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10008, б-р Старий, 7, м. Житомир, Україна
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/uk

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Editors office address:
Polissia National University
10008, 7 Staryi Bvld., Zhytomyr, Ukraine
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua/en

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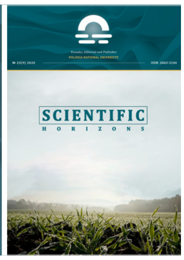

Evaluation of growth and development of barley plants of phenotype with three formed shoots at the end of the tillering phenophase at different sowing dates

Oleksandr Horash
Doctor of Agricultural Sciences, Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0001-9418-0310

Rita Klymyshena*
PhD in Agricultural Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
https://orcid.org/0000-0002-4643-7895

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Abstract. The purpose of this study was to substantiate the optimal combination of agroecological resources of the Western Forest-Steppe of Ukraine and the biological potential of spring barley productivity in cultivation technology. The organised research was aimed at analysing the state of growth and development of spring barley plants on the example of the phenotype with three formed shoots at the end of the tillering phenophase, depending on the influence of environmental conditions at different sowing dates. To describe and summarise the experimental data, the study employed the method of establishing the significance of the difference in sample means by the t-criterion (difference analysis) was used. As a result of the study of barley growth and development, on the example of the analysis of the phenotype of plants with three formed shoots at the end of the tillering process, a pattern of gradual decrease in the realisation of the biological potential of shoots was obtained when the sowing dates were shifted by 10 days starting from the first sowing date – March 10. The maximum values of the growth and development of shoots of plants of this phenotype were obtained as a result of ensuring the sowing process on March 10 at the earliest. According to the order of the biological sequence of formation of the first, second, and third shoots, the indicators were for crude biomass – 4.2 g, 3.2 g, 2.2 g; dry matter content – 0.77 g, 0.58 g, 0.43 g, leaf surface area – 37.9 cm^2, 34.8 cm^2, and 30.9 cm^2. According to the analysis of the factual material obtained as a result of an organised experiment of growing plants in abiotic conditions at different sowing dates, the process of modifying the influence on the morphogenesis of barley shoots was established. The best results of intensification of spring barley tillering according to the parameters of the established data of shoot development on the example of the indicated plant phenotype were obtained under environmental conditions at early sowing dates. From a practical standpoint, the use of favourable environmental resources at early sowing dates in ensuring consistently high grain yields of spring barley crops continues to be an underutilised reserve in cultivation technology

Keywords: spring barley; abiotic conditions; biomass; leaf surface area; t-criterion; biological potential

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**Corresponding author*

INTRODUCTION

Due to changes in agroclimatic resources in the Western Forest-Steppe of Ukraine, it has become relevant to investigate the growth and development of early spring cereals, including barley, at different sowing dates to improve cultivation technologies. Global barley grain production depends on yields under weather conditions and is characterised by data within 140-160 million tonnes per year. In the 2023-2024 season, it is estimated at around 144 million tonnes, which is down 5.6% year-on-year, according to experts. These results were influenced by lower yields and, accordingly, production volumes in several European countries and some regions of the African continent due to deteriorating weather conditions. Ukraine is a considerable influence on the global grain market, where the agricultural sector is essential for the global food balance. Ukraine produces approximately 7-10 million tonnes of barley annually, depending on weather conditions, growing technologies and global market conditions, and maintains its status as a leading barley producer in the world. Ukraine ranks 3rd in the global barley shipment ranking. Ukraine can produce up to 2.0 million tonnes of malting barley, of which the internal market can sell 0.9-1.0 million tonnes under favourable economic conditions.

The global climate change that has taken place in recent decades has markedly affected crop cultivation. Climate change in Ukraine is a part of global climate change, and it has its specific regional features, both as factors affecting barley grain production and the yield of all grain crops overall (van der Wiel & Bintanja, 2021; Appiah *et al.*, 2023). Barley is one of the oldest cultivated plants, with a history of cultivation spanning thousands of years (Lukinac & Jukić, 2022; Kaur *et al.,* 2024). It began to be cultivated 10-12 thousand years ago, along with other cereals, including wheat. Barley came to Europe in prehistoric times through the Balkans. It is known on Ukrainian lands according to the Tripoli culture of the 3-4 millennium BC. S. Tatsu *et al.* (2020) noted that barley is one of the leading crops used for the production of feed, beer, food, etc. Today, it continues to be one of the key crops in Ukraine's exports. D. Rico *et al.* (2020) argued that compliance with the requirements of cultivation technology will ensure stable and high barley yields.

Barley requirements for temperature conditions. Barley seeds begin to germinate at a temperature of 1-2°C. However, under such conditions, the germination process is very slow and is mostly directed towards the root system. At a temperature of 4ºC, seed hatching takes 5 to 7 days, at 10°C – 3 days, and at 16-19°C – 1-2 days. Accordingly, the sowing-germination period depends on the soil temperature regime, as well as on the biological and physiological quality of the seeds. The hotter the temperature, the earlier the seedlings appear on the soil surface. However, the most favourable temperature at the beginning of barley development is 10-15°C, which is slightly lower than the optimal parameters of seed germination, which are 20-23°C. R. Shivhare *et al.* (2020) noted that hot temperature accelerates plant development by shortening the duration of the tillering phase, which leads to a decrease in barley ear productivity.

Barley requirements for moisture supply. Barley seeds germinate when water is absorbed in an amount equal to half of their weight (Springer & Mornhinweg, 2019). This is somewhat less than is required for wheat, rye, and oats, which reflects the xerophilicity of barley. With sufficient moisture supply, barley seeds swell in 24 hours, while with insufficient moisture supply, this process takes longer. The water requirement of barley plants is constantly increasing from germination to earing, with the maximum amount occurring between the beginning of the tube and the onset of earing. Moisture deficit during grain filling leads to a loss of optimal kernel weight parameters, which definitely reduces the yield level. The accumulation of starch in the grain decreases, the protein content increases, and the uniformity and size of the grain decreases.

Barley grain production in Ukraine can increase due to modernisation of agricultural technology, investments in modern machinery, use of precision farming systems, improvement of technological methods, and logistics approaches in the growing process to adapt to climate change, creation, and introduction of new varieties resistant to disease and drought, will help to increase and stabilise spring barley grain yields. The purpose of this study was to assess the state of growth and development of spring barley plants at the end of the tillering phenophase depending on the influence of environmental conditions at different sowing dates to ensure adaptation to climate change, the cultivation technology, and maximum use of the agro-ecological resource of the Western Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study included the phenotype of spring barley plants of the Sebastian variety with three formed shoots in terms of growth and development at the end of the tillering process. The influence factor is abiotic environmental conditions at five different sowing dates, 10 days after the first one on 10 March. The experimental studies were conducted in 2018-2020 at the Podilskyi State University, in the soil and climatic conditions of the Western Forest-Steppe of Ukraine. The key determining factors of soil fertility in the experimental plots included the provision of barley plants with the necessary nutrients for growth and development. The soil of the experimental plots was podzolised medium loamy, structured, with a humus content of 3.2%, pH parameters were close to neutral, hydrolytic acidity and the amount of absorbed bases per 100 g of soil were

0.56-0.62 mg-eq and 32-36 mg-eq, respectively. The presence of macro- and microelements per 1 kg of soil was as follows: alkaline-hydrolysed nitrogen – 100 mg, mobile phosphorus – 176 mg, exchangeable potassium – 160 mg.

Formal characteristics of the field experiment: row spacing of 15 cm, depth of seed placement during sowing 2-3 cm, seeding rate of 250 germinating seeds/m^2. The homogeneity of the used seeds by grain weight was within 48-52 mg. The area of the accounting plots was 20 m^2, the number of replications was 4 times. The following indicators were determined: crude plant biomass by weighing on the FEH-600L balance, dry matter mass by thermogravimetric method, leaf surface area by the method of notches (Hrytsaenko *et al.,* 2003). For the mathematical analysis of the obtained research results, the Student's t-test was applied to determine the dependence of spring barley shoots crude biomass, dry matter content, and leaf surface area on the influence of sowing dates (Yeshchenko *et al.,* 2014). The conducted study did not violate the basic standards and protocols following the Convention on Biological Diversity (1992) adopted at the Earth Summit in Rio de Janeiro, as well as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

In the presented study results, the analysis included indicators of crude biomass of shoots, dry matter content, and leaf surface area. Crude biomass is a physiological indicator that characterises the intensity of photosynthesis, transpiration, and the efficiency of solar energy use. The dry matter content (DMC) of plants is an indicator that characterises their productivity and efficiency of using environmental resources. In the analysis of the efficiency of crop cultivation technologies, DMC characterises the state of plant development and reflects the accumulation of organic substances, which are products of photosynthesis. A high DMC obtained at different stages of plant development during cultivation reflects intensive growth and development of the crop. Controlling the dry matter content provides a reasonable opportunity to adapt the agricultural technology to the conditions of the region where crop production is performed.

The key aspect of the analysis of leaf area was the assessment of photosynthetic activity. The leaf surface is the principal organ of photosynthesis. The larger the leaf area, the more solar energy the plant can absorb for the synthesis of organic matter. Monitoring the leaf area at different stages of the growing season provides objective information on plant growth rates and their condition, which is an essential element in modern research to ensure the development of spring barley cultivation technology. The analysis of spring barley shoot biomass data at the end of the tillering process, i.e., at the beginning of the fourth stage of organogenesis, revealed that with each 10-day delay in sowing date, starting from the first one on March 10, the shoot biomass steadily decreased (Table 1).

***Table 1**. Evaluation of spring barley growth and development at the end of tillering process at different sowing dates based on the analysis of the phenotype of plants with three formed shoots (2018)*

Indicator	Sowing period				
	first	second	third	fourth	fifth
First shoot					
Crude biomass, g	3.88 ± 0.11	3.45 ± 0.12	3.04 ± 0.10	2.65 ± 0.13	2.33 ± 0.06
Dry matter content, g	0.77 ± 0.017	0.61 ± 0.015	0.51 ± 0.012	0.41 ± 0.010	0.32 ± 0.016
Leaf surface area, cm^2	34.18 ± 0.81	31.82 ± 0.77	29.71 ± 0.67	27.31 ± 0.55	23.25 ± 0.65
Second shoot					
Crude biomass, g	2.89 ± 0.10	2.59 ± 0.09	2.36 ± 0.07	1.92 ± 0.08	1.70 ± 0.06
Dry matter content, g	0.58 ± 0.013	0.46 ± 0.014	0.38 ± 0.016	0.29 ± 0.007	0.24 ± 0.012
Leaf surface area, cm^2	32.84 ± 0.69	30.04 ± 0.70	27.76 ± 0.53	24.75 ± 0.77	21.55 ± 0.79
Third shoot					
Crude biomass, g	2.11 ± 0.08	1.85 ± 0.10	1.53 ± 0.09	1.23 ± 0.07	1.00 ± 0.08
Dry matter content, g	0.41 ± 0.018	0.32 ± 0.017	0.26 ± 0.011	0.19 ± 0.014	0.15 ± 0.013
Leaf surface area, cm^2	28.07 ± 0.32	26.07 ± 0.81	24.05 ± 0.50	22.08 ± 0.83	18.64 ± 0.86

***Source:** compiled by the authors of this study based on the research results*

Specifically, the difference in the biomass of plants of the first shoot when comparing the data obtained at the first and second sowing dates was 0.43 g, which is statistically significant (t_f - 2.65 > $t_{0.05}$ - 2.009). When comparing the data of shoot biomass at the second and third sowing dates, the difference of 0.41 g was also significant (t_f - 2.62 > $t_{0.05}$ - 2.009). The difference in the biomass of the first shoot of spring barley at the third and fourth sowing dates of 0.39 g was statistically significant (t_f - 2.37 > $t_{0.05}$ - 2.009). And when comparing the obtained data on the biomass of the first shoot at the fourth and fifth sowing dates, the difference of 0.32 g is statistically significant (t_f - 2.23 > $t_{0.05}$ - 2.009). Thus, with each delay of spring barley sowing by 10 days after the first one on March 10, the biomass of the first shoot at the end of the vegetative state of development significantly decreased. The obtained indicators of dry matter of the first shoot under analogous comparison options also indicate that with each subsequent sowing date, the established indicators were significantly lower. Comparison of the data obtained during the first and second sowing periods was characterised by a statistically significant difference in the dry matter content of the shoots, which was 0.16 g (t_f - 7.07 > $t_{0.05}$ - 2.009). When comparing the data obtained at the second and third sowing dates, the difference of 0.10 g was also significant (t_f - 5.20 > $t_{0.05}$ - 2.009). Additionally, the dry matter content of the shoot at the fourth sowing date was significantly lower by 0.10 g compared to the data at the third sowing date (t_f - 6.41 > $t_{0.05}$ - 2.009). When sowing in the fifth term, the indicator was 0.32 g, which was significantly less by 0.09 g compared to the data for the fourth sowing term, statistical criterion t_f - 4.78 > $t_{0.05}$ - 2.009.

The following is an analysis of the data on leaf area using an analogous comparison format. When comparing the area of the first shoot according to the data obtained during sowing on 10 March, the value was greater and amounted to 34.18 cm^2 and on 20 March, where the value was lower – 31.82 cm^2, the difference of 2.36 cm^2 was significant (t_f - 2.11 > $t_{0.05}$ - 2.009). When analysing the results obtained during the second and third sowing periods, it was found that the leaf surface area of the shoot in the third period was significantly less by 2.11 cm^2 (t_f - 2.06 > $t_{0.05}$ - 2.009). When analysing the data obtained at the third and fourth sowing dates, the leaf surface area of the shoot at the fourth date was significantly lower by 2.40 cm^2, as evidenced by statistical analysis (t_f - 2.77 > $t_{0.05}$ - 2.009). The smallest leaf surface area for the biological development of the first shoot was at the fifth sowing date – 23.25 cm^2. Comparison with the same indicator obtained at the fourth sowing date showed a significant difference in data at the level of 4.06 cm^2, where the value t_f was 4.77 > $t_{0.05}$ - 2.009.

The following is an assessment of the growth and development of the second shoot of spring barley plants depending on the sowing date at the end of the third stage of organogenesis. The biomass of the shoot at the first sowing date was 2.89 g, and at the second sowing date 10 days after the first – 2.59 g. The difference in the comparison was significant and amounted to 0.30 g (t_f - 2.23 > $t_{0.05}$ - 2.009). The biomass of the second shoot at the third sowing term of 2.36 g compared to the index obtained at the second sowing term was 0.23 g less, the difference was statistically significant (t_f - 2.02 > $t_{0.05}$ - 2.009). When barley was grown under the conditions of the fourth sowing term, the biomass of the shoot was even lower and amounted to 1.92 g. Compared to the results of the analysis at the third sowing date, the difference of 0.44 g was statistically significant (t_f - 4.15 > $t_{0.05}$ - 2.009). And under the conditions of the fifth sowing term, the biomass of the second shoot of 1.70 g was significantly lower than the biomass of the shoot when sown in the fourth term. The difference of 0.22 g was statistically significant (t_f - 2.20 > $t_{0.05}$ - 2.009).

The analysis of the data on the dry matter content of the second shoot of spring barley at the end of the vegetative state of plant development under conditions of five different sowing dates shows that when comparing the data obtained at the first and second sowing dates, the differences were 0.12 g, which were driven by substantially lower values obtained at the second sowing date (t_f - 6.28 > $t_{0.05}$ - 2.009). In the third sowing term, the value of 0.38 g provided a statistically significant difference of 0.08 g compared to the results obtained in the second sowing term (t_f - 3.77 > $t_{0.05}$ - 2.009). Comparison of the data obtained under the conditions of the fourth and third sowing terms characterised statistically significant differences in the parameters of indicators with a lower value when sowing in the fourth term, the difference was 0.09 g (t_f - 5.17 > $t_{0.05}$ - 2.009). Under the conditions of the fifth sowing term, the dry matter content was the lowest at 0.24 g, which is 0.05 g less than the value obtained during the fourth sowing term, but the difference was statistically significant (t_f - 3.62 > $t_{0.05}$ - 2.009).

According to the study results, it was found that with each 10-day delay in sowing dates, starting from the first one on 10 March, the leaf surface area of the second shoot by the degree of development at the end of the vegetative state of plants became smaller. Specifically, the indicators according to the first, second, third, fourth, and fifth sowing dates were 32.84 cm^2, 30.04 cm^2, 27.76 cm^2, 24.75 cm^2 and 21.55 cm^2. The difference of 2.80 cm^2 between the first and second indicators was significant (t_f - 2.85 > $t_{0.05}$ - 2.009). When comparing the second and third indices, the difference of 2.28 cm^2 was also statistically significant, i.e., the leaf surface area of the second shoot at the third sowing date became smaller (t_f - 2.59 > $t_{0.05}$ - 2.009). At the fourth sowing term, the index became even smaller, the differences compared to the data obtained under the conditions of the third sowing term of 3.01 cm^2 were statistically significant (t_f - 3.22 > $t_{0.05}$ - 2.009). And at the fifth sowing date, the established value of the leaf surface area of the shoot was 21.55 cm^2 was the smallest. The difference in comparison with the data obtained under the conditions of the fourth sowing date of 3.20 cm^2 was significant (t_f - 2.90 > $t_{0.05}$ - 2.009).

The development of the third shoot of spring barley plants, depending on the conditions of sowing time, was analogous to the established pattern, both in relation to the first and second shoots. At the first sowing date, the biomass of the shoot was 2.11 g, at the second – 1.85 g, which was 0.26 g less, the difference was statistically significant t_f - 2.03 > $t_{0.05}$ - 2.009.

Under the conditions of the third sowing term, the indicator of 1.53 g was significantly lower by 0.32 g compared to the data obtained during the second sowing term (t_f - 2.38 > $t_{0.05}$ - 2.009). The index of shoot biomass at sowing in the fourth term was 0.30 g less compared to the data for the third sowing term, the difference was significant (t_f - 2.63 > $t_{0.05}$ - 2.009). The conditions of spring barley cultivation at the fifth sowing term provided a shoot biomass of 1.00 g. The difference of 0.23 g compared to the data obtained at the fourth sowing term was statistically significant (t_f - 2.16 > $t_{0.05}$ - 2.009).

Based on the analysis of the data on the development of the third shoot of spring barley in terms of dry matter content, it was found that in the first sowing period the index was the highest at 0.41 g. Under the conditions of the second sowing term, it decreased by 0.09 g, where the value of the indicator was at the level of 0.32 g. The difference was significant based on statistical calculation (t_f - 3.64 > $t_{0.05}$ - 2.009). The conditions of the third sowing term led to a further decrease in the accumulation of dry matter content by the shoot. The established value at the level of 0.26 g was lower than the value of the indicator obtained under the conditions of the second sowing term. The difference of 0.06 g was significant (t_f - 2.97 > $t_{0.05}$ - 2.009). When barley was sown in the fourth term, the accumulation of dry matter by the shoot decreased by 0.07 g compared to the results obtained in the third term of sowing. The difference was statistically significant at the established criterion t_f - 3.93 > $t_{0.05}$ - 2.009. Under the conditions of the fifth sowing date, the dry matter content of the third shoot was the lowest and amounted to 0.15 g. Compared to the data obtained under the conditions of the fourth sowing term, the difference of 0.04 g was statistically significant (t_f - 2.09 > $t_{0.05}$ - 2.009).

When analysing the leaf surface area of the third shoot of spring barley plants under growing conditions at sowing on 10 March, an indicator of 28.07 cm^2 was obtained, and upon sowing on 20 March it significantly decreased by 2.0 cm^2 (t_f - 2.29 > $t_{0.05}$ - 2.009). The development of the shoot at the third sowing date was characterised by a value of 24.05 cm^2, which was significantly less than the value of 26.07 cm^2 obtained under the conditions of the second sowing date. The difference in the comparison data was 2.02 cm^2, which was statistically significant (t_f - 2.12 > $t_{0.05}$ - 2.009). The leaf surface area of the shoot under the conditions of the fourth sowing term at 22.08 cm^2 was 1.97 cm^2 smaller than the leaf surface area of the shoot when grown under the conditions of the third term. The differences in the indicators were statistically significant, the factual value of the Student's t-test was greater than the theoretical one (t_f - 2.03 > $t_{0.05}$ - 2.009). The environmental conditions of the fifth sowing term provided the smallest size of the leaf surface area of the shoot – 18.64 cm^2. The indicator was 3.44 cm^2 smaller than the data for barley cultivation under the conditions of the fourth sowing term, the difference was statistically significant (t_f - 2.87 > $t_{0.05}$ - 2.009).

The results of the study in 2019 are presented in Table 2. The biomass of the first shoot during sowing in the first term was 3.81 g and was 0.41 g greater than the results of the second sowing term, the difference was significant (t_f - 2.50 > $t_{0.05}$ - 2.009). Under the conditions of the second sowing term, the indicator was 3.40 g, which was 0.42 g greater than the value of the indicator obtained under the conditions of the third sowing term in terms of statistical significance (t_f - 2.65 > $t_{0.05}$ - 2.009). The development of spring barley during sowing in the third term provided a biomass of the first shoot of 2.98 g, which was naturally statistically higher compared to the value of the same indicator obtained in the fourth term (t_f - 3.28 > $t_{0.05}$ - 2.009). The parameter of the shoot index at the fourth sowing term of 2.54 g was greater than the index of 2.13 g obtained at the fifth sowing term, the differences in the data were statistically significant (t_f - 2.77 > $t_{0.05}$ - 2.009).

***Table 2**. Evaluation of spring barley growth and development at the end of tillering process at different sowing dates based on the analysis of the phenotype of plants with three formed shoots (2019)*

Indicator	Sowing period				
	first	second	third	fourth	fifth
First shoot					
Crude biomass, g	3.81 ± 0.10	3.40 ± 0.13	2.98 ± 0.09	2.54 ± 0.10	2.13 ± 0.11
Dry matter content, g	0.75 ± 0.016	0.59 ± 0.025	0.48 ± 0.019	0.39 ± 0.015	0.29 ± 0.018
Leaf surface area, cm^2	38.28 ± 0.64	35.51 ± 0.87	33.25 ± 0.70	28.67 ± 0.91	22.93 ± 0.75
Second shoot					
Crude biomass, g	2.79 ± 0.11	2.45 ± 0.12	2.13 ± 0.10	1.80 ± 0.09	1.51 ± 0.11
Dry matter content, g	0.57 ± 0.014	0.45 ± 0.021	0.35 ± 0.024	0.27 ± 0.019	0.20 ± 0.020
Leaf surface area, cm^2	34.11 ± 0.72	31.54 ± 0.81	28.78 ± 0.82	21.07 ± 0.79	16.85 ± 0.80
Third shoot					
Crude biomass, g	2.10 ± 0.08	1.79 ± 0.10	1.43 ± 0.11	1.13 ± 0.07	0.84 ± 0.12
Dry matter content, g	0.47 ± 0.025	0.34 ± 0.022	0.24 ± 0.025	0.16 ± 0.015	0.10 ± 0.016
Leaf surface area, cm^2	29.94 ± 0.67	27.07 ± 0.71	23.20 ± 0.83	18.03 ± 0.70	15.00 ± 0.73

***Source:** developed by the authors of this study based on the research results*

The following is a characteristic of the dry matter content of spring barley shoots at the end of the vegetative stage of plant development. The parameter of the first shoot at the second sowing date was 0.59 g less than the one obtained at the first sowing date, the difference of 0.16 g was statistically significant (t_f - 5.40 > $t_{0.05}$ - 2.009). The result obtained at the third sowing date was 0.48 g less than the second sowing date, the difference of 0.11 g was significant (t_f - 3.50 > $t_{0.05}$ - 2.009). The dry matter content of the shoot at the fourth sowing date was 0.39 g, which was 0.09 g less than the data at the third sowing date, the difference was statistically significant (t_f - 3.71 > $t_{0.05}$ - 2.009). The results of the data obtained at the fifth sowing date were the lowest in the study, the dry matter content was 0.29 g. Differences in comparison with the indicators obtained under the conditions of plant development at the fourth sowing date at the level of 0.10 g were statistically significant (t_f - 4.27 > $t_{0.05}$ - 2.009).

The characteristics of the development of the leaf surface area of shoots were highlighted by an analogous comparison scheme. The largest leaf area of the first shoot at 38.28 cm^2 was obtained at the first sowing date. Compared to the data for the second sowing date at 35.51 cm^2, the difference of 2.77 cm^2 was statistically significant (t_f - 2.56 > $t_{0.05}$ - 2.009). The analysis of the shoot data obtained under the conditions of the third sowing term, where the indicator was 33.25 cm^2, which characterised the pattern of a significant decrease in the leaf surface area of the shoot compared to the data for the second sowing term by 2.26 cm^2, the difference was significant (t_f - 2.02 > $t_{0.05}$ - 2.01). The leaf surface area of the shoot at the fourth sowing date at 28.67 cm^2 was significantly less than that obtained at the third sowing date. The difference was 4.58 cm^2, statistical criterion t_f - 3.98 > $t_{0.05}$ - 2.009. And the area of the leaf surface of the first shoot of spring barley at the fifth sowing date at 22.93 cm^2 was the smallest. The difference was found at the statistical level compared to the indicator obtained at the fourth sowing date – 5.74 cm^2 (t_f - 4.86 > $t_{0.05}$ - 2.009).

Statistical analysis of spring barley plants growth and development based on the biomass of the second shoot shows that the value of 2.79 g at the first sowing date was significantly greater compared to the data established when growing plants under the conditions of the second sowing date (t_f - 2.09 > $t_{0.05}$ - 2.009). Shoot biomass at the second sowing date of 2.45 g was 0.32 g greater than the index when growing barley at the third sowing date, the difference was statistically significant (t_f - 2.05 > $t_{0.05}$ - 2.009). The obtained shoot biomass at the third sowing date of 2.13 g was significantly greater than the established biomass results at the fourth sowing date (t_f - 2.46 > $t_{0.05}$ - 2.009). And, accordingly, the biomass of the second shoot of spring barley 1.80 g in the process of cultivation under the conditions of sowing in the fourth term at a statistically significant level of data discrepancy was 0.29 g greater than the indicator of 1.51 g obtained in the fifth sowing term (t_f - 2.04 > $t_{0.05}$ - 2.009).

When analysing the data on the dry matter content of the second shoot under the conditions of the second sowing term, the value of 0.45 g was lower compared to the results obtained under the conditions of growing the first sowing term of 0.57 g. The difference in data was statistically significant (t_f - 4.76 > $t_{0.05}$ - 2.009). The dry matter content obtained at the third sowing date of 0.35 g was significantly lower than the results of the index when growing spring barley at the second sowing date. The difference of 0.10 g was statistically significant (t_f - 3.14 > $t_{0.05}$ - 2.009). According to the same pattern, the value of the index obtained at the fourth sowing term of 0.27 g was characterised by a significantly lower value of the parameter compared to the data obtained at the third sowing term. The difference at the level of 0.08 g was statistically significant (t_f - 2.61 > $t_{0.05}$ - 2.009). In plant development under the conditions of the fifth sowing term, the dry matter content of the second shoot was 0.20 g. The established difference of 0.07 g was statistically significant when compared to the corresponding values obtained under the conditions of cultivation of the fourth sowing term (t_f - 2.54 > $t_{0.05}$ - 2.009).

The highest value of the leaf surface area of the second shoot was found at the first sowing date of 34.11 cm^2. Under the conditions of the second sowing date, the value was 31.54 cm^2. The difference of 2.57 cm^2 was significant (t_f - 2.37 > $t_{0.05}$ - 2.009). The shoot index at the second sowing date was significantly greater by 2.76 cm^2 than the result of leaf area established under the conditions of plant vegetation at the third sowing date (t_f - 2.39 > $t_{0.05}$ - 2.009). Analogously, the indicator of leaf surface area of the shoot at the third sowing date of 28.78 cm^2 was greater than the results obtained at the fourth sowing date by 7.71 cm^2. The differences in the data were statistically significant (t_f - 6.77 > $t_{0.05}$ - 2.009). The index of leaf surface area of the second shoot at the fourth sowing date of 21.07 cm^2 was greater than the index of 16.85 cm^2 of the fifth sowing date. Statistically, the difference of 4.22 cm^2 was significant at t_f - 3.75 > $t_{0.05}$ - 2.009.

Based on the analysis of the biomass data of the third shoot of spring barley plants, it was found that in the first sowing term, the results of the index were 2.10 g greater than those obtained when growing under the conditions of sowing in the second term. When compared, the difference of 0.31 g was statistically significant (t_f - 2.42 > $t_{0.05}$ - 2.009). The shoot biomass at the second sowing date of 1.79 g was significantly greater compared to the data obtained at the third sowing date, the difference was 0.36 g (t_f - 2.43 > $t_{0.05}$ - 2.009). Analogously, when comparing the biomass of the shoot at the third sowing date, an indicator of 1.43 g was obtained, which was greater than the biomass of the shoot at the fourth sowing date. The difference of 0.30 g was statistically significant (t_f - 2.30 > $t_{0.05}$ - 2.009). According to the same pattern, the index of shoot biomass when grown under the conditions of the fourth sowing term was 0.29 g greater than the index obtained at the fifth sowing term, the difference is statistically significant (t_f - 2.10 > $t_{0.05}$ - 2.009).

The analysis of the data on the development of the third shoot of spring barley plants in terms of dry matter content shows that the second sowing term yielded a value of 0.34 g, which is lower than the result obtained under the conditions of the first sowing term of 0.47 g, the difference of 0.13 g was statistically significant (t_f - 3.90 > $t_{0.05}$ - 2.009). The figure obtained at the third sowing date at 0.24 g in the statistical comparison was also 0.10 g smaller than the result of the second sowing date (t_f - 3.00 > $t_{0.05}$ - 2.009). As a result of the analysis of the data on the dry matter content of the third shoot under the conditions of plant development of the fourth sowing term, a value of 0.16 g was established, which at the statistical level was significantly less by 0.08 g compared to the data obtained in the third sowing term (t_f - 2.74 > $t_{0.05}$ - 2.009). Under the conditions of cultivation of the fifth sowing term, the value of the indicator was only 0.10 g, but when statistically compared with the data obtained under the conditions of the fourth sowing term, the difference of 0.06 g was significant (t_f - 2.73 > $t_{0.05}$ - 2.009).

Based on the analysis of the data of the third shoot of the leaf surface area, the highest parameter of the indicator was 29.94 cm^2 at the first sowing date. When grown at the second sowing date, the leaf surface area of the shoot was 27.07 cm^2. The difference of 2.87 cm^2 was significant, the statistical value of t_f was 2.94 > $t_{0.05}$ - 2.009. The parameter of the indicator at the third sowing date of 23.20 cm^2 was lower than the results obtained under the conditions of growing plants of the second sowing date. The difference in data at the statistical level of 3.87 cm^2 was significant (t_f - 3.54 > $t_{0.05}$ - 2.009). The established value of the leaf surface area of the shoot at the fourth sowing date at 18.03 cm^2 was smaller than the data established under the conditions of the third sowing date. The difference of 5.17 cm^2 was significant (t_f - 4.76 > $t_{0.05}$ - 2.009). The parameter of leaf surface area at the fifth sowing date at 15.00 cm^2 was significantly lower than the previous sowing date. The difference in data at 3.03 cm^2 was significant (t_f - 2.99 > $t_{0.05}$ - 2.009). The analysis of the biological development of spring barley on the example of the phenotype of plants with three developed shoots under different sowing dates at the end of the tillering process in 2020 is presented in Table 3.

***Table 3**. Evaluation of spring barley growth and development at the end of tillering process at different sowing dates based on the analysis of the phenotype of plants with three formed shoots (2020)*

Indicator	Sowing period				
	first	second	third	fourth	fifth
First shoot					
Crude biomass, g	4.81 ± 0.17	4.11 ± 0.15	3.56 ± 0.12	2.96 ± 0.16	2.48 ± 0.13
Dry matter content, g	0.80 ± 0.018	0.64 ± 0.034	0.55 ± 0.023	0.42 ± 0.027	0.36 ± 0.012
Leaf surface area, cm^2	41.13 ± 0.75	38.57 ± 0.78	35.69 ± 0.91	31.00 ± 0.81	25.30 ± 0.83
Second shoot					
Crude biomass, g	3.99 ± 0.13	3.32 ± 0.18	2.70 ± 0.11	2.15 ± 0.12	1.70 ± 0.14
Dry matter content, g	0.59 ± 0.031	0.49 ± 0.028	0.40 ± 0.033	0.30 ± 0.020	0.22 ± 0.019
Leaf surface area, cm^2	37.51 ± 0.86	34.55 ± 0.90	30.89 ± 0.83	25.83 ± 0.99	19.79 ± 1.00
Third shoot					
Crude biomass, g	2.50 ± 0.13	2.09 ± 0.11	1.69 ± 0.12	1.30 ± 0.13	0.96 ± 0.10
Dry matter content, g	0.42 ± 0.025	0.33 ± 0.029	0.25 ± 0.021	0.19 ± 0.016	0.14 ± 0.015
Leaf surface area, cm^2	34.84 ± 1.10	31.67 ± 0.77	27.12 ± 0.98	20.99 ± 1.00	15.25 ± 0.87

***Source:** compiled by the authors of this study based on the research findings*

It was found that the biomass of the first shoot of 4.11 g at the second sowing date was 0.70 g smaller than the biomass of the shoot of 4.81 g at the first sowing date, the difference was statistically significant (t_f - 3.09 > $t_{0.05}$ - 2.009). Under the conditions of the third sowing term, the shoot biomass index was 3.56 g. Compared to the biomass of the shoot at the second sowing date, the difference of 0.55 g was statistically significant (t_f - 2.86 > $t_{0.05}$ - 2.009). Under the conditions of the fourth sowing term, the value of the indicator was 2.96 g and, accordingly, 0.60 g smaller than the value of the same indicator obtained under the conditions of barley cultivation during sowing in the third term. The differences in the data were statistically significant (t_f - 3.00 > $t_{0.05}$ - 2.009). The index of biomass of the first shoot at the fifth sowing term of 2.48 g was 0.48 g smaller than the value obtained at the fourth sowing term, the difference was statistically significant (t_f - 2.33 > $t_{0.05}$ - 2.009).

The study found that the dry matter content of the first shoot at the first sowing date of 0.80 g was greater than the parameters of the indicator obtained at the second sowing date of 0.64 g, the difference at the level of 0.16 g was statistically significant (t_f - 4.16 > $t_{0.05}$ - 2.009).

The parameter of 0.55 g obtained under the conditions of sowing the third term was 0.09 g smaller than the second sowing term, the difference was statistically significant (t_f - 2.19 > $t_{0.05}$ - 2.009). The value of the shoot dry matter content at the fourth sowing term of 0.42 g was 0.13 g smaller than the parameter of the indicator obtained during sowing at the third term, which characterises the difference in data as statistically significant (t_f - 3.67 > $t_{0.05}$ - 2.009). The dry matter content of the first shoot at the fifth sowing date of 0.36 g was 0.06 g less than the dry matter content of the shoot of the fourth sowing date, the difference was significant (t_f - 2.03 > $t_{0.05}$ - 2.009).

The analysis of the development of the first shoot by the value of leaf surface area showed that the index for the second sowing date of 38.57 cm^2 was smaller by 2.56 cm^2 with a statistically significant difference in data compared to the results of the obtained plant vegetation conditions when sowing in the first term (t_f - 2.36 > $t_{0.05}$ - 2.009). The leaf surface of the shoot of 35.69 cm^2 at the third sowing date was 2.88 cm^2 smaller than the area parameter at the second sowing date, the difference was statistically significant (t_f - 2.40 > $t_{0.05}$ - 2.009). The indicator for the fourth sowing term of 31.00 cm^2 was smaller than the indicator obtained in the third sowing term by 4.69 cm^2, which characterised the difference in data as statistically significant (t_f - 3.85 > $t_{0.05}$ - 2.01). The data on the leaf surface area of the shoot at the fifth sowing date were characterised by a value of 25.30 cm^2. The difference with significantly lower parameters compared to the value obtained under the conditions of vegetation of plants of the fourth sowing term was 5.70 cm^2, which was statistically significant (t_f - 4.91 > $t_{0.05}$ - 2.009).

Based on the assessment of the development of the second shoot of spring barley plants by biomass parameters, it was found that the index for the second sowing term of 3.32 g was 0.67 g less than the result of 3.99 g obtained when growing under the conditions of sowing in the first term. The difference is statistically significant (t_f - 3.01 > $t_{0.05}$ - 2.009). The results obtained in the third sowing term showed that the biomass of the shoot was 2.70 g less than the value of the index obtained in the second sowing term, the difference of 0.62 g was statistically significant (t_f - 2.95 > $t_{0.05}$ - 2.009). The established index of shoot biomass under the conditions of the fourth sowing term of 2.15 g was 0.55 g less than the result obtained under the conditions of barley cultivation when sown in the third term. In this comparison, the difference was significant (t_f - 3.39 > $t_{0.05}$ - 2.009). And in the fifth term of sowing, the biomass of the second shoot of 1.70 g was 0.45 g less than the figure obtained during the fourth term, the difference was statistically significant (t_f - 2.44 > $t_{0.05}$ - 2.009).

The results of the dry matter content according to the state of biological development of the second shoot show that under the conditions of the second sowing term, the indicator of 0.49 g was less than the indicator of 0.59 g obtained during the organisation of sowing in the first term. The difference of 0.10 g was statistically significant (t_f - 2.39 > $t_{0.05}$ - 2.009). Under the conditions of plant development during sowing in the third term, the content of dry matter of the shoot was 0.40 g and was 0.09 g less than the value of the indicator obtained in the second term of barley sowing, the difference was statistically significant (t_f - 2.08 > $t_{0.05}$ - 2.009). The conditions of barley development of the fourth sowing term provided the content of shoot dry matter at the level of 0.30 g. The value of this indicator was lower at a statistically significant level of data discrepancy at the established difference of 0.10 g compared to the value obtained at the third sowing date (t_f - 2.59 > $t_{0.05}$ - 2.009). The dry matter content of the shoot at the fifth sowing date was 0.22 g. Compared to the value of the indicator obtained in the fourth term, the difference in the data discrepancy of 0.08 g was statistically significant (t_f - 2.90 > $t_{0.05}$ - 2.009).

The following is an analysis of the leaf surface area according to the biological stage of development of the second shoot of spring barley, depending on the influence of the conditions that developed at different sowing dates. When growing plants at the second sowing date, the area of 34.55 cm^2 was significantly smaller compared to the 37.51 cm^2 obtained at the first sowing date. The difference of 2.96 cm^2 was significant (t_f - 2.37 > $t_{0.05}$ - 2.009). Upon growing plants, when sowing was performed in the third term, the leaf surface area of the second shoot was 30.89 cm^2. Compared to the value of the same indicator obtained under the conditions of the second sowing term, the difference of 3.66 cm^2 was statistically significant (t_f - 2.99 > $t_{0.05}$ - 2.009). At the fourth sowing term, the obtained area of 25.83 cm^2 characterised the pattern of decrease in parameters compared to the results obtained at the third sowing term. The difference in data at the level of 5.06 cm^2 was statistically significant (t_f - 3.91 > $t_{0.05}$ - 2.009). The smallest leaf surface area of the second shoot was found at the fifth sowing date of 19.79 cm^2, which was 6.04 cm^2 smaller than the value obtained at the fourth sowing date, the difference was statistically significant (t_f - 4.29 > $t_{0.05}$ - 2.009).

Analysis of the data on the biomass of the third shoot according to the biological stage of development showd that the conditions at the second sowing date provided a parameter of 2.09 g. Compared to the results obtained during the cultivation of barley in the first sowing period, the indicator was 2.50 g, the difference of 0.41 g was statistically significant (t_f - 2.41 > $t_{0.05}$ - 2.009). The index of shoot biomass at the third sowing term of 1.69 g was naturally characterised by a decrease in the development potential compared to the results obtained under the conditions of development when sowing in the third term. The difference in the comparison data was 0.40 g and was statistically significant (t_f - 2.46 > $t_{0.05}$ - 2.009). Under the fourth sowing term, the shoot biomass of 1.30 g was estimated to be significantly lower than the results obtained when growing barley plants sown in the third term. The difference of 0.39 g was statistically significant (t_f - 2.21 > $t_{0.05}$ - 2.009). The following difference analysis showed that the biomass of the shoot at sowing in the fifth term was 0.96 g statistically less than the biomass of the shoot at the fourth sowing term, the difference of data at the level of 0.34 g was statistically significant (t_f - 2.07 > $t_{0.05}$ - 2.009).

Characteristics of the development of the third shoot of spring barley by estimating the dry matter content shows that the best result of 0.42 g was obtained under growing conditions when sowing in the first term. The value of the indicator at the second sowing date of 0.33 g was significantly less by 0.09 g (t_f - 2.35 > $t_{0.05}$ - 2.009). The dry matter content of the shoot under the conditions of development of plants of the third sowing date of 0.25 g compared to the dry matter content of the shoot at the second sowing date was lower, the difference of 0.08 g was statistically significant (t_f - 2.23 > $t_{0.05}$ - 2.009). At the fourth sowing date, the figure was even lower and amounted to 0.19 g. The difference of 0.06 g in comparison with the data of the dry matter content of the shoot of the third sowing term was significant (t_f - 2.27 > $t_{0.05}$ - 2.009). The influence of developmental conditions of the fifth sowing term provided the lowest accumulation of dry matter by the third shoot. A result of 0.14 g was obtained, where the difference of 0.05 g compared to the data of the same indicator at the fourth sowing date was statistically significant (t_f - 2.28 > $t_{0.05}$ - 2.009).

Based on the characteristics of the parameters of the leaf surface area of the third shoot at the second sowing date, a value of 31.67 cm^2 was established, which was lower than the result of 34.84 cm^2 obtained at the first sowing date. The difference of 3.17 cm^2 was statistically significant (t_f - 2.36 > $t_{0.05}$ - 2.009). Comparison of the index obtained at the third sowing term of 27.12 cm^2 with the same at the second sowing term characterises a decrease of the parameter by 4.55 cm^2. The statistical difference was significant at t_f - 3.65 > $t_{0.05}$ - 2.009. Under the condition of plant development at sowing in the fourth term, the leaf surface area of 20.99 cm^2 was 6.13 cm^2 smaller than that obtained when growing under the conditions of development at sowing in the third term. The difference in data was statistically significant (t_f - 4.37 > $t_{0.05}$ - 2.009). The smallest leaf surface area of the third shoot (15.25 cm^2) was obtained under the conditions of barley development when sown in the fifth term, which was smaller than the data obtained at the fourth sowing term. The difference of 5.74 cm^2 was significant (t_f - 4.33 > $t_{0.05}$ - 2.009).

As a result of the conducted study, the dependence of the processes of growth and development of spring barley on the state of plants at the end of the tillering phenophase on the conditions of vegetation factors of five sowing dates was established according to the structural analysis of the phenotype of plants with three formed shoots (Table 4).

***Table 4**. Evaluation of spring barley growth and development at the end of tillering process at different sowing dates based on the analysis of the phenotype of plants with three formed shoots (average for 2018-2020)*

Indicator	**Sowing period**				
	first	**second**	**third**	**fourth**	**fifth**
First shoot					
Crude biomass, g	4.17	3.65	3.19	2.72	2.31
Dry matter content, g	0.77	0.61	0.51	0.41	0.32
Leaf surface area, cm^2	37.9	35.3	32.9	29.0	23.8
Second shoot					
Crude biomass, g	3.22	2.79	2.40	1.96	1.64
Dry matter content, g	0.58	0.47	0.38	0.29	0.22
Leaf surface area, cm^2	34.8	32.0	29.1	23.9	19.4
Third shoot					
Crude biomass, g	2.24	1.91	1.55	1.22	0.93
Dry matter content, g	0.43	0.33	0.25	0.18	0.13
Leaf surface area, cm^2	30.9	28.3	24.8	20.4	16.3

***Source:** compiled by the authors of this study based on the research findings*

According to the first, second, third, fourth, and fifth sowing dates, morphobiological parameters on average for three years significantly decreased and were characterised by the following data: biomass of the first shoot – 4.17 g; 3.65 g; 3.19 g; 2.72 g; 2.31 g; the second – 3.22 g; 2.79 g; 2.40 g; 1.96 g; 1.64 g; the third – 2.24 g; 1.91 g; 1.55 g; 1.22 g; 0.93 g; dry matter content of the first shoot – 0.77 g; 0.61 g; 0.51 g; 0.41 g; 0.32 g; the second – 0.58 g; 0.47 g; 0.38 g; 0.29 g; 0.22 g; the third – 0.43 g; 0.33 g; 0.25 g; 0.18 g; 0.13 g; according to the leaf surface area of the first shoot – 37.9 cm^2; 35.3 cm^2; 32.9 cm^2; 29.0 cm^2; 23.8 cm^2; the second – 34.8 cm^2, 32.0 cm^2; 29.1 cm^2; 23.9 cm^2; 19.4 cm^2; the third – 30.9 cm^2; 28.3 cm^2; 24.8 cm^2; 20.4 cm^2; 16.3 cm^2 (Table 4).

