrastructure markedly affects the economy of rural regions. Modern logistics networks and efficient agricultural processing and storage systems are key to improving the productivity of the agricultural sector. Logistics, including transport and distribution, helps to reduce losses associated with storage and transport of goods and improve access to markets. The processing of agricultural products, especially in areas such as food production, textiles, and biofuels, contributes to adding value and creating jobs. Product storage systems help minimise losses during harvesting and ensure a stable supply to markets during the off-season. All these elements of rural infrastructure help to create a more sustainable and efficient system, which contributes to higher incomes for farmers and the development of rural areas. One of the key social effects of agricultural development is job creation. Agriculture has conventionally played a leading role in providing employment in rural areas. The introduction of modern technologies and the expansion of infrastructure create new employment opportunities in various fields, from work on farms and in agribusinesses to jobs in processing and transport. The development of the agricultural sector helps to improve the standard of living in rural areas, reducing migration to large cities in search of work. It is essential that these jobs are stable and provide good working conditions. Creating quality jobs in rural areas requires joint efforts by both government agencies and the private sector, which must actively invest in the development of agricultural production and rural infrastructure.

As one of the key sectors of the economy, agriculture greatly influences the environment. In recent decades, in the face of global challenges such as climate change, biodiversity loss and ecosystem degradation, it has become particularly significant to introduce sustainable agricultural practices and use natural resources efficiently. In this regard, support for environmentally sustainable agricultural practices and the role of public assistance in water and land resource management are crucial for ensuring the long-term environmental sustainability and development of the agricultural sector (Tan *et al.,* 2022). Sustainable agriculture includes agribusiness practices aimed at ensuring long-term productivity while conserving natural resources and minimising harmful impacts on the environment. Such methods include organic farming, agroforestry, crop rotation, minimum tillage, and integrated pest management. These practices help to preserve biodiversity and improve soil, water, and air quality. Government support for sustainable agricultural practices plays a key role in their widespread adoption. Countries with developed agricultural sectors have active subsidy and preferential lending programmes aimed at supporting environmentally friendly technologies and agronomic methods. For instance, farmers can receive subsidies for switching to organic farming, using environmentally safe fertilisers and pesticides, applying renewable energy sources and restoring ecosystems.

In countries with developing agricultural markets, government support is also required to introduce sustainable agricultural practices. Effective subsidies for environmentally friendly technologies, farmer training programmes, and the creation of environmental certification mechanisms contribute to the transition to more sustainable agricultural practices. It is crucial to strike a balance between environmental support and economic benefits so that farmers can not only follow environmental standards but also improve their competitiveness in the market. The use of water and land resources in agriculture is a key component of the production process. However, their excessive use, especially against a backdrop of water scarcity and land degradation, can negatively affect the environment. In this case, government support and effective regulation play a prominent role in optimising the consumption of natural resources. Government programmes aimed at the efficient use of water resources include support for the introduction of water-saving technologies such as drip irrigation, water management systems, and innovative irrigation methods. These measures help to minimise water losses, increase water efficiency and reduce the burden on water bodies and water sources.

In countries with developing agricultural sectors, water resource management requires special attention. Water, as the most valuable resource for agriculture, especially in arid areas, must be used as efficiently as possible. The introduction of technologies that promote water conservation, as well as educational programmes for farmers on rational water use, can considerably improve the condition of water bodies and water sources. In terms of land use, one of the key challenges is to prevent soil degradation, salinisation, and erosion. This requires measures to protect and restore soils, including crop rotation, limiting the use of chemical fertilisers and erosion control. State support in the form of subsidies for projects aimed at restoring ecosystems, using organic fertilisers, and introducing nature-friendly technologies plays an essential role in preserving and improving the condition of land resources. Furthermore, it is vital to develop mechanisms to monitor the condition of land resources and the environmental impact of agricultural practices, which will ensure more efficient use of budget funds and prevent unnecessary costs.

DISCUSSION

Assessing the effectiveness of government support for agricultural producers is crucial, as it helps identify real results and focus efforts on improving current programmes. The analysis revealed that in some cases, government subsidies substantially influenced the growth of productivity and profitability of farms. This was particularly true for subsidies for the purchase of agricultural equipment and the introduction of innovative technologies, which contributed to improving product quality and increasing production volumes.

T.C. Durham and T. Mizik (2021) concluded that a comparative analysis of traditional, organic, and alternative agricultural systems showed that each had its unique advantages and challenges. Conventional methods are usually focused on maximising productivity, while organic farming focuses on sustainability and ecosystem approaches. Government support plays a key role in facilitating the transition to more sustainable methods, which contributes to increased profitability and efficiency in the long term. R. Zhang *et al.* (2021) showed that government subsidies greatly influence agricultural production by providing support through funding and tax breaks for producers. Such measures contribute not only to improving product quality but also to more efficient use of natural resources. However, the environmental impact of these subsidies must be considered to prevent possible harm to the environment and ensure the sustainable development of agriculture.

These findings confirmed the above presented study, as they demonstrated that government support greatly influences agricultural productivity. Specifically, it promotes the introduction of innovative technologies, infrastructure improvements, and the development of sustainable production methods, which increase both financial and environmental efficiency. These changes are particularly noticeable in countries where subsidies are aimed at reducing environmental impact and supporting the transition to organic and alternative production methods. However, the study also found that government support did not always produce the expected outcomes. In some cases, subsidies did not markedly improve farmers' financial situation since they were often used inefficiently. Problems with access to preferential loans and insufficient information among farmers about the mechanisms for obtaining state aid created obstacles to the full use of these funds. Additionally, dependence on subsidies reduced farmers' motivation to seek new sources of income and modernise production independently.

Z. Guo *et al.* (2022) also found that farmers' perceptions of environmental standards and their adoption of green agricultural technologies largely depend on their level of awareness and readiness for change. In countries with developed government support programmes, farmers tend to adapt their production methods to environmental requirements, which helps reduce the impact on the environment. However, problems arise when farmers face challenges in adopting the latest technologies or lack information about the benefits of green practices, which reduces the effectiveness of government support. M. Guth *et al.* (2022) concluded that the effectiveness and sustainability of small family farms under government support depends on how well agricultural policies are adapted to their specific needs. Farmers often find themselves dependent on subsidies, which limits their ability to develop and innovate independently. Although government programmes can bring short-term benefits, their influence on the long-term sustainability of farms will be limited if the structural and economic characteristics of small farms are not considered.

These findings are consistent with the arguments presented in the previous section, emphasising the significance of targeted government support to encourage farmers to switch to environmentally friendly production methods. A prominent aspect is not only the provision of subsidies, but also the creation of training and advisory systems to facilitate the successful introduction of green technologies (Faichuk *et al.*, 2022). Examples of successful practices from other countries show that a comprehensive approach, including both economic and information support, greatly increases the effectiveness of government intervention in agriculture. A comparison with international practices revealed that in countries with more developed agricultural sectors, government support is clearly focused on long-term goals. These countries use programmes that not only support farmers in the short term but also encourage them to adopt sustainable and highly efficient technologies. In contrast to these countries, in some developing economies, such as Kazakhstan, support for agriculture is limited mainly to short-term measures, which do not always contribute to the sustainable growth of the sector. E. Benami *et al.* (2021) also conducted a study, the findings of which confirmed that the integration of remote sensing, crop modelling, and economics is a valuable tool for agricultural risk management, providing accurate information on crop conditions and predicting potential threats. Internationally, satellite data, climate models and analytics are actively used to optimise agronomic processes and minimise losses. The use of such technologies enables farmers not only to respond to emerging risks, but also to make strategic decisions aimed at sustainable agricultural development.

B. Kamguia *et al.* (2022) also found that foreign aid can both contribute to and hinder economic complexity in developing countries, depending on how it is used. In some cases, aid programmes are not sufficiently adapted to local conditions, which can limit their long-term effects and lead to dependence on external sources of funding. However, with a properly targeted approach, aid can markedly accelerate agricultural development, improve infrastructure, and increase productivity in the long term, provided that local economic reality is factored in. Upon comparing the findings, it can be noted that the integration of remote sensing and crop modelling significantly improves the accuracy of forecasts and reduces the risks associated with natural disasters. However, many developing countries face limited access to the necessary technologies and data, which reduces the effectiveness of these methods. It is vital to emphasise that the successful implementation of such technologies requires not only high-quality data, but also an effective training system for local farmers so that they can correctly interpret and apply the results obtained to improve the sustainability of agriculture. The problem of corruption and bureaucratic barriers, which greatly affect the efficiency of budget allocation, should be highlighted. In practice, farmers often face long processing times for subsidy applications and a lack of transparency when receiving support. This creates conditions for corruption schemes and leads to uneven distribution of funds, which reduces the effectiveness of the state support system and makes it not always focused on the needs of actual producers (Ketners *et al.*, 2024).

A.D. Nugroho *et al.* (2022) concluded that the impact of corruption control on malnutrition indicators in developing countries is intricately linked to the effectiveness of agricultural aid distribution. Corruption risks and bureaucratic obstacles can considerably slow down or even negate the effect of resources provided by state and international organisations. Problems with insufficient transparency in the aid distribution process mean that aid does not always reach the target groups, and resources may be spent inefficiently. N.A.O. Adewusi *et al.* (2023) found that blockchain as a tool for ensuring transparency in agricultural supply chains allows tracking the origin and movement of products, reducing the risks of corruption and fraud. This can have major implications for increasing consumer confidence and improving product quality. In the absence of transparency in agriculture, corruption schemes can lead to extensive losses and distort fair competition, which blockchain can minimise by ensuring reliability and transparency at all stages of the supply chain. Effective anti-corruption measures in the distribution of agricultural aid require a comprehensive approach that includes the creation of transparent mechanisms and the strengthening of institutions responsible for resource allocation (Shahini & Shtal, 2023). It is essential not only to identify cases of corruption, but also to implement sustainable monitoring systems that minimise bureaucratic barriers and ensure the fair distribution of funds. Thus, the fight against corruption plays a key role in improving the effectiveness of government aid and contributes to improving food security in developing countries.

Furthermore, insufficient coordination between distinct levels of government is a principal factor that also reduces the effectiveness of aid delivery. Local authorities often lack the capacity to assess the needs of agricultural producers promptly and provide them with the aid necessary. This leads to a mismatch between farmers' demands and the conditions offered by government programmes. F. Liu *et al.* (2022), also covered this problem, confirming that linking the coordination of the agricultural economy, ecology, and society is a key challenge in sustainable agricultural development. Problems of coordination between local and central authorities can manifest themselves in differences in priorities and resources, which hinders the effective distribution of agricultural support. This can lead to inefficient use of resources and a decline in the quality of services provided, which negatively affects social and environmental sustainability. C. Bernini and F. Galli (2024) also showed that the potential and limitations of subsidies in sustainable development management depend directly on the coordination between local and central authorities. Inconsistent decision-making often leads to agricultural subsidies being ineffective, as local authorities may not have sufficient information about centralised initiatives or vice versa. This creates barriers to the implementation of sustainable agricultural practices and slows progress towards environmental and economic sustainability.

The analysis of the study findings revealed that successful coordination between local and central authorities is a key factor for the effective distribution of agricultural aid. Differences in priorities and management strategies can create challenges in adapting agriculture to environmental and social changes. To achieve sustainable outcomes, it is vital to establish clear communication and coordination mechanisms that ensure coherence at all levels of governance and enhance the impact of agricultural programmes. Based on the analysis of the data, it can be concluded that structural changes are needed to improve the effectiveness of government support. First and foremost, mechanisms for monitoring the distribution of funds must be improved, making the process of receiving aid more transparent and accessible to all farmers. Furthermore, the focus should be on long-term goals and the introduction of innovative farming methods, which will not only support producers but also ensure the development of the agricultural sector overall.

CONCLUSIONS

The study yielded valuable findings regarding the effectiveness of state aid to agricultural producers. Specifically, between 2015 and 2024, total support for the agro-industrial complex in Kazakhstan increased from KZT 300 bn to KZT 750 bn, with subsidies increasing from KZT 150 bn to KZT 410 bn, and preferential lending from KZT 100 bn to KZT 280 bn. The key positive aspects included the growth in productivity and profitability of farms, which was particularly noticeable in cases where subsidies were used to purchase modern agricultural equipment and introduce the latest technologies. For instance, grain yields in Kazakhstan increased from 1.12 t/ha to 1.63 t/ha over the same period, milk production – from 4.8 mn t to 6.7 mn t, and meat production – from 0.8 mn t to 1.7 mn t. This made it possible to improve product quality and increase production volumes, which ultimately led to better financial performance for agricultural producers. However, the study also revealed serious problems in the implementation of state aid. It turned out that not all farmers can make effective use of the subsidies provided due to the low availability of preferential loans and insufficient information about state aid programmes. For example, the share of people employed in the agro-industrial complex fell from 24% to 15%, which shows the challenges farmers face in operating their farms. Plus, systemic problems in how funds are distributed, like bureaucratic barriers and corruption, seriously reduce the effectiveness of these programmes. As a result, many farmers do not receive adequate support, which hinders the sustainable development of the agricultural sector.

A comparison with foreign practices revealed that in countries with developed agricultural sectors, state aid focuses on long-term development, factoring in the introduction of sustainable and innovative technologies. For example, in 2020, the EU allocated EUR 58 bn to support the agricultural sector, a major part of which was directed towards subsidising environmentally friendly farming and modernising production. In the United States, USD 25 bn was allocated for analogous purposes in 2021, which made it possible to implement tax breaks and innovation support programmes. In Australia, government aid to agriculture amounted to AUD 4.8 bn in 2022, and CAD 3.8 bn in Canada. Meanwhile, in Kazakhstan, support is mainly focused on short-term goals, which does not always contribute to sustainable growth and modernisation of the industry. The study also found that insufficient coordination between multiple levels of government leads to a mismatch between farmers' needs and the conditions offered by government programmes. This complicates the process of obtaining state aid and reduces its effectiveness. For example, investment in Kazakhstan's agro-industrial complex has grown from KZT 230 bn to KZT 600 bn, but many farmers continue to be face challenges in accessing preferential financing.

Therefore, to increase the effectiveness of state aid to agricultural producers, it is necessary to implement comprehensive changes that will increase the transparency and accessibility of subsidies, improve coordination between government agencies and farmers, and focus on long-term strategies aimed at sustainable development and the introduction of innovative technologies. This is the only way to ensure stable growth in the agricultural sector and increase the competitiveness of Kazakh producers in the international market. For a deeper understanding of the effectiveness of state aid to agricultural producers, it is necessary to investigate the long-term effects of subsidies on the sustainable development of agricultural technologies and innovative practices.

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Анотація. Метою цього дослідження було визначення ключових факторів, що впливають на ефективність державної підтримки сільськогосподарських виробників у Казахстані, а також оцінка її впливу на розвиток агропромислового комплексу. У дослідженні було використано методи системного аналізу та порівняльної оцінки, які допомогли виявити особливості державної підтримки сільськогосподарських виробників, визначити її вплив на економічний розвиток агропромислового комплексу та обґрунтованість розподілу бюджетних ресурсів. Аналіз показав, що загальний обсяг бюджетних коштів, виділених на підтримку сільського господарства в Казахстані, зріс з 300 млрд тенге у 2015 році до 750 млрд тенге у 2024 році, при цьому частка субсидій зросла зі 150 млрд тенге до 410 млрд тенге. Однак більша частина фінансування надходить до великих сільськогосподарських холдингів, тоді як малі та середні фермерські господарства стикаються з труднощами у доступі до фінансових та матеріальних ресурсів. Аналіз показав, що державна допомога позитивно впливає на зростання продуктивності сільського господарства. Наприклад, врожайність зернових зросла з 1,12 т/га у 2015 році до 1,63 т/га у 2024 році, тоді як виробництво молока зросло з 4,8 млн т до 6,7 млн т. Однак наявність субсидій не завжди призводить до підвищення прибутковості. Наприклад, незважаючи на розширення пільгового кредитування зі 100 млрд тенге до 280 млрд тенге, дрібні фермери все ще стикаються з надмірними витратами та труднощами в отриманні фінансових ресурсів. Темпи цифровізації в агропромисловому комплексі продовжують бути недостатніми: впровадження точного землеробства обмежується браком інфраструктури та фахівців. Досвід ЄС, США та Австралії, де державна підтримка стимулює інноваційні рішення, свідчить про необхідність розширення програм технологічної модернізації. У результаті дослідження зроблено висновок, що субсидії необхідно перерозподілити на користь малих та середніх фермерських господарств, посилити контроль за цільовим використанням коштів та активно впроваджувати цифрові технології для підвищення ефективності аграрного сектору

Ключові слова: субсидії; пільгове кредитування; аудит бюджетних витрат; врожайність сільськогосподарських культур; технічна модернізація

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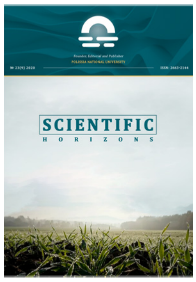

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Global approaches to evaluation of intellectual assets in agriculture: Experience of leading countries in context of the Republic of Azerbaijan

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Abstract. The study aimed to analyse global approaches to the valuation of intellectual property assets in agricultural production and the adaptation to the conditions of the Republic of Azerbaijan. The methodology included a comparative analysis of the practices of the United States of America, Germany, Switzerland and the People's Republic of China, as well as a detailed study of the activities of agricultural companies John Deere, Bayer CropScience, Syngenta, COFCO Group and Azersun Holding. Data

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from financial reports, analytics from the World Intellectual Property Organisation, the Organisation for Economic Cooperation and Development, and calculations performed in IBM SPSS Statistics version 27 were used. The results demonstrated that the United States of America uses an income approach with a focus on patents and biotechnology, Germany uses a cost approach to value licences and trademarks, the People's Republic of China uses a comparative approach to value digital platforms and artificial intelligence, and Switzerland uses a hybrid approach. The correlation analysis revealed a high correlation between investment in research and development (R&D) and the number of patents ($r = 0.82$), which confirmed the impact of investment on the accumulation of intellectual assets. Brand value showed the highest correlation with revenue ($r = 0.96$) and net profit ($r = 0.94$). The highest value of intellectual assets in 2024 was found in COFCO Group (USD 15.6 billion), which generated revenue of 130 billion USD. In Azerbaijan, Azersun Holding uses cost and comparative methods due to limited international patent protection and an underdeveloped licensing market. The findings confirmed the key role of intellectual assets and brand value in ensuring the financial sustainability of the agricultural sector

Keywords: patent portfolio; economic priorities; income method; cost method; comparative method; agricultural sector

INTRODUCTION

Intellectual assets in agriculture are becoming increasingly important in the context of global competition and rapid technological progress. These include patents, technologies, breeding achievements, trademarks and other intellectual property objects that ensure innovative development and economic sustainability of the agricultural sector. Effective management of intellectual assets is particularly relevant for countries with economies in transition, such as the Republic of Azerbaijan, undergoing active economic restructuring and seeking to diversify sources of income. In addition, in the context of an underdeveloped intellectual property market and limited law enforcement practices, it is necessary to introduce modern valuation methods to stimulate investment in innovation and enhance the competitiveness of national companies in the international arena. Given the diversity of intellectual asset valuation methods and differences in institutional and economic conditions, it is necessary to adapt the international experience to achieve maximum returns from innovation.

Profitable methods for assessing the intellectual assets of US farmers were studied by J. Xu and Y. Zhang (2021), and Y. Liu *et al.* (2021). J. Xu and Y. Zhang emphasised that these methods are widely used to evaluate precision farming technologies, such as automated irrigation control systems and crop monitoring drones. Their use has increased farm incomes by 15-20% due to the effective commercialisation of intellectual property. However, the study noted that the successful application of revenue-generating methods requires a developed institutional infrastructure and a high degree of commercialisation, which limits their applicability in countries with limited investment opportunities, such as Azerbaijan. Y. Liu *et al.* showed that income-based valuation methods also contributed to a 20% increase in farmland productivity, a 25% reduction in fertiliser and irrigation costs, and a 15% reduction in carbon dioxide emissions. However, their study did not address the specifics of countries with seasonal agriculture, where seasonality and limited funding could reduce the efficiency of intellectual asset management.