The results of the morphobiological analysis of the phenotype of spring barley plants with three formed shoots at the end of the tillering phase in terms of individual data of shoot biomass, dry matter content, and leaf surface area at different sowing dates indicated the effectiveness of the implementation of abiotic resources of the environment when forming crops during the vegetative state of plant development. The significance of analysing the growth and development of spring barley plants from the beginning of the seed germination process to the end of the tillering phenophase is that this is the period of growth and development of vegetative organs. This is a separate part of the growing season, during which the potential for plant productivity and the structure of the agrophytocenosis overall are laid and formed. Next, the generative state of plant growth and development begins, the effectiveness of which largely depends on the vegetative state. Primarily, this applies to the functional element of the yield structure, namely productive shoots, the number of which, upon the onset of the generative state of development in barley plants, is determined and can no longer be controlled by both abiotic and technological factors. It is also significant that during the vegetative state of barley plant growth and development, the foundations of biological potential are laid by the number of spikelets in the ear. Therefore, considerable attention is paid to spring barley before the onset of the generative state of growth and development, since with its onset, the determination of this structural element of yield also occurs.

Abiotic environmental conditions during the period of barley vegetative development play a key role. R. Klymyshena and O. Horash (2024) argued that they are essential and are always influential on the processes of seed germination after sowing, on the accumulation of biological potential by barley plants before tillering, both from its beginning and its completion. Notably, at early sowing dates, the tillering process always occurs much earlier than at later dates. The conditions of abiotic factors of vegetation, specifically, such as the duration of daylight hours, which can be characterised by the process of energy flow of quanta, and temperature conditions (minimum, maximum, and optimal temperatures), which integrally interact and affect the duration of the tillering process regardless of sowing dates and determine their productivity. As a result of the influence of day length and air temperature, barley shoots enter a state of generative development, the fourth stage of organogenesis. Therefore, it is crucial to determine on which biological resource spring barley completes the tillering process, depending on the development conditions at different sowing dates, with reference to the most significant task of the technology process, which is to maximise the use of environmental resources.

The influence of abiotic factors of vegetation on the state of growth and development of spring barley at the end of the tillering process at different sowing dates can be established by analysing separately selected plant phenotypes. Accordingly, the results of barley development at the end of the tillering phenophase, depending on environmental conditions at different sowing dates, were presented on the example of analysing the phenotype of plants with three developed shoots according to individual indicators of each of them. The plant phenotype was the result of the interaction of genotype and environment. Plants with the same genotype exhibit phenotype traits according to the conditions of growth and development during the growing season. The phenotype itself includes morphological traits, physiological properties, resistance to environmental factors, and biometric parameters. Phenotype in crop production is a set of traits and properties of plants that are formed by the implementation of the genotype in the growing environment, which are also set by technology.

M. Zulkiffal *et al*. (2021) noted that the technological process of spring barley cultivation in the conditions of changes in abiotic factors requires a systematic solution. The primary types of abiotic factors include climatic factors, particularly temperature, distribution and instability of precipitation, reduction of surface water, intensity and duration of daylight hours, atmospheric pressure, and wind. The list also includes chemical and physical properties of the soil, including acidity, structure, density, soil porosity, water availability for plants and its ability to retain water, macro- and microelements, and the presence of toxic substances. S.I. Zandalinas *et al*. (2021) reported that hydrothermal conditions play a crucial role, characterising the interaction of water and thermal regimes in a particular area. They provide an opportunity for the development of vegetation. The key components of hydrothermal conditions include temperature regime – average, minimum, maximum temperatures, duration of the warm period; humidity – rainfall, soil moisture, groundwater level. The heat and moisture ratio is the balance between the amount of heat that ensures vegetation and the water required for plants. Abiotic factors form the conditions under which certain organisms can exist. According to V.O. Balabukh *et al*. (2021, 2023), the interaction of abiotic factors with biotic factors creates an ecosystem. In this aspect, the vector of spring barley breeding is also sufficiently focused on adaptation to changes in the parameters of abiotic factors that have occurred in recent decades. Environmental conditions are characterised by a rather significant impact on the existence and survival of biological organisms. A. Linchevskyi and I. Legkun (2020) addressed a new attitude towards culture and breeding in the context of climate change.

In the analysis of this area of the problem, there are relevant features that should be considered from the other perspective. In the southwestern Forest-Steppe of

Ukraine, from 2000 to 2010, there was a tendency for favourable conditions for spring barley sowing to occur earlier. In some years, the conventional sowing date of the first decade of April was shifted to the onset of favourable conditions after 20 March. Additionally, this decade saw an increase in the number of opportunities to sow spring barley in both the first and second decades of March. Spring conditions for spring barley cultivation over 2010-2020 were predominantly favourable for early sowing in the early part of March.

According to practical results, early sowing enables the efficient use of winter moisture reserves and fertilisers, which positively influences the tillering process and, ultimately, yields. If sowing is delayed, the field germination of seeds decreases, the root system of plants develops less well, and uniform tillering is not ensured. Based on these conditions, the relevance of the tasks of scientific research is the need to substantiate the optimal combination of the biological potential of spring barley productivity and agroecological resources in cultivation technology. In modern intensive systems of cereal crops cultivation, there is a requirement for increased attention to plants as a biological means of production. Particular significance is attached to the biological properties and characteristics of the crop in connection with the task of cultivation technology to maximise the potential of crop productivity. A series of scientific studies revealed that optimisation of plant growth and development in growing crops cannot be achieved without paying special attention to the biological object as the primary factor of technology.

The issue of spring barley cultivation under current changes in abiotic factors is receiving considerable attention both in Ukraine and around the world. Changes in the agroclimatic conditions of spring barley cultivation due to climate change are assessed. A. Polevoy *et al.* (2013a, b) showed that the A1B climate change scenario in Ukraine, the regional climate model MPI-M-REMO, and the global model ECHAM5-r3 were used to assess changes, as the most probable for the period up to 2050. The photosynthetic productivity and fluctuations in the average regional grain yield of spring barley in the districts of Odesa region, which belong to the Ukrainian part of the Danube Delta sub-basin, were also assessed using plant production models. Specifically, the analysis of spring barley development by phenological phases under climatic factors and the impact on spring barley yield in Europe was also given considerable attention by many scientists, particularly by M. Bicard *et al.* (2025).

Thus, the conducted study reflects the norm of spring barley response to environmental conditions, which characterises the properties of the crop based on the results of plant analysis, biologically fixed adaptation of ontogeny to changes in agroclimatic resources, resulting in the regulation of growth and development processes.

CONCLUSIONS

The conducted study established the dependence of the fulfilment of the biological potential of spring barley growth and development processes on the example of the analysis of the phenotype of plants with three formed shoots at the end of the tillering phenophase on the influence of vegetation factors at five equidistant 10-day sowing dates. It was proved that the key morphophysiological parameters of spring barley plants growth and development, specifically, crude biomass, dry matter content, leaf area of shoots, during the period of vegetative state of plants are limited by the resource of the environment, which gradually becomes smaller with the delay of sowing for every 10 days starting from the first one on March 10. As a result of the study, the maximum values of indicators were obtained for the first sowing date on 10 March. Accordingly, during the first, second, third, fourth, and fifth sowing periods, the obtained indicators decreased significantly. On average, according to the data of three years of research, they were characterised by the following parameters: biomass of the first shoot – 4.17 g; 3.65 g; 3.19 g; 2.72 g; 2.31 g; the second shoot – 3.22 g; 2.79 g; 2.40 g; 1.96 g; 1.64 g; the third shoot – 2.24 g; 1.91 g; 1.55 g; 1.22 g; 0.93 g; dry matter content of the first shoot – 0.77 g; 0.61 g; 0.51 g; 0.41 g; 0.32 g; the second shoot – 0.58 g; 0.47 g; 0.38 g; 0.29 g, 0.22 g; the third shoot – 0.43 g, 0.33 g, 0.25 g, 0.18 g, 0.13 g; leaf area of the first shoot – 37.9 cm^2, 35.3 cm^2, 32.9 cm^2, 29.0 cm^2, 23.8 cm^2; the second shoot – 34.8 cm^2, 32.0 cm^2, 29.1 cm^2, 23.9 cm^2, 19.4 cm^2; the third shoot – 30.9 cm^2, 28.3 cm^2, 24.8 cm^2, 20.4 cm^2, 16.3 cm^2. The obtained findings proved the expediency of ensuring early sowing in the organisation of the technological process of spring barley cultivation to favourably implement the productivity of the natural resource of plants during the vegetative state of the environment of the Western Forest-Steppe of Ukraine.

Prospects for further research include the assessment of fulfilling the productivity potential of spring barley plants during their generative state, depending on the influence of conditions at early sowing on the biometric parameters of shoots and elements of ear productivity to establish the degree of synchronisation and formation of homogeneity of the components of agrophytocenosis as characteristics of the perfection of the technological process of cultivation.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Оцінка стану росту та розвитку рослин ячменю фенотипу з трьома сформованими пагонами по завершенню фенофази кущення за різних строків сівби

Олександр Гораш
Доктор сільськогосподарських наук, професор
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0001-9418-0310

Ріта Климишена
Кандидат сільськогосподарських наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
https://orcid.org/0000-0002-4643-7895

Анотація. Мета досліджень полягала в необхідності обґрунтування оптимального поєднання агроекологічних ресурсів умов середовища Західного Лісостепу України та біологічного потенціалу продуктивності ячменю ярого в процесі технології вирощування. Організовані дослідження спрямовані на аналіз стану росту та розвитку рослин ячменю ярого на прикладі фенотипу з трьома сформованими пагонами на завершенні фенофази кущіння залежно від впливу умов зовнішнього середовища за різних строків сівби. Для опису та узагальнення експериментальних даних застосовано метод встановлення істотності різниці вибіркових середніх за t – критерієм (різницевий аналіз). В результаті проведеного дослідження росту та розвитку ячменю на прикладі аналізу фенотипу рослин з трьома сформованими пагонами станом на завершенні процесу кущення отримано закономірність поступового зниження реалізації біологічного потенціалу пагонів при зміщенні строків сівби на 10 днів розпочинаючи від першого строку сівби – 10 березня. Максимальні значення показників росту та розвитку пагонів рослин означеного фенотипу отримані в результаті забезпечення процесу сівби, як найраніше, 10 березня. У відповідності до порядку біологічної черги формування першого, другого та третього пагонів показники становили для сирої біомаси – 4,2 г; 3,2; 2,2 г; вмісту сухої речовини – 0,77 г; 0,58; 0,43 г, площі листкової поверхні – 37,9 см^2; 34,8 та 30,9 см^2. Відповідно аналізу фактичного матеріалу отриманого в результаті організованого досліду вирощування рослин в абіотичних умовах за різних строків сівби встановлено процес модифікаційного впливу на морфогенез пагонів ячменю. Найкращі результати інтенсифікації кущення ячменю ярого за параметрами встановлених даних розвитку пагонів на прикладі означеного фенотипу рослин отримано в умовах середовища за ранніх строків сівби. З практичного погляду до теперішнього часу залишається недостатньо реалізованим резервом в технології вирощування використання сприятливих ресурсів середовища за ранніх строків сівби в забезпеченні стабільно високої урожайності зерна культури ячменю ярого

Ключові слова: ячмінь ярий; абіотичні умови; біомаса; площа листкової поверхні; t – критерій; біологічний потенціал

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Sustainable weeds management in maize cultivation: Evaluating agroecological practices and tillage systems

Ihor Bezvershuck
Doctoral Student
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0009-0007-8081-9815

Tetiana Fedoniuk*
Doctor of Agricultural Sciences, Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-6504-0893

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Abstract. The study evaluated the effectiveness of agroecological approaches to weed control in maize crops. The experiment, conducted in 2023-2024, included three tillage systems (deep ploughing, disking, milling), two seeding densities (1.1 seeding units/ha and 1.3 seeding units/ha), and two herbicide control approaches (herbicide application and non-application), with a total of 12 variants in 36 replications. The largest weed level was recorded in the variant with disking, low seeding density, and no herbicides (S2H2A1) – 22.3 plants/m^2; the lowest – in the variant with ploughing, high seeding density, and herbicide use (S1H1A2) – 12 plants/m^2. Variants with compacted sowing, regardless of herbicide exposure, demonstrated a better ability to suppress weeds due to rapid closing of row spacings and reduced light access. Analysis of variance (ANOVA) showed that the greatest influence on the number of weeds was soil cultivation ($F = 95.28$; $p < 0.0001$), followed by sowing density ($F = 29.06$; $p < 0.000001$), while the contribution of herbicides was the smallest ($F = 5.37$; $p \approx 0.021$). The significant interaction between the cultivation system and density ($F = 62.85$; $p < 0.000001$) reflected the need for comprehensive planning of agrotechnical measures. Cluster analysis based on the Jaccard index revealed strong ecological relationships between weed species, specifically, *C. arvensis*, *E. repens*, and *R. sativum* had a similarity coefficient of 0.92, which allows predicting typical phytosocial combinations and developing targeted control measures. The findings indicated that agroecological strategies, including shallow tillage and compacted seeding, can successfully replace chemical methods, reducing the environmental burden and maintaining productivity stability. The practical value of this study lies in the proven possibility of minimising herbicide use while maintaining high maize yields by implementing adapted agrotechnical solutions

Keywords: agroecology; weed management; *Zea mays* L.; tillage systems; soil fertility; herbicide alternatives; plant productivity

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*Corresponding author

INTRODUCTION

Maize (*Zea mays* L.) is a crucial crop in agricultural production, occupying a substantial portion of cultivated land globally, including in Ukraine. The substantial output and many applications of these crops render them essential for food and feed security. O. Erenstein *et al.* (2021) emphasised that maize production encounters various obstacles, with crop weediness being one of the most significant. Weeds compete for essential resources – water, nutrients, and light – which can significantly reduce yield. O. Skydan *et al.* (2022) noted that widespread ways to control weeds, especially the use of herbicides, have many downsides, like creating weed species that do not die from these chemicals, harming the soil and environment, and being very costly. Therefore, it is imperative to ascertain alternative weed management practices that are ecologically sustainable and economically feasible. E. Radicetti and R. Mancinelli (2021) and A. Boutagayout *et al.* (2025) emphasised that agroecological approaches to weed management are gaining prominence in modern agriculture. These methods integrate mechanical, biological, and agrotechnical techniques to effectively reduce crop weediness while minimising environmental harm. Their application contributes to improved soil fertility, the preservation of agroecosystems, and lower cultivation costs.

O. Orlov *et al.* (2021) emphasised that weeds that are widely dominating crop fields typically require analogous growth and development conditions as the cultivated plants. Therefore, a comprehensive understanding of their adaptation strategies, typical responses to agricultural practices, and pesticide applications is essential for designing effective weed management systems that minimise crop losses. Over the past two decades, S. Fonteyne *et al.* (2022) observed significant and rapid shifts in the factors influencing the spread of weed species. These changes are largely driven by land use planning, the spatial configuration of agricultural zones, the introduction of short-rotation cropping systems, the adoption of minimal tillage practices, a reduction in technical interventions, and the limited use of organic fertilisers.

T. Fedoniuk *et al.* (2025) noted that throughout the last century, agricultural development has undergone several transformative phases aimed at restructuring land use practices. Although the government first acknowledged the strategic significance of maize in crop rotations in the early 1930s, large-scale expansion of maize cultivation did not begin until the late 1950s. This expansion coincided with debates between the grassfield concept – focused on maintaining soil fertility through perennial grasses – and the mineral concept, which emphasised mineral fertilisers. Furthermore, T. Fedoniuk *et al.* (2024) mentioned that between 1980 and 1984, the increased farming of row crops like maize and the use of herbicides such as atrazine and eradican in mineral oil emulsions caused major changes in the types of weeds found in crop fields. S. Cordeau (2022) claimed that it is possible to manage weeds effectively without chemical pesticides if a successful combination of mechanical, cultural, and biotechnical methods is used.

However, L. Schnee *et al.* (2023) warned that excessive tillage may facilitate the spread of perennial weeds through vegetative reproduction. B. Thapa and R. Dura (2024) noted that minimum tillage approaches, including no-till systems, minimise soil disturbance but can lead to the accumulation of weed seeds near the soil surface. Still, combining no-till practices with mulching and the use of cover crops has proven effective in suppressing weed emergence and growth. Furthermore, S. Liu *et al.* (2022) reported that dense crop planting can markedly reduce weed pressure. Densely sown maize forms a thick canopy that limits light penetration on the soil surface, thereby inhibiting weed germination and reducing competition for resources during the early growth stages of the crop. V. Mandić *et al.* (2024) demonstrated that optimised sowing densities of maize can play a crucial role in reducing weed density, thereby lessening their negative impact on crop productivity. However, the researchers also warned that planting too many maize plants can lead to competition among them, showing the significance of adhering to recommended planting rates to effectively control weeds without hurting crop growth. Thus, the purpose of the present study was to evaluate how well different eco-friendly methods work for controlling weeds in maize farming by combining various tillage systems, planting densities, and stopping the use of chemical herbicides, while also considering their effects on plant growth, productivity, and the overall farming environment.

MATERIALS AND METHODS

Experimental site and natural conditions. The experimental plot was situated inside the broader experimental field of Polissia National University (N 50°26′; E 28°4) (Fig. 1). The site mostly consists of Gleic Albic Luvisol, classified as Endoclayic, Cutanic, Differentic, Katogleyic, and Ochric types according to IUSS Working Group WRB (2022).

The climate of the research region is described as somewhat continental with humid conditions. The average annual air temperature is roughly 7-8°C, whereas the mean temperature in January is approximately 5°C. The summer temperature generally varies between 18°C and 20°C. Annual precipitation varies between 600 mm and 700 mm, primarily occurring in the summer months. The relative humidity of the air is significantly increased.

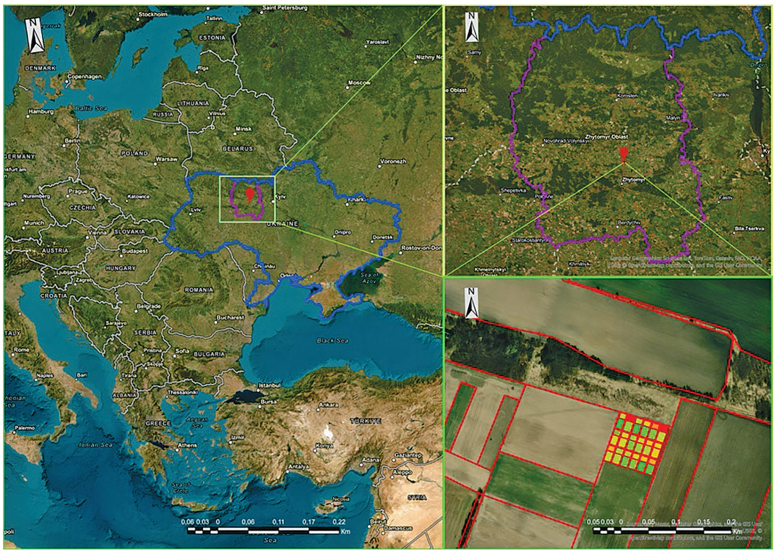

***Figure 1**. Location of the study area*
***Source:** generated in ArcGIS Pro software, digitised by the authors of this study based on factual field coordinates*

Experimental design and arrangement. Analysis of variance was employed to evaluate the effects of factors F1, F2, F3, and their interactions. The experiment was performed in three replications to minimise experimental error and improve the validity of the results. A 1-hectare area was partitioned into 12 experimental plots, with each plot replicated three times (Fig. 2). The study was conducted in 2023-2024. The research employed a factorial experimental design that included combinations of F1, F2, and F3. Each combination of F1×F2×F3 was performed in triplicate. The study investigated the impact of the following factors: F1 – tillage systems: S1 – deep soil ploughing at 18-20 cm (standard), S2 – soil disking at 10-12 cm (agroecological strategies – AES), S3 – soil milling at 5-7 cm (AES); F2 – sowing density: A1 – 1.1 sowing units per hectare (standard); A2 – 1.3 sowing units per hectare (AES); F3 – herbicide application: H1 – standard herbicide application; H2 – herbicide non-application (AES).

Data were collected weekly from each source. During field research, the parameters of main crops, cereal weeds, broadleaf, and short-leaved weeds were measured for height and density in each plot. The follow-up study was conducted in 2023-2024. The predicted expected impacts of various agroecological strategies are presented in Table 1.

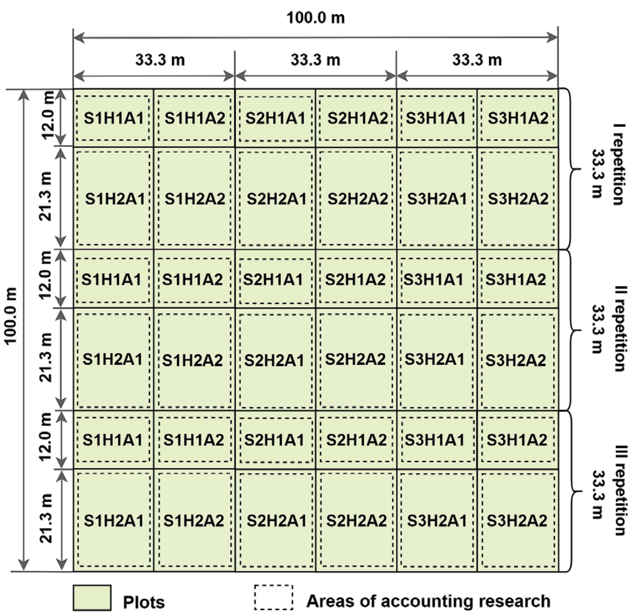

***Figure 2**. Experiment design*
***Source:** compiled by the authors of this study*

Table 1. Logic of applying weeds management strategies

Version	Impact of AE strategy
S1H1A1 S1H2A1	Standard maize seeding density when ploughing can help reduce competition for resources, but it also creates conditions for weed growth. In comparison with compacted crops, with a standard seeding density, plants are unable to quickly close the interrows, which allows weeds to actively develop. This reduces the effectiveness of weed control and can also negatively affect yields due to lower seeding density.
S1H1A2 S1H2A2	The high density of maize sowing allows the plants to close the interrows faster, reducing the number of weeds. This effectively limits the space for the development of weeds and increases the effectiveness of their control. The yield in this case is usually greater due to less competition between plants and better development of the root system.
S2H1A1 S2H2A1	With medium seeding density and disking, maize will compete better with weeds, while the interrows will close faster. This will increase the effectiveness of weed control and improve yields compared to low densities. However, in case of heavy weeding, the efficiency of disking may not be sufficient for complete control over weeds.
S2H1A2 S2H2A2	High seeding density against the background of disking allows maximising the competitive ability of maize against weeds. Maize quickly closes the rows, reducing the risk of weeding. This leads to greater yields, as plants make better use of soil resources and have less competition with weeds.
S3H1A1 S3H2A1	With medium seeding density, maize can provide more effective weed control. Tilling promotes a more even distribution of seeds and improves the structure of the soil, which promotes better plant development. Yields at this seeding density are usually stable and optimal because there is less competition with weeds and maize makes effective use of moisture and nutrients.
S3H1A2 S3H2A2	The high density of maize seeding during milling provides the best soil coverage and reduces weediness. Maize forms a dense leaf cover, which significantly limits the access of weeds to light and nutrients. This leads to high yields, as plants actively use resources and effectively compete with weeds.

Source: *compiled by the authors of this study*

Soil sample collection and physicochemical property analysis. The study was executed using a multi-phase experimental methodology. The experimental design was first established, subsequently leading to the evaluation of soil health, plant health, and weed prevalence. A total of 108 soil samples were collected and analysed at the Measurement Laboratory of PNU. The soil health of the experimental plots was evaluated using standardised methods grounded in internationally acknowledged protocols. Soil sampling was performed according to ISO 18400-201 (2017) series standards, assuring uniformity in the selection, safety, and methodology of sample collection. The granulometric composition was ascertained using the pipette method modified by N.A. Kaczynski, following DSTU 4730:2007 (2008). Soil compaction density and moisture content were assessed using the ISO 11272:2017 (2002) standard and the thermostatic-weight method, respectively. Organic matter, soil organic carbon density (SOCDb), and carbon balance (C:N ratio) were assessed using Tyurin's approach as modified by Simakov (DSTU 4289:2004, 2005). Supplementary factors including pH, electrical conductivity, accessible nitrogen, mobile phosphorus, potassium, sodium adsorption ratio, and cation exchange capacity were evaluated according to national and international standards pertinent to each indicator.

Weed accounting. Weed species and density were assessed weekly in 36 experimental plots from May to August 2024 according to the Handbook of Weed Management (2024). The current weediness of the crops was assessed using route surveys conducted annually during the emergence of all primary weed species. The primary survey for grain crops occurs during the earing period, while for row crops, it took place during their vegetative growth. Concrete strategies for herbicide application during the post-emergence phase were formulated based on weed records collected in the spring following the widespread emergence of seedlings. In each crop rotation field or its segment covering up to 50 hectares, a minimum of 10 monitoring sites must be established, each measuring 2-3 m^2 for perennial weeds and 0.25-1 m^2 for most annual weeds. Approximate accounting method: the density of weeds in the field was evaluated using point scales (Table 2).

For convenience, the scale of projective weed coverage of the soil surface was employed (in points and percentages) (Fig. 3).

Table 2. Six-point scale for assessing soil covered by weeds

Grade	Covering degree	Description
0		no weeds present
1		weeds present individually, with a covering density of around 0.1-3 weeds per 10 m^2
2	up to 5%	3-5 weeds per m^2
3	5-20%	5-15 weeds per m^2, cultivated plants predominate over weeds
4	20-50%	20-30 weeds per m^2, cultivated plants continue to prevail over weeds
5	50-70%	the number of weeds is equal to or greater than the number of cultivated plants, the culture is under threat
6	75-100%	persistent obstruction, weeds substantially dominate cultivated vegetation

Source: *Determination of the actual weediness of crops (n.d.)*

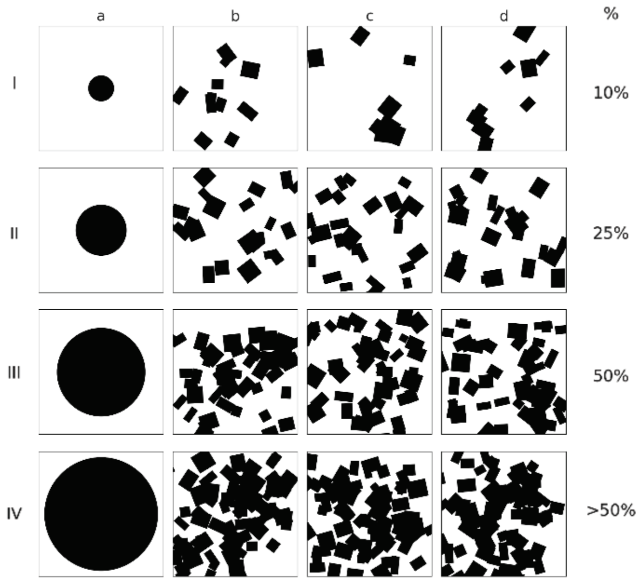

***Figure 3**. Cubic scale for evaluating weediness based on projected weed coverage of the soil surface (in points and percentages)*
***Note:** a, b is the consistent distribution of weeds across the area; c is the cellular coverage; d is the solid coverag*
***Source:** Determination of the actual weediness of crops (n.d.)*

The quantitative accounting method relies on enumerating the cultivated plants and weeds at the designated recording sites. Simultaneously, they use frames of suitable dimensions. Upon enumerating the weeds within the frames, the average quantity per frame and per meter is calculated, alongside a proportion of the cultivated plants, designated as 100%. The extent of crop blockage is assessed using the designated scale (Table 3).

***Table 3**. Scale for determining the degree of weeding of crops*

Number of weeds per 1m^2	Rating	Degree of weeding
1–5	1	Very weak
6–15	2	Weak
16–50	3	Average
51–100	4	Strong
Over 100	5	Very strong

***Source:** Determination of the actual weediness of crops (n.d.)*

The quantitative-weight accounting approach involves enumerating the quantity of weeds by species and their aggregate count, assessing their height, developmental stage, and biomass. All weeds are extracted at the registration site, their roots severed and weighed, thereafter dried to an air-dry condition and reweighed. The Jaccard Index was employed to analyse biodiversity data, which quantifies the similarity between two sets and is widely used in ecology to evaluate species commonality across different areas and experimental conditions.

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|}, \qquad (1)$$

where $|A \cap B|$ is the number of species common to both sites (variants); $|A \cup B|$ is the total number of species occurring in at least one of the sites.

The index varied from 0 to 1, where 1.00 is complete coincidence (species always occur together); 0.00 is no coincidence (species never occur together)

Statistical analysis methods. ANOVA and several statistical methods were used to assess the influence of pesticides and seeding density on weed density. Regression analysis was used to create models for predicting maize development levels. Only factors that maintained statistical significance post-correction were considered credible. The study was conducted following the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

Soil conditions. Before initiating the field experiment, a thorough assessment of the site's soil characteristics was conducted using soil profile analysis and an extensive review of physicochemical data. The soil was categorised as light grey forest loamy medium loam on loamy deposits, designated under the IUSS Working Group WRB (2022) classification as Gleic Albic Luvisol (Endoclayic, Cutanic, Differentic, Katogleyic, Ochric). The soils of experimental plots S1, S2, and S3 exhibited a mildly acidic reaction (pH 4.53-4.71), characteristic of podzolic or acidic soils. The organic carbon percentage varied between 1.68% and 1.9%, signifying a moderate supply of organic matter. The humus concentration was at a moderate level (1.68-1.9%), indicating a moderate buildup of humus (Table 4).

***Table 4**. Changes in agrochemical parameters depending on cultivation*

AS	S1		S2		S3	
	A	Cv, %	A	Cv, %	A	Cv, %
pH sol.. of/pH	4.71 ± 0.39	8.38	4.71 ± 0.71	15.17	4.53 ± 0.43	9.51
Organic carbon, %	0.97 ± 0.3	31.17	1.1 ± 0.3	27.41	1.03 ± 0.32	31.05
Hummus, %	1.68 ± 0.52	31.2	1.9 ± 0.52	27.43	1.78 ± 0.55	31.02
Alkaline hydrolysed nitrogen, mg/kg	75.64 ± 14.4	19.04	77.05 ± 15.41	20	76.28 ± 13.4	17.57
Mobile phosphorus, mg/kg	161.13 ± 93.33	57.92	143.9 ± 67.63	47	139.21 ± 52.84	37.95
Exchangeable potassium, mg/kg	107.38 ± 42.19	39.29	96.95 ± 63.04	65.03	108.62 ± 52.51	48.34
Iron content, mg/kg	5.04 ± 2.52	49.99	9.3 ± 11.63	125.08	6.92 ± 4.82	69.69
Copper content, mg/kg	0.18 ± 0.05	30.64	0.19 ± 0.07	37.22	0.17 ± 0.05	28.89
Zinc content, mg/kg	0.85 ± 0.37	43.56	0.86 ± 0.47	54.79	0.86 ± 0.94	109.82
Hydrolytic value, mmol/100g	2.74 ± 0.52	18.83	2.95 ± 1.04	35.11	3.27 ± 0.76	23.17
Sum of absorbed bases, mmol/100g	5.73 ± 1.98	34.58	6.37 ± 3.57	56.04	5.77 ± 1.93	33.49
Degree of bases saturation, %	65.74 ± 11	16.73	63.66 ± 18.39	28.89	62.11 ± 11.86	19.1

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

The alkaline hydrolysable nitrogen concentration ranged within 75.64-77.05 mg/kg, reflecting a moderate nitrogen supply. The available phosphorus varied within 139.21-161.13 mg/kg, signifying a substantial quantity of phosphorus feeding. The exchangeable potassium concentration ranged within 96.95-108.62 mg/kg, reflecting a medium-to-high potassium availability. The micronutrient makeup included iron at 5.04-9.3 mg/kg, copper at 0.17-0.19 mg/kg, and zinc at 0.85-0.86 mg/kg. The maximum iron concentration was recorded in plot S2. Hydrolytic acidity varied within 2.74-3.27 mmol/100 g, whereas the total absorbed bases ranged within 5.73-6.37 mmol/100 g. The base saturation degree ranged within 62.11%–65.74%, signifying a substantial saturation of the soil's cation exchange capacity with bases. The coefficient of variation (Cv, %) for most indicators varied within 15%-65%, signifying medium-to-high variability of the soils, especially for potassium, iron, and micronutrient levels. The soils of the experimental plots exhibited modest acidity, moderate humus content, adequate nitrogen supply, and elevated levels of accessible phosphorus and potassium, which are conducive to the cultivation of most agricultural crops, contingent upon the neutralisation of acidity.

Weed biodiversity observation. The average height of the main crop ranged from 153.3 cm (S2H2A1) to 176.7 cm (S1H1A2). Variants with H1 generally showed greater crop height than variants with H2, which may reflect better growing conditions. The amount of the main crop was stable for all variants: 8 plants/m^2 for conventional seeding rates and 10 for compacted crops. To control the number of weeds, the herbicide Premium Gold 4.5 L+ Quiet was used, which, according to farmer surveys, is an effective preparation in controlling a wide range of weeds in maize crops. Specifically, the results showed that in H1 variants, some annual cereals were practically absent, namely, *E. crus-galli*, *S. glauca* etc., which were found everywhere in these fields. However, some weeds stayed partially or completely: resistant dicotyledons: *Convolvulus arvensis*, *Raphanus sativum*, as well as perennial grasses: *Elymus (Elytrigia) repens (L.) Gould*. Clearly, weed biodiversity was more widespread in H2 variants. *C. album*, *R. sativum*, etc., were quite widespread.

The variants also differed in the number of weed plants, the largest number of weeds was observed in S2H2A1 (22.3 pcs), the smallest number in S1H1A2 (12.0 pcs). Variants with H2 had slightly more weed cover compared to H1, but the difference was not significant. Weed species were represented unevenly between variants. In some variants such as S3H1A1, they were dominated by a few key species, while in other variants, e.g., S3H2A2, greater diversity was observed. A smaller number of weed species (e.g., S1H1A1) may suggest that certain species dominated and suppressed others. Some weed species were dominant: *Co. arvensis*: highest abundance among all variants, especially in S2H2A2; *Setaria pumila*: significant abundance in many variants, especially in S3H1A1 and S2H1A1; *Equisetum arvense*: found in some variants such as S2H1A1. Other species, e.g., *Capsella bursa-pastoris* or *A. retroflexus*, were represented to a lesser extent or not at all in most variants. The greatest number of weeds was observed in variants S2H2A1 and S3H2A2. This indicates that the conditions of these variants contributed to their growth. In the S1H1A1 variant, the number of weeds was smaller, and their species composition was limited.

Some weed species were concentrated in certain variants, which may be related to agrotechnical conditions. *Chenopodium album* (quinoa): the highest abundance in S1H1A2; *Persicaria lapathifolia*: found only in a few variants, *R. sativum* (wild radish): widespread in almost all variants, but with varying quantities. Therefore, the growing conditions in the variants significantly affected the species composition and number of weeds. The variants with the greatest weed burden (e.g., S2H2A2) required additional weed management to reduce weed numbers and minimise competition with the main crop. During the present study, over 300 weed species were documented growing continuously in fields and uncultivated roadsides. As presented in Figure 4, weed groups in a single field typically consisted of 17-26 species, although in some cases there may be a sizeable number (53-200 species) (Fedoniuk *et al.*, 2024). Within the weed communities, dicotyledonous plants were the dominant species, accounting for 89% of the total. Most of the species consisted of winter weeds, (43%), whereas summer weeds made up only 16%. Regardless of the time of observation, all the current fields surveyed had four species of weeds: *E. repens*, *Co. arvensis* L., and *Sonchus arvensis*. Based on their share of the weed group of *E. repens*, *Co. arvensis*, and *S. arvensis* had a major impact on maize, as the most active portion of the weed block. Without exception, all observed fields contained these species, with mean numbers of during the period of growth of 6-20 pcs/m^2, whereas the projective coverage and ground mass were 16% and 9%, and 250 g and 90 g, respectively.

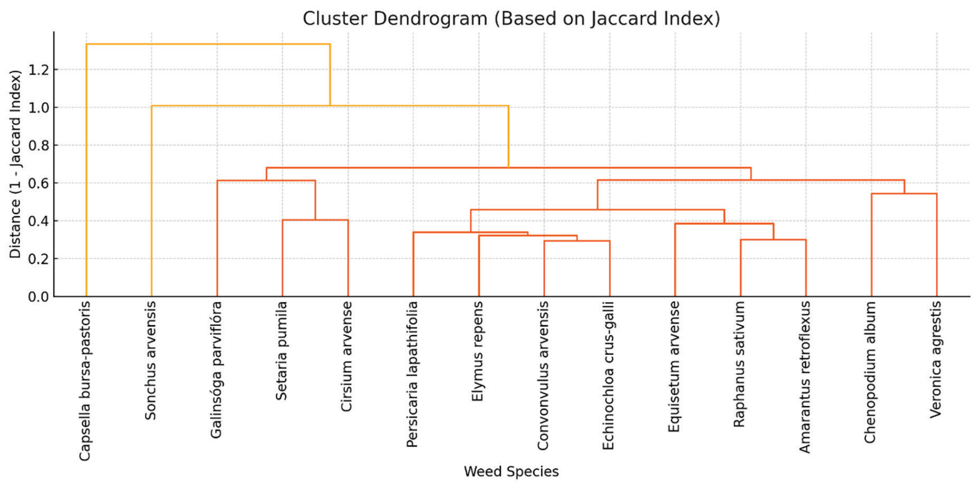

***Figure 4**. Cluster structure of weed species, created based on the Jaccard index, which indicates the similarity of their presence in maize agrophytocenoses*

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

Cluster analysis of weed species, performed using the Jaccard index, elucidated ecological similarities among species based on their presence in maize agrophytocenoses across 12 experimental variants. The Jacquard index served as a metric for the co-occurrence of two species under identical growth conditions. The study revealed that several weed species exhibited distinct clusters, signifying their ecological resemblance. *Co. arvensis*, *R. sativus*, *E. repens*, *E. arvense*, and *E. crus-galli* were identified as the closely associated species, consistently occurring in analogous combinations of soil management, seeding rates, and herbicide use. The similarity index was 0.92, indicating frequent co-occurrence in the same areas. This commonality is likely attributable to shared demands for moisture provision or the structural and mechanical makeup of the soil. Species of moderate prevalence, particularly those from the families *Setaria*, *Galinsóga*, and *Amaranthus*, exhibited less dense aggregations, suggesting greater adaptation potential to alterations in the agro-environment or competition from the primary crop (0.80). Conversely, *C. bursa-pastoris*, *S. arvensis*, and *Veronica agrestis* were allocated to distinct branches of the dendrogram, indicating their infrequent occurrence or reaction to a set of circumstances. These findings are of significant practical relevance: they facilitate the prediction of typical weed associations and the selection of control measure combinations, considering the co-occurrence of species. This is particularly advantageous for devising integrated crop protection strategies for maize. Clustering can be employed for the ecological assessment of weed composition in fields. Subsequent research may involve examining the interrelation of experimental variants and investigating the association between weed species composition and the agricultural characteristics of maize. The cluster technique utilising the Jaccard index is an excellent method for evaluating the composition of the weed component within agrophytocoenosis.

Weed amount observation. In contemporary agricultural production, weed management is a critical aspect influencing the efficacy of maize cultivation. Weeds compete with the primary crop for moisture, light, and nutrients, while also complicating mechanised field cultivation and diminishing yield and product quality. Consequently, in the context of the present study, which encompassed diverse tillage strategies, sowing density, and herbicide treatment, weed control is an essential variable. It facilitates the evaluation of the biological and economic viability of alternative technical options, particularly with the transition to energy-efficient agricultural systems (Fig. 5). The greatest weed development was noted in variants S1H1A2 and S1H2A2, whereas the least weed infestation occurred in S2H2A2. This suggests that the incorporation of surface tillage by disking, the exclusion of pesticides, and increased seeding density (AES) is more effective in weed management compared to conventional techniques. The results of the one-way analysis of variance (ANOVA) on changes in weed infestation were as follows: F-statistic: 13.42; p-value: 3.40×10^{-11}. This reflects statistically significant differences across the experimental variants for the number of weeds ($p < 0.001$). Table 5 presents the results of the analysis of variance (ANOVA), which allows assessing the influence of agrotechnical factors on the number of weeds in maize crops.

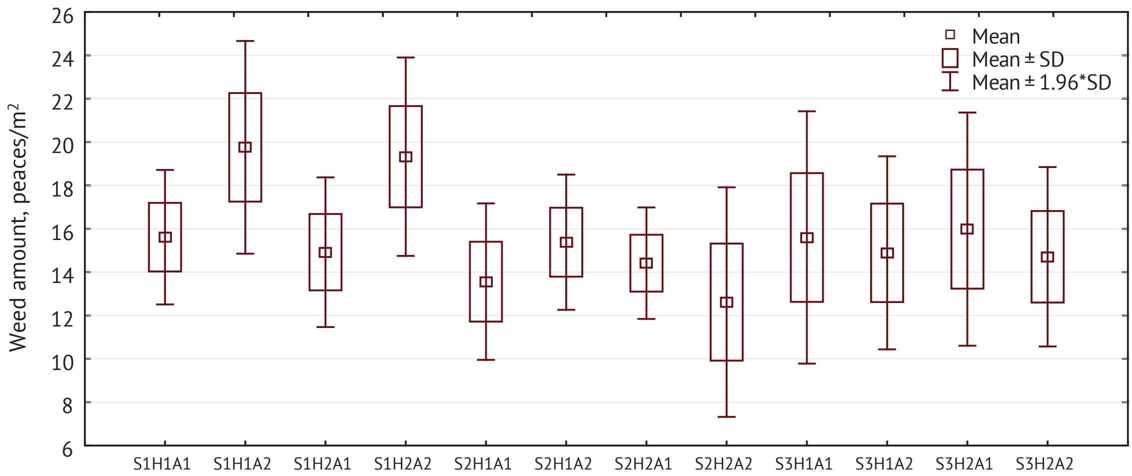

Figure 5*. Box plot depicting the mean and standard deviation of weed infestation (number of weeds per square meter) across 12 versions of the agro-experiment*
Source: *compiled by the authors of this study*

Table 5*. Analysis of variance (ANOVA) results for a three-factor experiment*

Effect	sum_sq	df	F	PR(>F)
C(F1)	924.4801	2	95.28186	2.66E-35
C(F2)	140.9995	1	29.06432	1.13E-07
C(F3)	26.06264	1	5.37231	0.020901
C(F1):C(F2)	609.8311	2	62.85245	7.79E-25
C(F1):C(F3)	22.25571	2	2.293792	0.102046
C(F2):C(F3)	50.01987	1	10.31063	0.001416
C(F1):C(F2):C(F3)	81.32895	2	8.382196	0.000266
Residual	2212.189	456		

Source: *compiled by the authors of this study*

The study considered three factors: tillage system (F1), seeding rate (F2), and herbicide treatment (F3). The results of the analysis of variance indicated that all three studied factors had a different degree of influence on the dependent variable. The most significant was the influence of the F1 factor. Its contribution to the total variation was the largest, and the corresponding p-value was extremely small, which reflected a statistically significant influence of this factor ($F = 95.28$, $p < 0.0001$). This means that different tillage methods do affect the degree of crop litter, and it is likely that milling (as one of the methods of surface tillage) contributes to the reduction of weed numbers by mechanically destroying their seeds or improving the conditions for maize growth. Seeding density, represented by factor F2, also has a statistically significant effect, although less pronounced compared to F1 ($F = 29.06$, $p < 0.000001$). Increasing the seeding rate

(1.1-1.3 seeding units per hectare) probably leads to a thickening of maize crops, which limits access to light and space for weeds, reducing their development.

Factor F3, which describes the use of herbicides, also turned out to be significant, but its effect was the smallest among all three main factors ($F = 5.37$, $p \approx 0.021$). This may suggest that under the conditions of this experiment, the herbicide did not provide the expected effectiveness. Possible reasons are the development of resistance in weeds, the mismatch of the type of herbicide to the spectrum of weeds, or errors in agricultural application techniques. Additionally, alternative methods of mechanical tillage were used in the herbicide-free treatment variants, which provided the desired effect. Furthermore, the analysis of variance revealed a significant interaction between the F1 and F2 factors. This means that the efficiency of seeding density depends on the soil cultivation system used. Such an interaction requires special attention when interpreting the findings, since the same density level can affect the result differently depending on the type of cultivation. At the same time, the interaction between F1 and F3 was not statistically significant, which indicates the absence of a noticeable combined effect between the soil cultivation system and the use of herbicides. Overall, tillage and seeding rates had the greatest impact on weed abundance in maize, while herbicide treatment was ineffective. This highlights the significance of agronomic decisions in an integrated weed control system and indicates the feasibility of improving tillage and seeding approaches.