S. Pishgar-Komleh *et al.* (2021) analysed the use of market-based methods of valuation of intellectual assets to assess breeding achievements in the EU and demonstrated improved determination of the market value of intellectual assets, facilitating their integration into international projects. One example of successful use was the introduction of breeding achievements into projects to increase grain yields by 18%. However, the study did not address the issues of adapting these methods to the conditions of developing countries, where intellectual property protection is still in its infancy. L. Zeynalli *et al.* (2022) noted that market-based methods have actively contributed to the development of breeding achievements, ensuring a balance between local characteristics and the international potential of intellectual assets. For instance, programmes to introduce drought-tolerant plant varieties have led to a 12% increase in yields in Southern Europe. However, the study did not address the standardisation of market-based methods, which could limit their adaptation in emerging economies.

Cost-based methods of valuation of intellectual assets have often been used in China due to simplicity and affordability for small and medium-sized businesses. K. Pawlak *et al.* (2021) noted that such methods provide minimal data collection and analytical processing costs, therefore convenient for small agricultural enterprises. The study demonstrated that cost-based approaches can be used for the valuation of intellectual assets with an accuracy of up to 12%, which is sufficient for use in local economic calculations. However, such methods did not incorporate the market potential of the assets, which limited their application in the long term. The effectiveness of cost-based methods has been confirmed in the example of agricultural engineering in China. A. Valiyev *et al.* (2022) analysed the use of cost-based methods for valuing intellectual assets in small and medium-sized enterprises and showed that such approaches reduced costs by 30%, therefore more affordable for local businesses. However, the limitations include the value of intellectual assets only on costs incurred, without future market returns, such as possible revenues from technology commercialisation or licensing agreements. This causes an underestimation of the real value of the assets, especially in a dynamic market where intellectual property can significantly increase a company's capitalisation.

From the perspective of institutional transformation, the creation of national platforms for intellectual property management is an important step towards the efficient use of intellectual assets. M. Campi and A. Nuvolari (2020) and M. Zhang *et al.* (2023) noted that national platforms contribute to the standardisation of valuation methods, improved monitoring and interaction between market participants. An example of the successful implementation of such initiatives is the German national programme "SIGNO Die Neue Initiative des BMWi" (2025), which increased the number of licences, patents and technology transfer agreements by 25% in five years (Fraunhofer, 2014). In this context, the commercialisation rate reflects the share of intellectual assets (patents, know-how, licences) that have been successfully implemented in production processes or transferred to third parties for economic benefit. However, the recommendations do not sufficiently address the specifics of transition economies, where more attention is required to financing and regulatory frameworks.

The study aimed to conduct a comparative analysis of the methods of intellectual assets valuation used in the agricultural sector of the USA, EU, China and other countries, as well as to develop adapted recommendations for their application in the Republic of Azerbaijan. Research tasks included studying the methods of intellectual assets valuation in different countries, identifying strengths and weaknesses, and analysing the impact on the economic sustainability of agricultural companies (incorporating market share, speed of innovation and profitability).

MATERIALS AND METHODS

The study was conducted in 2024 and included an analysis of global approaches to the valuation of intellectual assets in agriculture based on the experience of leading countries and their adaptation to the conditions of the Republic of Azerbaijan. The empirical basis was the Comprehensive Report on the work done by the Intellectual Property Agency of the Republic of Azerbaijan in 2024 (2024), data from the World Intellectual Property Organisation (2024), Organisation for Economic Co-operation and Development (2024; 2025), World Bank (n.d.), as well as data from leading agricultural companies. The study object was intellectual assets in the agricultural sector, including patents, copyrights, trademarks, know-how, databases and other intangible assets that affect the innovative potential of agriculture. Global practices of intellectual property valuation in countries with developed agricultural sectors, including the USA, Germany, Switzerland and China, were analysed.

Companies with different intangible asset management strategies were selected to analyse the methods of intellectual asset valuation. In John Deere (2024) (USA), the company's brand, innovation potential, patent portfolio and precision farming software were evaluated. The brand was assessed based on data from Brand Finance (n.d.) and the company's annual financial statements, which included information on the value of trademarks and reputational capital. John Deere's intellectual capital was also assessed based on the value of internal development and software licensing. Bayer (2022; 2024; 2025) (Germany) analysed the processes of commercialisation of biotechnological solutions, valuation of intangible assets in the form of genetically modified crops, licensing of technologies and trademarks. The sources of data were the company's annual reports and the Organisation for Economic Co-operation and Development (2024) iLibrary database containing analytical materials on the commercialisation of intellectual property.

Syngenta (n.d.; 2025) (Switzerland) was studied in the context of a comprehensive valuation of intellectual assets, including rights to chemical compounds, technology protection, biotechnology licensing and trademark valuation. The data was obtained from the company's financial statements. COFCO INTL (2024) (China) was analysed in terms of digital intellectual assets, including agribusiness software, platform solutions and databases. The assessment was based on the reports of the China National Intellectual Property Administration (n.d.) and the company's financial statements. The methods of valuation of intellectual assets in Azerbaijan were analysed on the example of Azersun Holding (2023), one of the largest agro-industrial holdings in the country. The valuation of the company's intellectual property included trademarks, technological know-how, copyrights for production processes and innovative solutions in the food industry. The information was collected from the company's official reports and the Comprehensive Report on the work done by the Intellectual Property Agency of the Republic of Azerbaijan in 2024 (2024).

The methods used to value intellectual assets included three main approaches:

- the income approach, based on an analysis of future cash flows from the use of intangible assets;
- the cost approach, which estimates the cost of creating and maintaining intellectual property;
- the comparative approach, which enables determination of asset value based on similar transactions and companies in the industry.

The calculations were based on the financial statements of the companies studied, information on the market value of patents and technologies from the Organisation for Economic Co-operation and Development iLibrary, and analytical reports by the World Bank. Statistical data processing was conducted using IBM SPSS Statistics (n.d.) (version 27). The correlation analysis was based on the Pearson coefficient calculated between the following pairs of indicators: number of patents, brand value (USD billion), number of licences, research and development (R&D) investments (USD billion), revenue (USD billion), EBITDA (USD billion) and net profit (USD billion). All indicators were obtained from the reports of the World Intellectual Property Organisation, the Organisation for Economic Co-operation and Development and financial data of the companies. The significance level was set at $p < 0.05$.

RESULTS

The valuation of intellectual assets in the agricultural sector varies significantly between countries, due to their economic priorities, level of technological development and legal systems (Table 1). In the United States, the predominant valuation method is the income approach, which is based on projected future income from the use of intellectual assets, such as patents for agricultural technologies and biotechnology developments. This is due to the high level of commercialisation of innovations and the country's developed intellectual property protection system. In Germany, the cost method is preferred, focusing on the analysis of investments required to create and maintain intellectual assets. This approach is driven by an emphasis on accurate estimation of R&D costs and a desire for transparency in investment in innovation. In China, the comparative method is widely used, where the value of intellectual assets is determined by analysing market transactions with similar technologies. This reflects the dynamic development of the market and the active borrowing of advanced technologies. Switzerland uses a hybrid approach that combines elements of all three methods to incorporate the diversity of intellectual assets, especially in the areas of digital technologies and precision agriculture.

***Table 1**. Approaches to intellectual asset valuation in developed countries*

Country	Evaluation method used	The main object of evaluation
USA	Profitable	Patents, biotechnology
Germany	Costly	Licences, know-how, trademarks
China	Comparative	Platform solutions, databases
Switzerland	Hybrid	Digital technologies, precision farming systems

***Source:** compiled by the authors based on World Bank (n.d.), World Intellectual Property Organisation (2024), Organisation for Economic Co-operation and Development (2025)*

The main objects of valuation of intellectual assets in these countries vary depending on national priorities and the level of technological development. In the US, the emphasis is on patents and biotechnology, reflecting the country's leadership in agricultural innovation (John Deere, 2024). In Germany, significant attention is paid to licences, know-how and trademarks, due to its developed industrial base and emphasis on product quality. In China, with its rapidly growing digital economy, platform solutions and databases are key objects of assessment (COFCO INTL, 2024). Switzerland, known for its advanced agricultural technologies, focuses on the evaluation of digital technologies and precision farming systems. These approaches and objects of assessment reflect the strategic priorities of each country in the field of agriculture and innovation, as well as their desire to effectively manage and capitalise on their intellectual resources. Large-cap agricultural companies, such as John Deere (USA), Bayer CropScience (Germany), Syngenta (Switzerland) and COFCO Group (China), apply different strategies for managing intellectual assets, which depend on their market positions, industry specialisation and available valuation methods (Table 2). Their approaches shape not only the internal economics of companies but also influence global trends in the management of intangible assets in agriculture.

***Table 2**. Intellectual assets of agricultural companies, 2024*

Company	Evaluation method used	The main object of evaluation	Estimated value of intellectual assets (USD billion)	Share of intellectual assets in total capital (%)
John Deere	Profitable	Software, patents, licences	9.1	35%
Bayer CropScience	Costly	Biotechnology, GMO crops, trademarks	7.5	30%
Syngenta	Hybrid	Chemicals, licences, biotechnology	4.8	25%

Table 2. Continued

Company	Evaluation method used	The main object of evaluation	Estimated value of intellectual assets (USD billion)	Share of intellectual assets in total capital (%)
COFCO Group	Comparative	Digital platforms, databases, artificial intelligence	15.6	40%

Source: *compiled by the authors based on Brand Finance (n.d.), World Intellectual Property Organisation (2024), Organisation for Economic Co-operation and Development (2025), financial reports of John Deere (2024), Bayer (2024), Syngenta (2025), COFCO INTL (2024)*

John Deere (2024) is a global leader in the development of agricultural equipment and digital solutions for precision farming. The company's key intellectual assets include patents, software, licensed technologies and brands. John Deere uses the income approach to valuation, which takes into account future cash flows from intellectual property. In 2023, the value of the John Deere brand was USD 9.1 billion, and the capitalisation of the company's intangible assets was estimated at 35% of total capital (Table 3). More than 70% of all the company's innovations are protected by patents, which provides income for John Deere by licensing technologies for agriculture automation.

***Table 3**. Financial and intellectual indicators of the companies under study, 2024*

Company	Patents (pcs.)	Brand value (billion USD)	Licences (pcs.)	Investments in R&D (USD billion)	Profit (billion USD)	EBITDA (billion USD)	Net profit (billion USD)
John Deere	250	9.1	80	5	44	6.2	2.9
Bayer CropScience	180	7.5	120	5.3	50.5	8.1	3.6
Syngenta	150	4.8	95	1.7	26.2	4.5	1.9
COFCO Group	90	15.6	60	3.2	130	38.4	10.5
Azersun Holding	30	0.25	10	0.012	2.4	0.35	0.18

Source: *compiled by the authors based on Brand Finance (n.d.), Azersun Holding (2023), World Intellectual Property Organisation (2024), financial reports of John Deere (2024), COFCO INTL (2024), Bayer (2024), Organisation for Economic Co-operation and Development (2025), Syngenta (2025)*

Bayer CropScience prioritises the development of biotechnology, genetically modified crops and crop protection products. Unlike John Deere, the company uses a cost-based approach, as its key assets are tied to long-term investments in research and development of new products. This maintained the leadership role of Bayer CropScience in the industry and provided innovative solutions for agriculture. In 2022, Bayer (2024) spent 5.3 billion EUR on R&D, 12.7% of the company's total turnover. These investments are aimed at developing new crop varieties with high yields, resistant to adverse climatic conditions and pests. In addition, the company is actively developing digital crop monitoring technologies and integrated agronomic process management systems. The patent portfolio of Bayer CropScience includes more than 7,500 active patents, which demonstrates the company's high innovation activity. The estimated value of Bayer CropScience's intellectual assets exceeds USD 7.5 billion, which confirms the strategic importance of R&D in its business model. In addition to patents, the company actively cooperates with leading research institutes, universities and start-ups, which helps to speed up the process of introducing new developments and expand their scope.

Syngenta (2025) employed a hybrid approach, combining income and cost methods. The company's main intellectual assets are chemical compounds, biotechnology licences and trademarks. This diversification of assets not only developed new products but also generate revenue from licensing technologies. In 2023, the value of Syngenta's patent portfolio was USD 4.8 billion and R&D expenditures were USD 1.7 billion. Licensing of chemical crop protection technologies brings Syngenta a significant royalty stream, which explains the use of the combined valuation method. It reduces financial risks associated with long-term investments in the development of new chemical compounds. In addition, Syngenta is actively developing precision farming technologies by offering digital platforms for managing agricultural processes. These platforms provide farmers with analytics based on artificial intelligence and satellite monitoring data, optimising the use of fertilisers, pesticides and other resources.

As a technology giant, COFCO INTL (2024) is actively investing in digital platforms, databases and artificial intelligence for agriculture. Unlike other companies, COFCO Group uses the comparative method to value its intangible assets based on market analogues. This ensures quick adaptation to changes in the market and effectively capitalises on its developments. In 2023, the capitalisation of the company's intellectual property totalled 15.6 billion USD, equivalent to 40% of the total market value of COFCO Group. One of COFCO Group's key activities in the agricultural sector is the development of intelligent supply chain management systems that use machine learning to forecast demand and optimise logistics. The company is also investing in e-commerce platforms that provides direct interaction with consumers, reducing intermediary costs. In addition, COFCO Group is actively developing big data solutions to help farmers analyse climate conditions, predict yields and improve agricultural production efficiency.

Thus, companies apply the methods of valuation of intellectual assets that best suit the strategy for commercialising intangible assets. John Deere prioritises generation of revenue from patents and software, Bayer (2022) evaluated assets according to costs as it develops long-term R&D investments, Syngenta uses a balance of cost and income approaches, and COFCO Group bases its valuation on the market value of digital assets. These models reflect not only business specifics but also global trends in intellectual property management in the agricultural sector. Azersun Holding (2023), being one of the largest agro-industrial companies in Azerbaijan, owns a significant amount of intellectual assets, which form an important component of the overall value of the business. The holding's intellectual property is represented in several key categories: trademarks, technological know-how, copyrights to production processes, licences and patents. The largest share in the structure of intellectual assets is occupied by trademarks, which provide competitive advantages in the domestic and foreign markets. According to the State Agency for Intellectual Property of Azerbaijan, the company has registered more than 150 trademarks (Comprehensive Report on..., 2024). The market value of Azersun Holding's brands is estimated at USD 250 million, which is equivalent to approximately 15% of the company's total capitalisation (Organisation for Economic Co-operation and Development, 2025).

Technological know-how includes developments in the field of multi-stage processing of agricultural raw materials, eco-friendly packaging methods and automated product quality control lines. The value of these assets, according to the company's internal sources and open data, is at least 40 million USD. However, the limited international patent protection reduces the possibility of their capitalisation in foreign markets. Azersun Holding's copyrights for production processes and internal innovations (2023) are estimated at approximately 15 million USD and cover technological operation algorithms, recipes and quality standards used at the holding's production facilities. Azersun Holding's portfolio of licences and patents includes approximately 10 licences and 30 patents, registered mainly in Azerbaijan. Their total value is estimated at USD 10 million, reflecting limited commercial application outside the domestic market. Overall, the total value of Azersun Holding's intellectual assets is approximately USD 315 million. This accounts for about 20% of the company's total asset value, according to analytical reports and market data from the World Bank (n.d.), which is a significant indicator of Azerbaijan's agro-industrial sector. The high share of intangible assets is explained by the diversified business structure of the holding and its focus on creating added value through branded products and proprietary technologies. The company also owns valuable technological know-how related to innovative methods of processing agricultural products, such as optimising heat treatment to preserve nutritional properties, a multi-stage cleaning and filtration system for food raw materials, and automated packaging lines using environmentally friendly materials. These technologies enable significant improvements in product quality and safety, reduce production costs and extend the shelf life of finished products.

All these technological solutions are protected by copyrights and registered patents at the national level. However, according to the World Intellectual Property Organisation (2024), Azersun Holding's patent portfolio is significantly inferior in terms of volume and coverage to similar indicators of international corporations. The reason for this is that most of the company's patents are registered exclusively in Azerbaijan and do not have international legal force, as there is no filing under international systems such as the Patent Cooperation Treaty or with patent offices of other countries. This restriction significantly reduces the possibilities of commercial use of these technologies outside Azerbaijan. Patents valid only at the national level do not provide legal protection in other jurisdictions, making international licensing or sale of technologies legally and economically difficult. This has a direct impact on the valuation methods of a company's intellectual assets: the use of the income approach becomes impossible, as the calculation of future flows from international licensing or sale of patents is not realistic. As a result, the value of these assets in the valuation is significantly lower compared to their internationally protected counterparts, as their market potential is limited to the domestic market.

In the assessment of intellectual property, Azersun Holding applies the cost method, which determined the value of assets based on investments in their development, maintenance and adaptation to market conditions. According to the World Bank (n.d.), the company's annual investment in the development of new technologies is about USD 12 million, which is equivalent to 8% of total production costs. This approach incorporates the actual costs of creating intellectual assets but does not reflect their future market value. In addition, Azersun Holding uses the comparative method to determine the market value of trademarks and brands based on the analysis of similar transactions in the region. This method is most effective when the company's intellectual assets are not related to patents but rather to brand recognition and reputation. In contrast to the leading international corporations, Azersun Holding does not use the income method, as its intellectual property is practically not licensed internationally, and the company's main income is generated through direct sales of products rather than through the capitalisation of intellectual assets. There are several reasons for this situation. Firstly, Azerbaijan lacks a developed intellectual property licensing market, especially in the agricultural sector, which limits the possibilities of commercialising technologies outside the country (Comprehensive Report on..., 2024). Second, the predominance of trademarks and production know-how in the company's asset structure, which is used exclusively within the holding, makes it economically unreasonable to calculate future income from their external transfer. Thirdly, Azersun Holding operates primarily in the domestic and regional markets, where the demand for licensed technologies is limited and government support for the commercialisation of intellectual assets is at an early stage of development. As a result, the use of the income method of valuation, which involves the calculation of future cash flows from the sale of rights to intellectual assets, is inefficient for the company in the current environment and does not reflect the real structure of its income.

The valuation of intellectual assets in the agricultural sector of Azerbaijan differs significantly from the practices used in the world's leading economies. In the United States and the European Union, intellectual property is viewed as a strategic resource that actively contributes to revenue generation through licensing and commercialisation of innovations. In Azerbaijan, however, the valuation of intellectual assets is primarily of an accounting nature, aimed at fixing the value rather than extracting profit from patents and licences. One of the key differences is the limited number of tools for commercialising intellectual assets. In the European Union and the United States, patent and know-how licensing mechanisms are widespread, generating income from developments without the need to production implementation (Mamasydykov *et al.*, 2019). In Azerbaijan, the practice of licensing intellectual property is underdeveloped; most developments are used exclusively within companies, which limits the application of the income approach to valuation. Institutional support also plays an important role in managing intellectual assets. Developed countries have government programmes aimed at funding research, protecting patents and creating innovation ecosystems (Hajiyev *et al.*, 2025). For instance, in Germany, there are specialised funds that support the commercialisation of intellectual assets, which stimulates investment in this sector. In Azerbaijan, despite the existence of the State Agency for Intellectual Property, systemic support for the commercialisation of patents and technological innovations is at an early stage, which reduces business interest in building a significant portfolio of intangible assets.

The digitalisation of intellectual property valuation and turnover is another distinguishing factor (Radchenko *et al.*, 2023). In countries such as China and the United States, online platforms for the sale and licensing of intellectual assets are actively developing, objectively assessing the market value of patents, software and know-how. In Azerbaijan, such digital platforms are practically non-existent, which makes it difficult to apply a comparative valuation method and limits the ability of companies to commercialise their developments. Comparison of national experience with international practices shows that traditional cost-based approaches to the valuation of intellectual assets prevail in Azerbaijan, while in developed economies (the USA, Germany, Switzerland) the emphasis is on intellectual property capitalisation tools. This creates certain barriers to the growth of intangible assets in the agricultural sector and limits their integration into the market turnover. The results of the correlation analysis revealed that intellectual assets have a significant impact on the financial performance of agricultural companies, but the degree of this impact depends on the specific type of asset (Table 4). One of the most significant factors was the amount of investment in R&D, which demonstrates a high correlation with the number of patents ($r = 0.82$) and licences ($r = 0.75$). This confirms that companies that systematically invest heavily in innovation have larger patent portfolios and actively use licensing to commercialise their technologies. For example, Bayer CropScience, which annually invests 5.3 billion EUR in R&D, has registered 180 patents and 120 licences, making it one of the leading companies in terms of intellectual assets in the agricultural sector.

***Table 4**. Correlation matrix of intellectual assets and financial indicators (averages for all countries surveyed), 2024*

Metric	Patents (pcs.)	Brand value (billion USD)	Licences (pcs.)	Investments in R&D (USD billion)	Profit (billion USD)	EBITDA (billion USD)	Net profit (billion USD)
Patents	1.000	0.28	0.74	0.82	0.02	-0.17	-0.04
Brand value	0.28	1.000	0.32	0.59	0.96	0.89	0.94
Licences	0.74	0.32	1.000	0.75	0.17	0	0.12
R&D investments	0.82	0.59	0.75	1.000	0.41	0.21	0.35
Profit	0.02	0.96	0.17	0.41	1.000	0.97	0.99

***Source:** compiled by the authors based on calculations made in IBM SPSS Statistics (n.d.)*

An equally important factor was brand value, which has a strong positive relationship with revenue (r=0.96) and net profit (r = 0.94). This suggests that a company's recognition and reputation in the market are directly related to its financial performance. The most illustrative example is COFCO INTL (2024), whose brand is valued at 15.6 billion USD, which provides the company with a stable position in the global market and revenue of 130 billion USD. This dependence is explained by the fact that well-known companies attract more customers, can set higher prices for their products and provide more favourable conditions for cooperation with partners. However, despite the high level of patent activity in some companies, the presence of many patents does not always lead to an immediate increase in profits. The correlation of the patent portfolio with EBITDA was negative (r = -0.17), and with net profit was almost zero (r = -0.04). This indicates that the process of introducing patented technologies requires significant time and financial costs. For example, Syngenta, which holds 150 patents, demonstrates a relatively low net profit of USD 1.9 billion, due to the long cycle of bringing new products to market and the need to conduct extensive testing before commercialisation.

The number of licences also demonstrated a strong relationship with R&D investment (r = 0.75), but a weak relationship with revenue (r = 0.17). This suggests that although licensing is an important tool for commercialising intellectual assets, not all companies effectively use this mechanism to increase their revenues. Azersun Holding, which has 10 licences, does not receive significant revenues from their monetisation, as the licensing market in Azerbaijan remains underdeveloped and companies are primarily focused on protecting their technologies rather than selling them. Additionally, the analysis demonstrated that companies' revenues are almost fully correlated with EBITDA (r = 0.97) and net profit (r = 0.99). This suggests that the financial strength of companies is determined not only by their intellectual assets but also by the overall efficiency of their business model, levels of automation, production scale and cost management strategies. For instance, John Deere, with a relatively small patent portfolio compared to its competitors, shows revenues of USD 44 billion and a consistently high level of operating profit due to a well-thought-out business strategy and the widespread use of digital solutions in agriculture.

Thus, the analysis confirmed that brand value is the most significant intellectual asset that has a direct impact on the financial performance of companies. R&D investments contribute to the accumulation of patent portfolios, but their commercialisation requires considerable time and additional investment. Technology licensing remains an underutilised tool in some companies, which limits the ability to increase revenues. These patterns broadened the definition of the role of intellectual property in the agricultural sector and identified ways to improve the efficiency of its use.

DISCUSSION

The study confirmed the significant impact of intellectual assets on the financial performance of agricultural companies, but it reveals differences in the effectiveness of different methods of valuation and commercialisation of intangible assets. In the United States, the income method dominates, which can be used to analyse future cash flows from intellectual property, which correlates with the findings of J. Beckman and A. Countryman (2021) and M. Grimaldi *et al.* (2021) in a study on the impact of patenting on the commercial sustainability of agricultural corporations. This is confirmed by a significant share of licence income and active commercialisation of innovations in the agricultural sector. At the same time, P. Sánchez-Bravo *et al.* (2021) and T. Sun *et al.* (2021) demonstrated that the valuation of intellectual assets based on projected revenues is subject to high uncertainty due to unstable market conditions, which is consistent with the identified limitations of this approach. However, the development of predictive analytical tools and more accurate revenue forecasting models can partially offset this disadvantage.

In Europe, the cost method of valuation, focused on investments in technology development, is widely used. This is confirmed by studies by S.H. Uzma (2016), D. Pastor *et al.* (2017), which demonstrated that R&D expenditures are the main factor in the formation of the value of intellectual assets in the agricultural sector. This method provides an accurate reflection of the funds invested, which makes it preferable for the valuation of scientific and innovative developments. It also promotes transparency in financial reporting and enables tracking of the effectiveness of investments in research and development, which is especially important for large agricultural holdings and multinational corporations. However, H. Wirtz (2024) and T.K. Amentae *et al.* (2024) noted that this method underestimates the market value of assets, especially in the context of rapidly growing digital technologies and the transformation of the agricultural sector, where the value of innovation is often determined not only by costs but also by the potential commercial benefits of their use. In addition, this method does not incorporate the rate of technology obsolescence and the impact of market conditions on asset values. To mitigate these risks, European companies are gradually beginning to combine the cost approach with income and comparative methods, which ensure a more comprehensive consideration of both internal costs and external market factors in the valuation of intellectual property (de-Almeida-e-Pais *et al.*, 2023).

In Azerbaijan, a combined approach to the valuation of intellectual assets using cost and comparative methods prevails. This choice is determined by the specifics of the national market, limited commercialisation and poor development of intellectual property protection institutions. Azerbaijan demonstrates a weak integration of the income method into the practice of valuation of intellectual assets, which limits the possibilities of capitalising assets. The use of the cost method recorded the investments made in development but does not reflect their market potential. This is confirmed by C. Antons *et al.* (2020) and A. Barragán-Ocaña *et al.* (2023), emphasising the need to introduce digital platforms and adapt international standards, which will increase the transparency and accuracy of intellectual asset valuation. It is also recommended to intensify licensing mechanisms and expand regional markets for intellectual assets, which will provide new sources of income and reduce dependence on internal factors.

Chinese companies mainly use the comparative method of valuation of intellectual assets, which reflects the dynamic development of the country's technology market. This conclusion is confirmed by Z. Aliyev (2018), H. Chuma-Okoro and I.A. Oluwasemilore (2022), highlighting the high efficiency of this method for valuing digital platforms and databases. The high liquidity of intellectual assets in the Chinese market facilitates the application of the comparative approach, especially in the context of the active development of e-commerce and digital technologies. However, B. De Jonge *et al.* (2022) and J. de Mévius (2022) criticise the comparative method for its dependence on market analogues, which can overestimate or underestimate the value of assets depending on the market situation. In this regard, several Chinese companies are beginning to introduce elements of hybrid valuation methods, including future income analysis and the cost approach, which improves the objectivity of consideration of the specifics of the national innovation market.

Swiss agricultural companies apply a hybrid approach that combines elements of different methods, which can be used to consider the diversity of intellectual assets and the specifics of the national innovation environment. This conclusion is consistent with the studies of M. Fredriksson (2021), and K. Goyal and S. Kumar (2021), which confirmed the high efficiency of the hybrid method in the context of the digitalisation of agriculture and the active development of biotechnology. The flexibility of this approach emables Swiss companies to consider both the costs of creating assets and the market value and potential income from their use, which is especially important in the context of high development costs and long investment cycles in agricultural science. In addition, this method provides a more accurate integration of risks and opportunities for commercialising intellectual assets in international markets. However, M.S. Hossain *et al.* (2021) and K. Gupta *et al.* (2023) note the difficulty of implementing such a method without developing unified standards and regulatory frameworks, which remains an urgent task for the international community, especially in the context of ensuring transparency and comparability of intellectual asset valuations between countries.

The analysis of agricultural corporations also demonstrated the dependence of the choice of valuation method on the industry specialisation and the structure of intellectual assets of companies. For example, John Deere focuses on the income method, which is confirmed by the studies of D.J. Jefferson and K. Adhikari (2019), and H. Johnson (2021), which revealed the effectiveness of this approach for companies that actively use licensing and software. This method can address future cash flows from the introduction of technologies in the field of precision agriculture, as well as revenues from the sale of software solutions and services for the agricultural sector. This model promotes active monetisation of intellectual assets and encourages companies to expand their patent portfolio and develop digital solutions. At the same time, Bayer CropScience applies a cost-based method that ensure accuracy of accounting of R&D investments, which is critical for biotechnology developments. This is due to the high cost of developing new crop varieties and plant protection products, which require extensive research and large-scale trials. At the same time, this approach ensures transparency in asset valuation but reflects their future commercial potential to a lesser extent, especially in the face of rapidly changing market conditions and the growing importance of digital technologies in agricultural biotechnology (Zakharchuk *et al.*, 2025).

The results of the correlation analysis, which revealed a high correlation between R&D investment and the number of patents and licences, are also significant. This confirms the findings of R.K. Joseph (2021), and L. Kant and F. Shahid (2022) on the strategic role of innovation activity in the formation of intellectual assets of agricultural companies. It is noteworthy that brand value shows a strong correlation with revenue and net profit, which indicates the direct impact of reputational capital on the financial stability of companies. However, the weak correlation between patent activity and final financial results demonstrates that having patents without a full-fledged commercialisation strategy does not automatically lead to profit growth (Svitlychnyi, 2024). This underscores the need for a comprehensive approach to managing intellectual assets, including not only their creation but also their active use and monetisation.

Thus, the analysis concluded that it is critical to choose methods of intellectual assets valuation incorporating industry specifics, national characteristics and the level of innovation development. The introduction of international standards, development of commercialisation infrastructure and digitalisation of intellectual asset valuation processes seem to be promising areas for further research and practical steps in the agricultural sector.

CONCLUSIONS

The valuation of intellectual assets in the agricultural sector varies significantly between countries and companies, due to national economic priorities, the level of technological development and specific legal regulations. In developed economies, different valuation methods are used: income approach (USA), cost approach (Germany), comparative approach (China) and hybrid approach (Switzerland). In agricultural companies such as John Deere, Bayer CropScience, Syngenta and COFCO Group, the choice of valuation methodology depends on the structure of intellectual assets and commercialisation strategy. In Azerbaijan, cost and comparative methods prevail, which limits the potential for capitalisation of intangible assets. Further development of the country's intellectual property accounting system requires the introduction of mechanisms to stimulate innovation, including tax incentives and R&D subsidies.

The study determined that brand value has the greatest impact on the financial performance of companies, providing a high correlation with revenue (r = 0.96) and net profit (r = 0.94). Investments in R&D contribute to the growth of the patent portfolio (r = 0.82) and licences (r = 0.75), but commercialisation of patents requires a long time and additional investments. Technology licensing remains an underutilised tool in some companies, which limits the opportunities to profit from intellectual property. The development of digital platforms for registering and managing licences could help to improve the efficiency of their use and expand international cooperation. Future research could focus on the impact of digitalisation and artificial intelligence on intellectual property management in the agricultural sector, as well as on the development of integrated valuation methods that combine elements of income, cost and comparative approaches.

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Глобальні підходи до оцінки інтелектуальних активів у сільському господарстві: досвід провідних країн у контексті Республіки Азербайджан

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Анотація. Метою дослідження був аналіз глобальних підходів до оцінки активів інтелектуальної власності в аграрному виробництві та їх адаптації до умов Республіки Азербайджан. Методологія включала порівняльний аналіз практик Сполучених Штатів Америки, Німеччини, Швейцарії та Китайської Народної Республіки, а також детальне дослідження діяльності аграрних компаній John Deere, Bayer CropScience, Syngenta, COFCO Group і Azersun Holding. Використано дані фінансових звітів, аналітику Всесвітньої організації інтелектуальної власності, Організації економічного співробітництва та розвитку і розрахунки, виконані в IBM SPSS Statistics версії 27. Результати показали, що Сполучені Штати Америки застосовують дохідний метод оцінювання з акцентом на патенти та біотехнології, Німеччина оцінює ліцензії та товарні знаки витратним методом, Китайська Народна Республіка застосовує порівняльний метод для оцінювання цифрових платформ та об'єктів зі штучним інтелектом, Швейцарія використовує гібридний підхід. Кореляційний аналіз виявив високий зв'язок між інвестиціями в наукові дослідження та дослідно-конструкторські роботи (НДДКР) і кількістю патентів ($r = 0,82$), що підтвердило вплив інвестицій на накопичення інтелектуальних активів. Вартість брендів продемонструвала найбільшу залежність із виручкою ($r = 0,96$) та чистим прибутком ($r = 0,94$). Найбільшу вартість інтелектуальних активів у 2024 році виявлено у COFCO Group (15,6 мільярдів доларів США), які забезпечили виручку в 130 мільярдів доларів США. В Азербайджані компанія Azersun Holding використовує витратний і порівняльний методи, що зумовлено обмеженим міжнародним патентним захистом і слабким розвитком ринку ліцензування. Висновки підтвердили ключову роль інтелектуальних активів і вартості брендів у забезпеченні фінансової стійкості аграрного сектора

Ключові слова: патентний портфель; економічні пріоритети; дохідний метод; витратний метод; порівняльний метод; аграрний сектор

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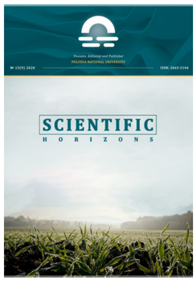

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Marketing strategies for the development of agricultural exports of Kazakhstan in world markets: Interregional comparative analysis

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Abstract. The present research was aimed at analysing the marketing strategies of agricultural exports and identifying effective approaches to the promotion in world markets. In the course of the work, the methods of comparative analysis of marketing strategies of leading exporting countries, research of official statistical data, assessment of the impact of international trade agreements and standards were used, as well as analysis of state export support programmes. The results of the

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study revealed key features of marketing approaches in different regions and the applicability to the Kazakhstan market, where wheat exports in 2023 amounted to 6.5 million tonnes, or 3.13% of the world volume of 208 million tonnes. Successful models of agro-product exports from countries such as the USA (19.8 million tonnes of wheat in 2023), Canada (22 million tonnes) and Australia (24.5 million tonnes) were studied to identify the most effective promotion tools, including branding and adaptation to market standards. The analysis showed that improving the competitiveness of Kazakhstani products required adapting strategies to the requirements of specific regions, taking into account consumer preferences and improving certification to international standards. It was noted that Kazakhstan's participation in the Eurasian Economic Union contributed to the doubling of mutual trade since 2015. The development of government export support programmes was also noted as an important factor, which also needed to be strengthened: financial and advisory assistance to exporters, modernisation of logistics (where wheat transportation costs were USD 80-100 per tonne versus USD 50-60 for competitors), and digitalisation of processes remained priorities. Based on the data obtained, recommendations were developed to improve Kazakhstan's marketing strategies for agrarian exports, aimed at optimising logistics, developing partnerships with international distributors, increasing brand awareness, and actively using digital technologies to promote products

Keywords: international standards; branding of agricultural products; consumer demand; logistics infrastructure; government support; digital platforms; cultural characteristics

INTRODUCTION

In the context of the dynamic development of international trade, agricultural export plays an important role in strengthening the economic potential of countries with a developed agricultural sector. However, simply having competitive products is not enough for successful entry into global markets, as effective promotion strategies adapted to the conditions of global competition are required. Modern trends such as digitalisation, changing consumer preferences, and increasing product quality requirements create new challenges for producers, demanding flexibility and a comprehensive approach to export activities. In this context, the study of marketing strategies in agricultural exports allows the identification of key factors affecting product competitiveness in various regions, as well as the development of recommendations that contribute to successful promotion in foreign markets. A comprehensive analysis of approaches to the development of agricultural exports is necessary to enhance its efficiency, sustainability, and integration into global economic processes.

One of the main areas influencing the success of agricultural exports is the adaptation of marketing strategies to the requirements of target markets, including consideration of local regulatory standards, consumer preferences, and the competitive environment (Penkova & Kharenko, 2023). In the work of T.P. Magay and K.R. Ergaliev (2020), the importance of marketing strategies for the development of the agricultural sector was noted, as well as the role in creating competitive advantages in foreign markets; however, the focus remained largely on general aspects of export policy without addressing the mechanisms for adapting strategies to the requirements of different countries. In the study by A.B. Makhanova *et al.* (2022), the significance of proper product positioning and the selection of effective promotion channels was emphasised, identifying key directions for the development of the agro-industrial complex, yet without delving into the specifics of marketing strategies applied in different market conditions, leaving the issue of the practical implementation open. The research by A. Cheirkhanova *et al.* (2024) examined the influence of market factors on agricultural exports of the Republic of Kazakhstan, including product assortment adaptation and pricing strategies, highlighting the role of marketing approaches in expanding international market presence, but without providing an analysis of the application in the context of specific countries and regions, which limits the practical applicability of the conclusions for exporters.

Another important factor is the analysis of the influence of foreign economic policy on the adaptation of marketing strategies in the agricultural sector. In the work of K.A. Akhmetova *et al.* (2020), attention was focused on the study of the influence of foreign economic policy on the export flows of Kazakhstan's agricultural products, but without examining the impact of specific market requirements and the needs of target countries, limiting the understanding of region-specific strategies. In the study by R. Lencucha *et al.* (2020), the focus was placed on the role of government support programmes for agribusiness, though the effectiveness of other tools and mechanisms, which could significantly improve marketing strategies in the agricultural sector, was not addressed. In the study by D. Fiankor *et al.* (2020), the influence of international quality standards on competition in foreign markets was examined, noting strategic approaches aimed at compliance with these standards, yet without discussing issues related to innovation in product promotion, which restricts a comprehensive understanding of effective marketing under conditions of global competition.

The study of the impact of modern technologies and innovative solutions on the development of marketing strategies in the agricultural sector also represents a promising research direction. In the work of A. Ollerenshaw *et al.* (2023), emphasis was placed on the implementation of digital platforms for market analysis and product promotion, which enabled the identification of key advantages of such technologies for exporters, although insufficient attention was paid to the analysis of cultural and social aspects, which may also play an important role in decision-making in foreign markets. In the study by M. Dayıoğlu and U. Turker (2021), the role of digital platforms in agricultural logistics was explored, highlighting the effectiveness of analytical tools, yet without considering the role of marketing strategies in adapting to specific regional needs, which are important aspects of engaging with local consumers. In the study by X. Du *et al.* (2023), the economic effect of digital innovations in the agricultural sector was considered, including the evaluation of new methods for product promotion, but without examining specific issues related to the conditions of each region and the influence on marketing strategies, which reduces the completeness of the picture for a comprehensive approach to the development of agricultural exports.

The purpose of this research was to study effective marketing strategies for the development of Kazakhstan's agricultural exports, oriented towards the requirements of international markets. To achieve this goal, the following tasks were set: to assess the current state of Kazakhstan's agro-industrial exports and the main barriers to its development; to conduct a comparative analysis of the marketing strategies of agricultural exporters in various regions of the world to identify key features, approaches, and successful practices; and, based on the obtained data, to develop general recommendations for improving marketing strategies to increase the competitiveness of Kazakhstani agricultural products in foreign markets.

MATERIALS AND METHODS

This research included the collection, processing, and analysis of statistical data, the conducting of an interregional comparative analysis, as well as the study of successful practices in other countries, which made it possible to formulate specific recommendations for improving Kazakhstan's export strategy. First and foremost, to analyse the current state of Kazakhstan's agricultural exports, official statistical data provided by the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.) and international organisations such as the World Trade Organization (n.d.), Food and Agriculture Organization (n.d.), and International Trade Centre (n.d.) were used. These data included information on the dynamics and structure of agricultural exports, as well as data on the volumes of exported goods such as cereals, meat, milk, oilseeds, and other products. The data for 2020-2024 made it possible to identify trends and key issues in the development of the agricultural sector, as well as to assess the degree of diversification of Kazakhstan's exports and its competitiveness in international markets. Particular attention in the research was paid to the comparison of marketing strategies of various countries that were leaders in agricultural exports, such as the United States, which allowed for the identification of the most successful and applicable methods for Kazakhstan. For this, data on marketing campaigns, packaging, logistics, certifications, and other aspects of product promotion in international markets were used. The comparative analysis covered various regions, including Europe, Asia, the Middle East, Africa, and the Americas, which made it possible to assess how different approaches were adapted depending on cultural, economic, and environmental features.