The findings of this study confirmed the value of agroecological strategies for sustainable weed management in maize agroecosystems. The conducted analysis of variance (ANOVA) revealed a statistically significant influence of tillage systems, which allows concluding that surface tillage, especially milling, markedly reduces the weed load and at the same time promotes the development of cultivated plants due to the improvement of the soil structure and the reduction of the weed seed bank plants in the upper soil layer. These data are consistent with the findings of S. Selvakumar and R. Ariraman (2022) that reducing the intensity of tillage disrupts the germination cycles of weed seeds and improves the conditions for growing maize. One of the key results is the minimal effect of herbicides on the level of crop contamination. Analogous findings emphasise the need to transition to integrated weed management systems, which focus on mechanical and agrotechnical methods. The data are consistent with the conclusions of N. Colbach *et al.* (2025), where, upon modelling sustainable weed management systems in three European cases, the researchers showed that the greatest contribution to sustainability is made by integrated agrotechnical measures adapted to local conditions, including the combination of minimal tillage and optimal sowing times. N. Sharma and M. Rayamajhi (2022) emphasised that the success of integrated weed management in maize crops depended on a complex combination of mechanical, agrotechnical, and biological methods adapted to concrete climatic and soil conditions.

The significance of sowing density deserves special attention. The increase in density provided both the suppression of weeds due to the accelerated closing of the rows, and the improvement of the competitiveness of maize. This result confirms the data of R. Leskovšek *et al.* (2025), where the significance of the density of the standing of cultivated plants for the development of a dense canopy and the reduction of soil illumination was emphasised, which complicates the successful germination for weeds. K. Nthebere *et al.* (2025) also showed that in systems of conservation agriculture based on minimal tillage and mulching, improvements in soil quality and crop stability in arid climates are achieved, which confirms the universality of the revealed patterns.

A valuable discovery of the present study was the absence of a significant interaction between soil treatment and the use of herbicides. This indicates that agroecological mechanical methods can completely replace chemical means of plant protection in certain conditions without losing the effectiveness of weed vegetation management. At the same time, the revealed significant interaction between the tillage system and the density of sowing emphasises the need for a systematic approach to the planning of agrotechnical measures. Cluster analysis using the Jaccard index revealed stable ecological and coenotic relationships between the primary types of weed plants. A stable coexistence of *C. arvensis*, *E. repens*, and *R. sativum* species was established under various cultivation technologies, which indicated their pronounced adaptability. These data are significant for forecasting weed complexes and developing targeted measures to combat them, which was also noted by N. Colbach *et al.* (2025) within the framework of approaches to spatial modelling of sustainable management systems.

Thus, the findings of the present study confirmed the expediency of the transition to the paradigm of agroecological intensification in the cultivation of maize. Such an approach reduces dependence on chemical means of plant protection, contributes to the preservation of soil fertility, biodiversity, and ensures the long-term stability of agroecosystems. Prospective areas for further research include the evaluation of the long-term ecological consequences of the proposed methods, their economic efficiency in the conditions of commercial agriculture, as well as the study of the synergistic effect of combining with cover crops and the use of organic fertilisers.

CONCLUSIONS

The research results validated the efficacy of agroecological weed management techniques in maize agroecosystems. The tillage system had the most substantial effect in diminishing field litter. Specifically, surface tillage, particularly milling, resulted in a notable decrease in weed populations and a concurrent enhancement in crop output due to enhanced soil structure and a reduction in the weed seed bank in the upper layer. Augmenting the seeding density positively influenced the suppression of weed germination, as the extensive coverage of the soil by the maize leaf surface restricted light penetration to the soil, hence inhibiting the proliferation of undesirable vegetation. The influence of herbicides was less significant than other factors, suggesting the possibility of diminishing reliance on chemical protective agents through the implementation of good agronomic methods.

The demonstrated correlation between tillage system and crop density underscored the necessity for a comprehensive approach to agroecosystem management. The integration of surface tillage and heightened crop density yielded optimum outcomes in weed management. Consequently, methodical planning of crop rotation, mechanical tillage, and optimisation of crop density are essential for effective weed control and consistent yields. The results validated the viability of agroecological intensification in maize production as a sustainable method that mitigates environmental burdens, enhances soil fertility, and guarantees the long-term stability of agricultural ecosystems. Future studies should focus on evaluating the long-term ecological consequences of these methods, assessing their economic viability in commercial farming contexts, and investigating synergistic effects with cover cropping and organic amendments. This study provides valuable empirical evidence endorsing the scalability and ecological viability of integrated weed management in maize cultivation.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Стале управління бур'янами у посівах кукурудзи: оцінка агроекологічних практик та систем обробітку ґрунту

Ігор Безверщук
Аспірант
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0009-0007-8081-9815

Тетяна Федонюк
Доктор сільськогосподарських наук, професор
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-6504-0893

Анотація. У дослідженні оцінювалася ефективність агроекологічних підходів боротьби з бур'янами у посівах кукурудзи. Експеримент, проведений у 2023-2024 роках і включав три системи обробітку ґрунту (глибока оранка, дискування, фрезерування), дві густоти посіву (1,1 та 1,3 посівних одиниць/га) та два підходи до застосування гербіцидів (застосування та незастосування гербіцидів), загалом 12 варіантів у 3 повтореннях. Найвищий рівень забур'яненості було зафіксовано у варіанті з дискуванням, низькою густотою посіву та без гербіцидів (S2H2A1) – 22,3 рослини/м²; найнижчий – у варіанті з оранкою, високою густотою посіву та застосуванням гербіцидів (S1H1A2) – 12 рослин/м². Варіанти з ущільненим посівом, незалежно від застосування гербіцидів, продемонстрували кращу здатність до пригнічення бур'янів завдяки швидкому змиканню міжрядь та зменшенню доступу світла. Дисперсійний аналіз (ANOVA) показав, що найбільший вплив на кількість бур'янів мав обробіток ґрунту ($F = 95{,}28$; $p < 0{,}0001$), далі йшла густота посіву ($F = 29{,}06$; $p < 0{,}000001$), а внесок гербіцидів був найменшим ($F = 5{,}37$; $p \approx 0{,}021$). Значна взаємодія між системою обробітку та густотою посіву ($F = 62{,}85$; $p < 0{,}000001$) свідчить про необхідність комплексного планування агротехнічних заходів. Кластерний аналіз на основі індексу Жаккара виявив сильні екологічні зв'язки між видами бур'янів — зокрема, *C. arvensis*, *E. repens* та *R. sativum* мали коефіцієнт подібності 0,92, що дозволяє прогнозувати типові фітосоціальні комбінації та розробляти цілеспрямовані заходи боротьби. Результати засвідчили, що агроекологічні стратегії, включаючи поверхневий обробіток ґрунту та ущільнений посів, можуть успішно замінити хімічні методи, зменшуючи навантаження на довкілля та підтримуючи стабільність продуктивності. Практична цінність дослідження полягає у доведеній можливості мінімізації використання гербіцидів при збереженні високої врожайності кукурудзи шляхом впровадження адаптованих агротехнічних рішень

Ключові слова: агроекологія; боротьба з бур'янами; *Zea mays* L.; системи обробітку ґрунту; родючість ґрунту; альтернативи гербіцидам; продуктивність рослин

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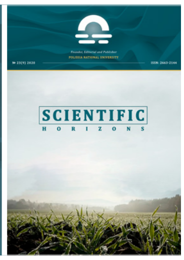

Comprehensive assessment of potato bacterial pathogens and development of resistance improvement methods

Sevinj Maharramova
Doctor of Philosophy, Associate Professor
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Azerbaijan
https://orcid.org/0000-0002-1599-7013

Maryam Mammadaliyeva
Doctor of Philosophy, Teacher
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Azerbaijan
https://orcid.org/0000-0002-4351-8286

Mehriban Yusifova
Doctor of Philosophy, Associate Professor
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Azerbaijan
https://orcid.org/0000-0001-7608-5950

Gunash Nasrullayeva
Doctor of Philosophy, Associate Professor
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Azerbaijan
https://orcid.org/0000-0003-2661-8354

Yuliia Kolomiiets*
Doctor of Agricultural Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-1919-6336

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Abstract. The study analysed the composition of potato bacterial pathogens and the effectiveness of different strategies for building crop resistance in agroecosystems. The study combined theoretical analysis of literature on pathogen properties and resistance mechanisms with experimental testing of its agrobiological methods under growing conditions for comparative evaluation of the effectiveness of controlling bacterial diseases of potatoes. The study determined that *Ralstonia solanacearum* showed the highest pathogenic activity under the experimental conditions, causing systemic wilt of plants. *Pectobacterium carotovorum* mainly affected tubers, forming foci of wet rot, while *Clavibacter sepedonicus* showed a slow infection process, which

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*Corresponding author

was more often diagnosed at the storage stage. The development of bacterial diseases of potatoes intensified under conditions of excessive soil moisture, temperatures above 27°C, mechanical damage and accumulation of organic residues. The formation of a stable rhizosphere microbiota, with the participation of representatives of the genera *Pseudomonas* and *Bacillus*, contributed to a 47-62% reduction in the sickness index and a 25-31% increase in vegetative mass compared to the control. Different tolerance mechanisms dominated in the studied varieties: vascular resistance in Solokha, which provided a 62% reduction in lesions, 31% weight gain and 2.2 additional tubers per plant. Dnepryanka showed a biochemical response, with a 3.1-fold increase in peroxidase activity and a 1.6-fold increase in phenylalanine ammonia lyase, and Lugovska showed a microbiological control, with a rhizosphere colonisation density of up to 1×10^5 colony-forming units per gram of soil and an increase in the number of tubers by 24. The obtained results are of practical importance for the development of integrated potato protection schemes that involve the use of bioagents and resistance inducers as an effective alternative to chemicals, as well as for the implementation of an early diagnostic monitoring system based on bioindicators in breeding and agricultural production technologies

Keywords: microbiota; soil; moisture; resistance; agroecosystem; endophytes; wilting

INTRODUCTION

Potatoes (*Solanum tuberosum* L.) are one of the four most widely produced crops in the world, behind only corn, rice and wheat. It is a key source of carbohydrates in the diets of more than 1 billion people and is widely used in the food, starch and alcohol industries. Bacterial diseases cause significant yield losses, reduce tuber quality, complicate storage and pose economic risks to producers. The rapid adaptation of pathogens, their ability to persist in the soil, and a wide range of host plants make controlling them particularly challenging, so the issue of increasing potato resistance to bacterial pathogens remains relevant.

In response to the growing threats posed by bacterial diseases of potatoes, several international organisations are actively implementing evidence-based programmes to reduce phytopathogenic risks. The Food and Agriculture Organisation studies the global spread of bacterial diseases of potatoes in the context of food security, develops recommendations for reducing phytosanitary risks and implements integrated plant health management policies (Rolot, 2012). A. Charkowski *et al.* (2020) conducted genetic characterisation of the main bacterial pathogens, in particular *Ralstonia solanacearum* and *Clavibacter sepedonicus*, investigated resistance mechanisms and developed varieties with increased resistance to pathogens. The European Food Safety Authority (2019) assessed the risks associated with the spread of phytopathogens through planting material, harmonised diagnostic methods and regulates quarantine measures within the European Union. All these organisations support integrated approaches to combating bacterial infections, including monitoring, breeding, early diagnosis and biological control.

In different regions of the world, bacterial diseases of potatoes have specific epidemiological features that necessitate the adaptation of control methods to specific agroclimatic conditions. In Eastern Europe, in Ukraine, phytopathogenic bacteria remain one of the key factors in reducing potato yields, as confirmed by N. Yarema (2023), who emphasises the importance of using resistant varieties and introducing biological control. In North America, J. Yuan *et al.* (2020) conducted an association genomic analysis of scab resistance based on Canadian potato collections, which identified candidate genes for breeding. In South Asia, in India, R. Manda *et al.* (2020) described the epiphytic spread of bacterial wilt caused by *Ralstonia solanacearum*, emphasising the role of high temperatures and moisture in exacerbating the pathogenesis. In Africa, namely in Ghana, together with the East Asian countries of Japan and South Asian Pakistan, S. Ismail *et al.* (2020) investigated the variability of *Streptomyces scabies* pathogenicity and resistance levels of varieties, confirming the wide ecological plasticity of the pathogen. Bacterial diseases of potatoes are transcontinental in nature, but effective control is possible only if regional biotic and abiotic factors are addressed.

In modern research, there is a growing interest in biological strategies for potato protection aimed at reducing the use of chemicals and increasing plant resistance to bacterial pathogens. The analysis of photosynthetic parameters has proved to be a promising tool for assessing the effectiveness of biological products: T. Khomenko *et al.* (2023) proved that the induction of chlorophyll fluorescence sensitively reflects the response of potatoes to biological treatment, which can be used to assess the physiological effect of the products in the field. H. Balan (2020) presented the concept of integrated crop protection, which involves the combination of agrotechnical techniques with biological methods, creating the basis for adaptive models of pathogen control depending on the stage of plant development. In addition, J.-M. Liu *et al.* (2020) identified endophytic bacterial strains from potato tubers that showed antagonism to phytopathogens and at the same time reduced solanine levels, indicating their potential as dual-acting biological products.

Modern approaches to improving potato resistance include the use of markers that can be used for a quick assessment of resistance in varieties. A. Khairy *et al.* (2021) found that the activity of peroxidase (POD), polyphenol oxidase (PPO) and the content of phenolic compounds correlated with tolerance to *Ralstonia solanacearum*, which confirms the feasibility of using biochemical parameters for breeding screening. In turn, P. Paluchowska *et al.* (2022) analysed the effectiveness of the Resistance to *Phytophthora infestans* genes in the formation of long-term resistance to late blight, emphasising the importance of the genetic combination of resistant alleles.

Despite the availability of numerous studies, the interaction between the species composition of potato bacterial pathogens, the peculiarities of the infection process and the effectiveness of available methods of increasing resistance in a changing environment remains insufficiently covered in the scientific literature. The study aimed to summarise information on bacterial pathogens of potatoes, assess the effectiveness of existing approaches to improving their resistance and develop agrobiological and biotechnological methods of resistance induction, incorporating varietal characteristics.

MATERIALS AND METHODS

The study included both theoretical and experimental components that were interrelated within the overall goal of a comprehensive assessment of the factors of bacterial damage to potatoes and the development and testing of effective agrobiological and microbiological methods to increase their resistance. The study covered the following aspects: morphological and molecular characteristics of pathogens, mechanisms of infection, conditions of infection development, host plant responses and control strategies. This approach provided an in-depth study of the material and was used to conduct a systematic analysis of pathogenic factors. To summarise the theoretical understanding of the key factors of pathogenesis, the analysis of their relative impact on the course of bacterial infections of potatoes was conducted. The degree of influence was assessed using a scale of conditional intensity (from 0 to 10), which was based on a critical comparison of the mechanisms of action described in leading sources of modern phytopathology (Ashmawy *et al.*, 2020; Mohamed *et al.*, 2020). The focus was on pathogens with high ecological plasticity and the ability to persist in agroecosystems, such as *Ralstonia solanacearum*, *Pectobacterium carotovorum* and *Clavibacter sepedonicus*.

Three potato genotypes, Solokha, Dnipryanka and Luhovska, were selected for the theoretical analysis of varietal differentiation by resistance type, which are the result of breeding work of the Institute of Potato Growing of the National Academy of Agrarian Sciences of Ukraine. The varieties are characterised by differences in their anatomical and morphological structure, enzymatic profile and ability to interact with the rhizosphere microbiota. Solokha belongs to the medium-early maturity group (vegetation period 90-95 days), has an average tuber weight of 90-110 g and demonstrates increased vascular resistance with a tolerance index of 7.8 points on a 9-point scale. Dnepryanka is a mid-season variety (growing season 100-110 days) with an average tuber weight of 80-100 g and pronounced biochemical reactivity, resistance index 6.9 points. Luhovska is a medium-early variety (95-100 days), with a tuber weight of 85-105 g, a well-developed rhizosphere microbiota and a resistance index of 7.2 points. These varieties were chosen due to their representativeness in terms of the main levels of the defence response: anatomical and vascular (Solokha), biochemical (Dnipryanka) and microbiological (Luhovska). This differentiation ensured the completeness of the comparative analysis and conducted a structured generalisation of typical mechanisms of potato resistance under pathogenic stress.

The synthesis of scientific sources integrated knowledge about the nature of bacterial pathogenesis with the understanding of potato resistance at different levels: genetic, biochemical and microbiological. Based on the repeated patterns, generalisations were made about the typical mechanisms of resistance formation, regardless of the pathogen type or regional conditions. To compare the effectiveness of control methods, the method of analogies and comparisons was used, which analysed classical agronomic strategies (crop rotation, sanitary measures) and modern biotechnological approaches (use of molecular markers (MAS), genome editing technologies (CRISPR), endophytes, resistance inducers). The comparison criteria included adaptability, environmental safety, labour costs, effectiveness in different epiphytic conditions and technological availability.

The experimental part of the study was aimed at testing the developed methods for increasing potato resistance to bacterial pathogens and validating diagnostic bioindicators identified in the theoretical analysis. The experiment was conducted in greenhouse conditions from April to July 2024, according to a scheme that modelled the infection load typical for central Polissya. The zone was chosen due to its typical soil and climatic characteristics favourable for the development of bacterial diseases. The substrate was a sod-podzolic sandy loam soil with a pH of 5.5-5.7 and an organic matter content of 1.5%. Humidity was maintained at 75-80%, with simulated total precipitation of 270 mm. The temperature regime was 22-26°C during the day and 14-18°C at night, under natural light. This ensured the reproduction of real agro-ecological conditions, which usually result in intensive damage to potatoes by bacterial pathogens.

The developed methodology was based on a combination of agrobiological techniques and microbiological biocontrol. The antagonistic strains of *Pseudomonas fluorescens* PF-07 and *Bacillus subtilis* BS-12 isolated from the rhizosphere of healthy plants were used as bioagents. The cultures were grown on LB and NA nutrient media for 48 hours at 28°C, after which the suspensions were standardised to a concentration of 10^8 CFU/ml. To induce systemic resistance, salicylic acid at a concentration of 0.5 mM and laminarin extracted from brown algae at a concentration of 0.1% were used. Plants were treated twice on the 7th and 14th day after planting. In the variants of combined action, tubers were pretreated with bioagents and the aboveground mass with inducers. The study included a control group that was not subjected to any of the active treatments and received only an aqueous suspension, which assessed the natural course of the infection process and basic indicators of the physiological state of plants.

The infection model involved inoculation of the root zone with a mixture of bacterial pathogens *Ralstonia solanacearum* and *Pectobacterium carotovorum* at a concentration of 10^7 CFU/ml. Infection was carried out on the 21st day after planting. For each variant of the experiment, 30 plants were used. Observations and data collection were conducted on the 14th and 28th day after the infection load was applied. The criteria for evaluating the effectiveness of the methods were the degree of damage (severity index on a 5-point scale), the activity of POD and phenylalanine ammonia lyase (PAL) enzymes in leaf tissues (determined by spectrophotometric methods), the density of rhizosphere colonisation by antagonists (in CFU/g soil), as well as the vegetative mass and number of formed tubers. The experimental design included control and experimental variants, with the separation of the effect of each factor and their combination. The collected data were used for empirical verification of theoretically defined resistance bioindicators and clarification of the differentiation of protection mechanisms by variety type. The results were processed using the methods of variation statistics using Microsoft Excel (version 2019) and Statistica (version 12.0). The significance of differences between variants was assessed using Student's t-test at a significance level of $p < 0.05$. For each indicator, the arithmetic mean and standard deviation were calculated based on the results of three replications. The model was tested in compliance with the requirements of bioethical responsibility and environmental safety. The use of bioagents did not violate international bioregulation standards and complied with the principles of biodiversity protection enshrined in the Convention on Biological Diversity (1992). Modelling of the infection process was conducted in isolated vegetation conditions without the risk of pathogens spreading to the environment.

RESULTS

Biological characteristics of common bacterial pathogens of potatoes. Bacterial pathogens of potatoes are one of the most dangerous groups of phytosanitary threats to modern potato production, causing yield losses both during the growing season and during storage. Their impact on the plant is implemented through a variety of pathogenesis models that include both local necrotic lesions and systemic infections of the conducting tissue. A thorough study of the biological properties of the main pathogens not only further analysed the mechanisms of infection, but also formulated sound strategies for diagnosis, prevention and selection of resistant varieties. Different bacterial pathogens of potato implement their infectious properties through specific biological strategies that differ significantly in dynamics, localisation and mechanism of spread. *Ralstonia solanacearum* is characterised by a high rate of disease development with early systemic symptoms that often lead to complete wilting of plants during the growing season. After entering the rhizosphere, the bacterium quickly colonises the conducting system, avoiding the surface immune response and creating significant phytosanitary pressure even with a moderate infection load.

Pectobacterium carotovorum implements a different model of damage based on the gradual destruction of tissues due to the accumulation of enzymes. In contrast to systemic wilt, its activity is accompanied by local destruction of the parenchyma, which is especially intense during the tuber ripening phase and storage. A characteristic feature of this pathogen is the rapid transition from subclinical to massive rotting under conditions of high humidity, which significantly complicates control during post-harvest processing. In the case of *Clavibacter sepedonicus*, the infectious process develops slowly and often goes unnoticed until the late stages. The latent nature of the course, poor visualisation of symptoms in the field and the gradual accumulation of bacterial mass in the conducting system make diagnosis difficult. The first signs of infection are recorded in storage facilities, which require a thorough inspection of planting material and technical equipment (Osdaghi *et al*., 2022). Based on the analysis of literature data, the biological parameters of the most common bacterial pathogens of potatoes are summarised (Table 1).

***Table 1**. Primary characteristics of bacterial pathogens of potatoes*

Pathogen	Type of bacterium	Main lesion	Key factors of pathogenicity	Place of defeat	Method of penetration
Ralstonia solanacearum	Gram-negative, mobile, aerobic	Bacterial wilt	Pectate lyases, cellulases, proteases, biofilms, type III secretion	Root, stem, xylem, leaves	Through the root system, mechanical damage

Table 1. Continued

Pathogen	Type of bacterium	Main lesion	Key factors of pathogenicity	Place of defeat	Method of penetration
Pectobacterium carotovorum	Gram-negative, optionally anaerobic	Wet rot	Pectolytic enzymes (pectate lyases, polygalacturonases)	Tubers, basal stem, and rarely leaves	Through wounds, natural openings, mechanical damage
Clavibacter sepedonicus	Gram-positive, immobile, aerobic	Ring rot	Mucosal colonies, xylem blockage, exudative activity	Xylem of tubers and stems	Due to injuries, infected planting material

Source: *compiled by the authors based on N.A. Ashmawy et al. (2020), B.F. Mohamed et al. (2020)*

The presented results distinguished pathogens by morphological and functional characteristics, type of infectious process and organs they affect. As such, *Ralstonia solanacearum* has the most aggressive model of systemic pathogenesis, penetrating the vascular system through the root zone and causing generalised wilting. While *Pectobacterium carotovorum* forms local necrotic lesions with obvious macroscopic symptoms, *Clavibacter sepedonicus* occurs mainly in the storage phase, when disruption of the conductive tissue leads to delayed rot of tubers. Of scientific value is the establishment of a link between the type of pathogen and the location of its action. This can be used for a differentiated approach to the development of control strategies, including the creation of targeted breeding models based on which plant organ needs protection. This division is a prerequisite for further integration of resistance biomarkers into diagnostic algorithms.

The study of the ecological dynamics of the main pathogens of bacterial infections of potatoes shows their ability to effectively maintain virulence under different environmental conditions. *Ralstonia solanacearum* is an example of a bacterium with a high degree of persistence: it can persist in soil, weeds, surface water and even in a latent state in infected plants. The ability to switch to the VBNC state ensures its survival under stressful conditions and re-infection after changes in the environmental situation. *Pectobacterium carotovorum* has a slightly different ecological profile: it is better adapted to moderately humid conditions and actively spreads in the presence of organic residues. Its persistence is maintained by preservation in affected tubers, plant residues and on the surface of machinery, which ensures long-term infectious pressure in the field and storage facilities. In contrast, *Clavibacter sepedonicus* shows a lower level of persistence in the open environment but can persist in tubers and on equipment for a long period of time. This makes it particularly dangerous in the post-harvest period, when the infection can be activated during transport and storage (Osdaghi *et al.*, 2022).

All three pathogens are characterised by marked ecological plasticity, which can be subsequently adapted to a wide range of climatic zones. For example, *R. solanacearum* has several phylotypes and biovars that differ in temperature adaptation: phylotype II remains pathogenic even in temperate regions, while phylotype I predominate in the tropics. *Pectobacterium* spp. are highly sensitive to humidity and temperature but can change their level of aggressiveness depending on the microbiological environment. In turn, *Clavibacter sepedonicus* is closely associated with cool climates, but even in such conditions, it shows great interstrain variability (Singh *et al.,* 2025). Molecular phylogenetic studies confirm that bacterial pathogens of potatoes have a high capacity for evolutionary restructuring under the influence of climatic factors. This adaptability is associated with horizontal gene transfer, variation in the expression of pathogenic proteins and changes in secretion systems. For example, *Ralstonia solanacearum* changes its transcriptional profile under warming conditions, which ensures more efficient penetration into plant tissues, while *Pectobacterium* spp. Changes its enzyme production profile with increasing humidity. Similar climate-mediated shifts in pathogenicity have also been identified in *Clavibacter sepedonicus*, which highlights the need to integrate variability data into phytopathogenic risk prediction systems.

Key factors in the development of bacterial infection in agroecosystems. The effectiveness of the pathogenesis of bacterial diseases of potatoes is due to the complex interaction of abiotic, biotic and agrotechnical factors that form the microenvironment of the agroecosystem. The systematic analysis identified at least seven main factors that can enhance or suppress the development of infection: air temperature, soil moisture, soil type, genetic vulnerability of the variety, presence of antagonistic microbiota, mechanical damage to plants and residual organic residues after harvesting. Their effect is non-additive: it is combinations of these conditions that create a favourable or suppressive environment for pathogens (Vega *et al.*, 2023). Temperature is the basic trigger for the activation of pathogenic systems in phytobacteria. For example, *Ralstonia solanacearum* is most aggressive at temperatures of 27-30°C, which coincides with the peak of the growing season. Under such conditions, the intensity of biofilm formation and mobility increases significantly, which increases the efficiency of colonisation of the root zone. *Pectobacterium* spp. Produce pectolytic enzymes more actively in wet and warm weather, which accelerates tissue decomposition. In contrast, *Clavibacter* *sepedonicus* remains pathogenic in moderately cool environments, which explains its spread in areas with prolonged storage of tubers (Leitão, 2020).

Soil moisture is a key factor for the survival and migration of pathogens in the rhizosphere. Excess water creates hypoxic conditions favourable for facultative anaerobic bacteria (such as *Pectobacterium carotovorum*) and reduces the barrier function of the root apoplast. In wet soils, the colonisation space expands, which is especially substantial in the early stages of plant growth when the immune system is not yet sufficiently formed (Wang *et al.*, 2023). Soil type determines not only the structure of the water-air regime, but also the composition of the microbial community. In sandy loam soils, with sufficient moisture, there is an increased mobility of *R. solanacearum* pathogens, while heavy clay soils delay their progress, but instead accumulate organic residues that serve as a secondary reservoir of infection. The presence of mulch, irrigation and acidity also affects the dynamics of infection.

The genetic vulnerability of a variety is manifested through a deficiency in the primary (PAMP-dependent) and secondary (effector-dependent) immune response. Potato varieties that do not express sufficient levels of phenolic metabolism enzymes, such as POD and PPO, are much more susceptible to early infection. At the same time, even genetically resistant varieties are susceptible to infection if tissues are weakened by calcium deficiency, mechanical damage or irrational nitrogen application (Tripathi *et al.*, 2024). The microbiota of the agroecosystem, especially endophytic bacteria, has a modulating effect on pathogenesis. The mechanisms of this influence include competition for a colonisation niche, secretion of bactericidal compounds (bacteriocins, siderophores, phenazines), induction of plant systemic resistance through JA/ET signalling pathways, and synthesis of phytohormones (auxins, cytokinins) that maintain physiological tissue integrity. The presence of microorganisms such as *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Enterobacter cloacae* in the rhizosphere significantly reduces the frequency of attachment of phytopathogens to the root epidermis (Vega *et al.*, 2023).

Mechanical damage is another critical factor that opens the entry gates for infection. Damaged areas lose their cellular integrity and barrier function, becoming the object of priority colonisation. In most cases, infection due to damage is rapid and is accompanied by the rapid development of rot. The presence of organic residues in the field after harvesting creates conditions for the long-term persistence of pathogens, especially *Pectobacterium* spp. Organic residues serve as both a physical substrate for bacterial preservation and a source of readily available carbohydrates that maintain microbial activity between growing seasons (Leitão, 2020). For generalisation, the author's assessment of the relative intensity of the main factors' influence on the development of bacterial diseases of potatoes was conducted. The conditional scores (0-10) were formed based on the analysis of scientific sources and comparison of the mechanisms of action of each of the factors described in the modern phytopathological literature (Fig. 1).

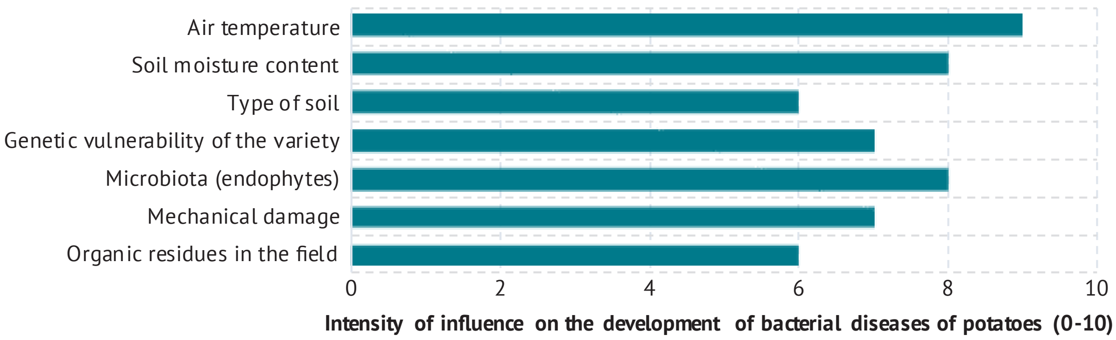

Figure 1*. The relative intensity of the influence of factors on the development of bacterial diseases of potatoes*
Source: *compiled by the authors based on N.A. Ashmawy et al. (2020), P. Nolte et al. (2020), C. Singh et al. (2025)*

The most influential factors in the development of bacterial infection are temperature, soil moisture and the presence of a functional microbiota. These three elements form the basis of the environmental pressure that determines the pace and extent of pathogenesis. At the same time, second-level factors such as genetic resistance of the variety, mechanical damage, and soil type play the role of "triggers" that can either neutralise the threat or sharply exacerbate it. The diagram also illustrates those subtle components such as organic residues have a cumulative effect, creating an infectious background for future seasons. This highlights the importance of a multifactorial risk assessment rather than an isolated analysis of individual parameters. Thus, further modelling of the risks of bacterial diseases of potatoes should be based on a comprehensive consideration of environmental factors, plant genotype and biotic environment. The obtained results confirm the importance of an adaptive phytosanitary approach that integrates prevention, biocontrol and ecologically oriented management of the agrosystem.

Integration of genetic, biochemical and microbiological resistance mechanisms. The resistance of potatoes to bacterial diseases is formed as a multicomponent system that includes genetically determined traits, biochemical reactivity of tissues and interaction with the regulatory microbiota. A systematic analysis of the data identified three levels of resistance, which operate independently and in interaction, and it is this multilevel integration that ensures stable tolerance to infection in agroecosystems with a changing environment (Muthoni *et al.*, 2020). At the genetic level, the critical factor is the presence of alleles associated with the perception of pathogen-associated molecular structures and the recognition of bacterial-derived effectors. These are primarily PRR receptors and NB-LRR class proteins that activate local signalling cascades. In modern breeding programmes, QTL mapping, marker-assisted selection and CRISPR-Cas are widely used to identify and record such traits. During the analysis of scientific sources by A. Sharma *et al.* (2022), the study determined that the Solokha variety has a stable tolerance to *Ralstonia solanacearum*, which was confirmed by field observations in high humidity conditions. Genetic analysis in the studies indicates the presence of QTL loci associated with resistance to vascular pathogens.

The biochemical component of defence is associated with the activation of enzymes that catalyse the formation of protective metabolites or strengthen cell walls. Among them are POD, PPO, and PAL. Their activity correlates with the ability of the plant to localise the infection in the first hours after infection. The study by S. Kaur *et al.* (2022) indicated that in the Dnepryanka variety, under the infection load of *Pectobacterium carotovorum*, an accumulation of phenolic compounds and an increase in POD and PAL activity were observed within 24 hours. This was accompanied by a partial limitation of the development of wet rot symptoms, which is typical for induced systemic resistance. The microbiological level of resistance is associated with the presence of antagonistic microorganisms in the rhizosphere or tissues of potatoes. These are mainly endophytes capable of producing antimicrobial metabolites, siderophores, cellulolytic enzymes and modulators of the phytohormonal profile. According to X. Huang *et al.* (2021), a high level of root colonisation by Pseudomonas fluorescens and *Bacillus subtilis* strains was found in the Luhovska variety adapted to Polissya conditions, which was associated with a reduction in the symptoms of ring rot caused by *Clavibacter sepedonicus*. The analysis of vegetative parameters in the studies showed the preservation of turgor and stable productivity, which confirms the effectiveness of biocontrol.

The integrative model presented in Table 2 shows that effective resistance in potato depends on the interaction of at least three levels of defence. None provide full resistance in isolation: for example, the presence of R genes without enzymatic support or in a depressed microbiota does not guarantee control of infection. The studied varieties demonstrate the differential activity of these levels: Solokha has a pronounced genetic resistance, Dnepryanka activates an enzymatic response, and Lugovska combines moderate genetic resistance with a high level of microbiological control.

***Table 2**. Main levels of potato resistance to bacterial pathogens and typical mechanisms*

Level of resistance	Typical mechanisms	Examples (varieties/pathogens)
Genetic	R-gene alleles, PRR, NB-LRR, QTL, CRISPR	Straw/Ralstonia
Biochemical	POD, PPO, PAL activity, phenol accumulation	Dnepryanka/Pectobacterium
Microbiological	Endophyte antagonism, induced systemic resistance, production of siderophores, and bacteriocins	Lugovskaya/Clavibacter

***Source:** compiled by the author based on S. Kaur et al. (2020), J. Muthoni et al. (2020) and X. Huang et al. (2021)*

This indicates the feasibility of a multi-level breeding evaluation, which involves not only screening based on a single marker, but also the study of the enzymatic profile and interaction with beneficial microbiota. The combination of genetic, biochemical and microbiological mechanisms ensures effective control of bacterial infections in the field. Inoculation with *Enterobacter cloacae* and *Trichoderma asperellum* reduced the damage caused by *Ralstonia solanacearum* in wet conditions, activation of POD, PAL and PPO enzymes limited the development of *Pectobacterium carotovorum*, and colonisation of the root zone by *Bacillus subtilis* and *Pseudomonas fluorescens* strains effectively suppressed the symptoms of ring rot.

Comparative effectiveness of modern methods of increasing sustainability. Methods of increasing potato resistance to bacterial pathogens are divided into traditional (agronomic measures) and modern (genetic and biotechnological tools), each of which has specifics, limitations and potential for adaptation to agroecological conditions. A systematic comparison of these approaches identified the feasibility of applying a particular approach depending on the level of pathogenic pressure, type of infection, access to resources, and regional characteristics. Traditional methods, such as crop rotation, use of healthy planting material, good machinery hygiene, and phytosanitary practices (removal of affected tubers, stems, and plant residues) that reduce the infection background and the risk of pathogen persistence in the following season, remain the basic tools for reducing the infection background. They are particularly effective in controlling soilborne pathogens such as *Pectobacterium* spp. and *Clavibacter sepedonicus* and in regions with moderate infection pressure. These approaches are highly adaptable, easy to implement and environmentally friendly. However, in the event of epiphytotic or systemic infections, their effectiveness is significantly reduced (Vilvert *et al*., 2022).

Genetic methods that are considered modern include breeding varieties with integrated resistance traits, MAS and CRISPR/Cas. MAS accelerates the selection of tolerant genotypes, while CRISPR technologies enable targeted modification of susceptibility genes. Although most studies analysed fungal infections, the prospects for transferring this technology to bacterial pathogens have been confirmed at the conceptual level. At the same time, the use of such methods requires complex laboratory support, high cost, and regulatory compliance (Kieu *et al*., 2021). Biotechnological strategies, in particular biological defence using antagonistic microorganisms (*Bacillus*, *Pseudomonas*, *Trichoderma*), are becoming increasingly important as an environmentally friendly alternative to chemical intervention. Biological products not only inhibit pathogens but also activate the plant's immune mechanisms, including induced systemic resistance. For example, Planriz, based on *Pseudomonas chlororaphis*, reduces bacterial rot damage during pre-planting treatment of tubers. However, the effectiveness of biocontrol can vary depending on soil type, weather conditions, and the competitiveness of local microflora (Devaux *et al*., 2021). The analysed data demonstrate that the integration of methods (e.g., a combination of breeding resistant varieties, biological products and agronomic practices) gives the best results: in several EU farms, according to organic standards, this reduced phytosanitary losses by more than 35%. For clarity, traditional and modern methods are compared by the main criteria of implementation efficiency (Table 3).

***Table 3**. Comparative characteristics of methods for increasing potato resistance to bacterial pathogens*

Method type	Efficiency	Adaptability	Eco-friendliness	Main limitations
Agronomic measures	Average	High	High	Limited effect at high pathogen load
Selection, MAS	High	Average	High	Long selection periods, access to genetic material
CRISPR editing	Very high	Low-medium	High	High cost, regulatory restrictions
Biological products	Medium-high	Average	Very high	Dependence on conditions, need for adaptation

Source: *compiled by the author based on J.C. Stark et al. (2020), E. Aksoy et al. (2021), J. Hao and K. Ashley (2021)*

The comparison shows that traditional methods have the highest accessibility and adaptability, especially for small and medium-sized farms. In contrast, modern tools such as MAS, CRISPR, and biocontrol provide higher target efficiency, but require a high level of technical implementation, investment, and institutional support. Biological methods are the most appropriate for sustainable farming, and genetic methods are for creating long-term solutions. Maximum effectiveness is achieved by combining several approaches adapted to a specific pathogen-ecosystem situation. Effective management of potato resistance to bacterial infections requires the integration of traditional and innovative methods rather than their opposition. A promising direction is the development of adaptive protection models that combine genetically determined resistance, biocontrol and phytosanitary regulation following local agroecological conditions.

Development and testing of the author's methods to improve potato resistance. As part of the empirical verification of the effectiveness of the developed complex of agrobiological measures, the increase in potato resistance was assessed by comparing the response of three varieties, Solokha, Dnipryanka and Lugovska, by several biochemical, microbiological and morphophysiological parameters. Each variety was characterised by a different level of initial tolerance to the main bacterial pathogens, which was used for a comparative analysis of the impact of the developed bioengineering approaches. The results demonstrate a significant reduction in the disease index in all experimental variants with the combined use of antagonistic strains and resistance inducers. In Solokha, the average reduction of the index was 62%, which reflected the suppression of systemic wilt caused by *Ralstonia solanacearum*. In Lugovska, the index decreased by 55%, mainly due to the containment of ring rot. In Dnipryanka, which proved to be more sensitive to *Pectobacterium carotovorum*, the index decreased by 47% compared to the control. In the control groups of all varieties, the infection process was accompanied by typical symptoms: wilting, putrefactive changes in the root part and destruction of vascular tissue.

Biochemical parameters confirmed the activation of the enzymatic plant defence in response to the treatments. The highest POD activity was recorded in Dnepryanka at 3.1 U/g protein, which was almost twice the value in the control variant. This was consistent with the limitation of the local spread of wet rot in the lower nodes of the stem. PPO activity in Solokha exceeded the control values by 1.8 times, indicating the effective incorporation of an enzymatic barrier against vascular pathogens. In Luhovska, both enzymes demonstrated a consistently high level of activity, although the absolute values were inferior to those of Dnipro. The colonisation of the rhizosphere by antagonistic strains of Pseudomonas fluorescens and *Bacillus subtilis* reached maximum values in Lugovska and Solokha of 1×10^5 CFU/g soil. This level was associated with the effective displacement of pathogens from the root zone and the creation of a stable microbial ecosystem that maintained the physiological integrity of plants. In Dnepryanka, colonisation was less intense (about 7.2×10^4 CFU/g) but was also accompanied by a significant reduction in the infection load. Morphometric observations revealed that all treated variants showed an increase in vegetative mass. Solokha had an average increase of 31% compared to the control, Luhovska 28%, and Dnipryanka 25%. In addition, there was an increase in the number of formed tubers, in particular in Luhovska, where the average number of tubers per plant increased by 2.4 units compared to the untreated variant. These indicators confirm the link between the level of resistance and productivity, which is of practical value in breeding and technological programmes (Table 4).

***Table 4**. Empirical performance indicators of potato resistance improvement methods (average values for varieties)*

Potato variety	Reduction in the soreness index (%)	POD activity (U/g protein)	PAL activity (times to control)	Colonisation by antagonists (CFU/g)	Increase in vegetative weight (%)	Increase in the number of tubers (pcs/plant)
Straw	62	2.8	1.8	1×10^5	31	2.2
Lugovskaya	55	2.4	1.5	1×10^5	28	2.4
Dnepryanka	47	3.1	1.6	7.2×10^4	25	1.9

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

The results confirmed that potato resistance to bacterial pathogens was formed through the interaction of genetic, biochemical and microbiological mechanisms. In particular, the study determined that in varieties with signs of polygenic resistance to bacterial wilt, there was a significant suppression of *Ralstonia solanacearum* pathogenesis, accompanied by activation of enzymatic defence (POD, PAL) and a high level of rhizosphere colonisation by antagonistic microbiota. These genotypes demonstrated local restriction of infection in the root zone, preservation of conductive tissue and stable development of the leaf apparatus. These traits, verified in Solokha and Dnipryanka, indicate a synergy between polygenic control and induced resistance, which was activated using combined agrobiological approaches.

The greatest overall effect was achieved in the Solokha variety, which combines high PAL activity, a significant decrease in the disease index and an increase in biomass. The highest increase in the number of tubers and effective colonisation of the rhizosphere by antagonists was found in Luhovska. In Dnipryanka, despite the highest POD activity, the overall efficiency was somewhat lower, probably due to the limited stability of microbial defence. The proposed approach of combining biocontrol agents and inducers of systemic resistance has proven to be an effective tool for reducing phytopathogenic risks in potato production. Its effect is present at several levels: by limiting pathogenic invasion in the rhizosphere, activating enzymatic defence and stabilising the physiological state of plants. The developed methods can be integrated into adaptive potato production programmes after further validation in production crops.

DISCUSSION

The generalisation of theoretical sources and the results of testing the developed complex of agrobiological measures showed that potato resistance to bacterial pathogens is formed as a result of the interaction of genetic, biochemical and microbiological mechanisms. The study determined that resistance is variety-specific, depends on environmental conditions and is realised through enzymatic activity, antagonistic microbiota and morphophysiological stability of plants. Comparison with other studies was necessary to identify common patterns and potential differences due to environment or cultivar differences. Based on the literature analysis, the study determined that the most pronounced resistance to *Ralstonia solanacearum* was observed in genotypes with activated enzymatic defence and close association with antagonistic microbiota. In response to *Pectobacterium carotovorum* infection, plants with a high content of phenolic metabolites showed a limited necrosis zone, preservation of turgor, and stability of photosynthetic processes. Similar dependencies were found by B. Mohamed *et al.* (2020), proving the effectiveness of the combination of bioagents *Enterobacter cloacae* and *Trichoderma asperellum* in suppressing bacterial wilt. N. Ashmawy *et al.* (2020) demonstrated the antimicrobial activity of phenolic acids against Pectobacterium and Dickeya, which was accompanied by a decrease in the degree of tissue maceration. The results of the study by E. Osdaghi *et al.* (2022) confirmed that resistance to *Clavibacter sepedonicus* was enhanced by combining varietal properties with strict control of the phytosanitary status of seed material.