As part of the research, successful examples from countries such as Brazil and Australia, which were among the largest exporters of agricultural products and had well-developed marketing strategies, were also considered. This included a detailed analysis of how these countries promoted the products, what innovations were implemented in the production and packaging process, what quality standards were adhered to, and what marketing channels were used to enter foreign markets. These data served as a basis for developing proposals to improve Kazakhstan's export strategy based on global experience. The study also used the method of analysing trade agreements and international standards, which allowed for the evaluation of the influence on the development of Kazakhstan's agricultural exports. Within this method, special attention was paid to analysing Kazakhstan's participation in such international economic associations as the Eurasian Economic Union, as well as considering various agreements with the EU and Asian countries. The evaluation of these agreements made it possible to identify how these countries contributed to expanding access to foreign markets for Kazakhstani agricultural goods and what economic and legal conditions these states created for exporters. Moreover, during the analysis process, various government support programmes for exporters were reviewed, such as the State Programme for Business Support and Development "Business Roadmap 2025" (2022) proposed by the Ministry of Trade and Integration of the Republic of Kazakhstan, which were aimed at increasing the competitiveness of agricultural producers and expanding trade links with international partners. These materials provided a foundation for further study of the methods and tools used by Kazakhstan to support and develop agricultural exports. An important element was the study of product certification measures, such as GlobalGAP, Hazard Analysis Critical Control Point, and ISO 22000, which were important tools for entering global markets. This made it possible to assess how domestic support measures from the government could increase the competitiveness of Kazakhstani goods in the international arena. Based on the analysis carried out, recommendations were developed to improve Kazakhstan's marketing strategies in the field of agricultural exports.

RESULTS

Kazakhstan's agricultural sector occupies an important place in the national economy, providing a significant share of gross domestic product (GDP) and being a key source of employment for millions of citizens. In 2024, the contribution of agriculture to the country's economy was about 4.5% of GDP, with the sector employing over 20% of the economically active population (Fig. 1).

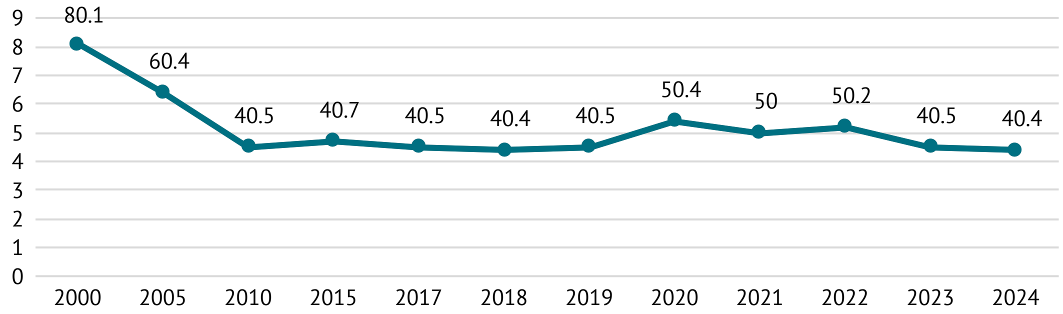

Figure 1. *Share of the agro-industrial sector in Kazakhstan's GDP*
Source: *developed by the authors based on the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.)*

The development of the agro-industrial complex was largely determined by – natural conditions: Kazakhstan possessed vast agricultural land covering around 215 million hectares, of which more than 24 million hectares were allocated to arable land. This created favourable opportunities for large-scale agricultural production and its export. After 2021, the export of agricultural products demonstrated stable growth. In 2022, Kazakhstan exported agricultural goods worth more than USD 5.5 billion, which was 16% more compared to 2021. The export was primarily based on cereal crops, primarily wheat, as well as flour products, oilseeds, meat, and dairy products. Kazakhstan established itself as one of the largest grain producers in the Eurasian region, and its products were in demand not only among neighbouring countries but also in more remote markets. The largest share of exports accounted for cereals and flour products. Kazakhstan consistently ranked among the top ten global suppliers of wheat and flour, holding a significant share in international trade. In 2022, wheat export volume exceeded 6.5 million tonnes, and the main importing countries traditionally included Uzbekistan, Tajikistan, Turkmenistan, Afghanistan, China, and a number of Middle Eastern states. On the global flour market, Kazakhstan accounted for over 10%, making it one of the leading suppliers of this product. In addition to cereals, oilseeds such as rapeseed, sunflower, and flax also played an important role in exports. The exports abroad increased due to growing demand for vegetable oils and the processed products. Kazakhstan actively exported oilseed products to China, European countries and the Commonwealth of Independent States. It should be emphasised that meat exports also developed: in 2022, more than 35 thousand tonnes of meat and meat products were sent to foreign markets, with key importers being countries such as Uzbekistan, China, and the Gulf states.

Nevertheless, despite positive trends, Kazakhstan's agricultural export faced a number of challenges that limited its competitiveness in global markets. Among the key problems were high logistics costs, insufficient diversification of export markets, and the need to adapt products to international standards of quality and safety. Since the country ranked ninth in the world by area (2.7 million km²), but lacked access to the sea, this complicated export deliveries and increased logistics costs. The main export routes passed through railways and highways, as well as through river and seaports of neighbouring countries. The railway network, covering more than 16 thousand km and connecting the main grain-producing regions with export hubs, played a crucial role in grain transportation. However, most of the infrastructure required modernisation, as the lack of specialised grain wagons led to increased delivery times. Key export hubs in Kazakhstan were concentrated on the borders with major trading partners. In the western direction, products were sent through the ports of Aktau and Kuryk on the Caspian Sea. In the east, the main transport hub was the International Centre for Border Cooperation "Khorgos", through which a significant portion of agricultural supplies to China passed. In the southern direction, Kazakhstan used road and rail routes to export products to Uzbekistan, Tajikistan, Turkmenistan, and further to Afghanistan. Infrastructure development remained a key factor in increasing the competitiveness of Kazakhstan's agricultural exports. In

2023-2024, projects were being implemented to expand transport corridors and modernise logistics capacities. Kazakhstan actively participated in the Chinese initiative "One Belt, One Road", which made it possible to develop transit routes and attract investment in transport infrastructure. However, for sustainable growth in export deliveries, comprehensive modernisation of the entire logistics system was necessary, including the improvement of railway transport, expansion of port capacity and construction of modern storage facilities.

It was important to note that in order to continue the development of the logistics system and increase the competitiveness of agricultural exports, particularly cereals, Kazakhstan was already implementing and planning a number of specific measures. In 2023-2024, projects to modernise the railway network began, including the procurement of around 500 new specialised grain wagons to increase the speed and volume of wheat transport, which should reduce delivery times from the current 20-25 days to 15-18 days on key routes such as to the port of Aktau. The capacity of ports on the Caspian Sea was also being actively expanded: a new grain terminal with an annual capacity of 1 million tonnes was launched at the port of Kuryk, and dredging works were being carried out in Aktau, which by 2025 would increase the transshipment capacity to 10 million tonnes per year. Within the framework of cooperation with China through the "One Belt – One Road" initiative, the "Khorgos" hub was being modernised, where the construction of a cargo airport was planned by 2027, which would accelerate the export of grain and flour to China and Southeast Asia, reducing delivery times from 12 to 14 days to 7-10 days. In addition, in 2024, the digitalisation of transport procedures with China began, including the exchange of digital permits, which had already reduced administrative delays at the border by 20%. An assessment of transportation costs in Kazakhstan showed that these costs remained higher than those of competitors with access to the sea. For example, the transportation of 1 tonne of wheat from Kazakhstan to China through "Khorgos" cost around USD 80-100, including railway tariffs and transshipment, while countries using Black Sea ports had a cost of USD 50-60 per tonne due to shorter routes and direct access to maritime routes. Compared to Australia, where wheat export costs through seaports ranged from USD 4-55 per tonne, Kazakhstan lagged behind due to the need for transit through third countries and outdated infrastructure. However, modernisation and optimisation of routes such as the Middle Corridor (Trans-Caspian route) could reduce costs by 10-15% by 2030, bringing these costs down to USD 70-85 per tonne, making Kazakh grain more competitive.

Potential opportunities for cooperation with international logistics hubs and transport corridors opened new prospects for agricultural exports. Within the framework of the "One Belt – One Road" initiative, Kazakhstan strengthened its partnership with China, using terminals in Xi'an and ports in Lianyungang, which had already increased container transit with grain products by 90% over the last five years (from TEU 18,000 in 2019 to TEU 50,500 in 2024). Cooperation with the ports of Georgia (Poti) and Azerbaijan (Baku) within the Middle Corridor made it possible to reduce delivery time of grain to Turkey and Europe from 40 days by sea to 15-20 days via the Caspian Sea, and the agreement with the German Rhenus and KTZ in 2023 aimed at developing logistics centres in Aktau and Kuryk, which would increase grain transshipment to 300,000 containers by 2030. These steps, supported by investments totalling USD 18 billion under the "Nurly Zhol" programme and BRI, strengthened Kazakhstan's role as a transit hub, providing access to EU, Gulf and South Asian markets, which was especially important for the export of wheat and flour.

An important factor was also that in 2022, more than 80% of all Kazakhstan's agro-exports accounted for the Commonwealth of Independent States, making it vulnerable to economic and political changes in the region. The global agricultural products market demonstrated steady growth, driven by population growth, urbanisation, and changing consumer preferences. Modern buyers increasingly focused on high-quality, environmentally friendly, and organic products, which was especially evident in developed countries of Europe and North America. At the same time, Asian markets, including China and India, showed high demand for innovative agricultural products, functional nutrition, and flexible pricing solutions. In the Middle East and Africa regions, cultural and climatic factors played an important role, requiring adaptation of products to specific conditions.

When considering the characteristics of different regions, it should be noted that the European agricultural market was distinguished by high requirements for quality, safety, and environmental friendliness. EU countries operated a strict certification system including GlobalGAP standards, Hazard Analysis Critical Control Point, ISO 22000, as well as national and regional regulations, such as the French Label Rouge or the German Bio-Siegel (Psuturi, 2023; Boisvert *et al.*, 2024). For exporters, this meant the need for full compliance with European regulations, requiring significant investments in production technologies, quality control systems, and logistics processes. This forced Kazakhstan, as an exporter of cereals and oilseeds, to comply with Commission Regulation No. 1881/2006 "Setting Maximum Levels for Certain Contaminants in Foodstuffs" (2006), which established permissible levels of mycotoxins in food. Also, one of the key trends in the European market was the concept of traceability – tracing the origin of products at all stages of the production and supply. This included the use of digital solutions such as RFID technologies that recorded data on the origin of raw materials, processing methods and storage conditions. Companies supplying organic products to Europe were obliged to provide full information about the supply chain, which increased trust from consumers and regulatory authorities. In addition, the concept of sustainable development played an important role: producers adhering to environmental principles gained competitive advantages, as European consumers were inclined to choose products with a low carbon footprint and minimal environmental impact (Rama *et al.*, 2023).

Marketing strategies in the European market were oriented towards a value-driven approach, where the main focus was on quality, environmental friendliness, and social responsibility of producers. Companies actively used certification labels and markings (such as Organic, Fair Trade, Rainforest Alliance), as well as storytelling strategies – telling stories about the origin of products, farms, and traditional production methods. This allowed forming an emotional connection with consumers, which was especially important in premium product segments. Another feature of promotion in Europe was the active use of digital marketing, including e-commerce platforms, content marketing and social media (Palamarchuk & Korkach, 2023). For example, large retail chains such as Carrefour and Tesco provided separate online platforms for certified organic and environmentally friendly products. For exporters from Kazakhstan, this created both opportunities and challenges, as it required compliance with high standards, transparency of production, and a well-thought-out marketing strategy adapted to the demands and expectations of European consumers. The Asian agricultural market was characterised by a high dynamic of demand growth, driven by population increase, rising incomes of the middle class, and changing consumer preferences (Prabhakar, 2021). For example, in China, the largest food importer in the region, the volume of agricultural imports in 2022 exceeded USD 250 billion, and there was a growing interest in organic products, functional nutrition, and highly processed goods. In India, another major economy in the region, demand for imported food products also grew, especially among urban youth oriented towards healthy eating. In Southeast Asia, including Vietnam, Indonesia, and Thailand, consumers valued variety and product accessibility, which required exporters to be flexible in pricing policies and offer formation.

Adapting marketing communications and packaging in the Asian market was a mandatory strategy for successful product entry. The diversity of cultural traditions, aesthetic preferences, and consumer expectations made a universal approach ineffective, so companies had to carefully tailor the products to the specifics of each individual market. In China, packaging played a key role in product perception. Here, consumers preferred bright designs with rich colours, such as red and gold, which were associated with luck and prosperity. Additionally, images of natural ingredients and emphasis on the beneficial properties of the product were valued. One such example – on packaging of flour or vegetable oils, symbols of health, longevity, or even traditional Chinese patterns could be placed to strengthen trust in the brand. Moreover, informativeness was an important element: Chinese consumers wanted to see clearly indicated composition, product benefits, as well as QR codes for quick access to information about product origin and certification. In Japan, by contrast, preferences leaned towards minimalism, environmental friendliness and a high level of aesthetics. Here, laconic packaging with soft colours, smooth lines, and strict design was popular. Japanese people highly valued compactness and convenience, so manufacturers had to consider the ergonomics and functionality of packaging. Additionally, Japanese consumers tended towards conscious consumption, so the use of recyclable or biodegradable materials became an important factor of competitiveness. For example, paper or fabric packaging instead of plastic was increasingly used, which was perceived as a sign of care for the environment and compliance with high production standards (Wandosell *et al.*, 2021). In Muslim countries of Southeast Asia, such as Indonesia and Malaysia, the key requirement was the presence of Halal certification. Without the appropriate Halal logo, products could not appear on store shelves, as the majority of local consumers chose only products that complied with Islamic dietary laws. In addition to certificates, cultural characteristics had to be taken into account: in these countries, packaging had to be modest, without images of pork, alcohol, or other prohibited elements. The colour scheme often included green, associated with Islamic symbolism, and Arabic phrases could appear on the packaging, emphasising compliance with Halal standards. Manufacturers who ignored these features risked facing low sales and difficulties entering local markets, whereas companies that considered the specifics of each region could gain a significant competitive advantage.

Effective marketing strategies in Asia included the use of localised digital marketing, cooperation with popular online retailers (Alibaba, JD.com, Shopee, Lazada) and working with social commerce platforms such as WeChat and TikTok (Hu, 2020; Hasani *et al.*, 2023). Also in China, promotion through sales on Taobao Live allowed companies to instantly interact with the audience and increase conversion (Zhang & Erturk, 2022). In addition, partnership programmes with local distributors and retailers played an important role, helping to overcome language and cultural barriers and adapt products to the specifics of the local market. For exporters from Kazakhstan, this meant not only ensuring competitive prices, but also developing specialised marketing strategies focused on the needs and preferences of various regions of Asia.

The markets of the Middle East and Africa represented dynamically developing regions with unique requirements for agricultural products, especially concerning storage conditions, packaging, and logistics. An important aspect of entering these markets was taking into account the climatic conditions: high temperatures and humidity required specialised packaging capable of protecting products from external factors. For the export of cereals and flour to the countries of the Persian Gulf, the use of multilayer moisture-resistant bags with barrier coatings was recommended, preventing the penetration of moisture and contaminants. For chilled and frozen meat, popular among Middle Eastern countries, strict temperature storage regimes were necessary, as well as special packaging methods such as vacuum or modified gas environment, extending the product's shelf life (McMillin, 2020). Logistics also played a critically important role, especially in African countries, where infrastructure often remained underdeveloped. For exports to regions such as Central and West Africa, careful route planning and provision of heat-resistant containers were required, as the lack of cold storage and unstable electricity supply could lead to product spoilage. In Middle Eastern countries, by contrast, there was a high level of port infrastructure development, which simplified imports; however, specific certification requirements (e.g., mandatory Halal certification for meat products) could become a barrier to market entry. In Saudi Arabia, the UAE, and Kuwait, product packaging was subject to increased safety requirements: toxic dyes were prohibited, special protective films were used, and labelling had to contain all necessary information in Arabic.

Despite fierce competition and complex logistical conditions, the markets of the Middle East and Africa offered significant prospects for niche segments of agricultural products. Growing demand for organic and environmentally friendly products opened opportunities for the export of organic cereals, fruits, and vegetables. In the countries of the Persian Gulf, consumers were willing to pay a premium price for high-quality products that met international standards, such as EU Organic, US Department of Agriculture Organic or Halal Organic. Another promising direction was the export of specialised products that took into account cultural and religious characteristics. In Muslim countries of the Middle East and North Africa, there remained a high demand for Halal meat, including lamb and beef certified according to Islamic slaughter norms. In African countries, there was increased interest in fortified products, such as dairy products with added vitamins and trace elements, since a number of regions still faced the problem of nutrient deficiency in the diet. It was also worth considering the growing interest in long-shelf-life products such as dry mixes, frozen semifinished products and canned foods. In countries where problems with cold chains remained relevant, such goods were highly popular. In particular, in Nigeria, Ghana and Kenya, the consumption of powdered milk was growing, as it was easier to store and transport than pasteurised or ultra-pasteurised milk.

The agricultural products market in North and South America was characterised by a high level of competition, which required exporters to have a clear positioning strategy and product differentiation. In the USA, Canada, and Brazil, large agro-industrial corporations dominated, with streamlined supply chains, high production efficiency, and significant marketing budgets. This created challenging conditions for new players to enter the market, especially from countries without strong brands or unique selling propositions. It was worth noting that the USA was the world's largest producer of soybeans and corn, as well as a significant exporter of wheat, making competition in these segments particularly intense (Gjata *et al.*, 2022). One of the effective ways to successfully enter the American market was to focus on the unique qualities of the product. Consumers in the USA and Canada actively showed interest in organic, environmentally friendly, and functional products (superfoods, high-protein products, gluten-free and plant-based alternatives to dairy and meat products). The demand for organic cereals and cereal-based products (oat flakes, flour, bakery products) grew on average by 10-12% per year, creating promising niches for export. For exporting countries from Asia, Europe, and Latin America, a successful strategy could be to enter the premium product segment with rare properties, such as ancient grain varieties (amaranth, quinoa, spelt) or specialised meat and dairy products, such as grass-fed beef or farm cheeses with unique ripening technologies.

For successful entry into the American market, the creation of a strong brand was also of great importance, as consumers in the USA and Canada were guided not only by quality but also by product recognition. Companies without a well-promoted brand faced difficulties getting onto the shelves of major retailers such as Walmart, Costco, Whole Foods and Kroger. According to Nielsen (2024), research, about 60% of Americans were willing to pay more for products with a strong marketing concept that inspired trust. Successful exporters actively used the story of the product's origin, emphasising traditional production methods, environmental friendliness, and social responsibility. Another critically important aspect for exports to the USA was compliance with strict safety and quality standards. The main regulators in this area were the Food and Drug Administration and the US Department of Agriculture, which set stringent product requirements. Dairy and meat products had to comply with Hazard Analysis Critical Control Point standards, while organic products required US Department of Agriculture Organic certification (Kudrenko & Hall, 2024). In turn, for exports to Canada, compliance with the Canadian Food Inspection Agency standards was important, which regulated labelling, packaging, and safety requirements. Table 1 showed the results of a comparative analysis of marketing strategies for Kazakhstan's agricultural exports in various regions.

***Table 1**. Results of comparative analysis of marketing strategies for agricultural exports of Kazakhstan*

Region	Key Features	Marketing Strategies
Europe	High quality standards, ecology, strict requirements for product safety	Certification (GlobalGAP, Organic, ISO). Transparency of production and traceability. Focus on environmental friendliness and sustainability of production.
Asia	Dynamic growth in demand, focus on innovative products, price flexibility	Adaptation of packaging and branding to cultural specifics. Emphasis on the functional and beneficial properties of products. Price flexibility.
Middle East and Africa	Specific certification requirements, difficult climatic storage conditions	Halal certification. Development of logistics for storage and transportation in hot climates. Taking into account cultural preferences.
America (USA, Canada, Latin America)	High competition, significant share of large agricultural corporations, branding	Strong brand positioning. Direct marketing and advertising. Participation in international exhibitions and trade missions.
Countries of the Commonwealth of Independent States (Russia, Central Asia)	Low entry barriers, traditional trade links, dependence on infrastructure	Simplified certification procedures. Focus on logistical accessibility. Using the Eurasian Economic Union trade agreements to reduce tariffs.

***Source:** developed by the authors*

The experience of leading agricultural exporters such as the USA, Brazil, and Australia demonstrated that successful promotion on global markets required a comprehensive approach, including infrastructure development, compliance with international quality standards, and active marketing policy. For example, the USA effectively used branding and product differentiation strategies, promoting organic and high-margin goods such as GMO-free products, functional foods, and premium meats. Government support also played an important role through export subsidy programmes, trade representations, and the signing of beneficial agreements such as NAFTA and USMCA, which reduced trade barriers. Brazil focused on large-scale agricultural production, optimised logistics, and expanded export deliveries through major ports. Key export directions included soybeans, meat, sugar, and grains to China, the EU, and Middle Eastern countries. Australia, in turn, focused on the premium segment, promoting high-quality wheat, meat, and dairy products with an emphasis on environmental friendliness and sustainability. This approach proved particularly successful in Asian countries, where demand for safe and certified products grew. For Kazakhstan, applying these strategies with consideration of national characteristics could have been beneficial.

State support was one of the key factors in the development of Kazakhstan's agricultural exports, contributing to the competitiveness of Kazakh products on global markets. Kazakhstan actively used mechanisms such as agricultural subsidies, concessional lending, and compensation of transport costs for exporters. Programmes such as the "Export Accelerator" and "Business Roadmap" provided grants and tax incentives for companies targeting foreign markets. In addition, Kazakhstan actively participated in the integration process with international trade unions such as the Eurasian Economic Union, of which it had been a member since its founding in 2015. This ensured the country duty-free access to the markets of Belarus, Armenia, and Kyrgyzstan, where a unified customs policy and the absence of internal trade barriers simplified export procedures for Kazakh agricultural products, particularly wheat and flour.

It should be emphasised that Kazakhstan expanded trade ties through bilateral agreements with China, Middle Eastern countries, and the EU, which contributed to the reduction of tariff and non-tariff barriers. After signing cooperation protocols with China in 2023 concerning the export of peas, lentils, and wheat, as well as introducing preferential tariff conditions, Kazakhstan's wheat exports to China grew by 15% per year, reaching around 0.8 million tonnes in 2023 compared to 0.7 million tonnes in 2022. The agreement with the EU under the Enhanced Partnership and Cooperation Agreement (effective from 2020) also increased wheat flour exports to EU countries by 12% in 2023 (around 0.35 million tonnes versus 0.31 million tonnes in 2022), thanks to simplified certification requirements and reduced tariffs. With Middle Eastern countries such as the UAE and Saudi Arabia, agreements were signed in 2023 for the supply of processed agricultural products, including flour and sunflower oil, which led to a 20% growth in flour exports to the UAE (about 0.2 million tonnes), facilitated by streamlined logistics and the removal of some phytosanitary restrictions.

However, despite these successes, not all trade agreements led to unequivocally positive results, and Kazakhstan faced a number of barriers and challenges in accessing agricultural markets, especially in the wheat and derivative niche. Within the Eurasian Economic Union, although mutual trade had almost doubled since 2015, Kazakh wheat exporters periodically encountered non-tariff restrictions such as sanitary inspections and temporary import bans. With China, despite export growth, there remained issues with high phytosanitary standards and logistics costs: transportation through remote ports such as Lianyungang increased costs by 10-15% compared to regional supplies. In the Middle East, although demand for Kazakh flour was growing, countries such as Saudi Arabia maintained high certification standards, which slowed market entry – in 2023, only 34 Kazakh companies received approval to export to KSA, and the potential export volume was estimated at USD 500 million, of which only about 30% was realised. The agreement with the EU also had its challenges: despite the growth in flour exports, European duty-free import quotas remained limited, and competition with local producers and Ukraine forced Kazakhstan to lower prices, reducing margins by 5-7%. Thus, although integration and bilateral agreements opened new opportunities, barriers such as standards, logistics, and protectionism continued to restrain the full export potential of Kazakh agricultural products, requiring further work to eliminate these obstacles.

The study of different support measures in various countries also showed that developed agricultural exporters such as the USA, the EU, and Australia emphasised long-term agricultural development programmes and state promotion of national brands in global markets. In the EU, for instance, the Common Agricultural Policy was in effect, aimed at farmer subsidies, supporting sustainable production, and protecting local producers through tariff regulation. The USA used a system of grants, tax incentives, and marketing support through programmes such as the US Department of Agriculture, which helped American farmers enter international markets. In Australia, significant attention was paid to certification, environmental standards, and the promotion of high-quality products on Asian markets. This highlighted the importance of strengthening Kazakhstan's position in global trade by expanding state support programmes and focusing on successful practices of other countries, including the development of export logistics, product certification, and promotion of the country's agricultural brand. A chart of the overall export trend of one of the key niches of the agro-industrial complex – grain (wheat) – in comparison with other countries, was presented in Figure 2.

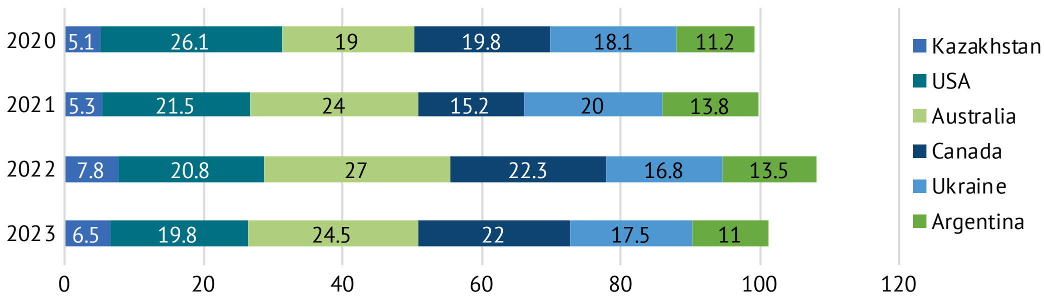

***Figure 2**. General trend of grain (wheat) exports on the world market in 2020-2023*
***Source:** developed by the authors based on Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (n.d.), International Trade Centre (n.d.), World Trade Organization (n.d.)*

It is worth noting that the analysis of wheat export data for the years 2020-2023 revealed both stable global trends and specific features of individual countries, including Kazakhstan. Thus, the USA and Canada remained among the key exporters on the global market, in the range of 19-27 million tonnes and 15-23 million tonnes respectively, although these states faced competition and internal challenges such as logistics and weather conditions. Australia and Argentina demonstrated volatility linked to climatic factors: Australia reached a peak of 27 million tonnes in 2022, while Argentina fluctuated between 11 and 13.8 million tonnes. Ukraine, despite its significant potential, lost ground after 2021 due to geopolitical upheavals, although a recovery to 17.5 million tonnes in 2024 indicated a gradual overcoming of the crisis consequences. Kazakhstan in this comparison stood out as a regional exporter with relatively modest but stable volumes, which grew from 5.1 million tonnes in 2020 to a record 7.8 million tonnes in 2022, although in 2023 there was a decline to 6.5 million tonnes due to drought. Overall, the trend indicated recovery, supported by improved weather conditions and demand from Central Asia and China. Unlike the global leaders, Kazakhstan did not aim for broad expansion into global markets but instead strengthened its niche in neighbouring countries, where low transport costs and established trade links played a key role. However, dependence on climate and limited production volumes (12-16 million tonnes of harvest) constrained its potential compared to countries like the USA or Australia. Nevertheless, the sustained export growth in 2022 and efforts to increase shipments to China demonstrated that Kazakhstan was capable of adapting to changes in demand and weather challenges, maintaining its significance on a regional scale, and also having prospects for entry into global markets. Figure 3 presented a chart showing Kazakhstan's share in global wheat exports for 2023, in comparison with other countries.

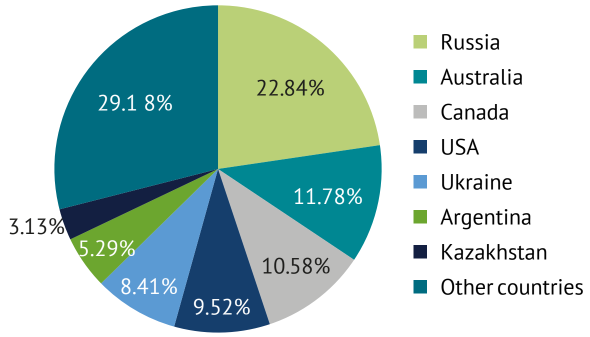

***Figure 3**. Kazakhstan's share in world wheat exports on the global market in 2023*
***Source:** developed by the authors based on the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), Food and Agriculture Organization (n.d.), International Trade Centre (n.d.), World Trade Organization (n.d.)*

The analysis of data on the share of wheat exports in the global market for 2023 shows a significant concentration of this sector in the hands of a few key players, with Australia (11.78%), Canada (10.58%) and the United States (9.52%) forming a group of leaders with a strong presence in Asia, Europe, and the Americas, where the success is driven by product quality and logistics. Also, Ukraine (8.41%) and Argentina (5.29%), despite certain difficulties – geopolitical in the case of Ukraine and climatic in the case of Argentina – retain the prominent positions, demonstrating the ability to adapt to challenges. Kazakhstan, with 3.13%, occupies a modest place in this structure, reflecting its limited global influence compared to the leaders, but emphasising its importance as a regional supplier, especially to Central Asia and the near abroad. This share suggests that Kazakhstan is successfully utilising its geographical advantages and established trade links to make a stable, albeit small, contribution to world wheat exports. At the same time, the significant share of 'other countries' (29.18%) indicates that the rest of the market is fragmented, with many small players together accounting for almost a third of shipments, leaving Kazakhstan with the potential for growth if it increases production and diversifies its markets, for example, by strengthening its position in China or other Asian countries. Based on the above comparative analysis, general recommendations have been proposed for improving marketing strategies for Kazakhstan, which are summarised in Figure 4.

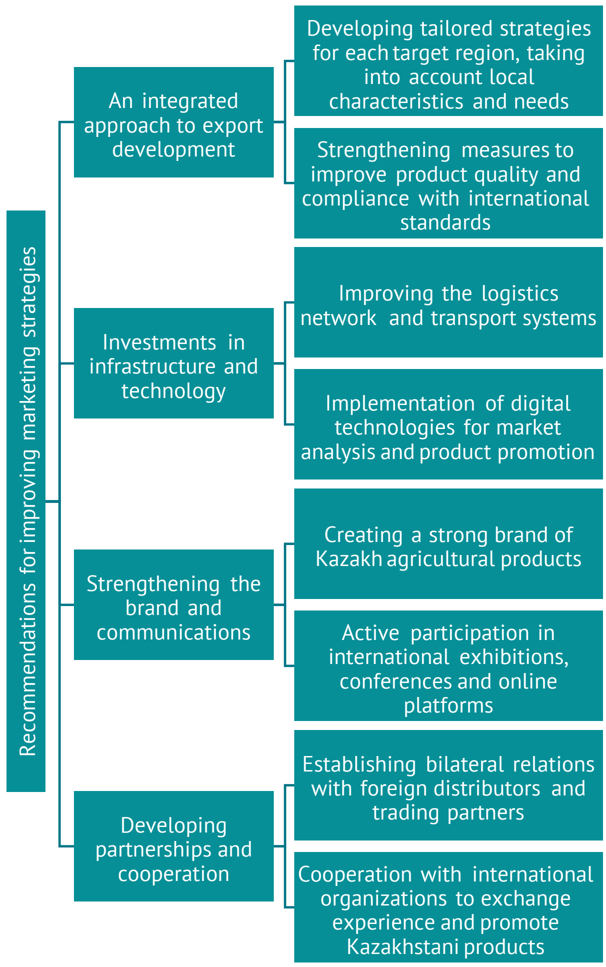

***Figure 4**. Recommendations for improving marketing strategies for Kazakhstan*
***Source:** developed by the authors*

Thus, for the successful promotion of agricultural exports, it was important for Kazakhstan to apply a comprehensive approach that included the development of adapted marketing strategies for each target region, taking into account the characteristics and needs. This meant that for Europe, Asia, the Middle East, and other key markets, it was necessary to create unique offers that matched the specific requirements of local consumers. For each market, a strategy had to be developed that considered cultural, economic, and legislative characteristics, as well as the preferences of end consumers. It was also necessary to strengthen measures to improve product quality and compliance with international standards, which required the implementation of certifications (GlobalGAP, ISO, Hazard Analysis Critical

Control Point), improvement of production conditions, and adherence to environmental standards; in the case of wheat, this could have included the introduction of innovative processing and storage methods that contributed to the preservation of its high-quality characteristics. Products that met international standards had better chances of successful promotion, especially in countries with high requirements for safety and quality, which was particularly relevant for cereal crops.

Investment in infrastructure and technologies was also one of the most important factors for increasing the competitiveness of the agricultural sector. The improvement of the logistics network and transport systems allowed for the reduction of delivery costs and increased delivery speed, which was especially important for goods such as fresh fruits, vegetables, and meat. The construction of modern warehouse complexes, the improvement of transport hubs, and the development of railway and road routes could have significantly enhanced Kazakhstan's export capabilities. The implementation of digital technologies for market analysis and product promotion became a key element of a successful strategy. The use of big data, analytical platforms, and marketing tools helped to accurately forecast demand, adapt product offerings, and effectively promote these offerings through digital channels. Technologies could also have been useful for monitoring and optimising supply chains, which reduced risks and increased the efficiency of the entire export system.

Also, for a successful entry into international markets, it was necessary for Kazakhstan to create a recognisable and attractive brand that would be associated with high-quality and environmentally friendly products. Branding had to focus on the unique advantages of Kazakh agricultural products, such as naturalness, safety, and high-quality standards. It was important that the brand reflected national identity, cultural traditions, and the benefits of the country's agricultural production. It had to be recognisable on the international stage, creating a positive impression among consumers. For this, it was necessary to develop a logo, slogan, and visual elements that would be easily perceived and associated with high-quality products. Another important step was the creation of marketing materials and advertising campaigns aimed at promoting the brand in various target markets. This could have included the production of videos, presentations, and online campaigns that emphasised the values and mission of the Kazakh agricultural sector. One of the effective ways to promote products was participation in international exhibitions and conferences that gathered leading industry players and potential buyers. These events provided an opportunity not only to showcase products, but also to establish important business contacts and exchange experience with colleagues from other countries. Kazakh exporters were encouraged to actively participate in agricultural product exhibitions such as SIAL in Paris, Anuga in Cologne, or Gulfood in Dubai. These platforms attracted the attention of international distributors, retailers, and wholesalers, allowing Kazakh companies to expand the client base. In the context of globalisation, online platforms and virtual exhibitions also played an important role in promoting products. Platforms such as Alibaba, Amazon, and other trade portals enabled exporters to enter new markets with lower costs by conducting successful online campaigns.

Establishing bilateral relations with foreign distributors and trade partners was a necessary step to expand the presence of Kazakh agricultural products in international markets. It was important to build long-term partnerships with reliable distributors who could effectively represent the products in target countries, ensuring the delivery and promotion. This cooperation could have included supply agreements, joint marketing campaigns, and the organisation of events for product promotion. For this, it was necessary to work actively with trade associations and export agencies, as well as participate in business meetings and negotiations with key market players. Kazakhstan also had to actively cooperate with international organisations such as the World Trade Organization, the International Federation of Agricultural Exporters, and other specialised institutions to use the platforms for product promotion and to gain valuable experience. Participation in international programmes and projects contributed to the exchange of knowledge about international markets, trends, and technologies, which helped Kazakh producers to optimise the processes and improve the quality of the products. It was also important to use international aid and funding programmes to modernise production facilities and improve product quality. Cooperation with such organisations and global agricultural market participants opened new prospects for export expansion and for raising the reputation of Kazakh products on the international stage.

DISCUSSION

In the course of this research, an interregional comparative analysis of marketing strategies for agricultural exports was carried out, which allowed the identification of key features and approaches applied in different parts of the world. The results of the analysis showed that marketing strategies for agricultural exports largely depended on economic conditions, the level of government support, regulatory requirements, and the structure of consumer demand. This demonstrated that there was no universal approach, and successful strategies had to take into account global trends as well as the specifics of each target region. The research also made it possible to identify a number of barriers faced by agricultural exporters, including trade restrictions, logistical difficulties, differences in certification requirements, and the level of competition. In the study by H. Willer *et al.* (2023), general trends in the development of agricultural exports in different regions were also considered, including key factors influencing its dynamics, but this work did not conduct a detailed comparison of marketing strategies of different countries, which limited the opportunities to identify effective approaches to promoting products in foreign markets. In the work by D. Huo *et al.* (2020), the impact of the market environment and competitive conditions on the development of agricultural exports was analysed, focusing on product positioning strategies, but without a detailed examination of interregional differences in marketing strategies, which reduced its practical relevance for countries with varying economic conditions. In the work by Y. Liu and X. Wang (2022), an analysis was conducted on the factors determining the competitiveness of agricultural exports, including pricing policy and product branding, but without considering the specifics of marketing strategies in different regions, which made the conclusions less universal. In the study by O. Bazaluk *et al.* (2020), successful examples of agricultural exports at the international level were considered, looking at ways to enter new markets, but without including a systematic interregional analysis of marketing strategies, which limited the opportunities to develop adaptive solutions. Thus, compared to the mentioned works, this research presented a more comprehensive approach, including a detailed interregional comparative analysis of marketing strategies for agricultural exports. This made it possible to identify key success factors of various strategies depending on the market environment and adapt these strategies to the conditions of Kazakhstan.

The results of the research showed that marketing strategies for agricultural exports differed depending on the region and the level of economic development of the country. In particular, it was noted that in countries with a developed agricultural industry, such as the USA and EU countries, strategies focused on promoting high value-added products, strengthening branding, and ensuring strict compliance with international quality standards. These countries actively used certification, environmental labelling, and sustainable agriculture programmes as marketing elements, which enabled these states to occupy strong positions in the global market (Chykurkova *et al.*, 2025). In the context of Kazakhstan's agricultural market conditions, it was noted that the country's agricultural exports faced a number of challenges, including logistical issues and insufficient diversification of sales markets. The research emphasised that successful marketing strategies required a comprehensive approach, including brand development, adaptation to the requirements of target markets, and the use of modern promotion tools. This opened up opportunities for Kazakhstan to use the experience of leading agricultural countries to develop an optimal export strategy focused on sustainable growth and increased competitiveness in the global market. In the course of the work by L. Lyubenov (2020), the specifics of marketing strategies for agricultural exports under global competition were also considered, showing that effective strategies included the use of certification and drawing attention to the quality characteristics of products, but without sufficiently detailed examination of the factors influencing the choice of the most appropriate promotion tools for different product groups. In the study by R.I. Molina *et al.* (2024), the issues of adapting marketing strategies to the requirements of different markets were examined, emphasising the effectiveness of combining price and non-price competitiveness factors, forming long-term strategies for entering new markets, but with limited coverage of regional differences, which did not allow for a full assessment of the effectiveness of individual strategies in different market conditions. In the research by I. Tomashuk (2023), the impact of various factors on the development of agricultural exports was analysed, paying attention to competitiveness and product promotion mechanisms, and noting that market diversification, infrastructure development, and logistics optimisation played an important role, but without addressing changing market conditions and global trends, which limited the applicability of the conclusions in the long term. It should be noted that the results of this study differed from the results of the mentioned works by the breadth of coverage of different markets and strategies. Since the mentioned studies limited the analysis to individual countries or regions, which did not allow a full assessment of the universality of the identified patterns, this study compared different approaches on a global scale, which allowed the examination of the applicability in various economic conditions.

The results of this study also made it possible to identify key features of marketing strategies for agricultural exports in Asia, the Middle East, Africa, and the Commonwealth of Independent States, which was an important aspect for understanding the development potential of exports. It was noted that in Asian countries, key elements of strategies included product adaptation to local requirements and flexible pricing. In the Middle East, the emphasis was placed on Halal certification, as well as consideration of cultural preferences and hot climate conditions. In African countries, the main success factors were flexibility in pricing and minimisation of logistical costs. In the Commonwealth of Independent States, export strategies were oriented towards intra-regional trade, price competitiveness, and standard unification. This confirmed the importance of using marketing approaches that considered the economic and regulatory characteristics of target markets, as well as consumer preferences, logistical constraints, and the level of competition in each region. In the study by J. Wang *et al.* (2022), regional marketing strategies for agricultural exports were also examined, noting the importance of adapting pricing policy and product packaging according to consumer preferences, but this work did not sufficiently consider long-term factors influencing the sustainability of export supplies. In the work by H. Keskin *et al.* (2021), an analysis of the competitive advantages of commodity exports was carried out, emphasising the importance of developing partnerships and cooperation with distributors in target markets, but not paying enough attention to the impact of trade barriers and tariff restrictions, which could significantly affect export flows. In the research by Q. Sun *et al.* (2022), the impact of risks on the structure of agricultural trade in countries with unstable economic situations was examined, where flexibility in market entry strategy was the main factor of competitiveness, but without considering the role of government export support programmes, which also played an important role in shaping long-term export strategy. In the study by H.H. Park and S.J. Cho (2021), the impact of logistical factors on marketing strategies for agricultural exports was noted, identifying the need to minimise costs to improve transport efficiency, but without examining the specifics of demand in various regional markets, which limited the completeness of the analysis. Thus, the results of this study expanded existing knowledge about marketing strategies for agricultural exports, providing a comprehensive understanding of key factors determining successful entry into foreign markets. Unlike the mentioned works, this research combined the analysis of marketing approaches with consideration of logistical, pricing, and cultural aspects, which allowed the proposal of a more holistic export development strategy.