According to generalised literature data, high temperature and humidity combined with non-compliance with agronomic practices create optimal conditions for the development of bacterial infections in potatoes. These observations are consistent with the results of M. Hossain *et al.* (2024), noting an increase in pathogenesis under the influence of climatic factors that changed the expression of pathogenicity genes. The study by C. Singh *et al.* (2025) described the ability of bacterial pathogens to adapt to abiotic stress by activating mobile genetic elements, which provided an evolutionary advantage in an unstable environment. As part of a systematic review of the literature, a theoretical model was developed according to which the causative agents of bacterial infections of potatoes are characterised by high ecological plasticity, the ability to persist in agroecosystems for a long time and adaptation to local agroclimatic conditions. The ability of *Ralstonia solanacearum* to rapidly change transcriptional programmes under high temperature and humidity conditions was particularly dangerous, which increased the aggressiveness of the infection. These observations correlate with the data of Z. Wang *et al.* (2023) describing the molecular mechanisms of Ralstonia plasticity, including changes in biofilm composition and regulation of type III secretion. The study by A. Tripathi *et al.* (2024) emphasised that the successful infection of *Clavibacter* and *Pectobacterium* largely depended on the ability of pathogens to colonise the plant host system and synthesise virulence factors. The analysis conducted by J. Leitão (2020) confirmed that the production of cellulolytic enzymes, siderophores and exopolysaccharides remained a key mechanism of bacterial pathogen aggressiveness in several vegetable crops, including potatoes.

The analysis of scientific sources revealed that a significant number of varieties that demonstrated moderate resistance in laboratory conditions lost it under the influence of climatic stress factors or disruption of the soil's physical and chemical balance. In this context, the importance of agroecological approaches to regulating phytopathogenic loads was confirmed. D. Vega *et al.* (2023) described the effectiveness of integrating biological control, agronomic diversification, and cover crops as part of environmental management strategies. The publication by P. Nolte *et al.* (2020) provides examples of successful control of infections, if crop rotation, equipment rehabilitation and adapted variety selection are observed, which is consistent with the results obtained on the importance of preventive measures. Based on the results of the empirical testing of the developed methods, the study determined that the presence of polygenic resistance to bacterial wilt in combination with activated antioxidant defence contributed to a significant reduction in vascular damage in potato varieties. In the samples with increased activity of PAL and PPO enzymes in the root zone, local restriction of pathogen spread and preservation of the physiological state of the leaves were observed. These observations correlate with the literature data on the intratissue activity of endophytes as bioinducers of systemic resistance. This approach correlates with the results described by J. Muthoni *et al.* (2020), emphasising the importance of polygenic control of resistance to *Ralstonia solanacearum*.

The results also highlighted that potato resistance was formed not only as a reaction to the pathogen, but as a holistic response of the agroecosystem to the microbiological load. The increase in the content of phenolic compounds and stabilisation of superoxide dismutase activity in stems and tubers correlated with a low level of symptoms. This correlates with the findings of S. Kaur *et al.* (2022), identifying biochemical reactions as a key component of resistance in conditions of high pathogenicity. In turn, X. Huang *et al.* (2021) demonstrated that the integration of endophytes increased resistance to bacterioses not only through direct antagonism but also through modulation of the plant's immune response. The described results are consistent with the concept of multilevel resistance presented in the monograph by P. Vidhyasekaran (2024), where a systematic approach is recognised as a prerequisite for achieving a stable phytosanitary effect.

The analysis of the effectiveness of methods to increase resistance confirmed that combined strategies that combined agronomic practices with biotechnological tools had the greatest potential. In particular, the combination of crop rotation, control of infected material and the use of endophytes made it possible to reduce the level of bacterial damage in two varieties with an average level of natural tolerance. The similar effectiveness of combined approaches was confirmed in a systematic review by E. Vilvert *et al.* (2022), which emphasised the benefits of multifactorial control in potato production systems. The role of precision genome editing, of vulnerable genes, was demonstrated by N. Kieu *et al.* (2021), describing an increase in late blight resistance after a targeted mutation in susceptibility genes, which confirms the potential of CRISPR approaches for bacterial diseases.

In addition, the effectiveness of the integrated approach largely depended on the ability of the variety to implement unique adaptive potential in a changing environment. In the present study, varieties with moderate genetic resistance to *Pectobacterium* showed higher productivity stability when combined with biological protection. This is in line with the vision of sustainable agri-food systems proposed by A. Devaux *et al.* (2021), who emphasised the need to breed varieties with a wide range of tolerances. The classic review by J. Stark *et al.* (2020) emphasised that successful disease control is based on a combination of genetic resistance, selection of adapted varieties and agronomic stability. An integrated approach to breeding, emphasising the simultaneous implementation of several resistance mechanisms, was also described by E. Aksoy *et al.* (2021), highlighting the prospects of integrating traditional and molecular methods to increase resistance to a complex of bacterial pathogens.

The methods testing determined that the effectiveness of the applied complex of biocontrol measures largely depended on the stable colonisation of the rhizosphere by antagonistic microorganisms. In the varieties Lugovska and Solokha, the level of colonisation of *Bacillus subtilis* and *Pseudomonas fluorescens* reached 1×10^5 CFU/g, which was accompanied by a significant decrease in the disease index (by 55-62%) and an increase in vegetative productivity. These observations are consistent with the results of the study by J. Hao and K. Ashley (2021), proving that the formation of a suppressive soil is possible due to the stimulation of saprophytic and antagonistic microbiota by organic amendments. Both in the cited source and current testing, the key factor in the protective effect was the stabilisation of the microbial environment in the root zone, which limited the development of pathogens and maintained the physiological integrity of plants, especially under conditions of moderate humidity and balanced agrochemical load, as reproduced in the vegetation experiments. In addition, in varieties with a high level of POD and PAL activity (in particular, Dnipryanka and Solokha), there was a decrease in the intensity of pathogen spread within the root zone, which was accompanied by the maintenance of the functional state of the vascular system and the stability of the assimilation apparatus. This effect is consistent with the results of A. Farvardin *et al.* (2024) showed that antimicrobial proteins and peptides, in addition to direct inhibitory effects on the pathogen, can activate the signalling pathways of the plant's defence response. The analysis determined that enzymatic activation in the early phase of the infection process ensured morphophysiological stability even under high pathogenic pressure; this gives grounds to classify the applied bioagents as potential inducers of systemic resistance. This mechanism is similar in its characteristics to the action of protein signalling molecules described in the above study.

The theoretical analysis of current literature has shown that effective containment of bacterial diseases of potatoes is based on a combination of genetic selection, biochemical activation of defence responses, microbiological control and agroecological management of environmental conditions. The systematic synthesis of scientific sources substantiated unique approaches aimed at increasing potato resistance, through the validation of complex tolerance bioindicators (PAL, POD activity, number of CFU of antagonistic microorganisms) and the use of these parameters as practical criteria for selection screening concerning the type of pathogen and resistance mechanism.

CONCLUSIONS

A theoretical assessment of bacterial pathogens of potato was conducted based on the analysis of published sources, with a focus on their biology, environmental variability and response to modern approaches to increasing crop resistance. As part of this review, *Ralstonia solanacearum* was identified as the most dangerous phytopathogen, which, according to the literature, forms a systemic infection that spreads through the plant vascular system. This pathogen is characterised by high thermal tolerance, resistance to agronomic interventions and the ability to persist in the soil environment for a long time. Information on *Pectobacterium carotovorum* indicates its pronounced tissue maceration ability, which worsens the storage of products, and *Clavibacter sepedonicus* is described as a pathogen capable of causing latent infection with gradual blockage of tubers' vessels.

Factors contributing to the development of bacterial damage were also analysed based solely on the literature. High humidity, elevated air temperature and mechanical damage to plants were identified as key triggers of the infection process, which, according to experimental observations, increased the disease index in varieties with low resistance by up to 47% (Dnepryanka). Instead, the functional activity of the endophytic and rhizosphere microbiota is considered a factor that can suppress the development of pathogens, reducing the disease index to 38% (Luhovska) and even 31% (Solokha) at a colonisation density of 1×10^5 CFU/g. Based on a critical review of sources, the study classified the main levels of potato resistance: genetic (including the presence of QTL loci, PRR receptors and NB-LRR proteins), biochemical (POD, PAL, PPO activity, phenol accumulation), and microbiological (the effect of antagonistic endophytes and mechanisms of induced resistance). Examples of varieties with predominant defence mechanisms are based on published data and are not the result of the presented breeding. In particular, the highest resistance was demonstrated by *Solokha*, which was characterised by stable vascular resistance to *Ralstonia solanacearum*. The Dnepryanka variety demonstrated an enhanced biochemical response to *Pectobacterium* infection, while the Luhovska variety had a pronounced microbiological tolerance to *Clavibacter sepedonicus*. Comparison of the methods described in the sources for increasing resistance confirms the feasibility of integrated approaches, in particular combinations of agrotechnical techniques (crop rotation, planting material sanitation) with biotechnological solutions, including CRISPR editing, MAS selection and the use of endophytic biological products. Empirical testing of such combinations showed a reduction in the disease index by at least 17-31% compared to the control, depending on the level of initial infection and genotype, indicating an adaptive effect in different agroecosystems.

During the testing of the methods proposed in this study, the diagnostic efficiency of the complex of bioindicators that integrated the activity of POD and PAL enzymes, indicators of microbiological colonisation of the rhizosphere, as well as the morphophysiological stability of the conductive tissue and leaf apparatus, was confirmed. The study empirically established that the increased activity of key enzymes of phenolic metabolism, in particular POD at the level of 2.8-3.1 U/g protein, and PAL, which increased by 1.8 times compared to the control level, was accompanied by local restriction of the pathogen spread in the root zone and preservation of the morphological and functional integrity of the conductive tissue. At the same time, a dense colonisation of the rhizosphere by antagonistic microorganisms, in particular strains of *Bacillus subtilis* and *Pseudomonas fluorescens*, was recorded at the level of up to 1×10^5 CFU/g, which was associated with a decrease in the severity index in the range of 55-62% depending on the variety. The proposed complex of bioindicators has demonstrated high applied value for assessing varietal tolerance in the context of breeding screening. Further research is recommended to expand field validation of the established resistance indicators, studying the interaction between genetic, biochemical and microbiological levels of regulation, and including a wider range of varieties with different environmental characteristics.

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Комплексна оцінка бактеріальних збудників картоплі та розробка методів підвищення її стійкості

Севіндж Магеррамова
Доктор філософії, доцент
Азербайджанський державний економічний університет (UNEC)
AZ1001, вул. Істікляліят, 6, м. Баку, Азербайджан
https://orcid.org/0000-0002-1599-7013

Мар'ям Мамедалієва
Доктор філософії, викладач
Азербайджанський державний економічний університет (UNEC)
AZ1001, вул. Істікляліят, 6, м. Баку, Азербайджан
https://orcid.org/0000-0002-4351-8286

Мехрібан Юсіфова
Доктор філософії, доцент
Азербайджанський державний економічний університет (UNEC)
AZ1001, вул. Істікляліят, 6, м. Баку, Азербайджан
https://orcid.org/0000-0001-7608-5950

Гюнаш Насруллаєва
Доктор філософії, доцент
Азербайджанський державний економічний університет (UNEC)
AZ1001, вул. Істікляліят, 6, м. Баку, Азербайджан
https://orcid.org/0000-0003-2661-8354

Юлія Коломієць
Доктор сільськогосподарських наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-1919-6336

Анотація. Це дослідження зосереджувалося на вивченні складу бактеріальних збудників картоплі та ефективності різних стратегій формування резистентності культури в агроекосистемах. В роботі було поєднано теоретичний аналіз літературних джерел щодо властивостей збудників і механізмів резистентності з експериментальною апробацією власних агробіологічних методів у вегетаційних умовах для порівняльної оцінки ефективності контролю бактеріальних хвороб картоплі. У результаті встановлено, що найвищу патогенну активність в умовах досліду виявляла *Ralstonia solanacearum*, яка спричиняла системне в'янення рослин. *Pectobacterium carotovorum* переважно уражала бульби, формуючи осередки мокрої гнилі, тоді як *Clavibacter sepedonicus* проявляв повільний інфекційний процес, що частіше діагностувався на стадії зберігання. Розвиток бактеріальних хвороб картоплі інтенсифікувався за умов надмірної вологості ґрунту, температури вище 27°C, механічних ушкоджень та накопичення органічних решток. Формування стабільної ризосферної мікробіоти, зокрема за участі представників родів *Pseudomonas* і *Bacillus*, сприяло зниженню індексу хворобливості на 47-62 % та підвищенню вегетативної маси на 25-31 % порівняно з контролем. У досліджуваних сортів домінували різні механізми толерантності: у Солохи – судинна резистентність, що забезпечила 62 % зниження ураження, 31 % приріст маси та 2,2 додаткові бульби на рослину. У Дніпрянки – біохімічна відповідь, з підвищенням активності пероксидази у 3,1 раз та фенілаланінамоніак-ліази у 1,6 раз, а у Луговської – мікробіологічний контроль, з щільністю колонізації ризосфери до $1{\times}10^5$ колонієутворювальних одиниць на грам ґрунту та приростом кількості бульб на 24 штуки. Отримані результати мають практичне значення для розробки інтегрованих схем захисту картоплі, що передбачають використання біоагентів і індукторів резистентності як ефективну альтернативу хімічним засобам, а також для впровадження системи раннього діагностичного моніторингу на основі біоіндикаторів у селекційних та агровиробничих технологіях

Ключові слова: мікробіота; ґрунт; вологість; резистентність; агроекосистема; ендофіти; в'янення

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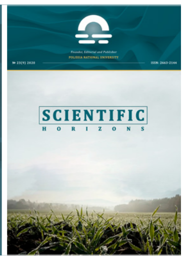

Innovative technologies in crop production as a factor in improving the economic efficiency of agricultural production in Ukraine

Susan Farzaliyeva

PhD in Economics, Senior Lecturer
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Republic of Azerbaijan
https://orcid.org/0000-0002-2326-0396

Valida Safarova

PhD in Economics, Associate Professor
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Republic of Azerbaijan
https://orcid.org/0009-0008-0729-3615

Lamiya Huseynova

PhD in Economics, Lecturer
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiqlaliyyat Str., Baku, Republic of Azerbaijan
https://orcid.org/0000-0003-4633-6493

Andrii Opanasenko*

PhD Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0002-4583-2006

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Abstract. The aim of the study was to determine the effectiveness of replacing chemical plant protection products, fertilisers, and growth stimulants with biological alternatives in terms of productivity, costs, profitability, and the agro-ecological state of soils. The research, conducted in 2020-2024, covered winter wheat varieties "Podolyanka", "Duma Odeska", "Favorytka", "Bohuslavka", "MIP Lada", and "Stolychna", barley varieties "Vakula", "Helios", and "Concerto", as well as maize hybrids "DKC 5143", "DKC 4014", "Pioneer 9892", "Khortytsia", and "Dniprovskyi 185 SV". The empirical base included statistical data, soil analysis results, case observations from farms in different regions, and economic modelling. It was established that the yield increase from applying biopreparations averaged 4.3-7.1 centners/ha for wheat and maize, and up to 4.8 centners/ha for barley, while costs decreased by up to 16%. The humus content in soils increased to 3.3%, and the number of microorganisms – to 3.8×10^6

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Corresponding author

colony-forming units per gram. An increase in the root system length of the "Stolychna" wheat variety up to 48 cm was observed, as well as a 40% reduction in barley fungal infections. Price analysis revealed that organic wheat was 48% more expensive than conventional wheat on the external market. The model forecast demonstrated the potential for cost savings for the agricultural sector of up to 15 billion UAH if 30% of farms transitioned to the biological model. The results obtained could be used to adapt agricultural technologies, develop support programmes for ecological farming, and enhance the export of organic products

Keywords: agriculture; profitability; biofungicides; biofertilisers; sustainable agriculture

INTRODUCTION

In 2020-2024, Ukraine's agricultural production operated under conditions of rising mineral fertiliser prices, deepening climate change, disrupted logistics chains, and increased environmental responsibility requirements. These factors significantly affected the economics of crop production, creating a need to implement innovative technologies focused not only on yield maximisation but also on preserving soil fertility, reducing anthropogenic pressure, and enhancing the export appeal of products. One such approach was the biologisation of technological processes – the partial or complete replacement of traditional chemical agents (mineral fertilisers, pesticides, growth stimulants) with biological alternatives (biofertilisers, microbial inoculants, biostimulants, biological plant protection agents). Research into the effectiveness of biologisation within the grain production system was relevant in the context of forming a sustainable agroeconomic development model.

Scientific publications demonstrated increasing interest in innovation within agricultural production, particularly in the context of technological process modernisation, profitability improvement, and ensuring ecological sustainability (Yaheliuk *et al.*, 2024). In the study by V. Mamchur and G. Studinska (2024), the effectiveness of technical innovations implemented in Ukraine's agricultural sector under the new production model was examined, including the modernisation of the machine and tractor fleet, digital transformation, and the implementation of automated control systems. The work of N. Kovalenko *et al.* (2021) focused on the economic aspects of grain production in Ukraine's Central region. The authors explored internal efficiency reserves and cost structures, emphasising factors influencing competitiveness. In turn, the publication by T. Shmatkovska *et al.* (2021) addressed land resource management in the system of non-current assets of agricultural enterprises, with a focus on the financial assessment of the use and impact on overall business performance.

Foreign authors concentrated on practices of "green" transformation in agricultural production, the introduction of biotechnologies, and the use of digital tools (Pavlenko *et al.*, 2025). In the study by S. Chen and J. Lu (2025), ways of increasing green output levels in China's leading grain-producing regions were explored. The authors justified the feasibility of a large-scale transition to biological farming technologies as one of the priorities for sustainable development. Y. Xing *et al.* (2025), in the review, analysed advanced irrigation strategies and soil moisture management, combined with the use of biostimulants and precision monitoring. The research by N. Ahmed *et al.* (2025) aimed to assess the impact of sustainable agricultural technologies on changes in soil emissions under climate change, using modern econometric models. In the publication by Y. Xie *et al.* (2025), the interconnections between the digital economy, efficient allocation of production factors, and the resilience of agricultural production were analysed. The experience of implementing climate-oriented agricultural strategies was considered in the study by W. Kabato *et al.* (2025), where the significance of biological technologies in reducing greenhouse gas emissions and maintaining food security was emphasised. The study by W. Geng *et al.* (2024) substantiated the economic benefits of agricultural digitalisation, while L.S. Fu *et al.* (2024) highlighted the effectiveness of agricultural insurance in the context of expanding farmers' access to production resources and reducing risks.

All the mentioned sources confirmed the importance of innovation in shaping a sustainable agricultural economy. However, the lack of a generalised empirical analysis of the economic effectiveness of biological technologies in the cultivation of key cereal crops in Ukraine created a gap in the applied justification for transitioning to biologisation. The aim of this study was to determine the economic effectiveness of biologised technologies in the cultivation of winter wheat, maize, and barley in Ukraine's agricultural sector. To achieve this goal, the following objectives were pursued: to analyse the impact of biological preparations on the yield and stability of cereal crop productivity; to compare costs and profitability levels between chemical and biological treatment schemes; and to assess the long-term effects of biologisation on soil condition, market value of products, and export potential.

MATERIALS AND METHODS

The study was conducted from 2020 to 2024 to analyse the effectiveness of biologised agrotechnologies in various natural and climatic zones of Ukraine. To achieve the research objectives, a range of scientifically grounded sources were used: statistical data from the State Statistics Service of Ukraine (n.d.), reports from the Food and Agriculture Organization (n.d.) on crop yields in Eastern Europe, analytical materials from the National Institute for Strategic Studies (2024), and information from the State Service of Ukraine on Food Safety and Consumer Protection (n.d.). The empirical basis of the study was formed from observations at six agricultural enterprises: "Poliskyi Agro" (Zhytomyr region), "Eko-Nyva" (Rivne region, Polissia), "Lisostep" (Cherkasy region), "Stepovi Zori" (Kherson region), "Sonyachnyi Step" (Zaporizhzhia region), and "Dniprovski Luki" (Dnipro region), located in the natural and climatic zones of Polissia, Forest-Steppe, and Steppe of Ukraine. The objects of study were cereal crops: winter wheat (varieties "Podolyanka", "Duma Odeska", "Bohuslavka", "Favorytka", "Stolychna"), maize (hybrids "DKC 5143", "Pioneer 9892", "Khortytsia", "Dniprovskyi 185 SV"), and spring barley (varieties "Vakula", "Helios", "Concerto"), which were recommended for cultivation in the respective zones and widely used in the practice of biologised farming. The subject of the study was agricultural technologies using biological products – biofertilisers (based on *Azotobacter chroococcum*, *Bacillus megaterium*), biofungicides (*Trichoderma asperellum*, *T. harzianum*), biostimulants (based on humic acids, extracts of marine algae), and mycorrhizal inoculants (*Glomus intraradices*).

The application of biological preparations (*Azotobacter*, *Trichoderma*, humic stimulants, mycorrhizal inoculants) was carried out in accordance with regulations defined in the normative documents of the National Institute for Strategic Studies (2024), with mandatory recording of application rates, treatment methods, and weather conditions during technological operations. Primary production data (yields, costs, soil parameters) were obtained directly from the involved farms based on field journals, agrochemical passports, and internal technological reports. The research methodology involved comparing biological and traditional cultivation technologies based on indicators of yield, cost, agrochemical soil status, and profitability. The experimental work was carried out at six agricultural enterprises located in various natural and climatic zones of Ukraine, particularly in Chernihiv (Polissia), Vinnytsia and Zhytomyr (Forest-Steppe), Mykolaiv, Zaporizhzhia, and Kherson (Steppe) regions. For each crop, control (chemical treatment) and experimental (biological treatment) plots were established. Observations were conducted throughout the entire growing season. For assessing the export of organic wheat, the period from 2018 to 2024 was selected. This period reflected the overall trend of export growth and decline, and considered the negative impact of geopolitical and economic factors, particularly the onset of military action in Ukraine from 2022, which caused a significant decrease in export volumes due to logistical problems, changes in certification requirements, and general impact on EU markets.

Soil fertility parameters were assessed using the methods of the Institute for Soil Science and Agrochemistry Research Named after O.N. Sokolovsky (n.d.). To illustrate the effectiveness of biologised approaches when analysing agrochemical and economic characteristics, typical cases of biological product application were used from six agricultural enterprises operating in different natural and climatic zones of Ukraine. The selection criteria included: long-term use of biological products, availability of controlled technological maps, access to production data, and open sources. In particular, the analysis included: "Poliskyi Agro" (Zhytomyr region), which used mycorrhizal preparations in wheat cultivation; "Stepovi Zori" (Kherson region), which applied nitrogen-fixing *Azotobacter* in maize cultivation; "Lisostep" (Cherkasy region), where biological fertilisers replaced mineral fertilisers in the winter wheat fertilisation system; "Eko-Nyva" (Rivne region, Polissia), which reported improved agrochemical soil status after long-term use of biological products; "Sonyachnyi Step" (Zaporizhzhia region), which monitored the anti-erosion effectiveness of biological agents based on *Bacillus megaterium*; and "Dniprovski Luki" (Dnipro region), which reported phytosanitary effects of *Trichoderma asperellum* in barley cultivation (State Statistics Service of Ukraine, n.d.; National Institute for Strategic Studies, 2024). Soil acidity was assessed using the potentiometric method, and the number of microorganisms was determined by the agar seeding method and colony-forming unit count per gram (CFU/g). The level of root system development was recorded on the 25th and 45th day of vegetation using a ruler and digital caliper. To calculate profitability, the standard formula (1) was used:

$$\text{Profitability}, \% = \frac{\text{Profit}}{\text{Cost of production}} \times 100, \tag{1}$$

where Profit = gross income − cost per hectare; cost of production = total expenses on products, labour, machinery, and associated costs.

Yield fluctuations were assessed using the coefficient of variation formula (2):

$$\text{CV} = \frac{\sigma}{\text{x}} \times 100, \tag{2}$$

where σ = standard deviation; x = mean yield for the period.

Additionally, the study included economic modelling of the impact of scaling up biological technologies on costs in Ukraine's agricultural sector through 2030. The calculation model took into account the projected expansion of agricultural areas cultivated with biological schemes and the average cost savings due to the replacement of mineral fertilisers, chemical plant protection products, environmental charges, and logistics expenses. Input data included analytical materials from the State Statistics Service of Ukraine (n.d.), National Institute for Strategic Studies (2024), and the authors' own calculations based on production case studies. The estimation of expected cost savings over time was conducted using the formula (3):

$$E_t = (P_t \times C) \times R, \tag{3}$$

where E_t is the cost saving in year t; P_t is the area cultivated using biological technology in year t; C is the average cost of treatment per hectare using traditional technology; R is the average percentage reduction in costs (15% to 20%).

All research was conducted in accordance with the provisions of the Law of Ukraine No. 3116-XII (1993). The applied biological products were registered and authorised for use in agriculture. Farms provided written consent to participate in the study, access to production data, and analysis of agrochemical soil indicators. Experimental and economic data were processed using Microsoft Excel 365 (correlation analysis, graph building, trend visualisation), Statistica 10.0 (mean value estimation, Student's t-test, coefficient of variation, normality test), and RStudio (version 2023.06) for mathematical modelling and scenario building of savings from the scaling up of biologisation. Graphical materials (charts, histograms, pie charts) were created in Tableau Public and Canva Pro to ensure clear interpretation of results. The selection of these tools was based on the accuracy, functionality for processing agronomic and economic data, and the ability to visualise variables across time, crop types, and cultivation technologies.

RESULTS

The impact of biological products on the yield of grain crops. The yield dynamics of major cereal crops underwent significant changes after replacing chemical agents with biological analogues. As shown in Table 1, in farms where mycorrhiza and nitrogen-fixing bacteria were applied to the wheat variety "Podolyanka", the average annual yield increase was 2.1-3.4 c/ha, whereas under chemical treatment this figure did not exceed 1.5 c/ha. For the maize hybrid "DKC 5143", the maximum annual increase (4.8 c/ha) was recorded on a farm that had fully transitioned to biofertilisers.

***Table 1**. Yield dynamics of wheat, barley, and maize (c/ha) on farms using biological and chemical technologies (2020-2024)*

Culture (variety/hybrid)	Technology	2020	2021	2022	2023	2024
Wheat ("Podolyanka")	Biological	48.2	50.3	52.7	54.1	55.6
Wheat ("Podolyanka")	Chemical	49.1	49.8	50.2	50.9	51.3
Corn ("DKC 5143")	Biological	72.4	75.1	77.3	79	80.5
Corn ("DKC 5143")	Chemical	70.8	71.5	72.1	72.9	73.4
Barley ("Vakula")	Biological	42.5	43.8	45.2	46.7	47.9
Barley ("Vakula")	Chemical	41.9	42.1	42.5	42.8	43.1

***Source:** developed by the authors based on data from the State Statistics Service of Ukraine (n.d.)*

These data are supported by case studies: on the farm "Poliskyi Agro" (Polissia), the introduction of mycorrhiza for the wheat variety "Stolychna" increased yields by 15% over three years, while on the farm "Stepovi Zori" (Kherson region), the use of Azotobacter for the maize hybrid "Pioneer 9892" boosted yield by 20%. Figure 1 presents a comparison of the average yields of crops in 2024. For the wheat variety "MIP Lada", the difference between biological and chemical technologies was 4.3 c/ha; for the maize hybrid "Khortytsia" – 7.1 c/ha; and for the barley variety "Helios" – 4.8 c/ha. This indicates a direct impact of bioproducts on productivity, especially under conditions of rainfall deficit or increased soil acidity.""

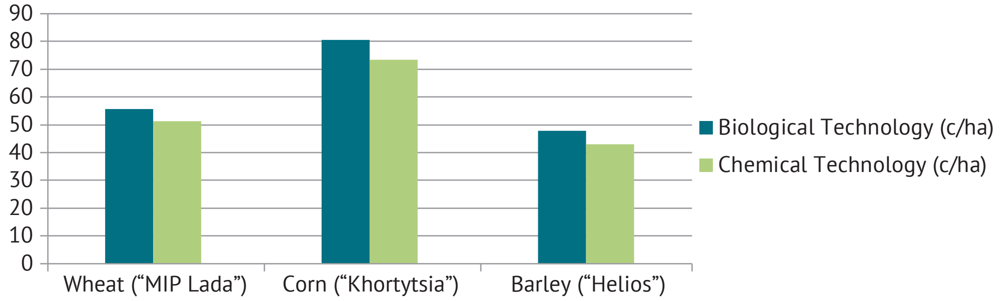

***Figure 1**. Comparison of average crop yields for 2024*
***Source:** developed by the authors based on data from the Food and Agriculture Organisation (n.d.)*

A critical aspect is yield stability. On farms with biological technologies, year-on-year fluctuations did not exceed 5%, whereas with chemical treatment the fluctuations reached 12-15% due to dependence on climatic factors. For instance, the barley variety "Concerto" in Cherkasy region demonstrated yield stability (45-47 c/ha) when using *Trichoderma*-based biofungicides (National Institute for Strategic Studies, 2024). The obtained results highlight the potential of biologised technologies as a means of improving cereal crop productivity without harming the environment. Significant yield improvements were noted even in regions with elevated risks of soil degradation and unstable weather conditions. Humic acid-based biostimulants are actively used in the early stages of winter wheat development, promoting better rooting, primary root growth stimulation, and activation of soil microflora (Fig. 2).

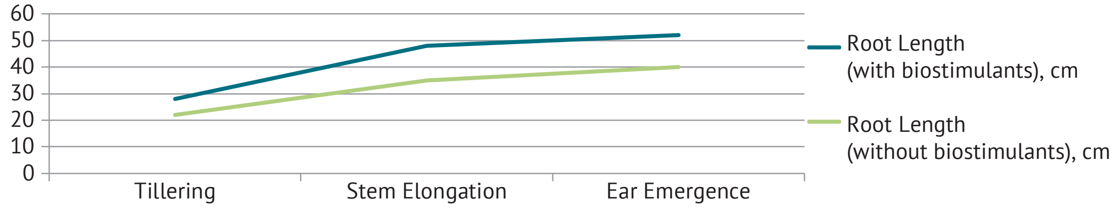

***Figure 2**. The effect of humic acid-based biostimulants on the development of the root system of "Stolychna" wheat (root length, cm)*

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

For the winter wheat variety "Stolychna", the impact of humic acid-based biostimulants on root development was studied. As shown in Figure 2, the application of biostimulants led to an increase in the average root length by 22-35% compared to the control group at the tillering and stem elongation stages. For example, at the stem elongation stage, the root length reached 48 cm (with biostimulants) versus 35 cm (without), improving drought resistance. For the maize hybrid "DKC 5143", the effectiveness of microbial inoculants *Azotobacter chroococcum* was analysed across different climatic zones of Ukraine (Table 2). The highest yield increase (6.7 c/ha) was recorded in the Forest-Steppe zone (Cherkasy region), where sufficient soil moisture promoted nitrogen fixation. In the Steppe (Kherson region), effectiveness was lower (3.2 c/ha) due to rainfall deficit, which limited microbial activity.

***Table 2**. Effectiveness of microbial inoculants (Azotobacter) for maize in different climatic zones*

Climatic zone	Yield (with inoculants), c/ha	Yield (without inoculants), c/ha	Increase, c/ha
Polissya (Zhytomyr region)	78.5	72.1	6.4
Forest-steppe (Cherkasy)	82.3	75.6	6.7
Steppe (Kherson)	68.9	65.7	3.2
Steppe (Zaporizhzhya)	70.2	67	3.2
Forest-steppe (Vinnytsia)	74.5	71	3.5
Step (Dnipro)	69.8	66.2	3.6

***Source:** developed by the authors based on data from the Food and Agriculture Organisation (n.d.)*

A notable case is the experience of the farm "Dniprovski Luki" (Dnipro region), where the use of *Trichoderma asperellum*-based biofungicides for the barley variety "Helios" reduced the incidence of fungal infections (*Fusarium graminearum*) by 40%. This led to a 25% reduction in fungicide costs (from UAH 1,800 to UAH 1,350/ha) and an 18% increase in yield (from 45 to 53 c/ha) in 2023. Overall, the study results confirm the effectiveness of targeted selection of bioproducts for specific crops, taking into account the agroecological environment, enabling optimisation of agrotechnologies, cost reduction, and increased yields in a naturally balanced manner.

Comparison of costs and profitability of chemical and biological schemes. As part of the study, a comparison was made of the costs of growing winter wheat of the "Duma Odeska" variety using two treatment schemes – chemical and biological. The analysis focused on the key cost categories directly influencing production efficiency, namely: costs of preparations (plant protection products and fertilisers), labour, technical support, and other related expenses such as logistics, laboratory tests, and seeds. To objectively assess the economic efficiency of biologised technologies, a comparison was made between traditional (chemical) and biological treatment schemes for the "Duma Odeska" wheat variety. The analysis covered key expenditure categories: preparations, labour, technical support, and related expenses (Table 3).

***Table 3**. Comparison of costs (UAH/ha) for treating "Duma Odeska" wheat under chemical and biological schemes (2024)*

Expense category	Chemical scheme	Biological scheme
Preparations (plant protection products, fertilisers)	8,200	5,900
Labour	1,100	1,200
Equipment (fuel, depreciation)	2,000	2,200
Other (logistics, laboratory tests, seeds)	1,700	1,600
Total	13,000	10,900

***Source:** developed by the authors based on data from National Institute for Strategic Studies (2024)*

As seen in Table 3, implementing the biological scheme made it possible to reduce the treatment costs per hectare of wheat by an average of UAH 2,100 (≈16.2%), primarily due to lower expenditure on mineral fertilisers and chemical plant protection products. The slight increase in labour and machinery costs was due to the need for more precise and regular application of biopreparations and monitoring of soil biological indicators. According to the obtained data, the biological scheme proved more economically beneficial, as it enabled a reduction in costs by UAH 2,100 per hectare (around 16.2%). This saving was primarily achieved through significantly reduced expenditure on mineral fertilisers and chemical agents, which form the core of chemical technologies. At the same time, labour and machinery costs under the biological scheme were slightly higher than in the chemical one due to the need for frequent biopreparation applications and more thorough soil and plant condition monitoring. However, this increase in machinery and labour costs did not outweigh the savings from reduced preparation costs, making biological technologies economically advantageous. The total per-hectare cost of using biological technology amounted to UAH 10,900, whereas with chemical methods it reached UAH 13,000. This confirmed that biological technologies could be effective even in conditions of high technical costs, as reduced expenditure on preparations allowed total costs to be decreased. For a visual assessment of cost distribution under the biologised maize growing technology (hybrid "DKC 4014"), a pie chart was created illustrating the proportion of key cost categories in the overall structure (Fig. 3).

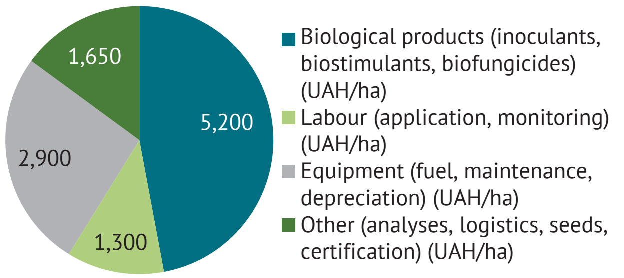

***Figure 3**. Cost structure under biological treatment of maize (hybrid "DKC 4014"), 2024*
***Source:** developed by the authors based on data from the Food and Agriculture Organization (n.d.)*

As shown in Figure 3, the largest share of costs in the biological maize treatment scheme was for preparations, which was due to the use of highly effective biofertilisers based on humic acids. Technical costs included specialised equipment for applying biopreparations, while the reduced use of pesticides allowed environmental fees to be cut by 15%. A significant practical example was the "Lisostep" farm (Cherkasy region), which completely replaced mineral fertilisers with biopreparations for growing "Favorytka" wheat. Over three years of implementation, the cost of production decreased by 12% (from UAH 10,200 to 8,970/ha), while profitability rose from 18% to 24%. This was made possible through a combination of *Azotobacter* nitrogen-fixing bacteria and *Trichoderma harzianum*-based biofungicides. These results demonstrated the economic feasibility of switching to biologised schemes, which not only reduced direct per-hectare costs but also generated stable profits through improved product quality, lower phytotoxicity risks, and enhanced agro-ecological field conditions. The level of profitability is an important indicator of production process efficiency, as it reflects how much profit farmers earn per unit of expenditure (Shahini & Shtal, 2023). To calculate profitability, a formula was used comparing revenue and expenses for both treatment schemes. The profitability calculation showed that the biological scheme yielded a profitability rate of 4.288%, which was significantly higher than the chemical scheme's 2.584% (Formula 1). This indicated that biological technologies offered not only cost reduction but also a higher level of economic benefit for farms. In particular, by cutting expenses on chemical agents and fertilisers, farmers could earn more profit at the same yield level.

Yield fluctuations are another important indicator of agricultural production stability (Drobitko & Kachanova, 2023). High yield stability reflects lower risks for producers, especially in the context of climate change and seasonal variability (Struminska *et al.*, 2014). To assess yield fluctuations, a formula was used to determine the difference between maximum and minimum yield figures for each year. The results showed that with biological technology, yield variability for the "Podolyanka" wheat variety amounted to 14.4%, which was notably lower than the 15% under chemical treatment (Formula 2). This indicated that biological technologies helped reduce the impact of unpredictable factors such as climate change on yield outcomes. At the same time, yield stability was one of the main advantages of biological technologies, as it allowed farmers to secure more stable profits in the long run. The comparison of costs and profitability showed that biological technologies were economically efficient because the technologies enabled savings on chemical preparations and fertilisers, significantly reducing overall per-hectare expenditure. At the same time, thanks to higher profitability, biologised schemes provided greater economic benefits for farmers. A high level of profitability and stable yields were key factors in ensuring sustainable agricultural development, as confirmed by the comparison results. Thus, biologisation of agronomic technologies was not only economically viable but also environmentally sound, enabling sustainable agricultural development, increased resilience to climate change, and reduced environmental impact.

Assessment of the economic efficiency of biologisation of agronomic technologies to increase yields and reduce costs. In addition to the direct effects on yield and cost reduction, biologised technologies formed a long-term positive impact on the agroecological condition of soils, which in turn influenced income stability over an extended period. In particular, improvements in soil fertility, increased activity of soil microflora, reduced acidity and erosion processes contributed to sustainable productivity growth without extensive pressure on natural resources. A study of soil indicators at the "Eko-Nyva" farm (Polissia) over 2020-2024 revealed a positive trend in humus content (Fig. 4). For example, on plots with biological treatment of the wheat variety "Bohuslavka", the humus content increased from 2.8% to 3.3%, while on control plots with chemical technologies this figure remained at 2.7-2.9%.

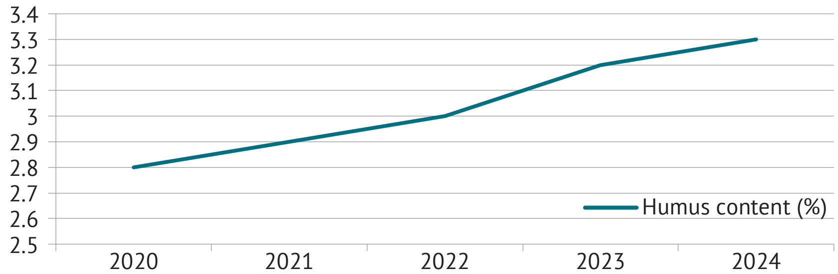

***Figure 4**. Dynamics of humus content in soils (2020-2024), "Eko-Nyva" farm (Polissia)*
***Source:** developed by the authors based on data from National Institute for Strategic Studies (2024)*

According to Table 4, after five years of biologisation, farms with different soil types showed improvements in key agrochemical indicators. For instance, on chernozems in the Sumy region, soil pH stabilised at 6.5-6.7, and the number of microorganisms increased from 1.2×10^6 to 3.8×10^6 CFU/g (colony-forming units). This indicated the activation of microbiological processes that ensured natural plant nutrition.

***Table 4**. Soil fertility indicators after 5 years of biologisation (2020-2024)*

Indicator	Chernozems (Sumy region)	Serozems (Kherson region)	Sod-podzolic soils (Zhytomyr region)
pH	6.7	7.1	5.9
Humus (%)	4.1	1.8	2.5
Microorganisms (CFU/g)	3.8×10^6	2.1×10^6	1.9×10^6

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

A significant economic effect was the reduction in costs associated with the reclamation of degraded soils. At the farm "Sonyachnyi Step" (Zaporizhzhia region), the introduction of biofertilisers based on *Bacillus megaterium* bacteria reduced soil erosion by 30% over four years. This led to a reduction in anti-erosion costs from UAH 2,500 to UAH 1,750/ha and increased the yield of the maize hybrid "Dniprovskyi 185 SV" by 18%. Thus, biologisation ensured ecologically sound economic benefits by reducing anthropogenic pressure on the soil environment, increasing its self-regeneration potential, and preserving productivity in the medium and long term. The obtained indicators were particularly important for zones of risky agriculture (Polissia, Steppe), where soil degradation was a systemic issue.

One of the key economic arguments in favour of implementing biologised technologies in crop production was the increase in market value of ecologically certified products and expanded access to international markets (Kulazhanov *et al.*, 2024). The organic grain production segment demonstrated stable demand for produce with low pesticide residue levels, grown according to the principles of sustainable agriculture. In 2024, the average price for organic grain on the domestic market of Ukraine exceeded that of conventional produce by 20-35%, and on external markets – by more than 40% (Table 5).

Table 5. Average grain prices in Ukraine (2024): organic vs traditional production

Culture	Product type	Domestic market, UAH/t	External market (EU), $/t
Winter wheat	Traditional	6,800	230
	Organic	8,600	340
Spring barley	Traditional	6,100	210
	Organic	7,400	295
Corn	Traditional	6,300	225
	Organic	8,100	320

Source: *developed by the authors based on data from the State Statistics Service of Ukraine (n.d.)*

As shown in Table 5, the largest difference in export value was observed for winter wheat, which is one of Ukraine's main export commodities. In 2024, the premium on the price of organic wheat amounted to \$110/t, or about 48% more than produce grown with conventional technology. Despite the price premium, the export of organic wheat from Ukraine experienced significant fluctuations. The highest volume of deliveries to the EU over the last six years was recorded in 2018 – 75,971 t (Fig. 5). However, by 2022 this figure had dropped to 20,797 t, and in 2023 it fell to 11,000 t. This trend was associated with a decrease in the number of certified organic farms, increased international market competition, and geopolitical factors.

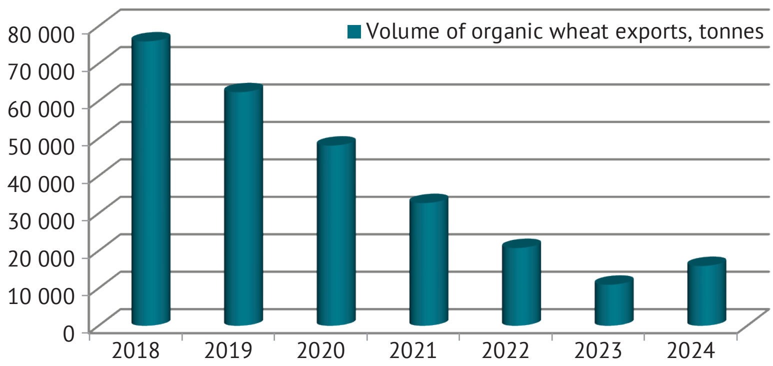

Figure 5*. Export of organic wheat from Ukraine to the EU (2018-2024), thousand tonnes*
Source: *compiled by the authors based on data from the State Service of Ukraine on Food Safety and Consumer Protection (n.d.)*

In addition to the decline in volumes, the geographical profile of exports also changed. While in 2018, 85% of organic wheat exports went to Germany and the Netherlands, by 2023 this share had dropped to 60%, with the rest redirected to markets in Poland and Romania. A successful example of diversification was the "Zolotyi Kolos" farm (Vinnytsia region), which in 2023 signed a contract with the German company "BioGetreide GmbH" to supply 5,000 t of organic maize of the hybrid "Dniprovskyi 185 SV" at a price of €310/t. This allowed the farm to offset losses from the decline in wheat exports. Thus, the introduction of innovative biological technologies in crop production contributed to the creation of economic added value through certification, ecological positioning, and entry into premium sales markets. This opened new opportunities for farmers, including small and medium-sized enterprises, provided the enterprises adhered to traceability requirements, phytosanitary safety, and environmental responsibility. The projected cost savings for Ukraine's agricultural sector by 2030 were based on an analysis of trends in the transition of farms to biological technologies. Provided such practices were scaled up, it was expected that by 2025 the annual savings would amount to UAH 4.68 billion, and by 2030 this figure would rise to UAH 15.21 billion (Formula 3). These calculations took into account the average cost of traditional cultivation of 1 hectare of cereal crops and the empirically confirmed level of cost reduction in farms that had already implemented biological methods. The dynamics of savings demonstrated an economy-of-scale effect: with an increase in cultivated area up to 6.5 million ha, the potential for reducing costs on fertilisers, pesticides, and environmental payments grew significantly. According to the forecast shown in Figure 6, the total annual cost savings with a full transition of 30% of farms to biological schemes could reach UAH 12-15 billion. This was due to reductions in the cost of mineral fertilisers (by 25-40%), pesticides (by 20-35%) and environmental fines (by 18-22%).