An important part of the work was also the development of practical recommendations for improving marketing strategies for agricultural exports. The developed recommendations were based on the interregional comparative analysis carried out, which made it possible to identify the most effective approaches and adapt these approaches to the specifics of various target markets. In particular, strategies were proposed that took into account key barriers faced by exporters, including logistical constraints, price competition, and differences in consumer preferences. Special attention was paid to the development of flexible strategies for entering foreign markets, which included the diversification of export destinations, improvement of product quality, and the use of modern promotion tools. The results of the research also showed that successful marketing strategies had to consider not only economic and regulatory conditions, but also sociocultural factors that influenced consumer behaviour. In this regard, recommendations were made for adapting advertising campaigns, developing packaging, and positioning products in accordance with the local characteristics of target markets. Thus, the conducted research had practical significance, as the conclusions and recommendations obtained could be used as a basis for developing effective export strategies. This contributed to increasing the competitiveness of the agricultural sector at the global level, as well as improving the position of Kazakhstani producers in international markets. In the work by N.M. Abdullahi *et al.* (2022), an analysis of the factors influencing the choice of agricultural export strategies was carried out, which made it possible to identify the effectiveness of the strategic export development model, but in this work, the issue of adapting marketing strategies to changing external economic conditions and regional specifics was not examined in detail, which limited its practical application. In the study by T. Andrei *et al.* (2022), the competitive advantages of agricultural products in international trade were studied, paying special attention to the factors increasing the attractiveness of products in foreign markets, but without sufficient analysis of the impact of consumer preferences and cultural factors, which could improve the accuracy of developed strategies. In the study by R. Birner *et al.* (2021), trends in the development of the agro-industrial sector were examined, analysing the impact of global changes such as technological innovations, but without a detailed analysis of marketing tools and product promotion methods, which reduced its applied value. It should be noted that, unlike the mentioned studies focused on analysing existing trends, this work also presented specific recommendations for increasing the competitiveness of Kazakhstan's agricultural exports, which made its results more significant for practical use and further research in this field.

Thus, the conducted research, as well as the mentioned works, confirmed the importance of a comprehensive analysis of marketing strategies for agricultural exports to increase the competitiveness of producers in the global market. These studies made it possible to identify successful approaches and adapt these approaches to various economic and sociocultural conditions, as well as to consider key barriers affecting the effectiveness of foreign economic activity. The development of substantiated recommendations based on comparative analysis contributed to optimising export strategies, taking into account various conditions. Such studies also played an important role in shaping long-term solutions aimed at the sustainable development of the agricultural sector, stimulating innovation, and expanding opportunities for international cooperation.

CONCLUSIONS

As a result of this research, a comprehensive analysis of the current state of Kazakhstan's agricultural exports was carried out, with a focus on marketing strategies aimed at expanding the presence of Kazakhstani agricultural products in global markets. The study considered the characteristics of the country's agricultural sector, including its contribution to GDP, which in 2024 was estimated at 4.5%, as well as the significance of exports of key goods such as wheat (6.5 million tonnes in 2023), oilseeds, meat, and dairy products, which formed the basis of export potential. An important aspect of the work was the assessment of global trends in the agricultural sector, such as the growing demand for organic and environmentally friendly products, and the increasing requirements for product quality and safety. These trends required Kazakhstan to adapt and improve product quality, as well as to enhance compliance with international standards. The study examined marketing specifics in different markets, identified specific consumer requirements, and outlined approaches to packaging, certification, and communication with markets in various regions. The research showed that successful strategies required deep adaptation to the needs of local markets, including consideration of cultural differences and specific consumer demand. In addition, the impact of foreign economic policy, including participation in the Eurasian Economic Union, showed a 100% increase in trade with partners since 2015. However, it was noted that logistical costs (USD 80-100 per tonne of wheat) remained a challenge compared to competitors such as Australia (USD 40-55 per tonne). Based on this data, recommendations were proposed, including the development of flexible marketing strategies for different regions, strengthening branding through participation in international exhibitions, improving infrastructure, and developing partnerships with distributors. These steps, supported by digitalisation and investment in transit corridors such as the "Belt and Road Initiative", were intended to increase the recognition and competitiveness of Kazakhstani agricultural products in international markets.

It should be noted that this study had some limitations due to its focus mainly on current marketing strategies without detailed analysis of the long-term effectiveness and impact on the sustainability of agricultural exports. Promising areas for further research included a more in-depth analysis of the effectiveness of different marketing strategies, taking into account the specifics of individual product groups and regions, as well as studying the impact of geopolitical and macroeconomic factors on agricultural exports. Another important step would be the practical testing and adaptation of the developed recommendations in real conditions, which would make it possible to assess the effectiveness and identify additional opportunities for optimising export policy.

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Маркетингові стратегії розвитку аграрного експорту Казахстану на світових ринках: міжрегіональний порівняльний аналіз

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Анотація. Дане дослідження спрямоване на аналіз маркетингових стратегій аграрного експорту та виявлення ефективних підходів до його просування на світових ринках. Під час роботи було використано методи порівняльного аналізу маркетингових стратегій провідних країн-експортерів, дослідження офіційних статистичних даних, оцінку впливу міжнародних торговельних угод і стандартів, а також аналіз державних програм підтримки експорту. Результати дослідження виявили ключові особливості маркетингових підходів у різних регіонах та їхню застосовність до казахстанського ринку, де експорт пшениці 2023 року становив 6,5 млн тон, або 3,13 % від світового обсягу в 208 млн тон. Було вивчено успішні моделі експорту агропродукції таких країн, як США (19,8 млн тон пшениці 2023 року), Канада (22 млн тон) та Австралія (24,5 млн тон), що дало змогу виокремити найрезультативніші інструменти просування, включно з брендингом та адаптацією до стандартів ринків збуту. Аналіз показав, що для підвищення конкурентоспроможності казахстанської продукції потрібна адаптація стратегій до вимог конкретних регіонів, врахування споживчих переваг і вдосконалення сертифікації під міжнародні норми. Було зазначено, що участь Казахстану в Євразійському економічному союзі сприяла зростанню взаємної торгівлі вдвічі з 2015 року. Також важливим фактором було відзначено розвиток державних програм підтримки експорту, які також потребують посилення: фінансова та консультаційна допомога експортерам, модернізація логістики (де витрати на перевезення пшениці становлять USD 80-100 за тонну проти USD 50-60 у конкурентів) і цифровізація процесів залишаються пріоритетами. На основі отриманих даних було розроблено рекомендації щодо вдосконалення маркетингових стратегій Казахстану у сфері аграрного експорту, які спрямовані на оптимізацію логістики, розвиток партнерських відносин з міжнародними дистриб'юторами, підвищення впізнаваності бренду та активне використання цифрових технологій для просування продукції

Ключові слова: міжнародні стандарти; брендинг агропродукції; споживчий попит; логістична інфраструктура; державна підтримка; цифрові платформи; культурні особливості

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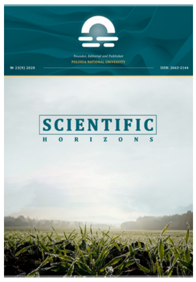

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Analysis of innovation potential of regional agroclusters

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Abstract. The study analysed the key resources and conditions affecting the development of innovation activities in regional agroclusters. The study conducted a comprehensive analysis of the innovation potential of agroclusters, including the assessment of key factors such as human resources, research base, financial support, and technological infrastructure, using SWOT-analysis, index method and experts. The analysis revealed that the level of innovation potential of regional agroclusters was determined by the degree of interaction between enterprises, scientific institutions, and government structures. Funding of agro-industrial cluster in Kazakhstan was USD 2.5 bn, of which

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USD 0.8 bn was allocated for innovation, while in the Netherlands, USA (California and Iowa) these indicators were much greater, reaching USD 10-15 bn with innovation costs within USD 2.8-6.5 bn. For example, in Kazakhstan, a stable growth of agro-industrial complex by 3.6% per year has been observed since 2010, which contributed to an increase in labour productivity to USD 6.6 thsd per person – 30% greater than the indicators of Ukrainian farmers. The study found that the availability of specialised infrastructure (agrotechnoparks, technology transfer centres) contributed to accelerated innovation. The study also confirmed that the key barriers to innovative development of agroclusters included insufficient research and development funding, lack of qualified personnel, and weak cooperation between participants. For instance, the use of precision farming and artificial intelligence technologies can increase crop yields by 20% and reduce water use by 30%. In regions with active state support and access to investment, such as Kazakhstan, an increase in the number of start-ups and venture capital investments was observed. Based on the analysis, recommendations for developing the innovation potential of agroclusters were proposed, including the creation of incentive support measures, the development of educational programmes, and the introduction of digital platforms for technology exchange. The findings obtained can be used to develop strategies to support and stimulate innovation activity in regional agroclusters, which contributes to improving their competitiveness and efficiency

Keywords: digitalisation; state support; cooperation; investment; technology; infrastructure

INTRODUCTION

In the context of globalisation and rapid technological advancement, agriculture faces new challenges that require finding effective solutions to improve the productivity and sustainability of the agricultural sector. In this regard, regional agroclusters are becoming crucial centres of innovative development, bringing together the efforts of agricultural producers, scientific institutions, technological and educational organisations. They play a key role in the introduction of modern technologies such as digitalisation, agrotechnologies, and biotechnologies, contributing to the competitiveness of the agro-industrial complex. Analysing the innovation potential of regional agroclusters allows identifying the strengths and weaknesses of existing models, as well as determining the factors affecting the success of their development. A prominent aspect is the integration of scientific research and technology into real production processes, which requires close interaction between multiple cluster participants. A systematic approach to assessing the innovation activity of agroclusters opens opportunities for the creation of effective development strategies, improvement of the investment climate, and stimulation of sustainable growth of agrarian regions.

The problem of assessing the innovation potential of regional agroclusters lies in the need for a comprehensive approach that would include analysing the interaction of participants, infrastructure development, and the introduction of new technologies. K. Sharma and S.K. Shivandu (2024) focused on the value of digitalisation in agro-production, stressing that technologies such as Internet of Things (IoT) and Artificial Intelligence (AI) enabled marked improvements in agricultural productivity and competitiveness. The researchers also argued that digital transformation was a key factor for successful development of agroclusters in the face of global change. V. Agarwal *et al.* (2023) investigated the role of public-private partnerships in the agricultural sector, emphasising that government support helped to stimulate the adoption of the latest technologies and innovative solutions. Their study showed how tax incentives and subsidies could be effective tools to attract investment in the agro-industry. M. Aydoğan *et al.* (2021) stressed the significance of cooperation between scientific institutions and agricultural producers, emphasising that such integration contributed to accelerated innovation and development of innovative technologies. The researchers believed that successful examples of collaboration considerably improved the production performance of agroclusters. L. Bjerke and S. Johansson (2022) investigated the relationship between human resource quality and the innovation capacity of agroclusters, arguing that the training of skilled agricultural professionals was a crucial element for the adoption of the latest technologies. Their study emphasised the need for a close link between educational institutions and agro-producers to build talent pools.

D. Akkaya *et al.* (2020) analysed the influence of government policies on the innovative development of the agribusiness sector, focusing on the significance of subsidies and tax incentives to create favourable conditions for business. The researchers also emphasised that such measures stimulated entrepreneurial activity and ensured the inflow of investments into the agro-industry. E. Mugoni *et al.* (2023) examined the value of logistics and marketing in the success of agroclusters, noting that efficient transport and marketing systems for agricultural products played a key role in the development of the industry. The researchers argued that without an established infrastructure, innovation in the agribusiness sector could not fulfil its full potential. M. Yazdani *et al.* (2021) investigated the risks associated with the adoption of the latest technologies in agribusiness and highlighted the significance of developing risk management strategies to minimise potential losses. The researchers emphasised that effective risk diagnosis and forecasting helped to increase the resilience of agroclusters to external and internal threats.

C.-I. Coman *et al.* (2024) investigated the prospects of adopting environmentally sustainable agro-technologies, emphasising their value for the long-term development of agroclusters. The study also analysed the effects of clusters in managing technological challenges and achieving sustainability of agri-food systems globally, highlighting the significance of cluster structure in addressing the world's environmental and economic challenges. G.A.B. Aggrey *et al.* (2022) addressed the need for SMEs to integrate into innovation processes, which they found to improve the growth dynamics of agroclusters. Their study emphasised that such enterprises could play a key role in the adoption of innovative technologies, providing flexibility and adaptability to the agribusiness sector. Despite significant contributions to the study of the problem, there is a series of gaps that require further investigation. Specifically, insufficient attention has been paid to a comprehensive analysis of the factors affecting the sustainability of innovation potential of agroclusters under conditions of market uncertainty and variability. Further research is required on the models of interaction between large and small enterprises within agroclusters, as well as the development of recommendations for optimising state support mechanisms at the regional level.

The purpose of the present study was to identify the factors that determine the innovation potential of agroclusters, as well as to analyse the existing methods of assessment and ways to develop this potential.

MATERIALS AND METHODS

The study comprehensively analysed the innovation potential of agroclusters, covering both theoretical foundations and practical methods of assessment. An essential task was to identify the key factors affecting the innovative development of agroclusters, as well as to highlight the best practices and successful examples of agrarian regions where innovative technologies are actively implemented. Within the theoretical framework of the study, the key components comprising the innovation potential of an agrocluster were considered. One of the key factors was the availability of human resources, including qualified specialists, level of education in the field of agrarian technologies, and competences in the field of entrepreneurship. The research base, including universities and agrarian institutes, also played a major role by ensuring that the latest technologies were tested in real-life conditions through experimental farms. Furthermore, attention was paid to financial support, including government subsidies and private investment as a catalyst for the implementation of innovative solutions.

The next stage of the study concerned the methodology for assessing the innovation potential of agroclusters. For this, various methods were employed, including SWOT analysis, which helped to identify the strengths and weaknesses of the agrocluster, as well as to assess opportunities and threats to its development. This analysis considered indicators such as gross regional product (GRP), farm profitability, and employment growth. SWOT analysis was used to identify the strengths, weaknesses, opportunities, and threats associated with innovation in the agricultural sector. This enabled the development of strategies to improve the economic performance of the region based on the data (Mastac & Vancea, 2024). The index method helped to quantify the level of innovation activity, through the number of patents and the degree of digitalisation. To comprehensively assess the innovation potential of agricultural clusters, an integral innovation index was constructed. This index included several separate indices: financial (share of investment in innovation, % of GRP), infrastructural (number of technoparks and technology transfer centres), human resources (share of STEM personnel), and digital (number of digital solutions per 100 agrarian enterprises) based on the data (Musayeva, 2024). This method was aimed at a systematic assessment of the state of innovation infrastructure and human resource potential in the agricultural sector. For this, the formula for calculating the integral innovation index of agrocluster was used (Equation 1):

$$I_{agrocluster} = w_1 \times I_{financial} + w_2 \times \\ \times I_{infrastructural} + w_3 \times I_{personnel} + w_4 \times I_{digital}, \quad (1)$$

where w_1, w_2, w_3, w_4 are weights assigned to each of the indices. These weights reflect the relative significance of each index to overall innovation activity. For example, if infrastructure is more significant than the human resources index, the infrastructure index may be given a higher weighting. $I_{financial}$ is the index reflecting the share of investment in innovation in the agricultural sector. $I_{infrastructural}$ is the index reflecting the level of development of infrastructure for innovation, such as technoparks or technology transfer centres. $I_{personnel}$ is the index reflecting the share of highly qualified personnel (e.g., STEM personnel) in the agricultural sector. $I_{digital}$ is the index reflecting the degree of digitalisation of the agricultural sector (e.g., number of digital solutions per 100 agricultural enterprises).

The cost-effectiveness method was employed to assess the feasibility of introducing innovative solutions such as digitalisation and agrodrones. It consisted of comparing the costs of implementing these technologies with the resulting economic benefits, such as increased yields, reduced losses, and increased value added. The method was employed to understand how effective investments in innovations can be in terms of their economic and financial returns based on the data

(Taishykov *et al.,* 2023). One of the key aspects of the study was to identify the factors influencing the innovation potential of agroclusters. Geographical location and climatic conditions, as well as the availability of natural resources, played a prominent role in determining the potential for the adoption of innovative technologies. The specifics of agriculture in each region required an individual approach to the use of technologies. Furthermore, the level of cooperation between cluster members, including partnerships between producers, research institutions, and processing enterprises, was a significant factor. Government support and infrastructure support, such as the availability of logistics centres and digital platforms, played a crucial role in the successful implementation of innovative projects.

The study also included examples of successful agroclusters with high innovation potential, such as the Kazakhstan agrocluster (Ryskeldi *et al.,* 2024), the Dutch agrocluster Foodvalley (n.d.), and the US (California) agroclusters (Love, 2024) and IOWA (2023). These examples demonstrated how the introduction of precision farming technologies, agricultural automation, and the use of biotechnology can considerably improve the productivity and sustainability of agricultural production. Kazakhstan has actively developed its agribusiness sector through digitalisation and innovative approaches, including the use of IoT and drones. In the Netherlands, pronounced levels of automation and sustainable agriculture served as an example of how innovation can reduce costs and improve sustainability. Agroclusters in the US have also used biotechnology and artificial intelligence to predict crop yields, enabling optimisation of agricultural processes.

RESULTS

The innovation potential of agroclusters is a set of factors and conditions that determine the ability of agrarian associations to introduce innovative technologies, improve agricultural efficiency, and adapt to changing conditions. Modern agriculture, facing the challenges of climate change, growing demands for food security, and global competition, requires active use of innovations. A prominent aspect in this process is to identify and analyse the key components that determine the innovation potential of agroclusters. These include human resources, research and development base, financial support, technological infrastructure, and institutional environment. The introduction of innovations in the agro-industrial complex (AIC) positively affects labour productivity and the share of gross regional product associated with this sector. For example, Kazakhstan experienced steady growth in agribusiness at 3.6% per annum since 2010, which contributed to an increase in labour productivity to USD 6.6 thsd per person – 30% greater than the performance of Ukrainian farmers. Analogous trends are observed in other regions, where a high innovation index correlates with higher labour productivity and increased contribution of agribusiness to the economy. These data emphasise the value of innovation for the sustainable development of the agricultural sector and the economy overall (Kazakhstan and Ukraine, n.d.).

The key component of the innovation potential of an agrocluster is the availability of qualified specialists who can develop, adapt, and implement the latest technologies in agrarian production. The level of education in the field of agrarian and innovative technologies plays a key role in the training of personnel capable of meeting the challenges faced by agroclusters. Specialists with a prominent level of education, including engineers, agronomists, biotechnologists, and information technology (IT) specialists, are needed to develop and implement innovative solutions such as precision farming systems, biotechnology, and process automation. Furthermore, competences in the field of innovative entrepreneurship are significant, which allow effectively transforming scientific developments into successful commercial projects. The availability of such specialists facilitates the creation of innovative start-ups, improvement of business processes, and implementation of advanced technologies.

The research base, which includes universities, agricultural research institutes and experimental farms, represents the basis for the development of innovative technologies and solutions. Universities and research institutions play a key role in training and research to address agricultural challenges such as increasing yields, improving product quality and climate resilience. Experimental farms, as a vital part of the research infrastructure, allow testing the latest technologies and putting them into practice. These farms form the link between scientific development and industrial implementation, where research results directly affect the efficiency of agricultural production. Assessment of the payback of innovative solutions is a key tool for analysing the effectiveness of investments in innovative technologies in agriculture. For example, the introduction of digital farm management systems such as AGRIVI enables farmers to increase profitability by 50-100% as early as in the first two years of use. Additionally, the use of precision farming and artificial intelligence technologies can increase crop yields by 20% while reducing water use by 30%. These examples demonstrate that investments in digital technologies not only pay for themselves in a short time but also contribute to major improvements in the efficiency and sustainability of agricultural production (Zulj, n.d.).

One of the crucial factors determining the innovation potential of agroclusters is financial support. The development of innovation in agro-production requires extensive investment from both the government and private investors. Government subsidies, grants, and programmes to support innovative projects are an incentive for the introduction of innovative technologies and improvement of production processes. Private and venture capital investments also play a valuable role in stimulating innovation activity. Agricultural technology-focused companies and funds help finance start-ups and projects aimed at introducing innovations such as new biotechnologies, production automation, and improving agricultural resilience to environmental changes. Technology infrastructure is the set of facilities and services needed to implement and disseminate innovations. Agrotechnoparks and technology transfer centres are the basis for creating, testing, and implementing the latest agricultural solutions. These infrastructural elements provide access to high-tech equipment, resources for the development of innovative technologies and opportunities for the exchange of knowledge and experience between scientists, entrepreneurs, and producers. The development of digital platforms for agribusiness also forms an integral part of the technological infrastructure. The digitalisation of agribusiness allows for better management of agricultural processes, improved resource efficiency, and the adoption of the latest technologies such as yield monitoring and forecasting systems, the use of drones, and satellite data to assess crop health.

The institutional environment includes the regulatory framework governing innovation in the agricultural sector, as well as programmes and initiatives to support and promote agro-innovation. Legal and institutional frameworks play a key role in creating favourable conditions for the adoption of innovative technologies and business models. Regulations governing intellectual property protection, subsidies, and tax support for innovative projects provide stability and predictability for participants in agroclusters. Government support programmes, such as research grants, subsidies for the introduction of the latest technologies or training programmes for specialists, are key tools to stimulate innovation in the agricultural sector. Furthermore, the integration of agroclusters into international networks and participation in international projects allow sharing experience and adopting best practices.

Overall, the innovation potential of agroclusters depends on many interrelated factors. Human resources, research and development base, financial support, technological infrastructure, and institutional environment create conditions for the development of innovations and increase the competitiveness of agricultural regions. The development of these components contributes to improving the quality of agricultural products, enhancing the sustainability of the agricultural sector, and addressing global challenges such as climate change and food security. Innovation plays a major role in increasing the profitability of agricultural enterprises. As the level of innovation increases, such enterprises become more efficient and competitive. The introduction of innovative technologies can considerably improve production processes, optimise resources, and increase product quality, which ultimately leads to higher profits. Companies that actively innovate often find new markets and ways to increase profitability, which allows them to compete in the face of globalisation and rapidly changing market conditions (Table 1).

***Table 1**. Profitability of agricultural enterprises depending on innovation potential*

Level of innovation activity	Profitability (%)
Low	5
Medium	12
High	20

***Source:** compiled by the authors of this study based on R. Kosfeld and T. Mitze (2023)*

Clustering also has a noticeable impact on the economic performance of regions. Regions with a prominent degree of clustering have greater growth in indicators such as exports, labour productivity, and wages. Clustering facilitates the exchange of expertise and technology between companies, increases access to innovation, and improves infrastructure. This leads to increased efficiency of the entire region, incentivising both small and large businesses. Moreover, the development of clusters helps to optimise processes and reduce costs, which improves the economic situation in the region (Table 2).

***Table 2**. Dynamics of exports, productivity, and wages in regions with varying clustering levels*

Level of clustering	Export growth (%)	Productivity growth (%)	Wage growth (%)
Low	3	4	2
Medium	10	12	8
High	18	25	15

***Source:** compiled by the authors of this study based on S. Andros et al. (2021)*

Assessment of the innovation potential of agroclusters plays a key role in designing strategies for their further development. This approach allows identifying both strengths and weaknesses of an agrocluster, as well as understanding what opportunities and threats may affect its ability to introduce innovative technologies. There are several techniques that can be used for a comprehensive assessment of the innovation potential of an agrocluster, among which the most popular are SWOT analysis, index method, expert questionnaire survey, and socio-economic analysis.

One of the most widespread assessment methods is SWOT-analysis, which enables a systematic assessment of internal and external factors affecting the innovation potential of an agrocluster. This analysis considers strengths and weaknesses, as well as opportunities and threats to innovation development. For instance, strengths may be the availability of highly qualified specialists and a developed research base, which contribute to the introduction of innovative technologies. Weaknesses may include a lack of financial resources or outdated infrastructure. Opportunities for growth may be related to the development of new markets or the introduction of environmentally sustainable solutions, while threats may include economic instability or fierce competition from other regions. A SWOT analysis identifies areas for improvement and optimisation of the cluster's innovation activities (Arion *et al.,* 2023). SWOT analysis by economic indicators, such as GRP, household income, and employment growth, allows identifying key factors that influence the development of a region or industry (Table 3).

***Table 3**. SWOT analysis for economic indicators*

Strengths	Weaknesses
High level of investment in key sectors (positive impact on GRP)	Low farm profitability, limited access to finance
Growing digitalisation index, which contributes to improved productivity	Lack of highly qualified personnel, which limits innovation processes
Increased cooperation between enterprises, leading to increased employment	Low diversification of the economy, dependence on several industries
Stimulating small and medium-sized businesses, increasing the number of jobs	Infrastructure problems hampering the development of some industries
Opportunities	**Threats**
Development of innovative technological and scientific solutions that can increase farm profitability	Economic instability, possible external shocks that may reduce GRP
Attraction of foreign investment in innovative industries	Obsolescence of production facilities and lack of technological upgrades
Improvement of the education and training system to raise the skills of the workforce	Decrease in employment due to automation and digitalisation of processes
Increased cooperation between regions, which contributes to economic growth	Shortage of natural resources, which may complicate further growth of the economy in the long term

***Source:** compiled by the authors of this study based on L. Mastac and D.P.C. Vancea (2024)*

The strengths include the pronounced level of investment in key sectors, which positively influences GRP growth and economic development in the region. A significant contribution to the improvement of economic performance is also made by the growth of the digitalisation index, which increases labour productivity and reduces costs, leading to increased farm profitability. A prominent factor is cooperation between enterprises, which contributes to employment growth and improved economic sustainability. Furthermore, the stimulation of SMEs creates new jobs, which also contributes to employment growth. However, there is a series of weaknesses. For example, the low profitability of farms caused by underfunding or the use of obsolete technologies limits their potential and does not contribute to GRP growth. Lack of highly skilled labour constrains innovative development, while infrastructure problems hinder the development of certain industries, slowing overall economic growth. Some regions also have poorly diversified economies, making them vulnerable to external shocks.

At the same time, there are opportunities that can contribute to improving the situation. The development of innovative technological solutions and scientific advancement can markedly increase the profitability of farms and make a valuable contribution to GRP growth. Attracting foreign investment in innovative sectors will modernise production, create additional jobs, and accelerate economic growth. Improvement of the education and training system also helps to improve the skills of the labour force, which will positively influence labour productivity and economic activity. However, threats such as economic instability or global crises may arise in the long term, which could negatively affect investment and GRP growth. Furthermore, automation and digitalisation of processes, despite their positive effects on efficiency, may lead to a decrease in employment, especially in conventional industries. There may also be a shortage of natural resources, which will limit further economic development, especially in sectors that are highly dependent on them. This SWOT analysis helps to understand which aspects need attention and which factors may have the greatest impact on the economic development of the region.

Another significant tool is the index method, which involves the use of quantitative indicators to assess the level of innovation activity of an agrocluster. Among these indicators can be the number of patents and technologies, the degree of digitalisation, the amount of investment in research and development. For instance, a great number of patents may indicate a robust level of R&D activity, while the adoption of digital technologies such as precision farming systems may indicate a strong level of technological maturity. The index method collects data on the current state of innovation and systematises it for further analysis (Bernard *et al.,* 2023). To build an integral innovation index of Kazakhstan's agrocluster, it is necessary to collect data on key indicators such as the share of investment in innovation, the number of technology parks and technology transfer centres, the share of STEM personnel in the agricultural sector, and the number of digital solutions per 100 agrarian enterprises. Each of these indices should be standardised, bringing the values to a common scale from 0 to 1 so that they can be compared and integrated into an overall indicator.

Data for Kazakhstan can be used as an example (Musayeva, 2024). For instance, the share of investment in innovation was 1.5% of GRP, which with a maximum value of 5% gives a standardised value of 0.30. The number of technoparks in Kazakhstan is 4, with a maximum of 10 technoparks, this gives a value of 0.40. The share of STEM personnel in the agricultural sector is 12%, which at a maximum of 30% also gives an index of 0.40. Finally, the number of digital solutions per 100 agricultural enterprises is 25, which with a maximum of 50 solutions gives an index of 0.50. Once all the indices are standardised, it is possible to assign them weights that reflect their significance for innovation activity. In this example, all indices have the same weighting of 0.25. Based on these data, the integral innovation index of the agrocluster is calculated as follows:

$$I_{\text{agrocluster}} = 0.25 \times 0.30 + 0.25 \times 0.40 + \\ + 0.25 \times 0.40 + 0.25 \times 0.50 = 0.40.$$

This means that innovation activity in Kazakhstan's agricultural sector is at an average level, with potential for improvement in the areas of investment, human resources, and digitalisation. Thus, the integral innovation index allows assessing the current level of innovation activity in the agricultural sector of Kazakhstan and identify key areas for further development. The Cost-Effectiveness Analysis (CEA) method is employed to assess the costs of implementing innovative solutions and their corresponding economic benefits. This method compares the costs of technologies such as digitalisation or agrodrones with the results they bring, e.g., in the form of increased yields, reduced losses, or increased value added. The essence of the method is to assess how effective a particular technology investment is in terms of the economic results obtained. This allows agricultural enterprises to make informed decisions on the feasibility of implementing certain innovations based on the cost-benefit ratio (Table 4).

Table 4 *. Costs and economic benefits of implementing innovative solutions in the agricultural sector of Kazakhstan*

Technology	Implementation costs (KZT mn)	Yield growth (%)	Reduction of losses (%)	Increase in value added (%)	Economic benefit (KZT mn)
Digitalisation of processes	10	15%	10%	12%	12
Agrodrones for monitoring	5	10%	5%	8%	6
Precision farming systems	7.5	20%	15%	18%	15

Source: *compiled by the authors of this study based on Z. Taishykov et al. (2023)*

Each technology requires varying implementation costs but brings its own economic benefits. For example, digitalisation of processes requires an investment of KZT 10 mn, while it can increase yields by 15%, reduce losses by 10% and increase value added by 12%, which in total brings benefits of KZT 12 mn. Agrodrones require less cost (KZT 5 mn) and produce lesser results, but they also positively influence the growth of yields and reduction of losses. Precision farming systems, albeit requiring greater costs (KZT 7.5 mn), provide the greatest economic benefits, including a 20% increase in yields, 15% reduction in losses, and 18% increase in value added, giving an economic benefit of KZT 15 mn. Thus, the cost-effectiveness method enables a comprehensive assessment of the economic feasibility of introducing innovative solutions in the agricultural sector, providing information on which technologies will provide the greatest return on investment. Expert questionnaire survey is a method in which the opinions of agrocluster participants such as farmers, representatives of scientific institutions, and entrepreneurs are collected. This method helps to obtain qualitative information on the perception of innovation within the cluster, as well as to identify barriers and obstacles that may hinder the introduction of innovative technologies. The survey questions can be related to the level of innovation readiness, assessment of the need for innovative technologies, as well as problems of interaction between different cluster members. The data obtained offers a better insight into the internal problems and needs of the agrocluster, which helps to develop adequate measures to stimulate innovative development (Trushkina & Dzwigol, 2024).

Socio-economic analysis is also significant to assess the level of investment in R&D activities and the agrocluster's involvement in global supply chains. This method helps to understand how integrated the agrocluster is in the international economy and what resources it uses for its development. Significant indicators here are the amount of investment in R&D, which directly affects the cluster's ability to develop and implement the latest technologies, and the extent to which the cluster is involved in global supply and knowledge sharing networks. An elevated level of integration of an agrocluster into international processes indicates its competitiveness and ability to adapt to changing global market conditions (Duy & Huong, 2024). Thus, the methodology for assessing the innovation potential of agroclusters includes several complementary approaches, each of which provides a better understanding of the current opportunities and constraints for innovation development in the agricultural sector. The use of SWOT-analysis, index method, expert assessments, and socio-economic analysis helps to form a comprehensive picture and develop a strategy aimed at increasing innovation activity and competitiveness of the agrocluster. These methods together allow not only understanding the current level of innovation potential, but also identifying ways to improve it, which contributes to more effective development of the agricultural sector overall.

The innovation potential of agroclusters depends on a variety of factors that can both favour their development and limit the opportunities for the introduction of innovative technologies. These factors include geographical location, climatic conditions, the level of cooperation between cluster members, government support, and infrastructure provision. Geographical location and climatic conditions play a vital role in determining the opportunities for agricultural development and, consequently, innovation in agro-production. The availability of natural resources such as water, land, minerals, and climatic conditions directly influence the choice of agricultural products that can be successfully grown in a particular region. For instance, for northern regions with short growing seasons, innovations in greenhouses, agrotechnics, and crop protection are particularly valuable to maximise the use of limited resources. Whereas for southern regions, where the climate favours a longer growing season for a variety of crops, special attention can be given to drought tolerance, innovative irrigation methods, and high-yielding varieties. Thus, geographical location and climatic conditions not only determine the specificity of agriculture but also dictate areas for the introduction of innovative technologies aimed at overcoming the specific challenges of the region (Yuan *et al.,* 2024).

Regions with developed cluster infrastructure demonstrate significantly higher rates of investment attraction. For instance, in Central and Eastern Europe (CEE), around 1,000 startups from more than 110 cities attracted a combined EUR 2.1 bn of investment in 2023, indicating high investment activity in these regions. Specifically, countries such as Poland, Ukraine, and Estonia contributed significantly to the total investment volume, with EUR 49 bn, EUR 28 bn, and EUR 28 bn, respectively. Furthermore, in Central Asia and the South Caucasus, including Kazakhstan, Uzbekistan, and Armenia, venture capital funding has grown 5.5-fold over the past five years, reaching USD 110 mn in 2023, and the number of start-ups has increased six-fold to 6,000. This data emphasises that regions with developed cluster infrastructure not only attract extensive amounts of venture capital but also contribute to the growth of the number of start-ups and their investment attractiveness (Over 1,000 startups..., 2024). The level of cooperation between cluster members also markedly affects the innovation potential of agroclusters. The existence of active partnerships between the different actors – producers, research institutions, processors, and technology companies – facilitates faster innovation. When farmers, researchers, and entrepreneurs work in close cooperation, it allows not only to share knowledge and experience, but also to jointly develop innovative technologies, solve practical problems, and reduce the risks associated with the introduction of new solutions. For example, close cooperation with scientific institutions can lead to the development of new plant varieties resistant to diseases and adverse conditions, while cooperation with processing companies can optimise supply chains and improve the quality of end products. It is essential that collaboration and trust mechanisms exist in an agrocluster to enable participants to share information and resources effectively, and to ensure successful innovation at all levels of the production process (Wardhana *et al.,* 2021).

Government support and policies are key factors that stimulate innovation activity in agroclusters. Subsidy programmes and grant support for innovation projects in the agribusiness sector play a leading role in financing research, developing innovative technologies, and bringing innovations into production. In countries with active state support for the agricultural sector, innovations are often implemented much faster, as farmers and entrepreneurs have access to the necessary finance to implement innovative solutions. Technology subsidies, tax incentive programmes for innovative enterprises, and research grants help to attract investment and stimulate innovation. Additionally, public policies can include an enabling environment for the adoption of digital technologies, biotechnology, and cleaner production methods, which also positively influence the innovation potential of agroclusters (Sarma *et al.,* 2022).

Investment in digital technologies considerably affects economic growth, especially in agriculture. For example, studies suggest that the development of digital agriculture positively affects the green total factor productivity (GTFP). One study found that as digital financial services increased by 1 percentage point, GTFP productivity increased by 0.0866 percentage points. Analogously, a one unit increase in the digital economy improved rural export competitiveness by 1.596

units. These findings confirm the existence of a multiplier effect of digital investment leading to pronounced economic growth in the agricultural sector (Zhou *et al.,* 2023). Infrastructural support forms an integral part of the innovation potential of agroclusters. The availability of logistics centres, digital platforms, laboratories, and agrotechnoparks can markedly improve the efficiency of innovation processes in the agribusiness sector. Logistics centres that ensure fast and efficient transport of products help to reduce costs and expedite the process of bringing new products to market. Digital platforms that enable data exchange between agribusiness participants optimise agricultural production management processes, improve yield forecasting, and increase the accuracy of agronomic calculations. Agrotechnological parks and laboratories play a key role in the development and testing of the latest technologies, providing access to the necessary equipment and professional specialists. All these infrastructure elements create conditions for effective innovation, provide support for start-ups and new agro-projects, and help create synergies between academia and industry (Bahodirjon & Hafizaxon, 2021).

The innovation potential of agroclusters depends on many interrelated factors. Geographical location and climatic conditions determine the specifics of agrarian production, the level of cooperation between cluster members promotes knowledge sharing and accelerated technology adoption, while government support and infrastructure provision create favourable conditions for innovative development. The integrated development of these factors is the key to the successful functioning of agroclusters and their ability to introduce innovations, increase productivity, and adapt to changes in the conditions of modern agribusiness. Agroclusters with strong innovation potential play a crucial role in the development of agriculture, introduction of innovative technologies, and increasing the sustainability of agro-production. Examples of such clusters can be found in different parts of the world, where innovations are actively implemented to improve the efficiency, sustainability, and competitiveness of agricultural regions (Table 5).

***Table 5**. Level of financing, innovation costs, and technology adoption in successful agroclusters*

Agrocluster	Level of financing (USD bn)	Innovation costs (USD bn)	Technology adoption (%)
Kazakhstan agro-industrial cluster	2.5	0.8	60%
Foodvalley (the Netherlands)	10	4.2	85%
California agrocluster (USA)	15	6.5	90%
Iowa agrocluster (USA)	7	2.8	75%

Source: *compiled by the authors of this study based on A. Tkacheva et al. (2024)*

Kazakhstan's agro-industrial cluster is one of the examples of successful implementation of innovative technologies in agriculture. In recent years, Kazakhstan has been actively developing its agro-industrial complex, emphasising the introduction of precision farming technologies and digital solutions. In 2023, investments in agro-technologies totalled USD 2.5 bn, and the level of implementation of digital solutions reached 60%. One of the key areas of focus is the use of IoT to monitor crop health, control soil moisture, and determine the best timing for agronomic interventions. Currently, over 1,200 farms across the country are using IoT sensors to monitor soil microclimate. Drones are used for aerial photography and plant health monitoring, allowing farmers to react quickly to changes and make prompt decisions to improve crop yields. Kazakhstan has more than 500 agricultural enterprises using advanced digital technologies, including automated irrigation systems, AI-based crop forecasting, and cloud-based farm management platforms. Kazakhstan is also actively investing in innovative technologies to improve agricultural logistics, including warehouse automation and blockchain-based supply chain management systems. As a result, product losses at the storage and transport stages have decreased by 15%, and average yields on leading farms have increased by 20% (Ryskeldi *et al.,* 2024).

The specifics of agro-industrial complex development in different regions of Kazakhstan also play a significant role in the development of innovation potential (Table 6). For instance, North Kazakhstan Oblast is known for its grain production, where innovative methods are actively implemented to increase yields and improve grain quality. South Kazakhstan Oblast, specialising in cotton and vegetables, actively uses technologies to improve irrigation and minimise water losses. Almaty Oblast, with developed horticulture and livestock farming, is actively introducing modern technologies for herd management, as well as applying monitoring systems in greenhouses to improve fruit and vegetable yields. These specific regional features require distinctive approaches to technology implementation, which makes Kazakhstan one of the leaders in agrarian innovation in the post-Soviet space.

***Table 6**. Key agrarian specialisations and indicators of agricultural production in the regions of Kazakhstan*

Region	Primary specialisation	Major agrarian areas	Notes
North Kazakhstan Oblast	Grain production	Production of wheat, barley, maize, introduction of precision farming technologies, improvement of grain quality.	In 2023, the wheat harvest was 3.5 mn t, the average yield was 2.2 t/ha.
South Kazakhstan Oblast	Cotton and vegetable cultivation	Cotton growing, vegetable growing (tomatoes, cucumbers), improvement of irrigation system, application of the latest agro-technologies.	Cotton production – 60 thsd t/year; 250 thsd ha of irrigated land.
Almaty Oblast	Horticulture and animal husbandry	Horticulture (apples, grapes), development of dairy and beef cattle breeding, innovations in herd management and monitoring systems in greenhouses.	Apple harvest – 150 thsd t; cattle population – 1.2 mn heads.