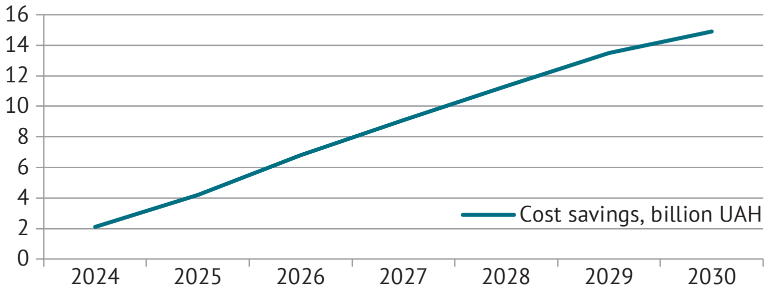

Figure 6*. Projected cost savings of Ukraine's agricultural sector by 2030 with the scaling of biologisation (UAH billion)*
Source: *developed by the authors based on data from the State Statistics Service of Ukraine (n.d.)*

To maximise the effect, it was necessary to consider the soil-climatic characteristics of the regions. As shown in Table 6, the optimal technologies for chernozems included mycorrhiza and biofertilisers based on humic acids, which increased yield by 15-20%. For serozems in the steppe zone, the use of nitrogen-fixing bacteria (*Azotobacter*) and seaweed-based biostimulants was critical, because of reducing the impact of drought. On sod-podzolic soils, effective measures included biopesticides based on *Trichoderma* and phosphorus-mobilising microorganisms, which increased phosphorus availability by 30-35%.

Table 6*. Recommended technologies for different soil types*

Soil type	Priority biological technologies	Efficiency (yield increase, %)
Chernozems	*Mycorrhizae*, biofertilisers based on humic acids	15-20
Serozems	*Azotobacter*, biostimulants from seaweed	10-15
Sod-podzolic	*Trichoderma*, phosphate-mobilising bacteria	12-18

Source: *developed by the authors*

Implementation of these recommendations required state support, including subsidies for the purchase of bioproducts and training of farmers. For instance, the experience of the "Stepovi Zori" farm (Kherson region) demonstrated that combining biofertilisers with drip irrigation enabled maize yields of 80-85 c/ha even under arid conditions. This highlighted the importance of integrating biological and technical solutions for stabilising agricultural production. Summarising the modelling results, it could be stated that scaling up biologisation had strategic significance for Ukraine's agricultural economy, as it allowed: reducing production costs without compromising yields; preserving and improving soil resources; creating an export advantage in the ecological products market; and integrating Ukraine's agro-industrial complex into global sustainable development trends. The effectiveness of biologised technologies in Ukraine's agricultural sector manifested both in the short and long term – through increased yields, reduced costs, improved soil quality, and expanded export opportunities. In view of this, it was advisable to develop a national strategy for incentivising biologisation as a key component of the country's agroecological policy.

DISCUSSION

The results obtained demonstrated the significant effectiveness of biologised technologies in improving yields, economic viability, and the agroecological condition of soils. Comparison with current scientific research indicated alignment with conclusions on the potential of bioproducts for achieving the goals of sustainable agriculture. Yield increases in wheat, maize, and barley due to the use of mycorrhizae, nitrogen-fixing bacteria, and biostimulants confirmed the findings of H. Lu *et al.* (2024), who identified agglomeration benefits in cereal production under conditions of optimised ecological efficiency in the agricultural environment. Similarly, in China, the application of biological treatments and digital tools led to increased agricultural productivity under conditions of water and soil scarcity. The observed reduction in yield fluctuations in farms using biological systems – at levels up to 5% – correlated with the findings of M.J. Usigbe *et al.* (2023), who proved that adaptive technologies, including microbial and digital monitoring systems, significantly enhanced the resilience of agricultural systems to climate risks. It was found that the use of artificial intelligence platforms combined with bioproducts enabled precise application and control of agri-inputs, thus improving production stability.

The study recorded a consistent increase in humus content and soil bioactivity following five years of bioproduct use, aligning with the analysis by Y. Pan *et al.* (2024), which emphasised the importance of innovations – particularly farmer-led initiatives introducing microbiological solutions – for long-term restoration of soil functions. The research highlighted that introducing biofungicides and humic substances had positive effects on pH, soil structure, and microbial biomass. The economic efficiency of biologised technologies, documented in the form of a 16.2% reduction in costs and increased profitability, corresponded with the analysis by C. Bernini and F. Galli (2024), who showed that agricultural entities with high ecological efficiency delivered better economic performance under spatially diversified policies. Similarly, S.K. Kuchimov (2021) emphasised the importance of transitioning to innovative farming models to lower production costs and optimise spending on crop protection and fertilisers. Cost structure analysis for biologised maize cultivation revealed a dominance of spending on bioproducts, explained by the high effectiveness under arid conditions. Similar conclusions were presented in the work of S. Alharbi *et al.* (2024), noting that in arid and semi-arid regions, the use of *Azotobacter* and phytostimulants improved water retention capacity in plants and resistance to stress. The study also mentioned reduced environmental fees, corresponding with the findings of L. Aldieri *et al.* (2021) regarding the link between technological modernisation and reduced environmental impact through knowledge-intensive innovations.

The forecasted cost savings from scaling biologisation to 30% of farms (up to UAH 15 billion annually) matched the macroeconomic estimates presented by J. He *et al.* (2025). The researchers showed that introducing digital and biological technologies could increase total factor productivity by 12-15% in the medium term. The work of Y. Hu *et al.* (2024) noted that the digital economy in agriculture delivered maximum effect when combined with biologised farming schemes. This alignment with the current study was evidenced by farms that implemented biological technologies alongside technical elements (e.g., precision application, regular lab monitoring, soil condition control), which recorded not only yield increases (up to 6.7 c/ha in maize) but also a reduction in annual yield variability to 5%. Additionally, improvements in agrochemical indicators were observed (humus content increased by 0.5-0.6%) and production costs decreased by 16.2%.

Premium organic product market results – particularly a price difference of up to 40% – were consistent with the findings of L. Ma *et al.* (2021) and K.K. Shah *et al.* (2021), who noted a stable rise in demand for organic agricultural products amid global consumer shifts towards sustainable food models. The recorded decline in organic wheat exports from Ukraine to the EU aligned with the observations of O. Adisa *et al.* (2024) regarding the need to strengthen certification, traceability, and smallholder support systems to maintain market positions. Performance indicators for *Azotobacter chroococcum* in various climate zones (up to 6.7 c/ha in Forest-Steppe regions) confirmed the findings of G. Papadopoulos *et al.* (2024), which noted that synergistically combining bioproducts with precision farming technologies produced maximum effect in moderately humid regions, while under drought conditions, supplementary irrigation or improved soil structure was needed. The outcomes from "Dniprovski Luki" and "Sonyachnyi Step" farms demonstrated that targeted use of biofungicides *Trichoderma asperellum* and *Bacillus megaterium* reduced yield losses from fungal infections and erosion. This supported the models proposed by D.M. Hemathilake and D.M. Gunathilake (2022), who recommended prioritised microbial protection in regions with high soil degradation risk and phytopathogen prevalence.

The application of humic acid-based biostimulants, which promoted 22-35% growth in wheat root systems, fully correlated with the research by M. Pisante *et al.* (2012), which confirmed that early root formation was a critical factor for stress resistance and high yield potential. Similar approaches were supported in the review by K. Takacs-Gyorgy (2012), which pointed to the economic feasibility of transitioning to precision farming with biological inputs. The importance of accounting for soil types in selecting biological technologies was supported by the research of S. Algarni *et al.* (2023), which stated that bioproduct effectiveness significantly depended on pH, organic content, and microbial activity. The research by R. Reddy (2022) emphasised that applying modern agricultural machinery – including precision seeding units, application systems, and digital field management platforms – significantly improved bioproduct usage efficiency. This approach aligned with findings showing that while technical costs in biologised schemes partly increased, ensuring better process control. Additionally, results from implementing adaptive crop varieties and hybrids in combination with biological technologies confirmed the assertion by A. Abdul-Rahaman *et al.* (2021) that bridging the technological gap in agriculture was only possible through aligned adoption of both genetic innovations and agrotechnological practices. Yield increases of 15-20% indicated the high effectiveness of combining breeding achievements with biological stimulation under regional conditions.

In conclusion, the study's results aligned with the international theoretical and empirical discourse on the benefits of biologised technologies in the context of sustainable development, economic efficiency, agro-ecological safety, and climate adaptation. The findings confirmed the rationale for developing a national policy to support biologisation in agriculture, taking into account regional specifics, certification needs, digitalisation, and expert support for farmers.

CONCLUSIONS

Within the study, it was established that the introduction of biological technologies in the cultivation of winter wheat, maize, and barley under Ukrainian conditions contributed to increased economic efficiency of production by reducing costs, increasing yields, and improving soil quality. A comparative analysis over 2020-

2024 showed that when bioproducts were applied, the average yield of the wheat variety "Podolyanka" increased from 48.2 to 55.6 c/ha, whereas under the chemical scheme it remained around 51.3 c/ha. For the maize hybrid "DKC 5143", the yield increase amounted to 8.1 c/ha, and for the barley variety "Vakula" – 4.8 c/ha. The overall reduction in per-hectare costs for the wheat variety "Duma Odeska" amounted to UAH 2,100 (16.2%), including reductions in input costs of up to UAH 2,300 per hectare. The profitability of cultivating the wheat variety "Favorytka" in the Cherkasy region increased from 18% to 24%.

Soil improvements were recorded over the five-year application of biofertilisers: humus content increased to 3.3% (0.5% higher than the control), acidity stabilised at 6.5-7.1 pH, and the number of microorganisms rose from 1.2×10^6 to 3.8×10^6 colony-forming units per gram of soil. A 30% reduction in soil erosion activity was also confirmed in farms in Zaporizhzhia region. For individual crops, it was established that the root length of the wheat variety "Stolychna" increased to 48 cm, and fungal infection in the barley variety "Helios" decreased by 40%. Price analysis showed that organic products were sold at a premium: on the foreign market, the price of organic wheat reached USD 340 per tonne – USD 110 per tonne more than conventional wheat. The forecast of economic modelling suggested that if the biologised model were scaled to 30% of farms by 2030, the annual savings for the agricultural sector could amount to UAH 14.9 billion. Prospective directions for further research included the development of local agrotechnological maps with consideration of soil types, the creation of digital solutions for monitoring biological processes in the field, and the long-term evaluation of the effectiveness of bioproducts.

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Інноваційні технології у рослинництві як фактор підвищення економічної ефективності аграрного виробництва України

Сузан Фарзалієва
Кандидат економічних наук, старший викладач
Азербайджанський державний економічний університет
1001, вул. Істиглаліят, 6, м. Баку, Азербайджанська Республіка
https://orcid.org/0000-0002-2326-0396

Валіда Сафарова
Кандидат економічних наук, доцент
Азербайджанський державний економічний університет
1001, вул. Істиглаліят, 6, м. Баку, Азербайджанська Республіка
https://orcid.org/0009-0008-0729-3615

Ламія Гусейнова
Кандидат економічних наук, викладач
Азербайджанський державний економічний університет
1001, вул. Істиглаліят, 6, м. Баку, Азербайджанська Республіка
https://orcid.org/0000-0003-4633-6493

Андрій Опанасенко
Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0002-4583-2006

Анотація. Метою роботи було встановити ефективність заміни хімічних засобів захисту рослин, добрив і стимуляторів росту на біологічні аналоги в контексті продуктивності, витрат, рентабельності та агроекологічного стану ґрунтів. Дослідження, проведене у 2020-2024 роках, охоплювало сорти озимої пшениці «Подолянка», «Дума одеська», «Фаворитка», «Богуславка», «МІП Лада» та «Столична», ячменю «Вакула», «Геліос» і «Концерто», а також гібриди кукурудзи «ДКС 5143», «ДКС 4014», «Піонер 9892», «Хортиця» та «Дніпровський 185 СВ». Емпірична база включала статистичні дані, результати ґрунтових аналізів, кейс-спостереження в господарствах різних регіонів та економічне моделювання. Було встановлено, що приріст врожайності при застосуванні біопрепаратів становив у середньому 4,3-7,1 ц/га для пшениці й кукурудзи та до 4,8 ц/га для ячменю, при цьому витрати знижувалися до 16 %. Вміст гумусу у ґрунтах зріс до 3,3 %, а кількість мікроорганізмів – до 3,8×106 колонієутворювальних одиниць на грам. Спостерігалося збільшення довжини кореневої системи пшениці сорту «Столична» до 48 см та зменшення ураження ячменю грибковими інфекціями на 40 %. Аналіз цін виявив, що органічна пшениця коштувала на 48 % дорожче за традиційну на зовнішньому ринку. Прогноз моделі засвідчив потенціал економії для аграрного сектору до 15 мільярдів гривень за умов переходу 30% господарств на біологічну модель. Отримані результати можуть бути використані для адаптації агротехнологій, формування програм підтримки екологічного землеробства та розвитку експорту органічної продукції

Ключові слова: сільське господарство; рентабельність; біофунгіциди; біодобрива; стале землеробство

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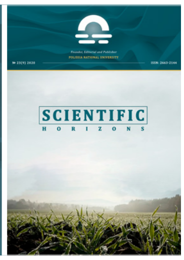

Biosecurity of agroecosystems under technogenic and environmental risks

Anar Zhumadilova

PhD in Technical Sciences

Kazakh National University of Water Management and Irrigation

080000, 28 K. Satpayev Str., Taraz, Republic of Kazakhstan

https://orcid.org/0000-0003-2321-4370

Saule Zhigitova

Master of Sciences, Senior Lecturer

Kazakh National University of Water Management and Irrigation

080000, 28 K. Satpayev Str., Taraz, Republic of Kazakhstan

https://orcid.org/0000-0002-7997-4304

Maira Turalina

PhD, Senior Lecturer

Kazakh National University of Water Management and Irrigation

080000, 28 K. Satpayev Str., Taraz, Republic of Kazakhstan

https://orcid.org/0009-0008-2368-2557

Alina Kudriavytska*

PhD in Agricultural Sciences, Associate Professor

National University of Life and Environmental Sciences of Ukraine

03041,15 Heroiv Oborony Str., Kyiv, Ukraine

https://orcid.org/0000-0003-2888-1981

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Abstract. The study aimed to establish the relationship between technogenic and environmental factors affecting the biosecurity of agroecosystems in Ukraine, with the development of adaptive monitoring and risk mitigation strategies through the integration of digital technologies. The research methodology was based on an interdisciplinary approach combining ecotoxicological analysis, biogeochemical modelling, and spatiotemporal assessment of anthropogenic impacts using geographic information systems, satellite observation, and algorithmic risk prediction based on Artificial Intelligence and big data analytics. The application of machine learning methods, spectral pollution analysis, and multi-level agroecosystem mapping revealed hidden patterns of agri-landscape degradation, assessed their ecological resilience, and formulated adaptive approaches to environmental management to reduce biological risks. The findings indicated an elevated chemical load on Ukrainian agroecosystems, manifested in exceedances of maximum permissible concentrations for ammonia (20-28 μg/m^3 in air), nitrogen oxides (over 35 μg/m^3), nitrates (over 50 mg/L in water), and pesticides (up to 0.05 mg/L). Humus content in chernozems decreased to 1.2-1.5%, accompanied by soil degradation. A correlational link was established between

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*Corresponding author

increased technogenic pressure and higher prevalence of oncological diseases, cardiovascular and respiratory pathologies, as well as reduced life expectancy (by 7-10 years) in highly polluted regions. Negative demographic trends were recorded, including rising child mortality, declining fertility, and increased environmentally driven migration. The results confirm the efficacy of digital technologies in enhancing the quality of monitoring, diagnostics, and risk management in agroecosystems undergoing transformational anthropogenic pressures

Keywords: artificial intelligence; machine learning; risk management; agri-landscape degradation; biosphere

INTRODUCTION

The escalation of technogenic and environmental threats has significantly impacted the biosecurity of agroecosystems, leading to adverse consequences for public health and quality of life. Emissions of hazardous substances, climate change, water and air pollution, and the aftermath of industrial disasters are considered potential factors contributing to increased morbidity, mortality, and deteriorating socio-economic conditions. As an integral indicator of physical, social, and environmental well-being, quality of life has been used to assess the biosecurity of agroecosystems and health risks for populations in agricultural regions.

Large-scale urbanisation, soil degradation, agro-landscape pollution, and industrial accidents have contributed to rising chronic diseases, immune system suppression, and oncological pathologies among residents of agrarian territories (Rahman *et al.,* 2021). Chemical and radioactive contamination has created threats at both regional and global scales, necessitating the development of effective biosecurity strategies in agriculture (Khomutinin *et al.*, 2024). The lack of comprehensive measures, low environmental awareness among agricultural producers, and inadequate monitoring of ecological hazards exacerbate risks to agricultural products and public health. A review of scientific literature confirms the importance of an interdisciplinary approach to assessing technogenic and environmental risks in agriculture. C. Piskunova and V. Bondar (2022) emphasise the need for integrated methodologies to analyse biological threats and physiological responses of organisms under critical conditions. The significance of the discipline "Life Safety" in training crisis management and risk analysis specialists is highlighted, along with the necessity for further empirical research in agroecosystem biosecurity.

A crucial aspect of studying technogenic and environmental threats is the development of effective mitigation and management strategies for agricultural impacts. In this context, the work of M.V. Kustov *et al.* (2021) is noteworthy, focusing on a comprehensive monitoring and control system for atmospheric pollution in agrarian regions by chemical and radioactive substances. The proposed approach is based on predictive mathematical modelling, artificial precipitation methods for hazardous substances, and decision-making systems, enhancing the ecological safety of the agricultural sector. S. Bondarenko *et al.* (2022) analysed threat forecasting mechanisms and optimisation of managerial decisions in Ukraine's agrarian security. Emphasis is placed on a holistic risk assessment framework, improving hazardous substance monitoring efficiency, and developing informational-analytical platforms for rapid response to ecological challenges in the agro-sector. The rise of legal and ethical challenges associated with biotechnology, agrochemicals, and digital systems in agriculture has necessitated a revision of regulatory frameworks for agrarian biosecurity (Polukarov *et al.*, 2024).

O.V. Mudrak *et al.* (2023) analysed the impact of environmental determinants on demographic processes in rural Ukraine. The authors note that industrial pollution and socio-economic factors contribute to the depopulation of agrarian regions, rising youth mortality, and demographic aging, directly affecting agroecosystem stability The study by D. Hryhorczuk *et al.* (2024) examines the ecological consequences of Russia's war against Ukraine, revealing large-scale degradation of agricultural lands, soil contamination, and pollution of water resources, which pose long-term threats to public health and food security. Similar factors were analysed by D. Rawtani *et al.* (2022), who investigated the environmental impacts of the war in Ukraine: water pollution, soil degradation, and biodiversity loss. The authors emphasise the associated health risks and the need to criminalise environmental crimes; however, ecosystem restoration mechanisms require further research.

Y.M. Kopytsia and E.Y. Tulina (2021) explored the legal regulation of invasive alien species in Ukraine within the context of climate change. The authors note that climate change facilitates the spread of undesirable species, threatening biodiversity and the agricultural sector, while effective legislative control mechanisms remain absent. However, the study does not examine the implementation mechanisms of these regulations within Ukraine's legal framework. Similar conclusions were drawn by R. Gentili *et al.* (2021), who investigated the legal regulation of invasive alien species (IAS) in the context of climate change. The authors highlight that these factors act synergistically, posing risks to biodiversity; however, Ukrainian legislation addresses them separately, complicating effective environmental risk management. Beyond the legal regulation of IAS, a critical issue of environmental security is the impact of war on the environment.

O. Grybko *et al.* (2022) identified biosecurity as a critical national interest for Ukraine, necessitating international cooperation. An algorithm for responding to biological threats was developed in accordance with the strategic directions of the National Security and Defence Council. However, the mechanisms for its integration into state governance remain undetailed, requiring further research. The integration of assessment methodologies, biomonitoring, and digital platforms into the environmental risk management system of the agricultural sector has become systemic, as evidenced by the increasing number of scientific and applied developments in the digital monitoring of agroecosystems. The refinement of relevant tools has contributed to the development of comprehensive biosecurity management models. Nevertheless, the long-term effects of anthropogenic pollution and the efficacy of mitigation measures remain understudied, necessitating further standardisation of methodological approaches.

The aim of this study was to assess quality of life as an indicator of agroecosystem biosecurity under technogenic and environmental risks. A series of interrelated tasks were addressed to achieve this objective. Specifically, the primary environmental and technogenic factors influencing agroecosystem biosecurity and the quality of life in agrarian regions were identified. The long-term consequences of anthropogenic pollution on agro-landscape transformation, public health dynamics, and socio-demographic processes were evaluated. Additionally, the efficacy of modern digital technologies in environmental threat monitoring, biosecurity management, and the development of adaptive protection mechanisms for agro-systems was analysed.

MATERIALS AND METHODS

The study employed an applied approach incorporating elements of analytical, evaluative, and digital monitoring methodologies. The geographical scope included six regions of Ukraine – Donetsk, Dnipropetrovsk, Zaporizhzhia, Kharkiv, Kyiv, and Mykolaiv oblasts – which exhibited the highest levels of technogenic pressure according to environmental reports and satellite-based indices of agro-landscape degradation. Primary data for analysis were obtained from open government and international sources. Ukrainian datasets included statistical information from the State Service for Geodesy, Cartography and Cadastre of Ukraine (n.d.), data from the Center for Public Health of the Ministry of Health of Ukraine (n.d.), analytical materials from the National Scientific Center "O.N. Sokolovsky Institute of Soil Science and Agrochemistry" (n.d.), the Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine (n.d.), and records from the Ministry of Agrarian Policy and Food of Ukraine (n.d.).

International sources comprised digital platforms for satellite monitoring and agroanalytics: EOS Data Analytics (Sushchuk, 2025), FarmFacts (n.d.), John Deere (n.d.), Reports Netafim (n.d.), AgriTechHub (n.d.); as well as data from the World Health Organization (WHO) (n.d.), the European Environment Agency (EEA) (n.d.), the International Agency for Research on Cancer (IARC) (n.d.), the United Nations Environment Programme (UNEP) (n.d.), the Chornobyl Research Institute (n.d.), the European Society of Human Reproduction and Embryology (ESHRE) (n.d.), the United Nations High Commissioner for Refugees (n.d.), Ukrainian Hydrometeorological Center the State Emergency Service of Ukraine (n.d.), and the World Bank (n.d.). Additionally, materials from the European Educational Research Association (n.d.) and the State Institutuin "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine" (n.d.) were utilised.

Assessment of agroecosystem status was conducted using satellite-derived indices Normalized Difference Vegetation Index (NDVI) (Li *et al.,* 2021), Serial Peripheral Interface (SPI) (Laimighofer & Laaha, 2022), and CIred-edge (Yadav *et al.,* 2024). Spatial analysis was implemented through k-means clustering followed by risk zone mapping in QGIS 3.22, with geodata processing in Python using the geopandas, rasterio, and scikit-learn libraries. For soil degradation assessment, data on organic matter (humus) content, acidity indices, residual agrochemical concentrations, and satellite observations of land-use structure were employed. Chemical load was evaluated based on concentrations of ammonia, nitrogen oxides, nitrates, and pesticides in air, water, and soils, in accordance with hygienic safety standards (Order of the Ministry of Health of Ukraine No. 721, 2022).

Biosurveillance was implemented using the conceptual model proposed by model proposed by Wagner, integrating satellite, ecological, and demographic data to identify environmentally hazardous clusters (Tan *et al.,* 2023). Additionally, the model by A.J. Kim and S. Tak (2019) was adapted, incorporating digital degradation indicators to spatially delineate high-risk zones with elevated anthropogenic impact. Data interpretation followed a systems-based analytical approach: risk zone delineation was cross-referenced with soil degradation metrics and population demographic structure. The study incorporated insights from countries with advanced digital agroecological monitoring systems (e.g., Germany, the USA, and Israel), as well as Kazakhstan as an example of a nation transitioning to such frameworks. This facilitated the identification of potential strategies to enhance biosecurity governance in Ukraine's agricultural sector. The analysis enabled systematic data organisation for developing a digital biosecurity assessment model for agroecosystems, grounded in digital monitoring, satellite analytics, and spatial modelling.

RESULTS

Ecological and technogenic factors as threats to quality of life and agroecosystem biosecurity. The analysis of ecological and technogenic factors is fundamental for assessing agroecosystem biosecurity and the overall quality of life in agrarian regions. Anthropogenically induced environmental changes are multidimensional, encompassing chemical, biological, and physical factors that affect public health, demographic dynamics, and socio-economic stability. Amid global ecological transformation, particular attention must be paid to the interplay between technogenic pressures and the adaptive capacity of agroecosystems to sustain the viability of human communities.

Ecological and technogenic threats to agroecosystems vary in origin, scale, and destructiveness. Key ecological risks include anthropogenic soil pollution, agri-landscape degradation, reduced agro-biodiversity, and microclimatic shifts. Technogenic factors comprise agricultural facility accidents, agrochemical use, and pesticide/fertiliser contamination of groundwater and surface water, posing direct threats to agroecosystem equilibrium and public health. Ukraine's agroecosystems face significant anthropogenic pressure due to intensive farming, industrial agricultural production, irrational pesticide use, and monoculture dominance. These factors drive the accumulation of hazardous substances (e.g., ammonia, nitrogen oxides, pesticides, and nitrates) in air, soils, and water bodies. Consequences include air pollution, acid rain, soil degradation, water eutrophication, and declining land productivity. Empirical statistical data detail the extent and nature of key pollution sources' impact on agroecosystems (Table 1).

***Table 1**. Impact of harmful emissions on agroecosystems of Ukraine*

Pollution source	Harmful substances	Statistical indicators	Environmental consequences
Intensive agriculture	Ammonia (NH_3)	Average NH_3 levels: 20-28 μg/m³ in air	Acid rain, eutrophication, soil degradation
Industrial agroproduction	Nitrogen oxides (NO_x)	NO_2 concentration: exceeding 35 μg/m³	Soil acidification, reduced crop yields
Agrochemical use	Pesticides, nitrates	Nitrates in water: >50 mg/L; pesticides: up to 0.05 mg/L	Water pollution, toxicity, reduced biodiversity
Monoculture farming	Reduced humus content	Humus decline to 1.2-1.5% in chernozems	Erosion, reduced fertility, degradation of agrolandscapes

***Source:** compiled by the authors based on Center for Public Health of the Ministry of Health of Ukraine (n.d.), M. Sushchuk (2025)*

The presented statistical data indicate a significant level of chemical load in Ukraine's agricultural regions, manifested through elevated concentrations of ammonia, nitrogen oxides, nitrates, and pesticides. These metrics substantially exceed recommended hygienic norms, particularly in cases of air and water pollution (Order of the Ministry of Health of Ukraine No. 721..., 2022). Specifically, atmospheric ammonia concentrations and nitrate levels in groundwater pose direct threats to both the environment and public health. Simultaneously, structural issues in agroproduction, such as monoculture farming and excessive agrochemical use, contribute to rapid soil degradation, erosional processes, and the decline of ecosystem functions in agrolandscapes. This situation necessitates urgent improvements in environmental monitoring systems, particularly through the integration of digital technologies for precise identification of risk zones and the development of adaptive ecological strategies.

Accidents at agro-industrial enterprises, including releases of agrochemical pollutants, heavy metals, and radionuclides, lead to prolonged ecological destabilisation of agroecosystems, causing the accumulation of toxic compounds in soils and water (Makhazhanova *et al.*, 2024). Radiation and chemical pollution, particularly the use of persistent organic pollutants (POPs) in agriculture, impose significant genetic and epigenetic stress on populations, evidenced by high rates of endocrine and oncological pathologies among rural communities. For instance, following the accident at RivneAzot in July 2021, a substantial volume of nitrogen oxides (NO_x)was released into the atmosphere, forming an orange toxic cloud over populated areas (Romanenko, 2021). Emissions of this type are classified as Class I hazards, and their concentrations exceeding 0.085 mg/m³ in air cause acute respiratory irritation, methaemoglobinaemia, increased cardiopulmonary disorder risks, and possess mutagenic properties. Releases of toxic chemical agents create persistent anthropogenic pressure on agroecosystems, disrupting metabolic processes in living organisms and elevating the risk of ecological catastrophe.

Agroecosystem degradation is a factor of socio-economic destabilisation, driving increased morbidity and premature mortality among rural populations, which in turn exacerbates strain on national healthcare systems (Ongayev *et al.*, 2024). Negative demographic trends linked to environmental factors include reduced life expectancy in agricultural regions, declining birth rates, and rising forced migration levels. The depletion of natural resources, particularly soil degradation, compromises food security, necessitating the development of adaptive agroecosystem management strategies and environmental governance. Table 2 presents a structured analysis of ecological and technogenic threats, integrating anthropogenic impact sources, environmental consequences, public health risks, and strategic mitigation measures in the context of agroecosystem biosecurity. The outlined data reflect a multifactorial approach to assessing environmental degradation processes, including mechanisms of natural ecosystem disruption, toxic load dynamics, and socio-economic consequences for agricultural territories. The proposed systemic analysis enables the evaluation of technogenic-ecological threat scales, underscores the need for enhanced environmental policies, improved technological efficiency in risk monitoring, and the adaptation of ecological strategies to align with global biosecurity challenges.

Table 2*. Analysis of ecological and technogenic threats to agroecosystems: Threat assessment and strategic mitigation measures*

Factor	Primary anthropogenic sources	Primary ecological consequences	Impact on agroecosystem biosecurity	Prevention and adaptation methods
Atmospheric pollution	Emissions from agricultural/industrial enterprises, transport, biomass combustion	Smog formation, increased precipitation acidity, ozone layer depletion, degradation of plant cover	Soil quality deterioration, reduced crop productivity, weakened plant immunity	Transition to eco-friendly technologies, emission control, phytoremediation
Soil degradation	Intensive farming, agrochemicals, deforestation	Reduced fertility, humus depletion, erosion	Declining yields, spread of phytopathogens, disruption of soil microbiota	Implementation of soil conservation technologies, organic farming
Water resource pollution	Discharge of agricultural/industrial wastewater, pesticide/fertiliser use	Eutrophication, groundwater contamination, aquatic ecosystem collapse	Accumulation of toxins in soils, plants, and food products, increased zoonotic disease risks	Biological water treatment methods, reduced chemical use
Radiation pollution	Nuclear power plant accidents, radionuclide leaks, nuclear waste disposal	Biosphere contamination by radioactive isotopes, radionuclide bioaccumulation, genetic mutations	Radioactive contamination of soils/water, mutations in agrocenoses	Development of safe disposal technologies, radiation monitoring, bioremediation
Technogenic disasters	Chemical/oil spills, transport accidents, industrial explosions	Mass contamination of air/water/soil, ecosystem disruption	Agroecosystem poisoning, toxic accumulation in food products	Environmental monitoring, eco-safe technology development
Global climate change	Greenhouse gases, deforestation	Increased extreme weather events (droughts, floods, temperature extremes), rising sea levels	Disrupted agricultural cycles, yield reduction, emergence of new pests/diseases	Sustainable agricultural development, crop adaptation
Socio-economic impacts	Rising disease prevalence, food crises, economic losses	Deterioration of public health, migration, heightened social tensions	Food shortages, increased zoonotic epidemic risks	Investments in biosecurity, agroecological programme development

Source: *compiled by the authors based on M.V. Kustov et al. (2021), S. Bondarenko et al. (2022), D. Garcia-Caro (2023), O.V. Mudrak et al. (2023), D. Hryhorczuk et al. (2024), D. Rawtani et al. (2022), L. Moldavan et al. (2024), S. Sharafi and F. Salehi (2025)*

Effective management of ecological and technogenic threats to agroecosystems requires an integrated approach encompassing legislative regulation, technological innovation, and international cooperation. Key policy directions include implementing environmental monitoring tools for agricultural territories, modernising agro-industrial technologies to reduce pollution, and enhancing ecological awareness among farmers and local communities. The integration of digital technologies – particularly artificial intelligence (AI) and Big Data – enables precise forecasting of ecological risks and optimises agroecosystem management mechanisms (Li *et al.,* 2022). Ecological and technogenic factors are decisive determinants of biosecurity levels in agroecosystems and population well-being, influencing ecological resilience, public health, and socio-economic development. Large-scale air, water, and soil pollution exacerbate disease incidence, while technogenic disasters increase risks of genotoxic and mutagenic effects. Effective ecological risk management demands comprehensive adaptive strategies to strengthen agro-industrial biosecurity, environmental governance, and international cooperation within the sustainable development framework.

Long-term consequences of technogenic pollution for health and demographic processes: Transformation of agro-landscapes in the context of agroecosystem biosecurity. Technogenic environmental pollution is a primary driver of ecological destabilisation, causing systemic adverse effects on public health and demographic processes. In agroecosystem biosecurity, anthropogenic pollution triggers transformative changes in agro-landscapes, affecting soil quality, hydrosphere conditions, and biotic communities. The bioaccumulation of xenobiotics correlates with reduced quality of life, eco-pathological syndromes, and increased general and disease-specific morbidity. These processes directly impact sustainable agricultural development and food security. A comprehensive assessment of technogenic pollution's effects on population health and demographics in Ukraine's agrarian regions identifies key risks arising from environmental components. Table 3 systematises major toxicants, their sources, clinical manifestations, and potential demographic consequences, elucidating the interplay between technogenic pressure and agroecosystem biosecurity.

***Table 3**. Long-term consequences of anthropogenic pollution on health and demography*

Impact factor	Key toxicants	Health consequences	Demographic consequences
Atmospheric pollution	PM2.5, NO_x, SO_2, polycyclic hydrocarbons	Chronic obstructive pulmonary disease (COPD), lung cancer, ischaemia, hypertension	Reduced life expectancy by 7-10 years
Hydrosphere pollution	Nitrates, heavy metals, pesticides	Nephrotoxicity, reproductive disorders, mutagenesis	Increased child mortality, reduced fertility
Pedosphere pollution	Cadmium, lead, arsenic, mercury	Oncological diseases, developmental disorders in children	Rising infertility, congenital anomalies
Complex anthropogenic impact	Multicomponent mixtures	Multi-organ failure, chronic diseases	Declining birth rates, depopulation

***Source:** compiled by the authors based on World Health Organization (n.d.), European Environment Agency (n.d.), International Agency for Research on Cancer (n.d.), United Nations Environment Programme (n.d.), State Institutuin "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine" (n.d.)*

The statistically aggregated data presented demonstrate a broad spectrum of adverse health effects caused by chemical and physical environmental pollution. Exposure to atmospheric toxicants, such as fine particulate matter ($PM_{2.5}$), nitrogen and sulphur oxides, is directly linked to the increased prevalence of COPD, cardiovascular pathology, and reduced life expectancy. Similarly, hydrosphere contamination with pesticides and nitrates threatens the development of nephrotoxic and mutagenic processes, particularly among children and pregnant women. Furthermore, significant anthropogenic pressure on the pedosphere due to heavy metal accumulation induces oncogenic processes and reproductive dysfunction, adversely affecting the demographic structure of rural populations. The most critical factor is the combination of multiple pollution sources, which leads to multi-organ pathologies, declining fertility rates, and increased risks of depopulation trends. Thus, the table underscores the necessity of implementing comprehensive measures for monitoring, prevention, and mitigation of environmental threats within national biosecurity strategies.

The study examines region-specific manifestations of anthropogenic hazards in Ukraine, particularly the consequences of the Chornobyl Nuclear Power Plant accident. The 1986 disaster caused radioactive contamination, creating a zone of persistently high background radiation with long-term ecological and biological impacts. Excess levels of caesium-137 in soils (exceeding 370 Bq/kg) are associated with increased frequencies of chromosomal aberrations, thyroid neoplasms, haematological malignancies, and reduced reproductive function (Chornobyl Research Institute, n.d.). Bioindicators in these territories demonstrate reduced species diversity, genetic mutations in biocenoses, and slowed ecosystem recovery, indicating persistent agro-landscape transformation. The presence of radionuclides in food products, soil, and aquatic ecosystems poses long-term biosecurity risks for the population.

A separate category comprises airborne anthropogenic hazards in industrially burdened regions of Ukraine, particularly Donetsk, Dnipropetrovsk, and Zaporizhzhia oblasts. Concentrations of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and polycyclic aromatic hydrocarbons (PAHs) exceed permissible limits by 2-5 times, as confirmed by European Environment Agency monitoring data. These conditions correlate with increased incidence of COPD, broncho-obstructive syndrome, ischaemic heart disease, cancers, and other pathologies linked to toxicological exposure. Combined with soil degradation, chemical water pollution, and microclimatic changes, this creates a persistent risk framework for demographic trends, including declining birth rates, rising mortality, and outmigration from ecologically disadvantaged areas. The pathophysiological mechanism involves oxidative stress, proinflammatory cytokine activation (*IL-6*, *TNF-α*), and apoptotic cascades in alveolocytes, progressively impairing lung parenchyma functionality (Li *et al.,* 2022; Hashemi *et al.,* 2023). These effects are particularly pronounced among agricultural workers, elevating occupational disease risks.

Atmospheric pollutants, including polycyclic aromatic hydrocarbons and heavy metals, contribute to atherosclerotic pathogenesis via endothelial dysfunction and oxidative modification of vascular structures. High airborne toxicant concentrations trigger sympathetic nervous system activation, inducing hypertension, ischaemic heart disease, and cerebrovascular complications. Epidemiological studies confirm that prolonged exposure may reduce average life expectancy by 5-10 years (Tsai *et al.,* 2023). Accumulation of carcinogens (e.g., benzo[a]pyrene, formaldehyde, cadmium, arsenic) induces mutagenesis through DNA damage, activating oncogenic signalling pathways and disrupting apoptosis (Goodman *et al.,* 2022). Radioactive contamination causes genomic instability, increased chromosomal aberrations, and elevated risks of lung carcinoma, haematological malignancies, and thyroid neoplasms. In agroecosystems, this leads to toxicant bioaccumulation in food chains, threatening food security. Xenobiotics in water resources and food (phthalates, dioxins, pesticides) act as endocrine disruptors, impairing neurohormonal regulation of reproductive systems. Effects include reduced fertility, ovulatory cycle disruption in women, spermatogenic dysfunction in men, higher miscarriage rates, and congenital anomaly risks (Ghosh *et al.,* 2022). In agroecosystems, these compounds alter biogeochemical processes, affecting soil microbiomes and agri-biocenoses.

Chronic heavy metal exposure (lead, mercury, manganese) induces neurotoxicity via glutamatergic excitotoxicity and blood-brain barrier disruption. Central nervous system damage correlates with cognitive impairment, neuropsychiatric disorders, and elevated risks of neurodegenerative diseases (e.g., Alzheimer's, Parkinson's) (Shabani, 2021). Trophic chain bioaccumulation exacerbates ecological impacts. Anthropogenic pollution has caused significant long-term public health effects, increasing morbidity, demographic crises, and socioeconomic instability. Risk mitigation requires innovative environmental strategies, expanded monitoring, and integrated biosecurity/sustainable development policies. Ecological degradation stimulates migration, reducing labour resources and exacerbating socioeconomic disparities. Similar threats have been documented in the agroecosystems of Kazakhstan, where anthropogenic pressure on water bodies was chronic, and the primary sources of pollution were the mining industry and the agricultural sector. As noted in the study by G. Abenova *et al.* (2024), industrial effluents, particularly from mining enterprises, contained high concentrations of heavy metal compounds, leading to their accumulation in aquatic environments. Additionally, inefficient irrigation systems and excessive use of agrochemicals in agriculture contributed to the eutrophication of water bodies and secondary soil contamination, disrupting the biochemical balance of agro-landscapes.

A separate concern was thermal pollution caused by the discharge of heated water after its use in cooling systems of thermal power plants. This resulted in localised increases in water temperatures and disrupted biotic interactions in aquatic ecosystems. Such changes significantly affected microbial activity, led to the displacement of autochthonous flora and fauna, and promoted the proliferation of toxic algae. The overall ecological state of water bodies in Kazakhstan was characterised as critical, necessitating urgent measures to restore biodiversity and implement integrated water resource protection strategies (Abenova *et al.*, 2024). The accumulation of toxicants in Kazakhstan's aquatic environment had a multiplicative effect on agricultural ecosystems, as contaminated water was used for irrigation, leading to secondary chemical loading on soils and crop production. Consequently, elevated levels of heavy metals were observed in the food chain, exacerbating public health risks and posing a potential threat to food security. These trends highlighted the need for enhanced regional monitoring and the implementation of transboundary biosecurity programmes for Central Asian agroecosystems.

A synthesis of key parameters was conducted to assess the long-term impact of anthropogenic pollution on public health, demographic processes, and agrolandscape transformations within the context of agroecosystem biosecurity. The data presented in Table 4 illustrate the correlations between pollutant concentrations in the environment and the incidence of oncological, cardiovascular, and neurological pathologies, as well as their influence on birth rates, mortality, and migration trends in regions with high anthropogenic pressure. Particular attention was given to agro-landscape degradation, contamination of groundwater and water resources by heavy metals, pesticides, and radionuclides, which disrupt ecosystem processes, reduce agroecosystem productivity, and lead to the accumulation of toxic substances in food chains. The analysis of the effects of chemical pollution, radiation levels, and agro-landscape degradation on reproductive health, infant mortality, and depopulation processes underscores the need for further development of comprehensive biosecurity measures, ecological balance restoration, and demographic stabilisation.

Table 4*. Comprehensive analysis of the long-term impact of anthropogenic pollution on health, demographic processes, and agroecosystems*

Parameter	Health impact	Demographic consequences	Additional data
PM2.5 concentration in industrial zones (μg/m^3)	Increased risk of COPD, asthma, lung cancer	Reduction in average life expectancy by 7-10 years	Exceeds safe limits by 2-5 times
Heavy metal content in soils (mg/kg)	Neurotoxicity, developmental disorders in children	Elevated infant mortality, congenital anomalies	Cadmium, lead, and mercury exhibit the highest toxicity

Table 4. Continued

Parameter	Health impact	Demographic consequences	Additional data
Radiation contamination (Bq/kg)	Oncogenic mutations, leukaemia	Increased infertility cases, genetic abnormalities in new-borns	Recorded in areas of nuclear power plant accidents
Consumption of contaminated water (mg nitrates/L)	Methaemoglobinaemia, liver damage	Higher infant mortality, reduced birth rates	Exceeds permissible concentrations in river water
Sulphur dioxide emissions (tons/year)	Cardiovascular diseases, respiratory disorders	Increased overall mortality	Particularly prevalent in coal energy zones
Infertility rate in polluted areas (%)	Reproductive disorders, hormonal imbalance	Population ageing, declining birth rates	Infertility rates rise by 20-30% in industrial regions
Frequency of environmentally induced migration (%)	Stress disorders, mental exhaustion	Depopulation, demographic imbalance	High internal migration driven by environmental factors
Cancer incidence (per 100,000)	Malignant tumours, mutagenic effects	Increased mortality, reduced life expectancy	Clear correlation with pollution levels
Outmigration from industrial-agrarian regions (%)	Social instability, adaptation disorders	Economic decline, labour shortages	Urbanisation hindered by environmental threats

Source: *compiled by the authors based on State Service for Geodesy, Cartography and Cadastre of Ukraine (n.d.), Center for Public Health of the Ministry of Health of Ukraine (n.d.), National Scientific Center "O.N. Sokolovsky Institute of Soil Science and Agrochemistry" (n.d.), Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.), M. Sushchuk (2025), FarmFacts (n.d.), John Deere (n.d.), Netafim (n.d.), AgriTechHub (n.d.), World Health Organization (n.d.), European Environment Agency (n.d.), International Agency for Research on Cancer (n.d.), United Nations Environment Programme (n.d.), State Institutuin "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine" (n.d.)*

The data presented in Table 4 demonstrate a clear correlation between the level of anthropogenic environmental pollution and the increase in medical-demographic risks in industrial-agrarian regions. The most critical parameter is the concentration of fine particulate matter ($PM_{2.5}$), which exceeds safe levels by 2-5 times and is directly associated with the development of chronic respiratory diseases, oncological pathology, and a reduction in life expectancy by 7-10 years. Equally significant are the levels of heavy metals in soils and background radiation, which affect reproductive health, induce mutagenic processes, increase infant mortality, and contribute to rising infertility rates. From a demographic perspective, the most pronounced consequences include depopulation, declining birth rates, and intensified migration trends driven by deteriorating environmental quality. The proportion of environmentally motivated relocations is increasing, indicating a tangible threat to the social structure and economic potential of these regions. The incidence rates of oncological and cardiovascular diseases in polluted areas further confirm the adverse impact of environmental determinants on public health. Thus, the table clearly illustrates the complex effect of anthropogenic pressures on the biosecurity of agroecosystems, necessitating the implementation of preventive environmental strategies.