***Source:** compiled by the authors of this study based on G. Alibekova et al. (2023)*

The Dutch agrocluster Foodvalley (n.d.) is an example of one of the most technologically advanced agricultural clusters in Europe. The Netherlands, being a world leader in agricultural technology, has created a unique agrocluster Foodvalley, which has become a centre for research and implementation of innovative solutions in the agricultural sector. In 2023, funding for innovative projects in this cluster totalled USD 10 bn, with the share of R&D expenditure reaching USD 4.2 bn. One of the key areas of focus in Foodvalley is the prominent level of automation in agricultural production, which includes the use of robotic systems for planting and harvesting, as well as automatic systems for controlling temperature and humidity in greenhouses. As a result, the level of automation in greenhouse farms has reached 85% and the average yield of tomatoes and cucumbers has increased by 40% compared to conventional methods. Importantly, up to 95% of all greenhouses in the Netherlands use closed-loop water recycling systems, which reduced freshwater consumption by 60%. The Netherlands is also focusing on sustainable agriculture, including developing environmentally friendly technologies, minimising the use of chemical fertilisers and pesticides, and applying innovative water management solutions. A prominent component of the agrocluster is innovative greenhouses that utilise LED lighting, vertical farming, and autonomous moisture control systems. These advances made the Netherlands a global example of sustainable and highly efficient agricultural production, with exports valued at EUR 120 bn per year, making the country the second largest exporter of agricultural products in the world after the US.

US agroclusters, such as those in California and Iowa, also demonstrate a prominent level of innovation potential. These regions are actively using biotechnology and artificial intelligence to solve agricultural production problems. In California, in 2023, the volume of investments in biotechnological developments totalled USD 15 bn, which allowed implementing 90% of automated agricultural solutions. Here, genetically modified crops resistant to disease, drought, and pests are widely used, which increased maize and soybean yields by 25% and reduced pesticide use by 40%. Automated farm machinery technology is also being actively developed here, including unmanned tractors, Global Positioning System (GPS) navigation, and machine vision for automated fruit and vegetable harvesting (Love, 2024). In Iowa, USD 7 bn was allocated for innovation, with AI adoption rates reaching 75%. AI is being used to predict crop yields, analyse soil and weather data, enabling a more accurate determination of the best timing for planting and harvesting. The adoption of these technologies resulted in a 20% reduction in agricultural production costs and a 35% increase in average farm yields (IOWA, 2023).

Furthermore, water-saving agriculture plays a significant role in the innovative development of US agroclusters: California has introduced intelligent drip irrigation systems that reduce water losses by 50%, while Iowa is actively using carbon-neutral farming technologies to reduce carbon dioxide emissions by 30% through the use of biochar fertilisers and crop rotation. Examples of agroclusters show how implementing innovative solutions in agriculture leads to greater yields, lower costs, reduced wastage, and increased environmental sustainability. The use of digital technology, artificial intelligence, robotic systems, and precision farming is achieving a highly competitive position in the global market. Importantly, the success of each of these clusters is driven by a systemic approach, government support, investment in R&D, and effective cooperation between academic institutions, businesses, and producers. These examples highlight the value of an integrated approach to the development of agricultural technologies and can become a basis for the development of effective agricultural modernisation strategies in other countries. To achieve sustainable growth and innovative development of agroclusters, it is necessary to take comprehensive measures aimed at creating a favourable environment for the introduction of innovative technologies and effective use of existing capabilities. In this context, several key recommendations can substantially contribute to increasing the innovation potential of agrarian regions.

Establishing agro-innovation centres is a major step towards introducing the latest agrarian technologies and accelerating knowledge transfer between scientific institutions, entrepreneurs, and farmers. These centres can become key platforms for testing and disseminating innovative solutions in agriculture, as well as for conducting research aimed at solving specific problems of the agricultural sector. They can include research laboratories, agro-technoparks, and educational institutions where advanced technologies are developed and implemented. Agro-innovation centres can also act as intermediaries between public and private investors, helping to find resources for start-ups and agricultural projects. Such an approach will accelerate innovation and improve the competitiveness of agro-production. State support for startups in the agribusiness sector is a prerequisite for stimulating innovation activity. In conditions where agrarian start-ups face financial and organisational difficulties, support from the state through subsidies, grants, and tax incentives can become a decisive factor for their successful functioning. Government programmes aimed at the development of startups will provide them with access to the necessary resources, help them overcome the initial stage, and reduce financial risks. Grant and subsidy programmes can range from developing innovative technologies to supporting environmentally friendly and sustainable agriculture. Tax incentives for such enterprises will favour their long-term development and attract investment. Thus, support for innovative start-ups will facilitate the creation of fresh solutions and increase competition in the agricultural sector.

The development of digital infrastructure, including IoT, Big Data, and AI technologies, is key to increasing the innovation potential of agroclusters. Agriculture, like many other industries, faces the need to optimise processes, improve accuracy, and reduce costs. The adoption of IoT technologies allows farmers to monitor crop health, soil moisture levels, air temperature, and other critical parameters in real time to help make informed decisions. The use of Big Data and AI can markedly improve yield forecasting processes, analyse soil health data, and predict risks associated with climate change or pests. The creation and development of digital platforms for agribusiness and the implementation of such technologies at all levels of production will help agroclusters to significantly increase their efficiency, reduce losses and improve product quality. Integration of educational programmes for training specialists in agro-innovation is another valuable recommendation for increasing the innovation capacity of agroclusters. In the context of rapid technological progress, agriculture needs highly qualified specialists who can effectively work with the latest technologies and adapt them to the specifics of the region. The development of educational programmes focused on agro-innovation should include courses on modern technologies in agriculture, biotechnology, sustainable development, and digital solutions. It is vital that educational institutions work in close cooperation with agribusiness, research centres, and government agencies, which will not only train specialists, but also introduce relevant knowledge and solutions into the learning process. Additionally, the development of advanced training and retraining programmes for existing specialists will help to improve the overall technological literacy of the agricultural sector and prepare it for the challenges of the future.

Thus, the recommendations on the creation of agro-innovation centres, state support for startups, development of digital infrastructure, and integration of educational programmes are aimed at creating a sustainable and innovative ecosystem in the agricultural sector. These measures will help accelerate the process of introducing the latest technologies, improve the knowledge and skills of agricultural workers, and make agroclusters more competitive in the international arena. In the face of global challenges such as climate change and a growing world population, these steps will play a crucial role in ensuring food security and sustainable development of the agricultural sector.

DISCUSSION

The analysis of the innovation potential of agroclusters revealed that the key factors determining the success of such clusters include the availability of qualified personnel, research base, financial support, as well as developed technological infrastructure. First of all, human resources play a fundamental role. In regions with highly developed agroclusters, such as the Netherlands or the USA, the level of education and competence of specialists in the field of agricultural and innovative technologies directly affects the implementation of new solutions. For instance, in the agrocluster Foodvalley, due to the strong level of education and close interaction between universities and scientific institutions, successful projects in the field of sustainable agriculture and automation are implemented.

C.-I. Coman and V. Cojanu (2024) also investigated this problem, with their findings confirming that the value of human resources and education for the innovative development of agroclusters lies in their ability to ensure the effective implementation of the latest technologies and management practices. Highly skilled professionals play a key role in developing and implementing innovative solutions that help to improve agricultural competitiveness. Education and training in agroclusters contribute to the development of professionals capable of integrating advanced knowledge and skills into practice, leading to increased productivity and sustainability of agricultural enterprises. S. Imanuella *et al.* (2025) also showed that the role of skilled labour and innovative entrepreneurship in agroclusters is intricately linked to the development of social entrepreneurship and rural support. Social entrepreneurship creates more employment opportunities and improves the quality of life in rural areas through the implementation of sustainable business models. Such initiatives help to attract investment and improve infrastructure, which supports the long-term development of agroclusters, increasing their social and economic significance.

Notably, successful innovative development of agroclusters requires not only a strong level of education and qualification of personnel, but also the creation of a favourable environment for innovation. This includes access to modern information technologies, as well as support from public and private investors. It is essential that specialists not only have theoretical knowledge, but also can apply it in practice, which is possible in close c-operation with agricultural enterprises, scientific institutions, and business (Ussenova *et al.*, 2023). The methodology for assessing the innovation potential of agroclusters was also analysed in detail. The findings showed that the use of SWOT-analysis allows identifying the strengths and weaknesses of the agrocluster, as well as possible threats and opportunities for further development. Innovation activity indices, such as the number of patents and the level of digitalisation, play an essential role in assessing the effectiveness of innovation processes. These methods allow identifying potential areas for improvement and directing efforts towards the most promising areas. Expert questionnaires and socio-economic analyses also showed the significance of involving all actors in the agrocluster, including farmers, research institutions, and processors, to obtain a comprehensive assessment of the situation.

O.I. Sayitkulovich *et al.* (2024) concluded that the methodology for assessing the organisational and economic efficiency of agroclusters includes an integrated approach combining various analytical tools. The use of expert surveys provides valuable information on the current state and needs of agroclusters, as well as identifying the primary problems and obstacles to their development. This method provides an opportunity to gain a deeper understanding of subjective factors that affect innovation processes and form an accurate picture of the potential and risks of agrarian enterprises. A. Foglia *et al.* (2021) found that socio-economic analysis is a significant element in assessing the innovation activity of agroclusters, as it reveals the relationship between the adoption of innovative technologies and social outcomes. This method allows assessing how innovation initiatives affect the improvement of living conditions of the population and the development of the region. Combining expert surveys with socio-economic data provides a more comprehensive picture of the influence of innovation projects on the economy and social sphere of the agrocluster, which contributes to more objective policy and management decisions. These results corroborate the conducted study as they demonstrate analogous findings on the significance of an integrated approach to assessing the performance of agroclusters. Expert surveys and socio-economic analyses identify not only current problems but also prospects for sustainable development of agribusinesses. These tools help to identify the factors affecting innovation processes more accurately and allow developing recommendations to improve the organisational and economic structure of agroclusters, which was confirmed by analogous studies in other regions.

Factors affecting the innovation potential of agroclusters were also considered in the context of geographical and climatic conditions. For instance, the North Kazakhstan region, known for its grain production, is characterised by specific climatic conditions that require the introduction of precision farming technologies to increase yields. At the same time, South Kazakhstan Oblast, which specialises in cotton and vegetables, needs technologies that optimise water and energy consumption. The influence of government support and policies also proved to be a decisive factor for the development of innovative solutions in agroclusters. In countries with developed agro-economies, such as the Netherlands, USA, and Kazakhstan, government programmes aimed at subsidising innovative projects and stimulating private investment are actively implemented (Malik *et al.*, 2024). A. Mukumov *et al.* (2021) also found that geographical and climatic conditions play a crucial role in the innovation potential of agroclusters, as they influence the choice of applied agricultural technologies and business practices. The specificity of the region determines the opportunities to adopt sustainable agronomic solutions such as drip irrigation, use of crop rotation, and adapted crops. In regions with unfavourable climatic conditions, innovative approaches become particularly significant to increase productivity and minimise the risks associated with climate change.

D.B. Olimjonovich and K. Jakhongir (2024) concluded that state support and cooperation of agrocluster participants serve as a basis for the development and implementation of innovative technologies in the agricultural sector. Effective interaction between government agencies, research institutions, and entrepreneurs contributes to the creation of a favourable innovation ecosystem, where the exchange of knowledge and resources helps to overcome technological barriers. A vital element in this process is support from the authorities, which stimulates the development of business activity in rural areas and promotes the implementation of the latest solutions aimed at improving the competitiveness of agroclusters (Khrystenko *et al.*, 2025). These findings are consistent with the theses presented in the previous section, as they confirm that geographical and climatic factors form an integral part of the innovation potential of agroclusters. The specific location and natural conditions influence the choice of appropriate technologies and strategies to optimise agricultural production (Shuvar *et al.*, 2022; Andreitsev *et al.*, 2024). Thus, the integration of modern solutions in the agricultural sphere is impossible without factoring in the specifics of the region, which is also reflected in the successful examples discussed in the previous section of this study.

Examples of successful agroclusters with prominent innovation potential, such as the Kazakhstan agro-industrial cluster, Foodvalley in the Netherlands, and agroclusters in the USA, demonstrated remarkable achievements in the implementation of innovative technologies. For example, in Kazakhstan, the application of precision farming technologies and the use of drones to monitor crops resulted in improved agricultural efficiency and reduced losses in storage and transport of produce. In the Netherlands, high levels of agricultural automation, including robotic harvesting systems and innovative greenhouses, resulted in high productivity and sustainable agro-production. These examples showed how the integration of innovative technologies can substantially improve the competitiveness and sustainability of agricultural sectors in different countries.

M.W. Sitnicki *et al.* (2024) confirmed that examples of successful agroclusters with high innovation potential demonstrate the value of strategically forming agrarian market clusters to achieve global competitive advantage. In agroclusters such as the one in Ukraine, there is a synergy between agricultural producers, research institutions, and government agencies, which facilitates the adoption of innovative technologies and increases overall productivity. These clusters actively utilise modern agro-technologies and allocate resources efficiently, making them role models in the international arena. M. Saidov and I. Ochilov (2023) also found that the sustainability of agroclusters becomes a key factor in their long-term development as it enables them to adapt to changing market conditions and environmental challenges. Sustainability is achieved through the adoption of sustainable agricultural practices such as the utilisation of renewable resources, ecological innovation, and support for biodiversity. Good governance and the ability to respond flexibly to changes in the external environment ensure that such agroclusters are sustainable, which is particularly significant in the context of global competition and climate change.

Comparing the data from the studies, it can be observed that successful agroclusters with prominent innovation potential do share a series of features, such as close cooperation between different actors in the ecosystem and active adoption of innovative technologies. These clusters demonstrate the ability to adapt to changing market conditions and ensure long-term economic sustainability. Their success can be attributed not only to the integration of innovation, but also to a strategic approach to resource management, as evidenced by studies in different countries. It was noted that the development of innovation potential of agroclusters plays an essential role in ensuring sustainable development of the agricultural sector and increasing its competitiveness. An integrated approach, including scientific research, government support, technological infrastructure development, and human resources, contributes to the creation of effective agroclusters (Pavliv, 2023). The development of agro-innovation in such clusters leads to the creation of new jobs, improved product quality, and increased economic sustainability of the regions.

P. Rambe and P. Khaola (2022) concluded that the influence of innovation on the sustainability and competitiveness of agricultural regions cannot be underestimated, as the introduction of innovative technologies helps to improve production efficiency and reduce risks associated with climate change and market fluctuations. Innovation allows agricultural regions to optimise pro cesses, use resources more efficiently, and reduce production costs, making them more resilient to external economic and environmental challenges. The application of advanced technologies in agriculture also contributes to the improvement of product quality, which is a significant factor for competitiveness in the global market (Mamasydykov *et al.*, 2019). T.S. Jayne *et al.* (2021) revealed that the innovation capacity of the agricultural sector directly affects economic growth and stability, as the introduction of new methods and solutions increases productivity and stimulates job creation. The development of high-tech industries, such as agro-processing or the use of smart agricultural systems, contributes to the diversification of the region's economy and the creation of sustainable supply chains. Innovation plays a key role in long-term economic stability, as it provides greater incomes for farmers and businesses, and helps reduce dependence on external economic factors such as changes in commodity prices or climate risks.

Analysis of the findings of the study, clearly shows that innovation plays a key role in improving the sustainability and competitiveness of agricultural regions. The introduction of innovative technologies not only improves production processes but also helps agrarian enterprises to adapt to changes in the external environment, such as fluctuations in market prices or changes in climate (Pasichnyk *et al.*, 2023). These factors make regions that actively innovate more flexible and can respond to challenges effectively, which is confirmed by the successful examples of agroclusters considered in the study. Based on the findings, recommendations for further development of agroclusters were proposed. First of all, it is necessary to create agro-innovation centres, which will facilitate the introduction of innovative technologies and knowledge transfer between participants in agro-production, scientific institutions, and government agencies. The development of state support for start-ups in the agribusiness sector through subsidies, grants, and tax incentives is also a major step. Finally, it is necessary to develop digital infrastructure, including the use of IoT, Big Data, and artificial intelligence to better manage agribusiness and increase yields.

CONCLUSIONS

The study of innovation potential of agroclusters revealed that their development directly depends on several key factors such as human resources, research and development base, financial support, and technological infrastructure. Successful interaction between government agencies, research institutions, and private companies plays a crucial role in achieving meaningful outcomes in the agricultural sector. Examples of such effective agroclusters are regions with prominent levels of innovation, such as the Netherlands, Kazakhstan, and the USA. In Kazakhstan, the level of agribusiness financing is USD 2.5 bn, of which USD 0.8 bn is allocated to innovation spending. This demonstrates the government's commitment to investing in the development of innovative technologies and solutions for the agribusiness sector. In the Netherlands, particularly in Foodvalley, the level of agrocluster financing is much higher, reaching USD 10 bn, of which USD 4.2 bn is allocated on innovation spending. In the US, in agroclusters such as California and Iowa, funding reaches USD 15 bn and USD 7 bn respectively, with innovation spending of USD 6.5 bn and USD 2.8 bn. These data underscore the significance of investment in innovation, which directly contributes to improving the technology base and agricultural productivity.

Furthermore, successful agroclusters are actively adopting advanced technologies such as precision farming, IoT, biotechnology, and artificial intelligence. These technologies not only increase productivity but also make agriculture more resilient to climate change and economic fluctuations. The methodology for assessing the innovation potential of agroclusters, including SWOT analysis, index method, and expert questionnaires, allows accurately identifying strengths and weaknesses and directing efforts to the development of the most promising areas. For instance, the introduction of innovations in Kazakhstan's agro-industrial complex has led to a 3.6% annual growth since 2010, while labour productivity has increased to USD 6.6 thsd per person. This is 30% greater than the indicators of Ukrainian farmers. The introduction of digital technologies in agriculture can considerably increase profitability by 50-100% in the first two years of use, highlighting the value of innovation for sustainable growth of the agricultural sector. For a deeper understanding, it is necessary to examine the impact of climate change on the innovation capacity of agroclusters and their ability to adapt to changing conditions.

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CONFLICT OF INTEREST

None.

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Аналіз інноваційного потенціалу регіональних агрокластерів

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Анотація. В рамках дослідження аналізуються ключові ресурси та умови, що впливають на розвиток інноваційної діяльності в регіональних агрокластерах. У дослідженні було проведено комплексний аналіз інноваційного потенціалу агрокластерів, що включає оцінку ключових факторів, таких як кадрові ресурси, науково-дослідна база, фінансова підтримка та технологічна інфраструктура з використанням SWOT-аналізу, індексного методу та експертів. Аналіз показав, що рівень інноваційного потенціалу регіональних агрокластерів визначається ступенем взаємодії між підприємствами, науковими установами та державними структурами. Фінансування агропромислового кластера в Казахстані становить 2,5 млрд доларів, з яких 0,8 млрд прямують на інновації, тоді як у Нідерландах, США (Каліфорнія та Айова) ці показники значно вищі, досягаючи 10-15 млрд доларів з інноваційними витратами від 2,8 до 6,5 млрд доларів. Наприклад, у Казахстані з 2010 року спостерігається стабільне зростання агропромислового комплексу на 3,6 % на рік, що сприяло збільшенню продуктивності праці до 6,6 тис. доларів на людину – на 30 % вище за показники українських фермерів. Встановлено, що наявність спеціалізованої інфраструктури (агротехнопарків, центрів трансферу технологій) сприятиме прискореному впровадженню інновацій. Дослідження також підтвердило, що ключовими бар'єрами для інноваційного розвитку агрокластерів є недостатнє фінансування науково-дослідних та дослідно-конструкторських робіт, нестача кваліфікованих кадрів та слабка кооперація між учасниками. Наприклад, використання технологій точного землеробства та штучного інтелекту може збільшити врожайність на 20 % та знизити використання води на 30 %. У регіонах з активною державною підтримкою та доступом до інвестицій, таких як Казахстан, спостерігається зростання кількості стартапів та венчурних інвестицій. На підставі проведеного аналізу запропоновано рекомендації щодо розвитку інноваційного потенціалу агрокластерів, включаючи створення стимулюючих заходів підтримки, розвиток освітніх програм та впровадження цифрових платформ для обміну технологіями. Отримані результати можуть бути використані для розробки стратегій підтримки та стимулювання інноваційної активності в регіональних агрокластерах, що сприяє підвищенню їхньої конкурентоспроможності та ефективності

Ключові слова: цифровізація; державна підтримка; кооперація; інвестиції; технології; інфраструктура

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