Digital technologies in environmental threat monitoring, biosecurity management, and agroecosystem protection. Digital technologies play a pivotal role in monitoring environmental threats, managing biosecurity, and protecting agroecosystems. Amid intensifying anthropogenic impacts, climate change, and the globalisation of pathogenic threats, the integration of modern information technologies enhances the efficiency of agro-landscape condition analysis, optimises environmental monitoring systems, and enables adaptive risk management. The use of Big Data, AI, IoT, and satellite monitoring contributes to improving environmental safety in the agricultural sector and the early detection of threats related to soil degradation, phytopathogen spread, and toxic compound exposure (van Wynsberghe, 2021; Li *et al.,* 2022). The application of AI and machine learning in agroecosystem environmental management is becoming increasingly relevant for optimising biosecurity monitoring and governance. These technologies facilitate the effective interpretation of complex agroecological data, identification of hidden patterns, and improved risk prediction accuracy. Below is a table illustrating the key applications of AI in an agroecological context.

Table 5*. Applications of artificial intelligence in agroecological monitoring*

Application area	Specific technology/Method	Expected outcome
Agroecological data analysis	Neural networks, clustering	Identification of pollution distribution patterns
Soil condition monitoring	Spectral image analysis	Classification of degradation types
Crop risk prediction	Machine learning (regression models)	Yield forecasting, pest infestation probability
Phytopathogen detection	Deep learning	Automated recognition of disease symptoms

Table 5. Continued

Application area	Specific technology/Method	Expected outcome
Eco-protection efficacy assessment	Algorithmic modelling	Comparative analysis of impact mitigation measures

Source: *compiled by the authors based on Ministry of Agrarian Policy and Food of Ukraine (n.d.), M. Sushchuk (2025)*

The table analysis highlights the broad potential of AI in agroecosystem biosecurity. Deep learning holds the greatest promise, enabling precise phytopathogen detection, as well as spectral analysis of satellite imagery for diagnosing soil degradation. Machine learning allows adaptive responses to dynamic environmental changes, which is critical in the context of climatic challenges and anthropogenic threats. The structural model of the biosurveillance system, presented in Figure 1, outlines the operational principles of digital environmental monitoring platforms (Tan *et al.*, 2023). This system encompasses multi-source data collection, including information from agricultural enterprises, monitoring stations, environmental laboratories, satellite observation systems, and sensor networks. The acquired data undergo analytical processing to identify ecological risks, map agroecosystems, model spatial pollution dynamics, and comprehensively assess agro-biodiversity status.

The integration of digital agroecosystem monitoring systems enables the combination of data analysis across different levels – from local sensor platforms to global satellite observations. The use of deep learning and satellite image processing facilitates the automatic identification of degradation processes in agricultural landscapes, such as soil erosion, salinisation, or declining organic matter content. Additionally, spatial change analysis algorithms allow for the assessment of pesticide, heavy metal, and microplastic contamination, which is crucial for ensuring sustainable agricultural development. In turn, Figure 2 presents an integrated data collection and analysis system in agri-biosecurity, combining continuous monitoring of soil, water, atmospheric parameters, and plant community status. The detection of environmental threats, particularly abnormal changes in agro-biocenosis composition, enables timely decision-making for optimising land use and ensuring ecological safety in agricultural production.

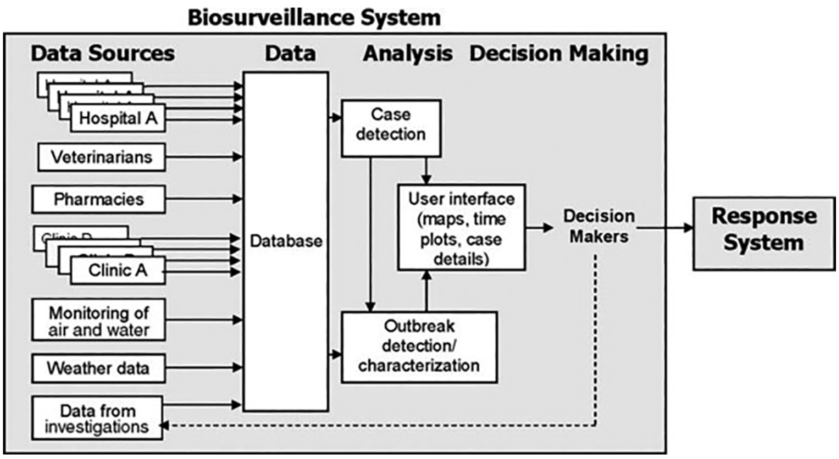

Figure 1*. Wagner's systemic surveillance framework*
Source: *compiled by the authors based on A. Tan et al. (2023)*

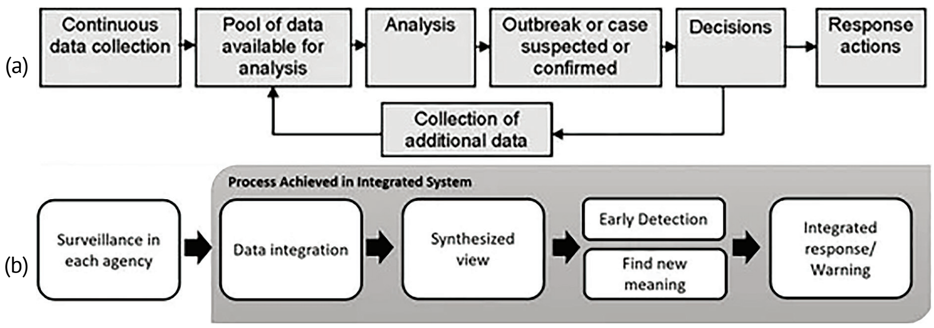

Figure 2*. Biosurveillance process according to (a) Wagner, (b) Kim and Taka*
Source: *compiled by the authors based on A.J. Kim and S. Tak (2019), A. Tan et al. (2023)*

Particular attention should be given to the use of convolutional neural networks (CNNs) for satellite image analysis, which enables the automatic identification of anomalous changes in natural ecosystems, such as deforestation, toxic algal blooms, or illegal industrial emissions. Furthermore, pattern recognition algorithms facilitate the tracking of atmospheric and aquatic geochemical changes, which is critical for early ecological risk detection. The integration of such technologies into environmental monitoring systems enhances governmental biosecurity efficiency, enabling prompt threat response policies and laying the groundwork for adaptive ecological management mechanisms. The advancement of the Internet of Things (IoT) in agroecological monitoring supports the development of sensor networks that continuously track soil moisture, acidity, toxic substance levels, and pathogenic microorganism concentrations (van Wynsberghe, 2021). The deployment of autonomous sensor platforms combined with drones and underwater unmanned vehicles improves the monitoring of water resources, particularly in assessing eutrophication levels, agrochemical pollution, and soil degradation processes.

Geographic Information Systems (GIS) serve as a tool for spatial analysis of ecological risks, enabling the integration of satellite data, remote sensing, and real-time sensor networks (Mouha, 2021). This technology facilitates the creation of multi-layered risk maps that display pollution levels, hotspots of ecological disasters, and demographic parameters, thereby supporting comprehensive biosecurity management. GIS technologies enhance environmental management by enabling rapid identification of critical zones, prediction of anthropogenic accident consequences, and optimisation of mitigation measures (Remeshevska *et al.*, 2021). Spatial analysis allows for the assessment of long-term environmental changes on public health, promotes adaptive urban planning, and improves infrastructure resilience. The integration of GIS into national biosecurity monitoring systems enables more effective risk forecasting and the development of preventive strategies at a global level (Llupa, 2025).

Bioinformatics and genomic data analysis hold significant potential in ensuring agro-biosecurity, particularly in detecting resistant pathogens, analysing soil microbiomes, and assessing the impact of anthropogenic pollution on biodiversity. Next-generation sequencing (NGS) technologies allow for the identification of mutational changes in pathogenic microorganisms, which is critical for early threat detection in agriculture (John *et al.,* 2021). Automated algorithms for analysing genetic reserves can predict evolutionary trends, enabling rapid adaptation of bioprotection strategies. Satellite monitoring technology for agroecosystems provides remote assessment of agricultural land conditions, crop yield dynamics, and changes in landscape moisture balance. Earth remote sensing (ERS) data are used to model climatic changes and their impact on agro-landscape productivity (Janga *et al.,* 2023). Spectral analysis enables the detection of plant stress factors, such as water deficiency, disease spread, or phytotoxic effects of pollution. In contrast, digital platforms and cloud technologies allow the integration of data from multiple sensor sources, automate real-time analysis, and generate predictive models of agroecosystem conditions (Kadyraliev *et al.*, 2024). The use of blockchain technology ensures transparency and protection of environmental data, which is crucial for sustainable agricultural development. The creation of global ecological databases enables researchers and government agencies to access high-precision analytical reports on environmental status.

The development of cyber-physical systems and ecological process modelling is facilitated by the creation of digital twins of natural ecosystems. These technologies enable real-time environmental monitoring, prediction of ecological threats, and testing of various climate change adaptation scenarios. Particularly promising are models simulating pollutant circulation in soil and the atmosphere, allowing for the development of pre-emptive measures to minimise pollution impacts. The integration of bio-digital technologies into biosecurity monitoring has enabled detailed analysis of microbial environments, identification of hazardous microorganisms, and assessment of their interactions with biosystems. Advances in nanotechnology for environmental monitoring have led to the development of highly sensitive biosensors capable of detecting pollutants at the molecular level, opening new prospects for early diagnosis of ecological threats. An evaluation of digital technology implementation in agroecological monitoring demonstrates significant progress in improving diagnostic accuracy, agroecosystem adaptability, and strategic environmental planning. The use of artificial intelligence, satellite platforms, GIS, and the IoT in countries with advanced agricultural sectors confirms the high efficiency of such solutions. Table 6 presents examples of practical innovations implemented in various countries, including Ukraine, with an analysis of key outcomes.

Table 6. *Examples of digital technology implementation in agroecosystem monitoring*

Country/Region	Technology	Implementation	Results/Effects
Ukraine	Artificial Intelligence, Satellite Monitoring	EOS Data Analytics, (agrolandscape monitoring)	Soil degradation mapping, satellite-based crop rotation and yield tracking
Ukraine	GIS	Landscape zoning models, agrobiocartography	Digital mapping of biodiversity and regional pollution patterns

Table 6. Continued

Country/Region	Technology	Implementation	Results/Effects
USA	IoT, Machine Learning	John Deere – Smart Farming Technologies	Reduced agrochemical costs, precision farming, increased productivity
Germany	Big Data+Soil Analysis	FarmFacts – Field Management System	Automated fertiliser application, minimised soil erosion
Israel	Sensor Platforms+AI	Netafim – Digital Irrigation Control	Optimised water regime, improved crop yields under resource scarcity
Kazakhstan	GIS, AI, Agri-Data Analytics	AgriTechHub, Kazhydromet	Indexing of agro-water resources, heavy metal monitoring in soil/water, climate risk forecasting

Source: *compiled by the authors based on State Service for Geodesy, Cartography and Cadastre of Ukraine (n.d.), Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine (n.d.), M. Sushchuk (2025), FarmFacts (n.d.), John Deere (n.d.), Netafim (n.d.), AgriTechHub (n.d.)*

Based on an analysis of digital agroecosystem monitoring technologies implemented in Ukraine and abroad, it is advisable to formulate recommendations for enhancing the national environmental management system. Primarily, state support must be ensured for the development and implementation of innovative digital platforms capable of conducting high-precision real-time monitoring of agro-landscape ecological conditions. Such support should include funding for IT infrastructure and fostering collaboration between research institutions, agribusinesses, and government agencies. A key objective is the establishment of an integrated satellite monitoring system for agroecosystems using GIS modules, enabling timely detection of ecological risks, assessment of natural resource degradation levels, and the development of predictive risk models. This requires institutional framework improvements, standardisation of data collection and processing methodologies, and interdepartmental data sharing. Equally important is human capital development – implementing training programmes and workshops for farmers, agronomists, ecologists, and local authorities to enhance digital literacy and skills in working with intelligent ecosystems. Special attention should be given to establishing digital laboratories at leading Ukrainian agricultural universities, specialising in ecological data analysis, risk modelling, and the development of biosecurity solutions using AI, Big Data, and bioinformatics.

Overall, the implementation of these measures will enhance strategic agroecosystem management, reduce anthropogenic environmental pressure, and ensure national-level biosecurity and food stability. Thus, digital technologies have become a key instrument in transforming agroecosystem biosecurity monitoring and ecological threat assessment. The integration of artificial intelligence, IoT, satellite data, and GIS not only enables real-time environmental analysis but also creates opportunities for precise forecasting of agro-landscape changes and their impact on ecosystem processes. Through digital platforms and bioinformatic approaches, adaptive response strategies can be developed to minimise anthropogenic impacts and optimise natural resource management.

DISCUSSION

Within the framework of this study, the chronic accumulation of technogenic pollutants was identified as a key factor driving destructive changes in Ukraine's agroecosystems. The most pronounced adverse effects were associated with elevated levels of persistent organic compounds, heavy metals, and radionuclides. It was established that these substances induced profound transformations in the microbiological composition of soils and water bodies, disrupted biogeochemical cycles, contributed to the degradation of agricultural landscapes, and intensified the ecological burden on land use. A decline in agro-biological characteristics of soil resources, deterioration of water quality, and reduced resistance of crops to abiotic and biotic stressors were documented. The identification of correlations between pollution types, microbial community transformation parameters, and ecosystem degradation indicators provided a basis for justifying the need to implement digital risk prediction models as part of adaptive environmental governance.

In the publication by G.N.T. Hasnat (2021), the impact of emerging pollutants – including pharmaceutical residues, nanomaterials, flame retardants, and persistent organic compounds – on agroecosystems was characterised. It was demonstrated that these substances disrupted biogeochemical equilibrium, triggered toxicant bioaccumulation, and altered the microbiological structure of ecosystems. The obtained results align with empirical observations recorded in the analysis of toxic load effects on soil and water microbiomes. The presence of such parallels underscores the necessity of continuous ecotoxicological monitoring using digital tools for adaptive biosecurity management. The study by M. Fenzi *et al.* (2024) analysed the consequences of uncontrolled dissemination of genetically modified organisms in Mexican agroecosystems. It was found that the lack of interaction between traditional farming practices and regulatory policy facilitated genetic diversity erosion and the destruction of local biocultural structures. Despite the study's focus on genetic risks, a typological similarity was observed with the changes induced by chemical and radiological contamination. Both approaches demonstrate a decline in agroecosystem resilience due to the disruption of equilibrium between natural and anthropogenic factors, as well as the loss of adaptive potential in agroecological environments.

The work of R.I.A. Briseño *et al.* (2023) presented an example of integrating molecular technologies and machine learning algorithms into biosanitary monitoring practices. Combining high-throughput sequencing (HTS) with mathematical models enhanced the accuracy of phytovirus detection and enabled the prediction of viral load in plant systems. The efficacy of using satellite indices, AI elements, and digital platforms for identifying ecological degradation hotspots was demonstrated. A comparative analysis with digital agroecological risk monitoring results confirmed the feasibility of employing digital technologies as the foundation for intelligent environmental governance in the context of agroecosystem biosecurity. The conceptual foundations of a multilevel biosecurity system, based on the interconnectedness of human, animal, plant, and environmental health, were further developed within the One Health framework proposed by L.L. Vázquez (2024). In this model, biosecurity is interpreted as a component of food security and sustainable development, requiring the integration of ecological and biomedical factors. Correlations were established between microbiome transformation, ecosystem process disruption, and increased demographic risks in areas with elevated technogenic pressure. The identified links between chronic pollution and structural disturbances in microbial communities align with findings from this study, which analysed agroecosystems under persistent toxicant accumulation.

The biological consequences of technogenic impact on agricultural environments manifest, in part, through adaptive mechanisms in biotic components (Shaforost *et al.*, 2024). The work of P. Neve and A.L. Caicedo (2022) described evolutionary processes such as hybridisation, mimicry, and herbicide resistance development, which emerge under selective pressure induced by agronomic practices. The presence of microbiological disturbances in soils, identified through pollution impact analysis, may be considered a factor amplifying this pressure and facilitating phytocenosis transformation. The obtained data confirm the increasing complexity of ecological control due to the growing adaptive variability of undesirable plant species. In contemporary contexts, the issue of cyberbiosecurity has gained particular significance, as explored in the study by S. Stephen *et al.* (2023). Vulnerabilities were identified in digital platforms used in precision agriculture, automated farm management, and supply chain logistics. The absence of unified biosecurity information standards was noted. Although the study did not directly focus on bioecological monitoring, it substantiated the importance of digital integration for risk prediction and rapid response to technogenic threats. The conclusions align with intelligent environmental monitoring approaches based on automated spatial and biological data analysis.

The implementation of nature-oriented stabilisation technologies in agroecosystems has been analysed in the publication by M. Mustafa *et al.* (2022). It has been demonstrated that agroforestry measures contribute to improved microclimatic conditions, reduced erosional processes, stabilised moisture levels, and decreased crop susceptibility to external stressors. The study established that increasing abiotic pressures caused by chemical and radioactive pollution negatively affect soil productivity. The identified need for integrating ecological and managerial solutions into strategies for maintaining ecosystem resilience confirms the efficacy of a multicomponent approach to agroecosystem adaptation. In the study by A. Tyczewska *et al.* (2023), the potential applications of agricultural biotechnology under global challenges induced by the COVID-19 pandemic and geopolitical risks in Eastern European countries were examined. Conclusions were drawn regarding the effectiveness of genetic modification technologies, as well as artificial intelligence (AI) tools, for enhancing crop yields, adapting agricultural crops to adverse conditions, and minimising environmental burdens. Furthermore, the study demonstrated the efficacy of AI algorithms and Big Data systems in detecting ecotoxicological threats and diagnosing degradation processes in agricultural landscapes. The obtained results confirmed the significant potential of digital and biotechnological innovations as tools for adapting the agricultural sector to conditions of environmental and socio-economic instability.

An expert assessment of pollinator population status and risk factors in European agricultural ecosystems was conducted in the study by B.K. Willcox *et al.* (2023). It was established that the primary threats to bee population stability remain high agrochemical loads, declining environmental biodiversity, parasitic infestations, and climatic anomalies. The study proposed integrating digital monitoring tools, particularly AI, the IoT, and Big Data, into adaptive ecological management systems to enhance biosecurity control efficiency. It was identified that toxic pollution and changes in microbial community composition weakened the functional resilience of agroecosystems, particularly through disruptions in mediated ecosystem services. Comparative analysis with degradation processes in agrosystems confirmed a general trend of declining adaptive capacity in ecosystems under anthropogenic pressures.

The study revealed a strong correlation between technogenic pollution of agricultural environments and a complex of changes, including transformations in soil and water microbiological composition, disruptions in biogeochemical equilibrium, and reduced ecosystem stability. Prolonged exposure to persistent organic pollutants, heavy metals, and radionuclides was found to contribute to chronic toxicological burdens, impairing regulatory mechanisms in agrobiocenoses. The accumulation of toxic components not only reduces agroecosystem productivity but also has indirect effects on rural demographic trends due to increased biological risks and deteriorating living conditions. The empirical data underscore the urgency of developing a systemic approach to agroecological safety monitoring using digital tools. Given the complexity of identified ecotoxicological interactions, it was proposed that monitoring systems should integrate spatial data, satellite observation indices, microbiological analyses, and AI-based predictive modelling. This approach enables early risk detection, long-term pollution impact assessment, and adaptive management responses at local and regional levels. Enhanced diagnostic accuracy for agroecosystem instability under variable technogenic pressures is critical for mitigating degradation processes (Fedoniuk *et al.*, 2024). A trend towards convergence in scientific methodologies was observed, particularly in interdisciplinary ecological risk assessment, digital ecosystem monitoring, and adaptive biosecurity management. The formulated concepts address escalating challenges posed by combined technogenic, biotic, and climatic threats, providing a theoretical foundation for sustainable agroecosystem tools under ecological instability.

CONCLUSIONS

Analysis of the obtained results confirmed the efficacy of a holistic approach to assessing the impact of technogenic and natural-ecological factors on agroecosystem biosecurity. Integration of ecotoxicological, biogeochemical, and agroecological parameters enabled a multi-level evaluation of agroecosystem conditions and identification of spatiotemporal degradation patterns. Specifically, ambient ammonia concentrations averaged 20-28 μg/m^3, nitrogen oxides exceeded 35 μg/m^3, while nitrate levels in water surpassed 50 mg/L, and pesticides reached 0.05 mg/L. Chernozem soils exhibited humus content reductions to 1.2-1.5%, indicative of degradation. Exposure to chemical, radioactive, and biological stressors correlated with increased malignancy incidence (showing clear pollution-dose dependency), reduced average lifespan by 7-10 years in industrial-agrarian regions, and higher frequencies of congenital anomalies and infertility. Areas with elevated PM2.5 particulate concentrations (2-5 times above permissible limits) showed prevalent cases of COPD, ischemic heart disease, and neurodegenerative pathologies. Soil radionuclide levels (exceeding 370 Bq/kg for Cs-137) were associated with elevated genetic mutations, endocrine disorders, and oncological haematological risks.

Concurrently, intensive technogenic pressures exacerbated environmentally driven migration, social tensions, and economic decline in agrarian regions. Infertility rates in polluted zones rose by 20-30%, while child mortality and declining birth rates confirmed critical demographic impacts. These findings underscore the necessity for systemic modernisation of ecological monitoring and adaptive biosecurity management in agroecosystems. The obtained results substantiated the feasibility of large-scale implementation of intelligent monitoring platforms based on satellite analytics, GIS, and machine learning methods. This approach facilitated the development of dynamic ecological threat maps, prompt identification of critical zones, and informed decision-making to minimise environmental risks. The necessity of developing adaptive management strategies was established, incorporating local pollution indices, soil-water resource conditions, and demographic characteristics. Strengthening interdisciplinary collaboration among agroecologists, toxicologists, digital technology specialists, and environmental medicine experts is a prerequisite for establishing robust biomonitoring systems capable of predicting agroecosystem transformations.

The study was accompanied by several limitations that must be considered when interpreting the results. The spatial coverage was restricted to six regions of Ukraine, complicating the extrapolation of findings to the national level. The assessment of agroecosystem conditions relied primarily on composite ecological indices without accounting for seasonal dynamics, which may have affected the accuracy of the established correlations. Further limitations pertained to the quality of satellite data, particularly in terms of resolution, as well as the availability of comprehensive geoecological databases. Demographic information was obtained from open sources, constraining the depth of causal relationship analysis. Promising directions for future research include the development of neuromathematical models for predicting long-term ecological consequences, evaluating the effectiveness of agroecosystem rehabilitation measures, and implementing automated data collection and analysis systems. The application of blockchain technologies for recording environmental data is advisable to ensure monitoring process transparency and enhance trust in biosecurity management systems. The establishment of adaptive regulatory mechanisms that account for spatial risk heterogeneity will contribute to the formulation of effective policies for sustainable agrosector development amid global ecological transformations.

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Біозахист агроекосистем в умовах техногенних та екологічних ризиків

Анар Жумаділова
Кандидат технічних наук
Казахський національний університет водного господарства та іригації
080000, вул. К. Сатпаєва, 28, м. Тараз, Республіка Казахстан
https://orcid.org/0000-0003-2321-4370

Сауле Жигітова
Магістр, старший викладач
Казахський національний університет водного господарства та іригації
080000, вул. К. Сатпаєва, 28, м. Тараз, Республіка Казахстан
https://orcid.org/0000-0002-7997-4304

Майра Тураліна
Доктор філософії, старший викладач
Казахський національний університет водного господарства та іригації
080000, вул. К. Сатпаєва, 28, м. Тараз, Республіка Казахстан
https://orcid.org/0009-0008-2368-2557

Аліна Кудрявицька
Кандидат сільськогосподарських наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, Київ, Україна
https://orcid.org/0000-0003-2888-1981

Анотація. Метою дослідження було встановлення зв'язку між техногенними та екологічними факторами, що впливають на біобезпеку агроекосистем в Україні, з розробкою адаптивного моніторингу та стратегій зменшення ризиків шляхом інтеграції цифрових технологій. Методологія дослідження базувалася на міждисциплінарному підході, що поєднує екотоксикологічний аналіз, біогеохімічне моделювання та просторово-часову оцінку антропогенного впливу з використанням геоінформаційних систем, супутникового спостереження та алгоритмічного прогнозування ризиків на основі штучного інтелекту та аналітики великих даних. Застосування методів машинного навчання, спектрального аналізу забруднення та багаторівневого картографування агроекосистем виявило приховані закономірності деградації агроландшафтів, оцінило їхню екологічну стійкість та сформулювало адаптивні підходи до управління навколишнім середовищем для зниження біологічних ризиків. Результати дослідження вказали на підвищене хімічне навантаження на українські агроекосистеми, що проявляється у перевищенні гранично допустимих концентрацій аміаку (20-28 мкг/м^3 у повітрі), оксидів азоту (понад 35 мкг/м^3), нітратів (понад 50 мг/л у воді) та пестицидів (до 0,05 мг/л). Вміст гумусу в чорноземах знизився до 1,2-1,5 %, що супроводжувалося деградацією ґрунту. Встановлено кореляційний зв'язок між підвищеним техногенним тиском та вищою поширеністю онкологічних захворювань, серцево-судинних та респіраторних патологій, а також скороченням тривалості життя (на 7-10 років) у регіонах із високим рівнем забруднення. Зафіксовано негативні демографічні тенденції, включаючи зростання дитячої смертності, зниження народжуваності та збільшення екологічно зумовленої міграції. Результати підтверджують ефективність цифрових технологій у підвищенні якості моніторингу, діагностики та управління ризиками в агроекосистемах, що зазнають трансформаційного антропогенного тиску

Ключові слова: штучний інтелект; машинне навчання; управління ризиками; деградація агроландшафтів; біосфера

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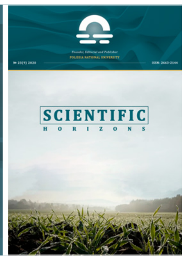

Analysis and assessment of water resources in the Kyrgyz Republic

Nurbek Ibragimov*

PhD in Economics, Associate Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0009-1069-8936

Arstanaly Botobekov

Doctor of Economic Sciences, Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0004-8332-8833

Baktygul Ishekeeva

PhD in Economics, Associate Professor
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0002-6858-1967

Adilbek Asankanov

Senior Lecturer
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0006-0123-7183

Manzura Khashimova

Senior Lecturer
Kyrgyz National University named after Jusup Balasagyn
720033, 547 Frunze Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0005-2468-0578

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Abstract. The study aimed to analyse the factors of water use, environmental impacts and efficiency of water management to develop recommendations for their optimisation. The study determined that water consumption in agriculture decreased from 80% in 2020 to 76% in 2024, but water losses in irrigation systems remained high, decreasing only from 39% to 38%. In the Chui region, the largest water consumer, the share of water use decreased from 45% to 41%, and economic losses reduced from USD 40 million to USD 35 million. In water-scarce Osh region, water consumption dropped from 18% to 14%, but water availability in agriculture and the municipal sector remained limited. Wastewater treatment improved from 50% in 2020 to 55% in 2024, but this figure was far below international standards, where Switzerland and Canada had treatment rates of 95% and 90%, respectively. Comparative analysis demonstrated

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*Corresponding author

that developed countries are actively using digital leakage monitoring systems, smart irrigation technologies and multi-stage water treatment, which have reduced losses by up to 6-8%. In Kyrgyzstan, such technologies were introduced locally and only in some agricultural enterprises. Investments in water infrastructure amounted to USD 7 per capita, compared to USD 200 in Switzerland and USD 150 in Canada, which limited the modernisation of the water supply system. The problems identified confirmed the need to reform the water management system, including reducing water losses, modernising wastewater treatment facilities, introducing digital solutions for water management and adapting infrastructure to changing climate conditions

Keywords: hydrological changes; glacier degradation; climate risks; environmental and economic analysis; strategic planning

INTRODUCTION

The research relevance is determined by the growing pressure on water resources, increased water consumption and the effects of climate change. The Chui region has developed irrigation and hydropower, while the Osh region suffers from water shortages and low water use efficiency. Pollution of water bodies by industrial and agricultural wastewater degrades water quality, which requires modernisation of treatment technologies. Kyrgyzstan needs effective mechanisms for water management, balanced water uses and the study of international experience, including the practices of Switzerland and Canada. The problem is caused by ineffective management, significant water losses and glacier degradation, which reduces river flows and groundwater reserves. In the Chui region, outdated irrigation systems increase water losses, and in the Osh region, poor wastewater treatment exacerbates resource shortages. Insufficient oversight and investment are slowing down the modernisation of the water sector. A comprehensive study of these aspects is needed to develop sustainable water use strategies and prevent a water crisis.

The issue of the economic importance of water resources is considered in various studies. For example, S.S. Kozhokulov *et al.* (2021) considered the water resources of Kyrgyzstan as a strategic resource for economic development. The study emphasised that agriculture and hydropower were the main sectors dependent on water resources, but inefficient distribution and high-water losses reduced their economic potential. The study by A. Boronbaeva (2024) addressed the ecological state of the Ak-Bury River, identifying the problem of water pollution by industrial and agricultural waste. The study emphasised the need to modernise wastewater treatment facilities and develop comprehensive measures to prevent the degradation of water bodies. Consequently, aspects of transboundary regulation of water resources in Central Asia were studied by M. Djalilova (2024). The study highlighted the significant regional dependence on transboundary water resources, which required international cooperation and the development of coordinated water use mechanisms. For instance, N. Jafarzadeh *et al.* (2021) analysed the risk of groundwater pollution by heavy metals, determining the spatial distribution of pollutants and predicting their potential spread. This data was relevant for analysing the state of groundwater in Kyrgyzstan and assessing the risks of its degradation. Moreover, K. Makanda *et al.* (2022) reviewed water protection practices, emphasising the importance of sustainable management to ensure long-term water supply. The conclusions could be applied in the development of strategies for the protection of water bodies in Kyrgyzstan, especially in regions with high anthropogenic pressure.

Furthermore, K. Gunasekaran and S. Boopathi (2023) studied the application of artificial intelligence technologies in water treatment and management. The study examined water quality forecasting algorithms and automated water flow distribution systems. Such technologies could be adapted to optimise water supply in Kyrgyzstan, especially in urban areas. Furthermore, M. Faragò *et al.* (2022) analysed the life cycle and cost-effectiveness of water recycling methods, including the pyrolysis of sewage sludge. This approach could be useful in developing a strategy for water treatment and sludge utilisation in Kyrgyzstan. Notably, Q. Zuo *et al.* (2021) proposed a method for assessing water resources at the regional level based on multi-criteria analysis and scenario modelling. The methodology could be used to predict the pressure on water resources in the Chui and Osh regions. In addition, X. Liu *et al.* (2021) assessed the restoration of soil and water resources in China using the conjugation index and the integrated assessment tool. This approach assessed the effectiveness of measures to conserve water resources and adapt to climate change. In addition, M. Ben-Daoud *et al.* (2021) presented an indicator system for integrated water resources management that takes into account environmental, economic and social factors. These indicators could be adapted to assess water use in Kyrgyzstan and identify key water management issues. Furthermore, K.N. Musselman *et al.* (2021) studied trends in winter snowmelt and predicted a significant reduction in snow water resources. The approach was used to assess the long-term impact of climate change on the water balance, which could be useful for forecasting water supply in the Chui and Osh regions. In addition,

A. Hojjati-Najafabadi *et al.* (2022) investigated the possibility of using magnetic sensors to monitor pollutants in water resources. This method ensured accurate detection of hazardous pollutants and could be adapted to control water quality in Kyrgyzstan, which is especially relevant given the increasing level of pollution in rivers and groundwater.

Thus, the analysis of existing studies confirmed the relevance of the topic of water resources in Kyrgyzstan and identified the main areas for further research. The study aimed to analyse the water resources of Kyrgyzstan and their economic and environmental status. The study objectives were to analyse the dynamics of water resources and their use in Kyrgyzstan, assess environmental changes in Chui and Osh regions, and compare national and international water management practices.

MATERIALS AND METHODS

The main sources of information were official statistical data from the Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.), including information on water resource dynamics in Kyrgyzstan's rivers, water consumption in various sectors of the economy, and the level of water pollution in the Chui and Osh regions for 2020-2024. The Chui and Osh regions were selected due to their significant role in agricultural production and industry, which leads to increased pressure on water resources and requires detailed analysis for the development of effective water management strategies. In the Chui region, the following enterprises were considered: Joint Stock Company (JSC) "Chon-Kemin", Agricultural Production Cooperative (APC) "Kyzyl-Oktyabr" and Joint Venture (JV) "Altyn-Arashan", which actively use irrigation systems for growing grain and fodder crops. In the Osh region, the SPK "Zhayyl", the Farming Enterprise (FE) "Bayysh" and the Peasant Agricultural Enterprise (PAE) 'Komintern', specialising in horticulture and livestock farming, were studied. The assessment of water uses by these enterprises included an analysis of the efficiency of existing irrigation systems, water losses, the introduction of drip irrigation and digital water management technologies. The data covered indicators of average annual river flow, water reserves, water losses in irrigation, groundwater mineralisation and changes in water temperature. Additional information on the hydrological balance, evaporation rates from reservoirs, and glacier retreat was also addressed, enabling an assessment of the impact of climatic factors on the national water resources.

In addition, reports of international organisations such as the World Bank Group (2022), the United Nations Development Programme (UNDP) (2023), the Food and Agriculture Organization (FAO) (2021) and the International Water Management Institute (IWMI) (2025) were used. The data from international organisations allowed for a comparative analysis of water management policies and the identification of key differences in approaches to investment, water redistribution and treatment. An important aspect of the analysis was the study of the effectiveness of water conservation programmes, as well as an assessment of the impact of international environmental safety standards on the development of the water sector. To perform a statistical analysis of the dynamics of water resources in the rivers of Kyrgyzstan, the methods of calculating the average annual change in flow, linear trend of time series, correlation analysis and assessment of glacier degradation were used. The average rate of change in runoff was calculated using formula (1):

$$\Delta Q = \frac{Q_t - Q_{t-1}}{Q_{t-1}} \times 100\%, \tag{1}$$

where Q_t – volume of runoff in the current year, and Q_{t-1} – in previous year.

Linear regression identified trends in water resources change using equation (2):

$$Y = aX + b, \tag{2}$$

where a velocity change determinant, and b – initial value.

The correlation between temperature and water resources was determined by Pearson's coefficient $r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$, which allowed to assess the influence of climatic factors, where X_i and Y_i-variable values $\bar{X}$ and $\bar{Y}$ – their average values. The average rate of glacier degradation was calculated using formula (3):

$$R = \frac{A_t - A_{t-1}}{T}, \tag{3}$$

where A_t and A_{t-1} – glacier areas in different years.

Changes in hydropower runoff were calculated as (4):

$$\Delta H = \frac{H_t - H_{t-1}}{H_{t-1}} \times 100\%, \tag{4}$$

where H_t and H_{t-1} – runoff volumes in different years.

These calculations made it possible to identify the dynamics of water use, assess the impact of climatic factors and determine the degree of degradation of water resources. The economic assessment of water use in Kyrgyzstan was based on the analysis of water consumption in agriculture, energy, industry and municipal sectors. The method of structural analysis was used to determine the share of water consumption by each sector, identify the main problems of water distribution and estimate economic losses from inefficient water use. Formula (5) was used to analyse water losses in water supply systems:

$$P = \frac{V_{in} - V_{out}}{V_{in}} \times 100\%, \tag{5}$$

where P – water losses level, V_{in} – supplied water level, and V_{out} – delivered to consumers.

To estimate the dependence of consumption on tariffs, the relationship was used (6):

$$W = k \times P^{-e}, \quad (6)$$

where W – water usage, k – demand elasticity coefficient, P – water price, e – price elasticity of demand.

The cost of water supply was calculated as (7):

$$C = \frac{T+O+M}{V}, \quad (7)$$

where C – cost per m^3, T – transport costs, O – operating costs, M – modernisation expenses, V – water volumes.

To analyse environmental changes in Chui and Osh regions, the method of comparative analysis of regional differences in the level of water pollution, changes in water temperature and glacier degradation was used. The data for the Chui region was compared with the Osh region to assess the impact of water supply infrastructure, climatic factors and the level of anthropogenic pressure on water resources. The analysis included calculation of the rate of change in water levels in lakes and rivers, the level of pollutants in water bodies and trends in groundwater salinity. The study assessed the factors that determine the level of pollution, including anthropogenic load, the efficiency of treatment facilities and changes in the flow of polluted water. SPSS and R statistical packages were used to process the data, which was used to conduct correlation and regression analysis of water resources dynamics and assess the impact of climate factors on the water balance. Spatial analysis of water pollution data was performed using GIS technologies, which ensured accurate visualisation of changes in the Chui and Osh regions.

A comparative analysis of water resource management was conducted based on a study of Swiss and Canadian practices in the areas of distribution, treatment and regulation of water use. Switzerland and Canada were selected due to their advanced water management methods, including highly efficient wastewater treatment, minimal water losses in distribution systems and significant investments in water infrastructure. The experience of these countries was assessed using MATLAB and STATA analytical tools, which made it possible to model the effectiveness of various water regulation strategies. Switzerland and Canada have introduced digital water monitoring systems that optimise water use in a changing climate. Data analysis using specialised software identified key mechanisms that can be adapted to improve water management in Kyrgyzstan. A method of comparing key indicators was used: wastewater treatment efficiency, water loss levels, government investment in water infrastructure, and water supply tariff policy. The integrated use of statistical, comparative and structural analysis identified key trends in the dynamics of water resources, assessed economic losses from inefficient water use and identified environmental threats to Chui and Osh regions. The identified differences in water management strategies identified promising areas for the development of the water sector and proposed mechanisms to improve the efficiency of water resource allocation.

RESULTS

Dynamics of water resources in the rivers of Kyrgyzstan. Between 2020 and 2024, Kyrgyzstan's water resources underwent significant changes. Glaciers continued to shrink, as evidenced by a decrease in their area by 1.0% in 2020, 1.2% in 2021, 0.8% in 2022, 0.5% in 2023 and 0.5% in 2024. Although the rate of glacier decline slowed, the overall trend remained negative, indicating a long-term decline in freshwater reserves. Average river flow also showed a steady decline. In 2020, it decreased by 0.5%, then by 0.6% in 2021, by 0.4% in 2022, and by 0.5% in both 2023 and 2024 (Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic, n.d.). These indicators highlighted the gradual depletion of river sources, which affected agriculture, hydropower and domestic water supply. River pollution, expressed in increased concentrations of nitrates and ammonia, remained a problem throughout the period. In 2020, pollution levels rose by 1.2%, in 2021 by 1.5%, in 2022 by 1.8%, and in 2023 and 2024, the growth rate slowed to 1.1% and 1.0%, respectively. Despite the slowdown in pollution growth, river water quality continued to deteriorate, posing a threat to ecosystems and human health. Water losses in irrigation systems remained consistently high. In 2020, they amounted to 39%, in 2021 to 38.8%, in 2022 to 38.5%, in 2023 to 38.2%, and in 2024 to 38%. Despite a slight decrease, the problem of irrigation infrastructure wear and tear remained unresolved, leading to significant water losses and reduced agricultural production efficiency.

The mineralisation of groundwater also increased, indicating a deterioration in its quality. In 2020, the indicator increased by 1%, in 2021 by 1.3%, in 2022 by 1.2%, in 2023 by 0.8%, and in 2024 by 0.7%. These data indicated an intensification of groundwater pollution processes, especially in areas with intensive agricultural and industrial activities. Evaporation from reservoirs showed a steady increase. In 2020, water losses due to evaporation amounted to 4.8%, in 2021 to 5.0%, in 2022 to 5.2%, in 2023 to 5.3%, and in 2024 to 5.5%. The increase in water losses indicated the impact of climate change, such as rising air temperatures and decreasing precipitation, which made the water supply problem even more pressing. The water level in Lake Son-Kul has been declining gradually. In 2020 and 2021, it decreased by 0.5 cm annually, in 2022 by 0.4 cm, and in 2023 and 2024 by 0.3 cm. Although the rate of decline decreased, the overall decline in water reserves in the lake indicated a continuing shortage of incoming water. Water consumption in cities has been increasing. In

2020, it increased by 1.5%, in 2021 by 1.7%, in 2022 by 1.6%, in 2023 by 1.3%, and in 2024 by 1.2%. The growth in water consumption was driven by population growth and the expansion of urban infrastructure, but the growth rate was slowed by water conservation measures and improved water supply systems.

Water losses in water supply systems remained high but showed a slight decrease. In 2020, they amounted to 30%, in 2021 to 29.5%, in 2022 to 29%, in 2023 to 28.7%, and in 2024 to 28.5%. Despite the reduction in losses, the problem of pipeline wear and tear and inefficient resource management remained a concern. The decline in groundwater reserves was moderate. In 2020, they decreased by 0.8%, in 2021 by 0.7%, in 2022 by 0.6%, in 2023 by 0.5%, and in 2024 by 0.4%. Although the rate of depletion slowed, further decline in groundwater remained a concern, particularly in the southern regions of the country. The water quality in Issyk-Kul has been deteriorating. In 2020, the level of biogenic pollution increased by 0.5%, in 2021 by 0.7%, in 2022 by 0.8%, in 2023 by 0.6%, and in 2024 by 0.5%. The pollution of the lake affected its ecosystem and the region's tourist appeal. The water temperature in rivers showed an increase in summer. In 2020, it increased by 0.1°C, in 2021 by 0.1°C, in 2022 by 0.1°C, in 2023 by 0.1°C, and in 2024 by 0.1°C. The gradual increase in temperature indicated climate change and could lead to further deterioration of water ecosystems.

The volume of hydropower flow decreased. In 2020, it decreased by 0.3%, in 2021 by 0.4%, in 2022 by 0.3%, in 2023 by 0.5%, and in 2024 by 0.5%. The decline in water reserves affected electricity generation, increasing the risk of energy shortages. Water reserves in the Chu and Naryn rivers also declined. In the Chu River, the water level decreased by 0.5% in 2020, 0.6% in 2021, 0.4% in 2022, 0.3% in 2023, and 0.3% in 2024. In the Naryn, the decrease was 0.6% in 2020, 0.5% in 2021, 0.5% in 2022, 0.4% in 2023, and 0.2% in 2024. These indicators confirmed the general trend towards a decrease in water reserves (Table 1).

***Table 1**. Water resources dynamics in Kyrgyzstan's rivers (2020-2024)*

Parameter	2020	2021	2022	2023	2024
Glaciers	-1.0%	-1.2%	-0.8%	-0.5%	-0.5%
Average river flow	-0.5%	-0.6%	-0.4%	-0.5%	-0.5%
River pollution (nitrates, ammonia)	+1.2%	+1.5%	1.8%	1.1%	+1.0%
Water losses in irrigation	39%	38.8%	38.5%	38.2%	38%
Mineralisation of groundwater	+1%	+1.3%	+1.2%	+0.8%	+0.7%
Evaporation from reservoirs	4.8%	5.0%	5.2%	5.3%	5.5%
A decrease in the water level in Son-Kul	-0.5 cm	-0.5 cm	-0.4 cm	-0.3 cm	-0.3 cm
Growing water consumption in cities	+1.5%	1.7%	1.6 %	+1.3%	+1.2%
Water losses in water supply systems	30%	29.5%	29%	28.7%	28.5%
Reduction of groundwater reserves	-0.8%	-0.7%	-0.6%	-0.5%	-0.4%
Water quality in Issyk-Kul	0.5%	+0.7%	+0.8%	+0.6%	0.5%
Water temperature in rivers in summer	+0.1°C	+0.1°C	+0.1°C	+0.1°C	+0.1°C
Volume of hydropower runoff	-0.3%	-0.4%	-0.3%	-0.5%	-0.5%
Water reserves in Chu	-0.5%	-0.6%	-0.4%	-0.3%	-0.3%
Water reserves in Naryn	-0.6%	-0.5%	-0.5%	-0.4%	-0.2%

***Source:** compiled by the authors based on the International Futures (IFs) model (2025)*

Thus, Kyrgyzstan's water resources experienced negative changes in 2020-2024. The shrinking of glaciers, reduced river flows, deteriorating water quality, and increased water consumption require measures to rationally use water resources and modernise infrastructure.

Economic assessment of water uses in Kyrgyzstan. In the period from 2020 to 2024, there was a gradual decrease in water consumption in all major sectors of the Kyrgyz economy. In agriculture, the share of water use decreased from 80% in 2020 to 77% in 2024. This was due to the gradual modernisation of irrigation systems and water conservation measures. However, despite the improvements, water losses remained significant. Economic losses in agriculture decreased from USD 100 million in 2020 to USD 90 million in 2024, indicating a partial improvement in water use efficiency. In the energy sector, the share of water consumption decreased from 10% to 9.5% over five years. This was due to a reduction in hydropower runoff and the introduction of water efficiency measures at hydroelectric power plants (HPPs). Accordingly, economic losses in the energy sector decreased from USD 40 million to USD 35 million, but the sector's dependence on water resources remained high.

The industrial sector, which consumed 8% of water in 2020, reduced this figure to 7.7% by 2024. This was driven by the introduction of more efficient water treatment technologies and a decline in industrial production in certain industries. Economic losses during this period decreased from USD 25 million to USD 21 million, indicating a partial stabilisation of water costs. The utility sector also showed a decrease in water consumption.

In 2020, the share of water use was 7%, but by 2024 it had fallen to 6.8%. This was due to increased efficiency of water supply in cities and partial modernisation of networks. Nevertheless, water losses remained high, with economic losses amounting to USD 16 million in 2024 compared to USD 20 million in 2020 (Table 2).

***Table 2**. Economic assessment of water uses in Kyrgyzstan (2020-2024)*

Economic sector	Metric	2020	2021	2022	2023	2024
Agriculture	Share of water consumption (%)	80%	80%	79%	78%	77%
	Economic losses (USD million)	100	98	95	92	90
Energy	Share of water consumption (%)	10%	10%	9.8%	9.7%	9.5%
	Economic losses (USD million)	40	39	37	36	35
Industry	Share of water consumption (%)	8%	8%	7.9%	7.8%	7.7%
	Economic losses (USD million)	25	24	23	22	21
Utilities	Share of water consumption (%)	7%	7%	6.9%	6.8%	6.8%
	Economic losses (USD million)	20	19	18	17	16

***Source:** compiled by the authors based on the International Futures (IFs) model (2025)*

Between 2020 and 2024, a decrease in water consumption among the largest farms was observed in the Chui and Osh regions, indicating the gradual introduction of water-saving technologies. In the Chui region, agricultural enterprises such as Chon-Kemin JSC, Kyzyl-Oktyabr Agricultural Production Cooperative and Altyn-Arashan Agricultural Production Cooperative reduced their water consumption by an average of 1% per year. This was achieved through the modernisation of the irrigation system and the transition to drip irrigation, which reduced water losses and increased efficiency. Despite these positive changes, further investment in infrastructure improvements was still needed, as old canals in some areas still caused significant water losses.

In the Osh region, where water shortages were more pronounced, farms, including Jail, Komintern, and Bayysh farms, also reduced water consumption. The main measures were the reconstruction of irrigation networks and the introduction of water-saving irrigation methods, which reduced the pressure on water sources. Nevertheless, water shortages remained a serious problem, especially during dry periods when the water supply was unstable. Economic losses during the analysed period showed a steady downward trend. In the Chui region, they decreased from USD 40 million to USD 35 million, and in the Osh region, from USD 25 million to USD 21 million. This confirmed the partial effectiveness of the reforms and the introduction of modern water use technologies. However, despite this, a significant portion of water resources was still being lost due to the imperfect water distribution system and the lack of comprehensive control over its efficiency (Table 3).

***Table 3**. Dynamics of water consumption and economic losses in the Chui and Osh regions (2020-2024)*

Farms/Parameters	2020	2021	2022	2023	2024
Chui region					
Chon-Kemin JSC					
Share of water consumption (%)	12	11.8	11.5	11.2	11
Economic losses (USD million)	10	9.8	9.5	9.2	9.0
Kyzyl-October SPC					
Share of water consumption (%)	10	9.8	9.6	9.3	9.0
Economic losses (USD million)	8	7.8	7.5	7.2	7.0
Altyn-Arashan JV					
Share of water consumption (%)	9	8.8	8.5	8.2	8.0
Economic losses (USD million)	6.5	6.3	6.1	5.8	5.5
Osh region					
SPC Zhayil					
Share of water consumption (%)	8	7.8	7.5	7.2	7.0
Economic losses (USD million)	5.5	5.3	5.1	4.9	4.7
Komintern State Farm					
Share of water consumption (%)	6	5.8	5.6	5.4	5.2
Economic losses (USD million)	4.2	4.0	3.8	3.6	3.5
FH Bayysh					
Share of water consumption (%)	4	3.8	3.6	3.4	3.2
Economic losses (USD million)	2.8	2.6	2.5	2.3	2.2

***Source:** compiled by the authors based on Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.)*

The analysis demonstrated that the introduction of new irrigation technologies and the modernisation of irrigation systems had a positive impact on rational water use. However, insufficient funding and the high degree of infrastructure wear and tear limited the speed and scale of the necessary transformations. To further reduce water losses, more active support from the government and international organisations was needed, as well as incentives for farms to switch to more efficient water use methods. Thus, water consumption in Kyrgyzstan in the period 2020-2024 showed a downward trend in all major sectors of the economy. Despite the partial modernisation of irrigation systems, agriculture remained the largest consumer of water, and resource losses remained significant.

Environmental changes in the Chui and Osh regions In 2020, the level of water pollution in the Chui region was 10% and in the Osh region 15%. The main sources of pollution are untreated wastewater and agricultural runoff. The impact of climate change has led to a reduction in water reserves by 5% in the Chui region and 7% in the Osh region. Glacier degradation amounted to 3% and 4% respectively, which began to affect river flows. In 2021, pollution levels increased by 12% in the Chui region and by 17% in the Osh region, due to the insufficient efficiency of treatment facilities. Water shortages worsened, reaching 6% in the Chui region and 8% in the Osh region. Glacial losses accelerated, increasing to 4% in the Chui and 5% in the Osh regions, which began to affect water supply in agricultural areas. In 2022, water pollution in the Chui region reached 14% and 19% in the Osh region, reflecting an increase in anthropogenic pressure. Climatic factors led to a decrease in available water resources by 7% in Chui and 9% in the Osh region. Glacial degradation continued, reaching 5% and 6%, respectively, contributing to the instability of water flows.

In 2023, water pollution increased to 16% in the Chui region and 21% in the Osh region, indicating a critical burden on ecosystems. The impact of climate change has intensified, leading to a reduction in water resources by 8% in Chui and 10% in Osh. Glacial degradation has accelerated by 6% and 7%, increasing the risk of seasonal water shortages. In 2024, pollution reached 18% in Chui and 23% in Osh regions, confirming the growing degradation of water bodies. The decline in water reserves was 9% in Chui and 12% in Osh, which exacerbated water supply problems. Glacier degradation increased to 7% and 8%, respectively, indicating long-term threats to water supply and hydropower (Fig. 1).

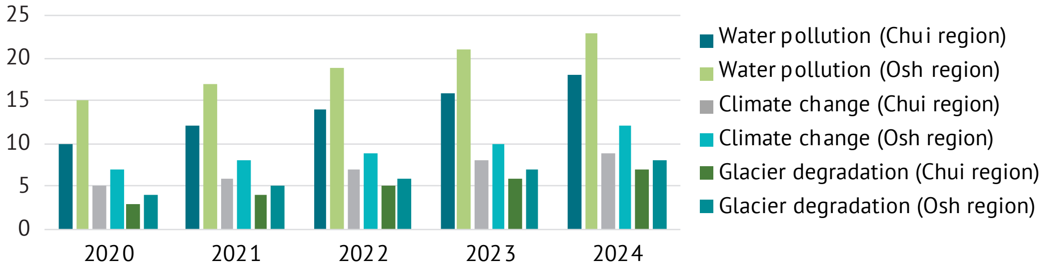

***Figure 1**. Environmental changes in the Chui and Osh regions (2020-2024)*

***Source:** compiled by the authors based on Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.)*

Thus, from 2020 to 2024, water pollution in the Chui and Osh regions increased, water reserves decreased, and glacier degradation increased the risk of water shortages. To stabilise water resources, comprehensive measures are needed to treat wastewater, adapt to climate change and modernise water infrastructure.

Comparative analysis of water management. In 2020, agriculture in Kyrgyzstan used 80% of water resources, with 45% in the Chui region and 18% in the Osh region. In Switzerland, agriculture consumed 3% of water, and in Canada, 10%. Water losses in Kyrgyzstan reached 34%, while in Switzerland they were 6% and in Canada 8%. These differences were due to the use of advanced technologies, including automated irrigation systems, soil moisture sensors and digital leakage control, which were actively used in Switzerland and Canada. The introduction of drip irrigation in Kyrgyzstan remained at an early stage, covering less than 5% of irrigated land, while in Switzerland and Canada, this figure reached 60% and 50%, respectively.

In 2021, water consumption in Kyrgyzstan's agriculture sector fell to 79%, and in the Chui and Osh regions to 44% and 17% respectively. Despite the reduction in consumption, wastewater treatment in the country remained inadequate, with only 50% of the total volume being treated, compared to 95% and 90% in Switzerland and Canada, respectively. Switzerland used multi-stage filtration systems, including mechanical, biological and chemical treatment of wastewater, followed by ultraviolet or ozone disinfection. This removes organic and chemical pollutants, ensuring high-quality treated water. In Canada, water reuse technologies were actively used, including closed water circulation systems in industry, water recycling in agriculture, and multi-stage wastewater treatment for reuse in municipal water supply. Intelligent irrigation systems used in developed countries include remote water supply control and automatic regulation of irrigation volumes depending on weather conditions. In Kyrgyzstan, such technologies remained uncommon, and only a few agricultural enterprises began to introduce automated systems.

In 2022, investments in Kyrgyzstan's water infrastructure amounted to just USD 7 per capita, compared to USD 200 in Switzerland and USD 150 in Canada. As a result, the national water supply systems remained worn out, with water losses in the Chui region reaching 38% and 45% in the Osh region. In Switzerland, government programmes were implemented to modernise pipelines and control water pressure, while in Canada, automated water supply systems were used to minimise leakage and increase the efficiency of water distribution. Digital technologies for water management, such as satellite monitoring and online water flow control systems, remained at the pilot project stage in Kyrgyzstan, while in Switzerland and Canada, they were applied at the state level, ensuring a rapid response to changes in the water balance.

In 2023, water consumption in Kyrgyzstan's agriculture decreased to 77%, but water losses in the systems remained at 30-32%. In the Chui region, losses dropped to 36%, and in the Osh region to 42%. In Switzerland, government subsidies for the introduction of water-saving technologies were in place, which reduced water consumption and cut operating costs. These measures included financial support for farmers to install drip irrigation and smart irrigation systems, soft loans for the modernisation of water supply networks and the introduction of water reuse systems, as well as subsidies to industrial enterprises for reducing water consumption and switching to closed water circulation technologies. Canada used water quota mechanisms that regulated the amount of permitted water consumption depending on the needs of the economy and available resources. The main methods included the division of quotas between sectors (agriculture, industry, utilities), seasonal regulation of consumption, when restrictions were imposed during periods of drought, and water quota trading, which redistributed resources between regions depending on priority needs. These mechanisms ensured the rational use of water and prevented water shortages during dry periods. The partial modernisation of irrigation allowed farmers, especially in the Chui region, to introduce automated irrigation systems regulated based on weather data, but their use remained localised. In Kyrgyzstan, there were no such mechanisms, which limited the introduction of modern water management technologies.

In 2024, water consumption in Kyrgyzstan's agriculture reached 76%, and water losses were reduced to 28-30% as a result of the partial modernisation of water supply. Wastewater treatment increased to 55%, but this figure remained significantly lower than in Switzerland and Canada. Switzerland had strict legislative standards for water quality control and a multi-level water management system. Canada used adaptive water regulation mechanisms, including dynamic quotas, where water consumption volumes were adjusted according to water availability and weather conditions. Flexible tariff systems encouraged water conservation through differentiated pricing, increasing the cost of consumption during periods of shortage. The water rights market allowed resources to be redistributed between sectors of the economy through the sale or lease of water use quotas. Regional agreements between regions ensured the redistribution of water resources according to the needs of industry, agriculture and municipal water supply, preventing shortages during dry periods. In Kyrgyzstan, legal regulation of water use remained weak, leading to the irrational use of water resources. The experience of developed countries has shown that adapting digital and intelligent water management systems to local climatic and economic conditions could significantly improve water use efficiency in Kyrgyzstan. The introduction of smart irrigation systems and the use of Big Data to forecast water demand would ensure more efficient resource allocation, especially in arid regions (Fig. 2).

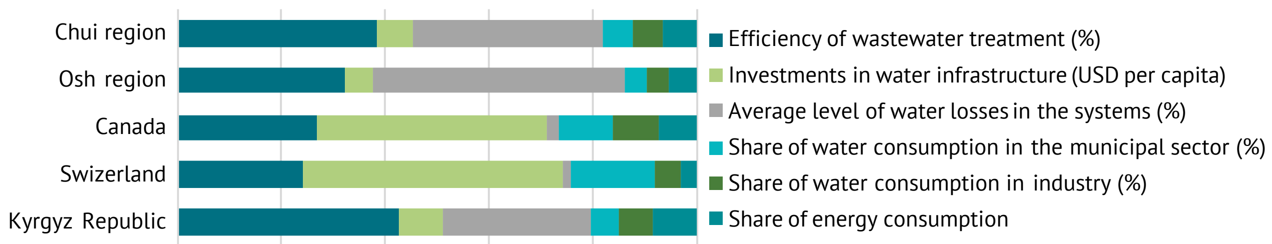

***Figure 2**. Comparative analysis of water management (2020-2024)*
***Source:** compiled by the authors based on National Statistical Committee of the Kyrgyz Republic (2021), Ministry of Natural Resources, Ecology and Technical Supervision of the Kyrgyz Republic (n.d.)*

The successful practices of Switzerland and Canada can be applied in Kyrgyzstan through the modernisation of irrigation systems, automation of water supply control and the introduction of water reuse systems. Government subsidies and tax breaks, similar to the Swiss and Canadian mechanisms, can help reduce water losses and increase the efficiency of water distribution. The introduction of advanced wastewater treatment technologies and investments in infrastructure are key to the sustainable management of the national water resources.

DISCUSSION

The study results demonstrated that Kyrgyzstan's water resources are significantly affected by climate and human factors. In the Chui region, water consumption was high, but significant water losses in irrigation reduced its efficiency. The Osh region experienced water shortages due to limited sources and poor wastewater treatment. Water pollution continued to increase, especially in areas with developed agriculture and industry. A comparison with Switzerland and Canada showed insufficient investment in water infrastructure and low efficiency of treatment systems. The development of water-saving technologies and the modernisation of resource management are necessary for sustainable water use. Research on water resource management demonstrates a wide range of approaches, but their results do not always take into account regional characteristics and the economic consequences of inefficient water use. For instance, S.K. Jain and V.P. Singh (2023) examined integrated water resources planning and management, emphasising mathematical modelling and strategic forecasting of water distribution. The study demonstrated that integrated management systems, including consumption forecasting and risk management, can minimise water losses and improve water supply efficiency. These findings confirm the problems of the Kyrgyz water sector related to insufficient investment and inefficient water resource allocation. However, this study is unique in that it includes a regional analysis of water use in the Chui and Osh regions, making it more applicable to the national conditions. In addition, a comparative analysis with international practices has allowed specific measures to be proposed for optimising water supply.

The issue of water pollution is considered in many modern studies. For instance, X. Yuan and Z. Jun (2021) assessed the risks associated with diffuse water pollution using quantitative forecasting models and found that the main sources of pollution are agricultural and industrial runoff, which correlates with the findings of this study on the growth of water pollution in Kyrgyzstan. However, the study emphasised the mathematical modelling of pollution, while this study considers not only its sources, but also the impact on the availability of water resources and the country's economy. The advantage of this study is its comprehensive approach, which includes not only environmental, but also economic and managerial assessments, proposing solutions to minimise water losses and improve water supply.

In the context of the issue of water security, T. Peng *et al.* (2020) analysed the impact of environmental change on water resources. The study identified three key challenges: a decline in freshwater reserves, deterioration in the quality of water bodies, and inefficient water allocation. These conclusions largely correlate with the results of this study, which also recorded trends in glacier degradation, water pollution and increased pressure on water resources. However, T. Peng *et al.* did not sufficiently address regional differences in the distribution of water resources, while this study examined in detail the specifics of water use in the Chui and Osh regions. This made it possible to propose specific measures to improve the efficiency of water management, taking into account territorial differences. Some studies examine the impact of seasonal changes on water quality. In particular, D. Hammoumi *et al.* (2024) analysed seasonal fluctuations in surface water quality using the Water Quality Index (WQI) and Principal Component Analysis (PCA). The study determined that climatic factors, including precipitation and air temperature, have a significant impact on water quality dynamics. These results are partly consistent with the present study, which also examined the impact of climate change on water resources in Kyrgyzstan. However, the study by D. Hammoumi *et al.* conducted a statistical analysis, whereas this study examined not only environmental but also economic and management aspects of water use. This provides a more comprehensive picture of the state of the national water resources and suggests ways to improve water use efficiency.

Various studies are devoted to assessing the sustainability of water resources and their distribution in the context of climate and anthropogenic changes. G. Wang *et al.* (2020) analysed water load trends using a system dynamic model and an improved fuzzy integrated assessment method. The results showed that the change in the water balance depends on the pace of urbanisation, industrial growth, and climatic factors. This partially coincides with this study, which also identified the impact of climate change and growing urban water consumption on Kyrgyzstan's water reserves. However, the study by G. Wang *et al.* was dedicated to forecasting changes, whereas this study examined the current situation and assessed the economic impacts of water use. In addition, this study sufficiently addressed the differences between the regions of the country, which provided more detailed recommendations for water management.

Other studies emphasise the cost-effectiveness and reuse of water resources. For instance, M. Faragò *et al.* (2021) studied the transition from wastewater treatment to integrated water resource recovery, analysing the environmental and economic impacts of the full implementation of such technologies. The findings confirmed that integrated wastewater management not only reduces the burden on water bodies but also increases the economic efficiency of water supply. These results are reflected in the present study, which also emphasises the need to modernise wastewater treatment facilities in Kyrgyzstan. However, the study by M. Faragò *et al.* analysed technological solutions and economic evaluation of processes, while this study considers systemic problems, including environmental and management aspects. Thus, the proposed integrated approach not only identified the need for technological changes but also ways to integrate them into the existing water use system.

Water quality and the degree of pollution of water bodies are important areas of water resource analysis. The study by H. Aydin *et al.* (2020) assessed water quality in rivers in northeastern Turkey using the Water Quality Index (WQI) and multiple statistical methods. The study determined that agricultural activities and industrial pollution are the main factors of water quality deterioration. These results are consistent with the data of this study, which also recorded an increase in water pollution in Kyrgyzstan, especially in the Chui and Osh regions. However, the study by H. Aydin *et al.* conducted a statistical analysis of water metrics, while this study considers not only the environmental but also the economic impact of pollution. This integrated approach not only assessed the degree of pollution but also proposed measures to reduce it, including the modernisation of water treatment facilities and the improvement of the water quality control system.

Spatial and seasonal analysis of water quality is also an important aspect of research. J.B. De Melo Carvalho Passos *et al.* (2021) conducted a multivariate statistical analysis of water quality in the Doce River basin in southeastern Brazil. The study demonstrated that water quality varies depending on the season and sources of pollution, which confirms the need for adaptive water management strategies. These results partially coincide with the present study, which also noted the dependence of the state of water bodies on climatic factors and seasonal changes. However, the study by J.B. De Melo Carvalho Passos *et al.* did not analyse the economic impact of water quality deterioration, while this study assessed the impact of pollution on water supply, agriculture and the municipal sector in Kyrgyzstan. Approaches to water management were considered from different perspectives, including the assessment of water availability, pollution and wastewater treatment efficiency. The study by M. Naderi (2021) analysed the level of water management based on the concepts of water supply and water availability. The study determined that the effectiveness of water management is determined by the balance between water demand and availability, as well as the quality of water supply infrastructure. These results confirm the conclusions of this study on the need to modernise water supply systems in Kyrgyzstan, especially in regions with high levels of water losses. However, the study by M. Naderi analysed a macro-level assessment of water management, while this study analyses in detail the regional differences affecting water use in the Chui and Osh regions. This approach identified specific water allocation problems and proposed targeted strategies to address them.

Other studies addressed the economic and environmental aspects of water use. Z. Shi *et al.* (2020) conducted a comprehensive assessment of the economic efficiency of water use, pollution levels, and wastewater treatment efficiency in China. The study determined that insufficient investment in wastewater treatment plants and weak control over industrial discharges lead to an increase in water pollution, reducing the availability of clean water for agriculture and the population. These findings are consistent with this study, which also noted the deterioration of water quality in Kyrgyzstan due to pollution from industrial and agricultural wastewater. However, the study by Z. Shi *et al.* conducted an economic assessment of production processes and their impact on the water environment, while this study covers not only industrial but also municipal and agricultural aspects of water use. This broader coverage included a comprehensive assessment of the water situation and the proposal of solutions to minimise water losses.

Changes in the hydrological cycle under the influence of climatic factors are an important area of research. D. Yang *et al.* (2021) reviewed the impact of global climate change on water resources, emphasising the role of rising temperatures, changing precipitation patterns and glacial melt in shaping the water balance. The conclusions coincide with the findings of this study, which recorded a decrease in water levels in Kyrgyzstan's rivers and lakes, as well as a reduction in ice cover, which poses a threat to the long-term water supply. However, the study by D. Yang *et al.* is more general in nature, considering hydrological processes at the global level, while this study emphasised specific regional changes and their impact on water use. This focus makes the results more relevant for the development of practical recommendations for adapting Kyrgyzstan's water systems to changing climate conditions. Thus, the reviewed studies confirm the problems identified in this study, including water scarcity, water pollution and insufficient efficiency of wastewater treatment plants.

A.C. Kharake and V.S. Raut (2021) and S. Hajji *et al.* (2022) investigated water resources from different perspectives. S. Hajji *et al.* assessed the decline in water reserves in the Amu Darya basin due to climate change and increased water consumption, which partially coincides with this study, which also identified a decrease in glaciers and an increase in water consumption in Kyrgyzstan. A.C. Kharake and V.S. Raut conducted the chemical analysis of pollution, while this study additionally considers economic impacts, such as losses in the utility sector and the need to modernise wastewater treatment plants. In contrast to the transboundary approach of S. Hajji *et al.*, this study analysed regional differences, especially in the Chui and Osh regions. K. Leonard *et al.* (2024) and M.D. Molekoa *et al.* (2022) studied climate change and water management. K. Leonard *et al.* analysed the impact of rising temperatures, decreasing snow cover and changing precipitation on water resources in New York State, which confirms the findings of this study on glacier degradation and lower river levels in Kyrgyzstan. However, K. Leonard *et al.* conducted forecasting, whereas this study provides a detailed look at current changes and their impact on water supply. M.D. Molekoa *et al.* studied spatial pollution of water bodies, but without an economic assessment of the consequences, which distinguishes their work from the present study, which also proposes measures to modernise the infrastructure.

Notably, A. Lohrmann *et al.* (2021) and K. Cheng *et al.* (2022) analysed water management from different angles. A. Lohrmann *et al.* assessed the water footprint of the European energy sector during the transition to renewable energy sources, which echoed the findings of this study on the impact of water consumption on hydropower in Kyrgyzstan. However, the study forecasted the long-term impact of energy transformation, while this study analysed current water use issues in detail. At the same time, K. Cheng *et al.* studied the coordination of water and soil resources, taking into account ecological and economic factors, and proposed a methodology for optimal resource allocation. Their study touched upon issues of sustainable management but did not include a detailed economic assessment, which distinguishes it from the present study, where water losses were analysed and measures for modernising water infrastructure were proposed. The analysis showed that Kyrgyzstan continues to face significant water management challenges related to high water losses, dilapidated infrastructure, and insufficient adoption of modern technologies.

CONCLUSIONS

The study conducted a comprehensive assessment of the state of Kyrgyzstan's water resources for the period 2020-2024, including an analysis of the dynamics of water use, economic losses, environmental changes and the impact of climate factors. The study covered key aspects of the water balance, such as river flows, glacier degradation, water quality, losses in irrigation systems and growth in water consumption in various sectors of the economy. The analysis of water consumption showed that agriculture remained the largest consumer of water, despite significant losses in irrigation, which reached 38-40%. The Chui region, which has a well-developed irrigation infrastructure, experienced high volumes of water losses, while the Osh region experienced an acute shortage of water resources due to insufficient water supply and inefficient wastewater treatment. The energy sector saw a decline in hydropower flows, which increased the vulnerability of the energy system to changes in precipitation and glacier degradation. The environmental change assessment revealed a deterioration in water quality due to increased pollution of rivers by industrial and agricultural runoff.

During the study period, the level of pollution in Chui and Osh regions increased by 3-5%, indicating that the efficiency of treatment facilities was insufficient. The water and environmental situation were further complicated by the progressive degradation of glaciers, which lost 0.5% to 1.2% of their volume per year, affecting the availability of water resources in the long term. The economic analysis of water use showed that inefficient water allocation led to significant financial losses. The largest losses were recorded in agriculture due to water losses in irrigation, as well as in the municipal sector, where up to 28-30% of water was lost in water supply systems. In the energy sector, the lack of water reduced the productivity of hydroelectric power plants, increasing the national dependence on seasonal fluctuations in water resources. A comparative analysis of water management in Kyrgyzstan and developed countries (Switzerland and Canada) demonstrated that Kyrgyzstan has insufficient investment in water infrastructure, low efficiency of treatment technologies and a high share of water losses. In countries with developed water policies, modern technologies for water treatment and redistribution are used to minimise the negative impact of pollution and shortages. Based on the data obtained, conclusions were drawn about the need for a comprehensive reform of the water sector in Kyrgyzstan. The key areas should include modernisation of water infrastructure, introduction of water-saving technologies, improvement of wastewater treatment and development of adaptive water management strategies to address climate change.

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Аналіз та оцінка водних ресурсів у Киргизькій Республіці

Нурбек Ібрагімов
Доктор економічних наук, доцент
Киргизький національний університет імені Юсупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0009-1069-8936

Арстаналий Ботобеков
Доктор економічних наук, професор
Киргизький національний університет імені Юсупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0004-8332-8833

Бактигуль Ішекеєва
Доктор економічних наук, доцент
Киргизький національний університет імені Юсупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0002-6858-1967

Аділбек Асанканов
Старший викладач
Киргизький національний університет імені Юсупа Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0006-0123-7183

Манзура Хашимова
Старший викладач
Юсуп Киргизький національний університет імені Баласагина
720033, вул. Фрунзе, 547, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0005-2468-0578

Анотація. Дослідження мало на меті проаналізувати фактори водокористування, вплив на навколишнє середовище та ефективність управління водними ресурсами для розробки рекомендацій щодо їх оптимізації. Дослідження визначило, що споживання води в сільському господарстві зменшилося з 80 % у 2020 році до 76 % у 2024 році, але втрати води в іригаційних системах залишалися високими, зменшившись лише з 39 % до 38 %. У Чуйській області, найбільшому споживачеві води, частка водокористування зменшилася з 45 % до 41 %, а економічні втрати скоротилися з 40 мільйонів доларів США до 35 мільйонів доларів США. У Ошській області, яка має дефіцит води, споживання води скоротилося з 18 % до 14 %, але доступність води в сільському господарстві та комунальному секторі залишалася обмеженою. Очищення стічних вод покращилося з 50 % у 2020 році до 55 % у 2024 році, але цей показник був значно нижчим за міжнародні стандарти, де Швейцарія та Канада мали рівень очищення 95 % та 90 % відповідно. Порівняльний аналіз показав, що розвинені країни активно використовують цифрові системи моніторингу витоків, інтелектуальні технології зрошення та багатоступеневу очистку води, що дозволило знизити втрати до 6-8 %. У Киргизстані такі технології були впроваджені локально та лише в деяких сільськогосподарських підприємствах. Інвестиції у водну інфраструктуру становили 7 доларів США на душу населення порівняно з 200 доларами США у Швейцарії та 150 доларами США в Канаді, що обмежувало модернізацію системи водопостачання. Виявлені проблеми підтвердили необхідність реформування системи управління водними ресурсами, включаючи зменшення втрат води, модернізацію очисних споруд, впровадження цифрових рішень для управління водними ресурсами та адаптацію інфраструктури до змін кліматичних умов

Ключові слова: гідрологічні зміни; деградація льодовиків; кліматичні ризики; еколого-економічний аналіз; стратегічне планування

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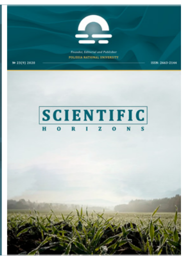

Agrochemical characteristics of mountain soils of the Fergana Valley

Gulbarchin Israilova*

PhD in Biological Sciences, Lecturer
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
https://orcid.org/0009-0005-1083-4724

Baigeldi Zhusupov

Lecturer
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
https://orcid.org/0009-0003-4307-5811

Gulom Yuldashev

Doctor of Agricultural Sciences, Professor
Fergana State University
150100, 19 Murabbilar Str., Fergana, Uzbekistan
https://orcid.org/0000-0003-3339-1768

Murodjon Isagaliev

Doctor of Biological Sciences, Professor
Fergana State University
150100, 19 Murabbilar Str., Fergana, Uzbekistan
https://orcid.org/0000-0002-7108-6011

Rachima Muratova

PhD in Agricultural Sciences, Associate Professor
Osh State University
723500, 331 Lenin Str., Osh, Kyrgyz Republic
https://orcid.org/0009-0004-3494-0815

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Abstract. The relevance of examining the soils of the Fergana Valley is due to their diversity and importance for the agriculture of the region. Different soil types differ in their granulometric composition, fertility, and ability to retain moisture, which affects their agrochemical properties. The purpose of the study was a comprehensive analysis of the agrochemical characteristics of the soils of the Fergana Valley, including granulometric composition, humus content, acidity, carbonate content, water properties, and biological activity. The methods included field research, sampling from different altitude zones, and laboratory chemical composition analyses. Nitrogen was determined by the Kjeldahl method, phosphorus – the Machigin and Kirukov method, and potassium – flame photometry. The results of the study showed substantial differences in the composition and properties of different types of soils. Brown forest

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*Corresponding author

soils demonstrated the most favourable agrochemical parameters. The granulometric composition of brown forest soils is medium loamy, with a sand content of 35-45%, silt of 30-40%, and clay of 15-25%. High levels of humus (4.5-6%), total nitrogen (0.2-0.3%), available phosphorus (20-40 mg/kg), and potassium (high levels) were recorded in the soils. The biological activity, estimated by microbial abundance, was 2-4 million/g, which confirmed the high metabolic activity of the soil microflora. Mountain-brown carbonate soils were characterised by a heavier granulometric composition, with an increased clay content (25-35%) and moderate fertility rates: 2.5-4% humus, 0.1-0.2% nitrogen, 10-25 mg/kg of phosphorus, and a medium potassium level. Sandy soils have low moisture capacity, weak aggregate structure, and extremely low fertility rates: 0.5-1.5% humus, <0.1% nitrogen, 5-15 mg/kg phosphorus, and low potassium levels. Biological activity does not exceed 1 million/g. The acidity of soils varied: brown forest soils have a slightly acidic or neutral reaction with a pH of 5.8-6.5, which is favourable for the absorption of nutrients. Mountain-brown carbonate soils are alkaline with a pH of 7.5-8.2, which reduces the availability of certain elements. Sandy soils have a slightly alkaline pH of 6.8-7.4. The data obtained can optimise land use, increase soil productivity, and minimise soil degradation

Keywords: humus; granulometric composition; carbonate content; erosion processes; acidity; minerals; organics

INTRODUCTION

Soils are a key component of ecosystems that play a crucial role in ensuring food security and the sustainability of agroecosystems. Agrochemical characteristics of soils, including granulometric composition, organic matter content, acidity and carbonate content, directly affect their fertility and ability to support plant growth. The Fergana Valley, located at the intersection of Uzbekistan, Kyrgyzstan, and Tajikistan, is one of the most important agricultural territories in Central Asia, with unique climatic and geographical features that shape the agrochemical properties of the region's soils. Despite a great amount of research on the soil cover of Central Asia, the agrochemical characteristics of mountain soils, in particular, the Fergana Valley, are still insufficiently reviewed. These soils, especially mountainous and carbonate soils, are characterised by a complex structure and high spatial heterogeneity, which makes it difficult to classify and agronomically evaluate them. Thus, in the paper of D. Kholdarov *et al.* (2024), a detailed analysis of the chemical composition of saline soils in Central Fergana is conducted, where the features of chloride-sulfate salinisation were displayed, and the way irrigation changes their granulometric composition was described. In the context of the development of sustainable land use methods, the importance of an integrated approach to the examination of chemical and biological properties of soils is being evaluated by B. Lei *et al.* (2022), emphasising the role of organic and green fertilisers as factors that improve soil fertility and microbiological activity.

The problem of insufficient supply of organic matter and macronutrients to soils is becoming particularly relevant, which limits their productive potential. L. Mhoro *et al.* (2024), examining soils on the slopes of Kilimanjaro, found that fertility in lowland areas is substantially lower, which is facilitated by a shortage of manure and limited use of inorganic fertilisers. These conclusions are confirmed in the study by R. Sidle *et al.* (2023), stressing that in high-altitude areas, soil depletion is associated with limited natural resources and requires an adaptive approach to agroecological management. The problem of soil degradation is also considered in a broader regional context. R. Lal (2024) notes that processes such as erosion, salinisation, humus depletion, and structural disruptions directly threaten food security in South and Central Asia. These threats are reflected in the data of S. Measho *et al.* (2022), which recorded an increase in soil electrical conductivity, an indicator indicating increased salinity, especially in pastures and marginal lands. In turn, I. Stavi *et al.* (2021) underline the importance of accurate monitoring and mapping of saline lands using modern remote sensing methods. Against the background of climate change and unstable land use, the agrochemical properties of soils are under increasing pressure. S. Song *et al.* (2025) have developed an indicator system to identify priority conservation areas in Central Asia, especially in mountainous and oasis areas, which highlights the importance of integrating agroecological and socio-economic approaches.

Finally, organic technologies play a special role in increasing soil resistance to degradation. B. Lei *et al.* (2022) have shown that the use of green fertilisers can increase the microbiological activity of the soil and improve its structure. Similar results were obtained by A.M. Visscher *et al.* (2024), conducted in the Andes, where the use of organic sheep manure helped preserve the yields of traditional crops with a warming climate and a shortening of the growing season in high-altitude areas. Despite the accumulated knowledge, key issues regarding the agrochemical potential of mountain soils in arid climates and intensive land use remain unresolved. There is no systematic analysis of the interaction of physico-chemical and biological properties of soils at various altitude levels, or consideration of anthropogenic and climatic factors affecting degradation processes. The mechanisms of changes in the content of organic matter, the transformation of macronutrients, and the dynamics of acidity depending on agrotechnical measures are not sufficiently covered. The problem of increasing fertility is particularly relevant in conditions of limited water supply and salinity typical of the Fergana Valley.

The purpose of this study was the agrochemical characterisation of the mountain soils of the Fergana Valley with an emphasis on their physico-chemical and biological properties.

MATERIALS AND METHODS

The study was conducted on the mountainous soils of the Fergana Valley within the Uzbek part of the region, covering the territories near the settlements of Rishtan, Vuadil, and Yaypan, at altitudes from 600 to 1,400 meters above sea level. The study examined brown forest soils, mountain-brown carbonate soils, and sandy soils typical of this orographic zone. The selection of sites was conducted considering their geographical location, altitude zone, climatic conditions, and features of soil-forming processes. At the first stage of the study, field work took place, which included the laying of soil sections with a morphological description of the horizons. 12 soil sections were laid with an even distribution over the area under study. The distance between the points ranged from 2 to 5 km, depending on the accessibility of the site and the uniformity of the relief. At each site, samples were taken from four standard depths (0-10, 10-30, 30-50, and 50-100 cm). The selection was repeated three times to ensure reliability. The climatic conditions at the time of sampling (April-May) were characterised by an average daily air temperature of +17°C and a total precipitation of about 40 mm, according to the Kokand weather station. Soil moisture was at the level of 15-25%, depending on the site, which is important when interpreting indicators of water balance and biological activity. GPS mapping was used to fix the coordinates of the sampling points, ensuring the accuracy of subsequent spatial analysis.

After the field stage, all soil samples were sent to the laboratory for physico-chemical analyses. The granulometric composition was determined by a combined pipetting and dry sieving method in accordance with ISO 11277:2020 (2020), which ensured reliable determination of the content of sandy, silty, and clay fractions. The organic matter content was determined by two methods: oxidation with a chromium mixture according to Turenne (ISO 14235:1998, 1998) and elemental analysis according to ISO 10694:1995 (1995). Soil acidity was measured potentiometrically in aqueous and saline suspensions (ISO 10390:2021, 2021). The soil carbonate content was assessed by the gasometric method using HCl solution, considering the requirements of ISO 10693:1995 (1995), which allows quantifying the content of calcium and magnesium carbonates in each horizon. The method of determining the cation exchange capacity (CEC) using ammonium acetate (ISO 23470:2007, 2007) was applied to assess the sorption capacity of soils. This indicator is critically important in assessing the ability of the soil to retain nutrients by ions. The macro- and microelement composition (N, P, K, Ca, Mg, Fe, Cu, Zn) was analysed using atomic absorption spectrometry (ISO 11047:1998, 1998) and flame photometry (ISO 9964-3:1993, 1993). Additionally, the content of mobile forms of phosphorus and potassium was determined by the Machigin and Kirukov method, which allowed assessing the availability of these elements for plants. The technique was chosen based on its high sensitivity to mobile forms and effectiveness in carbonate soils. The assessment was in accordance with the principles of ISO 11263:1994 (1994) for phosphorus.

The water-physical properties of soils were assessed by determining moisture by gravimetry (ISO 11465:1993, 1993), water-strength aggregation by wet sieving, and water permeability by cylindrical infiltration. The data obtained allow evaluating the ability of soils to retain moisture, resist destruction under the influence of external factors and provide optimal conditions for plant growth. Special attention was paid to the analysis of the soil water regime, including the groundwater level, capillary rise of moisture and filtration coefficient. A method of determining the content of easily eroded particles and the calculation of the erosion potential, considering the slope of the terrain and climatic factors, was used to assess the risk of soil erosion. Studies on the biological activity of soils were conducted, including the analysis of the microbiological composition by the method of sowing on nutrient media and the of the respiratory activity of the soil for the release of CO_2 (ISO 17155:2002, 2002). Thus, the use of an integrated approach, including field research, laboratory analyses, mathematical modelling, and statistical data processing, allowed obtaining a comprehensive agrochemical characteristic of the mountain soils of the Fergana Valley.

RESULTS

The Fergana Valley, being an important agricultural region, has a variety of soils due to difficult geographical and climatic conditions. Local soils are formed under the influence of many factors, including topography, climate, vegetation composition, and anthropogenic influences. As part of the study, a detailed examination of the morphological characteristics of soils was conducted, which allowed identifying the key features of soil types, their orientation, and structure. Brown forest soils occupy the central part of the Fergana Valley, which is characterised by a moderately arid climate and high rainfall. They formed in areas where vegetation prevails, actively contributing to the accumulation of organic substances. As a result of this process, brown forest soils have a pronounced horizontal character, which is due to the long-term processes of rotting of plant residues. The soils have a well-formed humus horizon with a thickness of 20-40 cm, which is an indicator of a high content of organic matter since humus is actively formed in conditions of moderate moisture. The colour of these soils is dark brown, which is associated with a high level of organic matter in the upper horizon. The structure of brown forest soils is dense, with a good aggregate structure, which contributes to their water-retaining properties. Such soils have a high content of water-soluble salts, which is important for the nutrition of crops. These soils have a high moisture capacity of up to 20-25%, which is especially important for regions where seasonal precipitation is not always sufficient for the needs of plants (Juliev *et al.*, 2022). The developed root system of plants, good mechanical properties of the soil, ensure their resistance to erosion processes. This allows the use of brown forest soils for intensive agriculture, including the cultivation of crops such as cotton, wheat, and fruits.

The mountain-brown carbonate soils common in the higher mountainous parts of the Fergana Valley are characterised by unique morphological features due to the mountainous landscapes and climate features. In these soils, a carbonate horizon is present at a depth of 40-60 cm, indicating a high content of calcite and other carbonate minerals, leading to an alkaline soil reaction (pH 7.5-8.2) (Abakumov *et al.*, 2023). This composition makes it difficult for plants to absorb certain macro- and microelements, such as phosphorus and iron, which requires the use of special agrotechnical techniques, such as acid fertilisers, to improve the availability of nutrients. Soils have a looser structure compared to brown forest soils, which contributes to better water penetration into deeper soil layers, but also reduces their water retention capacity (humidity is 15-20%) (Masharobich & Saidakbarovich, 2024). The medium-loamy composition makes mountain-brown carbonate soils good for growing some types of crops; however, due to the low humus content (2.5-4.5%), regular application of organic fertilisers is required to improve their fertility. In these soils, it is also necessary to consider the tendency to erosion, especially in areas with sudden temperature fluctuations and heavy rains.

Sandy soils were found in the eastern and southern parts of the Fergana Valley, where the climate is drier and precipitation levels are drastically lower. These soils have a weak horizontal orientation, which indicates their immaturity and limited opportunities for the accumulation of organic substances. The humus layer in sandy soils is thin, not exceeding 10-20 cm, which is explained by the rapid decomposition of organic substances in conditions of high temperature and low humidity. The colour of these soils is light, yellowish-beige, which also indicates a low content of humus and organic matter. Sandy soils have high water permeability, which means that water quickly escapes through them without lingering in the upper layers (Filss *et al.*, 1998). The moisture content of sandy soils varies from 5 to 10%, making them less suitable for non-irrigated farming. These soils have a low nutrient content, which reduces their fertility, and require regular application of organic fertilisers and pH adjustments to improve the structure and increase water retention.

The granulometric composition of the examined soils of the Fergana Valley revealed pronounced differences in the mechanical structure of various types of soils, which determines their agronomic and physico-chemical properties. The analysis showed that brown forest soils are mainly characterised by a medium-loamy composition, in which the content of the sand fraction varies from 35 to 45%, silt – from 30 to 40%, and clay – from 15 to 25% (Table 1). Such a ratio of granulometric fractions contributes to the formation of a loose and resistant to water erosion structure, which has a high moisture retention capacity and is favourable for the development of the root system of plants. Such soils have good aeration, heat capacity, and water permeability, which together make them promising for high-productivity agriculture.

***Table 1**. Granulometric composition of soils in the Fergana Valley*

Soil type	Sand, % fraction	Silt, % fraction	Clay, % fraction
Brown forest trees	35-45	30-40	15-25
Mountain-brown carbonate rocks	25-35	35-40	35-35
Sandy	Up to 80	10-15	5-10

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

In contrast, mountain-brown carbonate soils have a heavier mechanical composition due to an increased proportion of clay particles ranging from 25 to 35%. At the same time, the content of silt is in the range of 35-40%, and the sand fraction is about 25-35%. This structure gives soils a high density, reduces permeability and promotes caking, especially during waterlogging. However, a high proportion of clay has a positive effect on the water retention capacity and increases the cation exchange capacity of soils, contributing to the fixation and prolonged action of batteries. Notably, mountain-brown soils require a balanced approach to cultivation, especially in arid climates and when using heavy machinery, since excessive compaction can lead to deterioration of their structure. Sandy soils, on the contrary, are characterised by a light granulometric composition, in which the content of the sand fraction reaches 80%, while the content of silt varies from 10 to 20%, and clay – from 10 to 15%. This structure determines high porosity and water permeability, but extremely low moisture retention, which leads to rapid leaching of nutrients from the root layer and a decrease in overall productivity. In addition, the weak aggregation of sandy soils makes them vulnerable to wind and water erosion. In this regard, effective agricultural use of sandy soils is possible only if a complex of soil-improving measures is conducted, including the introduction of organic materials, the formation of moisture storage structures and the use of mulching technologies.

The revealed differences in the granulometric composition of the soils of the Fergana Valley indicate the need for a differentiated approach to their agrotechnical use. Medium-loamy brown forest soils have the greatest potential for crop production due to their balanced structure. Mountain-brown carbonate soils require increased attention to preventing compaction and caking, while sandy soils require active land reclamation and fertility maintenance. Consideration of the mechanical composition of soils in the development of agricultural technologies and fertiliser systems is crucial for increasing the sustainability and productivity of agroecosystems in the region. An analysis of the humus content in various types of soils in the Fergana Valley revealed substantial differences in the level of organic matter, reflecting the features of their formation, climatic conditions, and the nature of vegetation cover. The highest humus content was recorded in brown forest soils, where its concentration ranges from 4.5 to 6%. These soils are formed in a moderately humid climate, are characterised by a high level of biological activity and a rich vegetation cover, which contributes to the constant supply of organic residues to the upper horizons of the soil. The active activity of soil microflora and fauna in combination with sufficient humidity ensures an effective process of humus formation. The high humus content has a positive effect on the soil structure, its water-physical properties, cation exchange capacity and agrochemical activity, thereby increasing the overall fertility and stability of agroecosystems (Brovko *et al.*, 2025).

In mountain-brown carbonate soils, the humus content was moderate and ranged from 2.5-4%. These soils are formed in more arid conditions, with lower vegetation density and elevated temperatures, which contributes to accelerated mineralisation of organic residues. The carbonate nature of the soil-forming rocks also affects the processes of organic decomposition: carbonates contribute to the alkaline reaction of the soil solution, which is less favourable for the stability of humic compounds (Kruglov *et al.*, 2023). However, despite this, the organic matter content remains at a relatively good level, which indicates the presence of stable forms of humus and the compensatory role of clay components that contribute to the fixation of organic molecules in the soil matrix. Systematic application of organic fertilisers and green manure crops is recommended to increase the humus content in such soils.

The minimum humus content was found in sandy soils, where its level was only 0.5-1.5%. This is primarily due to the extremely unfavourable conditions for the accumulation of organic matter. Sandy soils are characterised by high water permeability and low moisture retention, which sharply limits biological activity and reduces the intensity of humus formation processes. In addition, the coarse-grained structure and the absence of clay fractions contribute to the rapid leaching of organic compounds and a decrease in cation exchange capacity. In conditions of high temperature and lack of moisture, the mineralisation of organic residues proceeds rapidly, while the weak development of vegetation cover limits the supply of new organic matter (Cholponbek *et al.*, 2025). These soils require a range of measures to improve their organic condition, including regular application of organic fertilisers, compost, siderates, and the use of mulch. Increasing the humus state of sandy soils is an important condition for improving their structure, increasing their water retention capacity, and ensuring sustainable crop growth. The level of humus content of the studied soils directly correlates with their granulometric composition, climatic, and biological conditions of formation.

The analysis of the acid-base state of the studied soils of the Fergana Valley demonstrated a clear dependence of the reaction of the soil solution on the granulometric composition and content of carbonate compounds. pH values vary in a wide range from slightly acidic to alkaline reactions, which has a substantial impact on the agrochemical properties of soils, primarily on the availability of nutrients and the activity of the microbiota. According to the data obtained, brown forest soils have a slightly acidic or close to neutral reaction, with a pH range from 5.8 to 6.5. This acidity is considered optimal for most cultivated plants, as it provides the best absorption of macro- and microelements, in particular, phosphorus, iron, manganese, and zinc. In addition, a slightly acidic environment promotes high biological activity of the soil, accelerates the processes of mineralisation of organic substances, and the formation of a stable structure. The presence of humus and clay particles contributes to buffering properties, preventing sudden pH fluctuations when applying fertilisers or in conditions of humidity changes.

Mountain-brown carbonate soils, on the contrary, are characterised by a pronounced alkaline reaction, with pH values in the range 7.5-8.2. The alkaline environment is caused by the high content of calcium and magnesium carbonates, which actively neutralise the acids formed during the decomposition of organic matter. Although such conditions can contribute to the stabilisation of organic forms of nitrogen, the alkaline reaction significantly reduces the availability of a number of nutrients, especially phosphorus, iron, copper, and manganese, which under these conditions turn into poorly soluble forms. This leads to hidden forms of deficiency of elements, even with their sufficient total content in the soil. To increase the agrochemical efficiency of mountain-brown soils, it is recommended to use acidifying fertilisers (for example, ammonium-containing ones), the use of organic additives, compost, and siderates that can partially compensate for carbonate buffering.

Sandy soils showed a slightly alkaline reaction with pH values from 6.8 to 7.4. Despite the absence of substantial amounts of carbonates, the neutral or slightly alkaline environment in these soils is due to the minimal buffer capacity and weak acid-neutralising ability. Such soils are subject to rapid pH changes in response to external influences, including watering, fertilisation, and climatic fluctuations. In addition, with a low content of organic matter and moisture, even a moderately alkaline environment can adversely affect the digestibility of nutrients. In this regard, to increase the agronomic efficiency of sandy soils, it is necessary to regularly apply organic fertilisers and maintain an optimal level of acidity using acid phosphates or humic additives. The content of macronutrients in soils is an important indicator of their agrochemical state and affects soil fertility, in addition to plant growth and development. The study found that the content of the main macronutrients – nitrogen, phosphorus and potassium – varies depending on the type of soil and its granulometric composition, which reflects the different abilities of the soil to provide plants with the necessary nutrients (Table 2).

***Table 2**. Humus content N, P, K*

Soil type	Humus, % fraction	Nitrogen, % fraction	Phosphorus, mg/kg	Potassium level
Brown forest trees	4.5-6	0.2-0.3	20-40	High
Mountain-brown carbonate rocks	2.5-4	0.1-0.2	10-25	Medium
Sandy	0.5-1.5	0.1	5-15	Low

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

Nitrogen is one of the key elements determining soil productivity, as it forms the basis for the synthesis of amino acids and proteins in plants. In brown forest soils, the nitrogen content varies from 0.2 to 0.3%, which is a relatively high level and sufficient to meet the nitrogen needs of most crops at the initial stages of growth. This is due to the good biological activity of the soil and the high content of organic matter, which gradually mineralises, providing plants with ammonium and nitrate forms of nitrogen. In mountain-brown carbonate soils, the nitrogen content decreases to 0.1-0.2%. This decrease is associated with a low level of organic matter and increased mineralisation in a warm climate. These soils may require additional doses of nitrogen fertilisers to maintain optimal nutrient levels for plants, especially in the early stages of their growth. In sandy soils, the nitrogen content does not exceed 0.1%, which is the minimum value among all types of soils. This is due not only to the low content of organic matter, but also to the high rate of mineralisation, which hinders the accumulation of nitrogen in an accessible form. For sandy soils, regular application of nitrogen fertilisers is especially important to maintain soil productivity.

Phosphorus is an essential element for the formation of the root system and photosynthesis processes (Bobunov *et al.*, 2023). In brown forest soils, available phosphorus ranges from 20 to 40 mg/kg, which is a high indicator that provides plants with good access to this element necessary for their growth and development. This is due to both the high content of organic matter and the moderate acidity of these soils, which contributes to good phosphorus mobility. In mountain-brown carbonate soils, the available phosphorus content varies from 10 to 25 mg/kg. Due to the high alkaline reaction of these soils, phosphorus in them is often deposited in insoluble forms, which limits its digestibility by plants. In such conditions, phosphorus becomes less accessible to plants, which requires the use of corrective measures, such as the introduction of acidifying fertilisers or organic additives. In sandy soils, the available phosphorus content ranges from 5 to 15 mg/kg. This is a fairly low level, which is due to both the low content of organic matter and its high permeability, which contributes to the leaching of phosphorus. It is necessary to regularly apply phosphorus fertilisers to increase the availability of phosphorus in sandy soils, which will help provide plants with the necessary elements for growth.

The potassium content in the soils of the Fergana Valley is quite high in all types of soils, but its availability differs depending on their structure. In brown forest soils, due to the high humus content and medium texture, potassium is available in a fairly good amount, which contributes to its effective absorption by plants. In mountain-brown carbonate soils and sandy soils, the availability of potassium is also rather high, but in sandy soils, this element tends to be quickly washed out due to its weak structure and low cation exchange capacity. During the examination of the soils of the Fergana Valley, an analysis of the number of microorganisms in various types of soils was conducted, which identified substantial differences in the level of biological activity. High microbiological activity is observed in brown forest soils, which is expressed in the number of microorganisms from 2 to 4 million per gram of soil. This indicator is the highest among all the soil types under study and indicates a high degree of humus content and active decomposition of organic substances in these soils. High biological activity is due to favourable conditions for microorganisms, such as optimal humidity, temperature, and the presence of a diverse vegetation cover, which serves as a source of organic residues. It also promotes increased mineralisation of nitrogen, phosphorus, and other elements needed by plants and supports the structural stability of the soil.

In mountain-brown carbonate soils, microbiological activity is slightly lower and ranges from 1-2 million microorganisms per gram of soil. Such indicators may be associated with a lower content of organic matter, which limits the number of available substrates for microorganisms. A more alkaline reaction of these soils can also negatively affect the activity of certain types of microorganisms, which leads to a smaller number of microbial fauna compared to brown forest soils. The lowest biological activity was found in sandy soils, where the number of microorganisms was less than 1 million per gram of soil. This indicator is due to the low content of organic matter, in addition to the high permeability of the soil, which contributes to the rapid leaching of organic residues and nutrients. The weak biological activity in these soils limits their ability to self-heal and requires regular application of organic fertilisers to maintain fertility.

One of the important aspects of the study was the assessment of the soil resistance of the Fergana Valley to erosion processes, including water and wind erosion. Soil erosion is the process of destruction and removal of the upper fertile soil layer, which can seriously affect its productivity and the sustainability of agricultural production (Yzakanov *et al.*, 2024). Brown forest soils are characterised by high resistance to erosion processes, both water and wind. This is due to their dense structure and good water-resistant aggregation. The high content of organic matter, especially humus, improves the soil structure, which increases its resistance to being washed out and loss of nutrients. The water-strength aggregates of these soils greatly exceed 85%, which minimises their susceptibility to water erosion. Due to this, brown forest soils can effectively retain moisture, which reduces the likelihood of their leaching and destruction under the influence of precipitation and water flows. Mountain-brown carbonate soils have less resistance to erosion compared to brown forest soils. Despite the presence of clay particles, which can contribute to some structural stability, these soils are prone to caking due to their denser structure and high content of calcium and magnesium carbonates. This reduces their water-resistant aggregates and makes them more vulnerable to surface washout, especially during heavy rains or strong water flows.

Sandy soils are the most vulnerable to erosion processes. They are characterised by a low content of organic matter and a weak aggregated structure, which makes them prone to weathering and washout. The low moisture retention capacity of sandy soils also contributes to their high susceptibility to water erosion. Under conditions of wind erosion, these soils lose their top layer, which is aggravated by the low content of humus and organic matter, which limits the ability to restore the soil structure. It is necessary to introduce agrotechnical measures, such as planting protective plants, using organic fertilisers, and improving soil structure using various soil-improving methods to lower the erosion processes on such soils. Differences in soil resistance to erosion emphasise the importance of an integrated approach to their use and protection. Brown forest soils have the best characteristics for agriculture in the conditions of the Fergana Valley, while mountain-brown and sandy soils require additional efforts to prevent erosion processes and improve their structure.

A quantitative assessment of the potential effect of the use of various agrotechnical measures was conducted, considering the local climatic and soil conditions of the region, to properly research the issue. The analysis indicated that applying organic fertilisers (compost or manure) on sandy soils at a dose of 25-30 t/ha over three years can increase the humus content from 0.5-1.5% to 2-2.2%. Thereby, the total nitrogen level increases from <0.1% to 0.12-0.14%, which, according to calculations, can increase the yield of grain and fodder crops by 35-40%. An additional effect is provided by the cultivation of perennial legumes (alfalfa, sweet clover), which increase microbiological activity by 2-2.5 times and improve the water-retaining properties of the soil. For mountain-brown carbonate soils (with a pH of 7.5-8.2), the combined use of organic fertilisers (15 t/ha) and ammonium sulfate (60 kg/ha) with superphosphate (40 kg/ha) is an effective measure. This reduces the pH to 7-7.2 and increases phosphorus availability by 40-50%, which increases grain yields by 20-25% under conditions of limited irrigation. On brown forest soils, despite the high natural fertility, measures to prevent erosion on the slopes remain effective. The use of mulch, minimal tillage, and green manure crops reduces the loss of humus and aggregate structure, retains moisture in the surface horizons, which contributes to sustainable productivity without additional fertiliser. The proposed measures, adapted to the conditions of the Fergana Valley, provide a projected increase in agrochemical indicators and yields by 20-40%, depending on the type of soil and the depth of intervention.

DISCUSSION

The conducted study on the agrochemical characteristics of the mountain soils of the Fergana Valley indicated pronounced differences in their composition, structure, and biological activity depending on the type of soil and relief conditions. The results obtained are compared with data from other studies conducted in various mountainous and arid regions of the world, which allowed for a comprehensive comparative analysis and identification of universal patterns and regional features. The brown forest soils of the Fergana Valley are characterised by a medium-loamy granulometric composition, with a predominance of silt and clay, which forms a good water retention capacity, stable structure, and favourable conditions for microbiological activity. The sand content is 35-45%, silt – 30-40%, clay – 15-25%. Such a combination of granulometric fractions contributes to the effective retention of moisture in the soil column and the formation of a structure with a high degree of porosity. As shown in the study by A.J. Franzluebbers *et al.* (2025), soils with a similar mechanical composition have an increased cation exchange capacity, are characterised by an active microbiological regime, and are resistant to physical and chemical degradation. Such properties are especially important during intensive exploitation of agricultural land and under conditions of increasing climatic stress. The humus content in brown forest soils is 4.5-6%, which represents a high level of organic accumulation, favourable for agrochemical balance and maintenance of the structure. H. Man *et al.* (2023) note that the thickness of the humus layer in China's boreal forests depends on height and slope, reaching up to 26.7 cm, and permafrost degradation accelerates humus depletion. Similar results are stated by M. Zhiyanski *et al.* (2017), where afforestation in the Central Balkans led to a decrease in organic carbon content and soil pH, especially after the replacement of hardwoods with conifers. The study also showed a decrease in humus content in mountain-brown soils (2.5-4%), and in sandy soils, it was only 0.5-1.5%.

Sandy soils containing up to 80% of the sand fraction exhibit extremely low moisture retention and weak aggregate structure. Such characteristics drastically worsen the conditions for plant development, increase the risk of erosion processes and contribute to the leaching of nutrients from the root zone. C.A. Brühl *et al.* (2024) underscore the serious danger associated with the accumulation of pesticides, which leads to a decrease in biodiversity and the destruction of soil structural stability, even in remote mountain ecosystems. This problem is becoming most relevant in agricultural regions with high intensity of land use and insufficient environmental control over the level of chemical pollution. The acidity of soils varies from slightly acidic to slightly alkaline. pH values from 5.8 to 6.5 were observed in brown forest soils, which is favourable for the absorption of macro- and microelements. In carbonate soils, the pH reaches 7.5-8.2, which may limit the bioavailability of certain forms of phosphorus and trace elements. In sandy areas, the pH value is in the range of 6.8-7.4. Similar results are presented in the paper of A.M. Belay *et al.* (2023), where the spatial distribution of pH in the mountainous regions of Ethiopia depends on precipitation, type of land use, and altitude. Y. Shen *et al.* (2021) also indicate that cyclical pH changes were observed in southern China from 1982 to 2018 under the influence of acid rain and organic matter reduction, which confirms the sensitivity of pH to exogenous factors. In this publication, the obtained values of soil acidity (from slightly acidic in brown forests to slightly alkaline in sandy soils) confirm the complex nature of pH regulation. Y.Y. Zhang *et al.* (2019) demonstrated that pH is particularly affected by variables such as slope exposure, precipitation, and parent rock, with the degree of influence varying between horizons A, B, and C. The use of CART models has shown high accuracy in acid prediction, which opens up opportunities for differentiated soil management in hilly and mountainous regions.

The nitrogen content in brown forest soils was 0.2-0.3%, which provided optimal conditions for plant development, especially in the early stages of vegetation. Mountain-brown soils showed a decrease to 0.1-0.2%, and sandy soils – less than 0.1%, which makes them dependent on external application of nitrogen fertilisers. Notable differences in phosphorus content were also found: in brown – 20-40 mg/kg, in carbonate – 10-25 mg/kg, in sandy – 5-15 mg/kg. The data is comparable to the results of Q. Li *et al.* (2021), where phosphorus availability was a limiting factor for meadows in the Qilian Mountains. B. Su *et al.* (2024) also emphasise the importance of spatial analysis of the distribution of nitrogen and phosphorus, considering terrain, temperature, and texture. The obtained patterns of changes in phosphorus and cation content depending on the type of soil and altitude above sea level are in good agreement with the results of P. De Bauw *et al.* (2016), who showed that soil fertility on the slopes of Mount Elgon decreases with increasing altitude due to a decrease in phosphorus and exchange cations. In addition, the authors identified the dependency of the mineral supply of plants on a specific relief zone: in the lower part of the slopes, magnesium deficiency occurs due to antagonism with potassium, and in the upper part – due to general depletion. This observation highlights the need for a localised approach to agrochemical regulation. Biological activity, estimated by the number of microorganisms, ranged from 2-4 million/g in brown forest soils to less than 1 million/g in sandy soils, which is fully consistent with the conclusions of D. Kodirova *et al.* (2023) on the key role of the humus horizon in maintaining the microbial community. Z.H. Aliyev and M.A. Quliyeva (2023) demonstrate that the introduction of perennial grasses leads to a substantial increase in microbiological activity due to the enrichment of soil with organic matter. Similar trends have been established by L. Rangel *et al.* (2019) and D. Salesa & A. Cerdà (2020), linking the degradation of the soil cover with trampling, excessive recreational loading and disruption of the pasture exploitation regime.

Special attention should be paid to soil resistance to erosion processes. According to the data, sandy soils are subject to the highest erosion due to their weak aggregate structure, while brown forest soils, due to their high water-strength aggregates (more than 85%), demonstrate stability even on slopes. Similar dependencies were identified in the study by H. Hag Husein *et al.* (2024), where, using the CORINE model, a high erosion vulnerability of soils was specified, including areas with dense vegetation, especially in conditions of intense precipitation. Researchers C. Jiang *et al.* (2021) and L. Wen *et al.* (2023) confirm that urbanisation and changing land use patterns immensely worsen erosion processes. The climate warming, according to J. Peng *et al.* (2021), can both contribute to an increase in organic matter in the soils of mountainous regions due to the lengthening of the growing season, and enhance rock weathering with sudden fluctuations in humidity. Such dual effects require monitoring, especially in vulnerable areas, as demonstrated by W. Sun *et al.* (2023) on the Tibetan Plateau. To stabilise the soil cover, it is necessary to introduce agroforestry measures, along with the systematic monitoring of landscape fragmentation as one of the key risk factors.

In general, a comparative analysis has shown that the agrochemical properties of the soils of the Fergana Valley are in the range typical for mountain systems of temperate and dry climates. However, features such as localised alkalinity, humus-poor sandy soils, and sensitivity to erosion require adapted land management programmes. This includes the use of organic fertilisers, the introduction of perennial crops, anti-erosion measures, and strategic land use planning based on topography, climate, and soil texture.

CONCLUSIONS

The analysis of the soils of the Fergana Valley revealed a substantial variety of their physico-chemical properties. Brown forest soils have a medium loamy composition (sandy fraction 35-45%, silt 30-40%, clay 15-25%), which contributes to a high moisture retention capacity. Mountain-brown carbonate soils contain 25-35% clay particles and less sand fraction. Sandy soils are dominated by sand particles up to 80%, which makes them unsuitable for agriculture without irrigation. The humus content is the highest at 4.5-6% in brown forest soils due to active biological activity. In mountain-brown carbonate soils, it is below 2.5-4%, and in sandy soils, it is at a minimum of 0.5-1.5% due to accelerated mineralisation of organic matter. In terms of soil acidity, there are pronounced differences: brown forest soils have a slightly acidic or neutral reaction (pH 5.8-6.5), which provides optimal conditions for the absorption of nutrients by plants. Mountain-brown carbonate soils are characterised by an alkaline environment (pH 7.5-8.2), which may limit the availability of certain macro- and microelements. A slightly alkaline reaction (pH 6.8-7.4) was established in sandy soils, while the low content of organic matter further reduces their agrochemical efficiency. The macronutrient composition differs, and the nitrogen content varies from 0.2-0.3% (brown forest soils) to less than 0.1% (sandy soils). Available phosphorus is higher in brown forest soils (20-40 mg/kg), and potassium is better retained in loamy soils. Water-physical properties affect erosion resistance, and in the process, it was determined that brown forest soils are characterised by high moisture capacity and erosion resistance. Mountain-brown soils are moderately moisture-intensive, while sandy soils require additional irrigation.

The data obtained allow formulating recommendations on the rational use of the soils of the Fergana Valley and developing measures to improve their fertility and resistance to degradation. However, the present study covered only a part of the territory of the Fergana Valley, which may limit the extrapolation of the data to the entire region. The analysis methods applied, although widely used, had certain errors related to the natural variability of soil characteristics. The study also did not account for seasonal changes in moisture and organic matter, which can considerably affect the agrochemical properties of soils. For more detailed research, it is necessary to conduct additional studies, including long-term monitoring of soil parameters and analysis of the influence of anthropogenic load and climatic factors.

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Агрохімічна характеристика гірських ґрунтів Ферганської долини

Гулбарчин Ісраїлова
Кандидат біологічних наук, викладач
Ошський технологічний університет ім. М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
https://orcid.org/0009-0005-1083-4724

Байгелді Жусупов
Викладач
Ошський технологічний університет ім. М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
https://orcid.org/0009-0003-4307-5811

Гулом Юлдашев
Доктор сільськогосподарських наук, професор
Ферганський державний університет
150100, вул. Мураббілар, 19, м. Фергана, Узбекистан
https://orcid.org/0000-0003-3339-1768

Муроджон Ісагалієв
Доктор біологічних наук, професор
Ферганський державний університет
150100, вул. Мураббілар, 19, м. Фергана, Узбекистан
https://orcid.org/0000-0002-7108-6011

Рахіма Муратова
Кандидат сільськогосподарських наук, доцент
Ошський державний університет
723500, вул. Леніна, 331, м. Ош, Киргизька Республіка
https://orcid.org/0009-0004-3494-0815

Анотація. Актуальність дослідження ґрунтів Ферганської долини зумовлена їх різноманітністю та важливістю для сільського господарства регіону. Різні ґрунтові типи відрізняються за гранулометричним складом, родючістю та здатністю утримувати вологу, що впливає на їхні агрохімічні властивості. Метою дослідження був комплексний аналіз агрохімічних характеристик ґрунтів Ферганської долини, включаючи гранулометричний склад, вміст гумусу, кислотність, карбонатність, водні властивості та біологічну активність. Методи включали польові дослідження, відбір проб з різних висотних поясів, лабораторні аналізи хімічного складу. Визначення азоту проводилося методом К'єльдаля, фосфору – методом Мачигіна і Кірукова, калію – полум'яною фотометрією. Результати дослідження показали значні відмінності у складі та властивостях різних типів ґрунтів. Бурі лісові ґрунти продемонстрували найбільш сприятливі агрохімічні параметри. Гранулометричний склад бурих лісових ґрунтів середньосуглинковий, із вмістом піску 35-45 %, мулу 30-40 % та глини 15-25 %. У ґрунтах зафіксовано високі рівні гумусу (4,5-6 %), загального азоту (0,2-0,3 %), доступного фосфору (20-40 мг/кг) і калію (високий рівень). Біологічна активність, оцінювана за мікробною чисельністю, становила 2-4 млн/г, що підтвердило високу метаболічну активність ґрунтової мікрофлори.

Гірничо-коричневі карбонатні ґрунти характеризувались важчим гранулометричним складом, з підвищеним вмістом глини (25-35 %) і помірними показниками родючості: 2,5-4 % гумусу, 0,1-0,2 % азоту, 10-25 мг/кг форсфору та середній рівень калію Піщані ґрунти мали низьку вологоємність, слабку агрегатну структуру та вкрай низькі показники родючості: 0,5-1,5 % гумусу, <0,1 % азоту, 5-15 мг/кг фосфору, низький рівень калію. Біологічна активність не перевищувала 1 млн/г. Кислотність ґрунтів варіювалась: бурі лісові ґрунти мають слабокислу або нейтральну реакцію з pH 5,8-6,5, що сприятливо для засвоєння поживних речовин. Гірничо-коричневі карбонатні ґрунти лужні з pH 7,5-8,2, що знижує доступність деяких елементів. Піщані ґрунти мають слаболужну реакцію pH 6,8-7,4. Отримані дані дадуть змогу оптимізувати землекористування, підвищити продуктивність ґрунтів і мінімізувати їхню деградацію

Ключові слова: гумус; гранулометричний склад; карбонатність; ерозійні процеси; кислотність; мінерали; органіка

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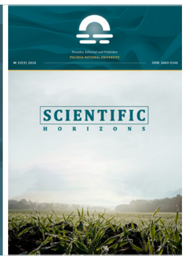

Efficiency of winter precipitation accumulation measures in climatic conditions of the North Kazakhstan region

Zhanna Lutchenko

Head of the Grain Crop Breeding Laboratory
North Kazakhstan Agricultural Experimental Station
150311, 19 Tsentralna Str., Shagalaly, Republic of Kazakhstan
https://orcid.org/0000-0002-0431-5398

Oleg Solovyov*

Head of the Farming Laboratory
North Kazakhstan Agricultural Experimental Station
150311, 19 Tsentralna Str., Shagalaly, Republic of Kazakhstan
https://orcid.org/0000-0002-7341-5851

Vitalii Zaika

Master of Science, Head of Organisation
North Kazakhstan Agricultural Experimental Station
150311, 19 Tsentralna Str., Shagalaly, Republic of Kazakhstan
https://orcid.org/0000-0002-2023-3755

Vladimir Shvidchenko

PhD in Agricultural Sciences, Researcher
North Kazakhstan Agricultural Experimental Station
150311, 19 Tsentralna Str., Shagalaly, Republic of Kazakhstan
https://orcid.org/0000-0001-7426-9115

Anzhelika Artys

Master of Science, Researcher
North Kazakhstan Agricultural Experimental Station
150311, 19 Tsentralna Str., Shagalaly, Republic of Kazakhstan
https://orcid.org/0000-0002-1945-0787

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Abstract. The study aimed to establish the patterns of formation of soil water resources due to winter precipitation using various agrotechnical methods in the steppe zone. The research methodology included field trials of various agronomic backgrounds with and without snow retention, followed by analysis of winter precipitation accumulation, changes in soil water regime and spring wheat productivity. The average snow depth in the variants with snow retention increased by 26.6-32% compared to the control without snow retention. Soil moisture reserves before sowing increased by 27.1-31.6% on fallow land and by 16-30% on stubble plots. Winter precipitation assimilation was most efficient on stubble backgrounds, where the moisture increase ranged from 21.8 to 37.5% compared to the initial values. The yield of spring wheat in areas with snow

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**Corresponding author*

retention exceeded the control figures by 0.15-0.47 t/ha, reaching maximum values of up to 2.76 t/ha on the backstage pairs. The correlation coefficient between total water consumption during the growing season and yield was 0.83, indicating a high influence of the water regime on productivity. The established relationship between the amount of moisture in the snow and yield was moderate, with a coefficient of 0.42, especially in stubble plots. The obtained results confirm the high efficiency of snow retention technologies for increasing the water supply of crops and the sustainability of yields in the steppe conditions of Northern Kazakhstan. Their use is recommended to optimise the system of agrotechnical measures in the face of increasing climate instability

Keywords: snow accumulation; soil moisture; snow retention; backstage steam; autumn tillage; yield

INTRODUCTION

Global climate change, manifested in higher average winter temperatures, changes in the structure and volume of atmospheric precipitation, reduced snow cover and more frequent droughts, are significantly transforming hydrological processes in the agricultural landscapes of arid and semi-arid regions, including Northern Kazakhstan, where a high proportion of the annual water balance is formed by winter precipitation, while the decline in snow resources and temperature instability pose significant risks to the sustainability of agricultural productivity. The loss of winter moisture necessitates the development and implementation of effective agrotechnical measures aimed at optimising the accumulation and retention of snowfall on fields. This task is particularly important in the context of ensuring the resilience of agricultural production systems to climate change and the adaptation of agriculture to new hydrothermal conditions.

Changes in snow cover and winter precipitation vary significantly depending on the climatic conditions of different regions of the world (Shahini, 2024). In Asian mountain systems, according to P. Kraaijenbrink *et al.* (2021), a decrease in snow moisture threatens the sustainability of water supply, especially in the face of rising temperatures. The study by Y. Qin *et al.* (2020) noted an increase in agricultural risks as a result of disruptions in snowmelt in areas dependent on snow resources. In northeastern China, as shown by M. Pan *et al.* (2022), a decrease in snow cover thickness leads to a decrease in soil moisture content in spring, which negatively affects the initial phases of crop growth. In European mountainous regions, according to P. Ebner *et al.* (2021), effective management of snow resources is becoming a key element of adaptive agricultural strategies in the face of climate instability. In Northern Kazakhstan, climate change is particularly acute, posing significant risks to the sustainability of agricultural ecosystems (Oshergina & Ten, 2023). As shown in the study by V. Salnikov *et al.* (2023), since the beginning of the 21st century, the region has seen a steady trend of increasing winter temperatures and decreasing total precipitation, which leads to a deterioration in the accumulation of snow moisture. M. Karatayev *et al.* (2022) highlighted that the instability of winter moisture increases the risk of spring droughts, which have a critical impact on the productivity of cereals, especially wheat. These changes necessitate a review of traditional agricultural practices to optimise the accumulation of winter precipitation and stabilise the water balance of arable land.

Adaptation of agricultural systems to changes in the winter water regime remains one of the least developed problems in modern agroclimatic research (Chabaniuk *et al.*, 2024). The high degree of vulnerability of agricultural production to changes in temperature and winter precipitation regimes was established in the study by A. Islyami *et al.* (2020), emphasising the insufficient development of adaptation scenarios that consider the specifics of snow moisture. A significant contribution to the development of spatial planning methodology was made by S. Baisholanov *et al.* (2024), proposing an agroclimatic zonal classification that integrates the impact of winter precipitation into the system for assessing the adaptive potential of agricultural land. Despite this, comprehensive models focused on optimising snow retention as one of the key factors in stabilising spring water availability remain underdeveloped. Optimisation of snowfall management methods to increase spring soil moisture remains one of the insufficiently studied areas of agrotechnical research (Pavlova & Litvinov, 2024). Increase in the content of organic matter in the soil is considered a promising direction, which contributes to an increase in its water-holding capacity and more efficient use of winter moisture, as confirmed by the results of numerical modelling presented in M. Feifel *et al.* (2024). An integrated approach to assessing the impact of different tillage technologies on seasonal moisture dynamics was first implemented by G. Blanchy *et al.* (2020) using geophysical survey methods, which revealed a high spatial heterogeneity of moisture distribution.

Despite the existence of studies on climate change and agronomic approaches to snow resource management, complex snow retention models and their impact on spring water supply in steppe agricultural landscapes are still insufficiently studied. The study aimed to evaluate the effectiveness of various agronomic backgrounds and snow retention technologies in ensuring the accumulation of winter moisture and its subsequent impact on the soil water regime.

MATERIALS AND METHODS

Experiment object and conditions. The field experiment was conducted in 2021-2024 at the experimental station of the North Kazakhstan Agricultural Experimental Station located in the steppe zone of northern Kazakhstan. The region was chosen due to a sharply continental climate, winter precipitation plays a key role in shaping the annual water balance, and the level of water availability in the spring is critical for the sustainability of crop yields. The study covered the winter period (November-March), during which snow cover and moisture accumulation dynamics were monitored, as well as the 2022-2024 growing seasons (May-August), including spring wheat sowing, development and harvesting. The object of the research was agronomic systems of soil preparation and snow retention aimed at regulating the water regime in the cold season. Fallow fields with flat-cut, minimal and zero tillage, backstage fallow, stubble plots after peas, spring wheat and oilseed rape, as well as autumn ploughing on grain stubble, were studied. Each background was studied in two variants: with and without mechanised snow retention. To evaluate the influence of water regime on productivity, spring wheat (*Triticum aestivum* L.), the most widespread and economically important crop in the region, was used, which is highly sensitive to moisture availability. Sowing was conducted in the third decade of May when the soil reached optimum physical maturity. Yields were measured on 50 m^2 plots in triplicate using the direct weighing method with the grain brought to standard moisture content (14%). Field studies in 2022-2024 were combined with an analysis of the dynamics of the soil water regime and accumulation of solid precipitation.

Characteristics of the soil and climatic conditions of the experimental plot. Characteristics of soil and climatic conditions of the experimental site. The climate of the experimental station is characterised by sharply continental conditions with a pronounced seasonal temperature amplitude and moderately low precipitation. The average annual amount of solid precipitation for the period November-March is 89 mm with an average air temperature of -12.5°C. The hydrothermal coefficient for the winter period is 0.85, indicating a deficit water regime (Kazhydromet, 2024). The soils of the site are carbonate-heavy loamy chornozems of medium power profile with neutral or slightly alkaline reaction (pH 7.2-8) and humus content of 4.5-5%. The mechanical composition is characterised by a predominance of fine particles. The relief is flat, with shallow closed depressions and the absence of forests, which contributes to the intensification of wind processes and affects snow accumulation conditions.

Methods of observation and analysis. Observations of snow cover were carried out following international standards set out in the World Meteorological Organisation (2024). Snow gauge surveys were carried out three times during the winter: in the third decade of December, in the first decade of February and before the snow melt in the second decade of March. At each stage, the snow cover height and water equivalent of precipitation were recorded using standard snow gauges and stratified transects to estimate snow density. The research covered agrotechnical backgrounds with mechanised snow retention (flat-cutting, minimal, zero, stubble plots after peas, wheat and flax, autumn tillage) and control plots without snow retention (flat-cutting, wheat stubble after peas, autumn tillage, backstage steam). For a comprehensive assessment of the water regime, the pre-winter soil moisture reserves, the moisture reserves in the snow at the time of melting and the moisture reserves before sowing were determined based on gravimetric measurements and the calculation of the water equivalent of snow. Winter precipitation absorption was calculated as the ratio of soil moisture gain to the water content of the snow cover, incorporating the initial moisture content. Soil moisture was determined by the gravimetric method with samples dried to a constant weight at a temperature of 105 ± 5°C following the recommendations of the Food and Agriculture Organisation (2020).

Statistical processing of the results was performed using one-way and two-way analysis of variance (ANOVA) with Microsoft Excel and Statistica 10. The reliability of differences between variants was assessed at a significance level of $p < 0.05$. Mean values, standard deviations and confidence intervals were calculated for all indicators. Correlation analysis included the calculation of pair coefficients (r) to assess the relationships between pre-winter moisture reserves, moisture reserves in snow and precipitation assimilation. The coefficients were interpreted using the Chaddock scale: $r = 0.5 - 0.7$ – moderate correlation, $r > 0.7$ – strong correlation. The research conducted complies with current ethical standards aimed at adhering to the principles of environmental responsibility when working with elements of agroecosystems. Agricultural practices used in the field experiments were in line with sustainable agriculture standards and did not harm biodiversity, soil structure or the environment. The research methodology correlated with the provisions of the Convention on Biological Diversity (1992), which regulates the principles of sustainable use of ecosystem components and conservation of agrobiodiversity.

RESULTS AND DISCUSSION

Meteorological conditions for the study period 2021-2024. During the 2021-2024 winter seasons in Northern Kazakhstan, there was a pronounced interannual variability in meteorological conditions, including the amount of precipitation and temperature. The data obtained showed both years with a deficit of precipitation relative to the average annual norms and seasons with a significant excess, which led to differences in the dynamics of snow moisture accumulation and potential water availability for agricultural land in spring. For a more detailed analysis, the total precipitation and average monthly temperatures for each winter period of the study are presented (Table 1).

***Table 1**. Meteorological indicators for the winter period, 2021-2024*

Year	Month	Metric		Year	Month	Metric	
		Precipitation, mm	Temperature, °C			Precipitation, mm	Temperature, °C
2021-2022	November	16.8	-7.1	2023-2024	November	74.4	-1.1
	December	17.6	-10.7		December	44.5	-14.2
	January	17.2	-14.4		January	31.6	-16.5
	February	3.8	-12.3		February	8.8	-16.3
	March	8.4	-9.2		March	12.6	-7.2
	Over the winter	63.8	-10.7		Over the winter	171.9	-11.1
	Average perennial	89	-12.5		Average perennial	89	-12.5
	+/- to the long-term average	-25.2	1.8		+/- to the long-term average	82.9	1.4
2022-2023	November	45.7	-8.4	Average (for 3 years)	November	45.6	-5.5
	December	10.7	-15.7		December	24.3	-13.5
	January	21.6	-13.5		January	23.5	-14.8
	February	16	-13.3		February	9.5	-14
	March	28	-3		March	16.3	-6.5
	Over the winter	122	-10.8		Over the winter	119.2	-10.9
	Average perennial	89	-12.5		Average perennial	89	-12.5
	+/- to the long-term average	+33	1.7		+/- to the long-term average	30.2	1.6

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

The obtained meteorological data for the winter periods of 2021-2024 indicate a pronounced interannual instability of moisture conditions, manifested in the alternation of seasons with a deficit and excess of solid precipitation. In 2021-2022, the amount of precipitation was 63.8 mm, which is 25.2 mm below the average annual norm (89 mm), indicating a deterioration in snow moisture accumulation and a potential decrease in water supply to agricultural land in the spring. In contrast, in the winter seasons of 2022-2023 and especially 2023-2024, the above-normal precipitation was recorded by 33 mm and 82.9 mm, respectively, which creates the preconditions for an increase in soil moisture reserves. Along with changes in precipitation, the 1.6°C increase in winter temperatures over the three years of the study increases the risk of premature snow melting and a shorter period of snow accumulation, which requires a new approach to the traditional timing of snow retention measures.

The tendency for winter moisture instability and an increase in average temperatures identified in the study is consistent with the results of W. Qi *et al.* (2020), which emphasises the crucial role of snow cover as a natural moisture accumulator, especially in agricultural ecosystems with a short spring growing season. Under conditions of insufficient accumulation of winter precipitation, as shown in this study for 2021-2022, the risk of moisture deficit in the early phases of crop growth increases significantly. The results of a study by G. Wilson *et al.* (2020) confirmed that even with an increase in total precipitation, changes in the physical structure of the snowpack and acceleration of melting processes are possible, which is also reflected in the recorded increase in average winter temperatures. These changes can lead to a decrease in the efficiency of the natural moisture reserve and an increase in the need for agronomic measures to preserve it.

The recorded fluctuations in the water regime were accompanied not only by a decrease in total moisture reserves in years with a deficit of precipitation, but also by the risk of premature snowmelt in seasons with increased precipitation, indicating instability of moisture accumulation processes. These results are comparable to the global trends of increasing snow drought described by M. Cowherd *et al.* (2023), which emphasise the need for agroecosystems to adapt to increasing climate instability. Additionally, the dependence of snowmelt rates on rising winter temperatures identified in the study is fully consistent with the findings of M. Meira Neto *et al.* (2020), demonstrating an increase in the sensitivity of hydrological processes to changes in snow cover characteristics. In the light of the data obtained on the threat of loss of stored moisture, the development of effective snow retention systems becomes a reasonable task, which is also confirmed by the results of Y. Xing and X. Wang (2024), who emphasise the importance of water-saving agricultural strategies to ensure the sustainability of agricultural production in the face of increasing climate risks. The fluctuations in winter precipitation recorded during the study period, from a deficit in 2021-2022 to an abnormal excess in 2023-2024, accompanied by a steady increase in average winter temperatures by 1.6°C above normal, indicate an increasing instability of the winter water regime. The established variability of snow moisture accumulation and the risk of its premature melting underline the need to improve snow retention technologies and adapt agricultural practices to new climatic conditions to ensure a sustainable soil water balance in spring.

Snow accumulation dynamics in winter. According to 1 snow accumulation measurement carried out in the third decade of December, 7.4 cm of snow was accumulated on the flat-cutting pair without snow retention, and moisture reserves amounted to 33.7 mm. At the same time, 14.9-16.3 cm of snow (+50.3-54.6%) was accumulated on the flat-cutting, minimum and zero tines with snow retention, and moisture reserves were 41.9-50.5 mm (+19.6-33.2%). The coulisse pair accumulated the maximum amount of solid precipitation of 20.6 cm, with moisture reserves of 59.7 mm (+43.5% of the flat-cutting pair), which is at the level of stubble of grain crops with snow retention. The difference was less pronounced in the context of the autumn tillage, with snow depth of 11.5 cm in the background of the autumn tillage without snow retention and moisture reserves of 40 mm, the increase in snow depth from snow retention was +5.3 cm (31.5%) and moisture reserves +5.9 mm (12.8%). The minimum efficiency at this stage was recorded for stubble backgrounds. Thus, when the snow depth and moisture reserves on wheat stubble without snow retention were 15.9 cm and 45.6 mm, the effect of snow retention provided an increase of 2.8-4.2 cm in height (+15-20.9%) and 4.7-8.7 mm in moisture (+9.3-16%). The dynamics of snow accumulation during the winter period by experimental variants are presented in Table 2.

***Table 2**. Dynamics of snow accumulation during the winter period in different agronomic backgrounds (November-March), average 2021-2024*

No.	Agricultural context	Height, cm	Water reserve in snow, mm	Height, cm	Water reserve in snow, mm	Height, cm	Water reserve in snow, mm
		1st measurement		2nd measurement		3rd measurement (before melting)	
		Snow retention					
1	Flat cutter steam	14.9	41.9	17	48.6	20.3	61.2
2	Minimal steam	15.3	48.9	18.3	55.3	22	66.1
3	No steam	16.3	50.5	19.9	59.9	22.9	68.8
4	Peas (on grain stubble)	16.5	50.6	19.9	62.7	23.1	73.5
5	Wheat (over pea stubble)	20.1	54.3	23.2	64.7	25.8	76.2
6	Wheat (on flax stubble)	18.7	50.3	21.5	62.8	24.2	69.5
7	flax (on grain stubble)	15.6	45.5	19.5	58.3	22.7	68.3
8	Crop stubble (grain stubble)	16.8	45.9	19.5	62.2	21.8	68.8
		Without snow retention (control)					
9	Flat cutter steam	7.4	33.7	8.7	34.7	9.5	37.3
10	Wheat (over pea stubble)	15.9	45.6	17.6	53	19	57
11	Crop stubble (grain stubble)	11.5	40	13.1	44.2	14.3	46.4
12	Backstage steam	20.6	59.7	26.6	69.8	30.3	85.7

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

The high amount of precipitation in the first half of winter (November, December, January) had a significant impact on snow accumulation by the time of the 2nd interim measurement in the first decade of February. According to the results of these measurements, there was an increase in water reserves in the snowpack by 16.1-22% for stubble backgrounds with snow retention, and only 14% for stubble backgrounds without snow retention, compared to the first accounting. Snow accumulation on fallow plots with snow retention amounted to 11.6-15.7% by the first accounting (exceeding the control by 8.7-12.8%), and on wedge fallow by 14.5% (exceeding the control by 11.6%). A high increase was noted on the backgrounds with autumn tillage, where the effect of snow retention provided an increase in moisture reserves of 26.2%, with an excess of 16.7% over the control.

According to the final record of solid precipitation, by the time of thawing in the second decade of March, high moisture reserves were noted on the background with snow retention and on the backstage steam. Thus, the increase in snow depth and water reserves in the steam plots, by the first accounting, is within the following limits: flat-cutting steam without snow retention (control) by 2.1 cm (+22.1%), and moisture by 3.6 mm (+9.7%), while for flat-cutting, minimal and zero pairs with snow retention by 5.4-6.7 cm (+26.6-30.5%), and by 17.2-19.3 mm (+26-31.5%) of accumulated moisture. The maximum efficiency of snow accumulation was observed on stubble backgrounds and autumn tillage with snow retention, as well as on the backdrop. Thus, the early winter tillage with snow retention additionally accumulated +5 cm (23%) of height and +22.9 mm (33.3%) of moisture, while the control showed an increase in height of 19.6% and moisture reserves of 13.8%. On the stubble of spring wheat, depending on the predecessor, 24.2-25.8 cm (+22.1-22.7%) and 69.5-76.2 mm of reserves (+27.6-28.7%) were accumulated, while the control showed an increase of 16% in height and 20% in moisture. On the stubble of legumes and oilseeds, the increase is also within the stubble background with snow retention, +28.6-31.3% in height, and +31.2-33.4% in moisture reserves. In the case of the wings, with a maximum snow layer height of 30.3 cm, the increase was 32%, while the moisture reserves increased by 30.3%.

The effectiveness of snow retention according to the results of snow accumulation assessment is expressed by an excess of moisture content by 16.5-25.2% on stubble backgrounds, by 32.6% on early winter crops, and by 39.1-45.8% on fallow plots, compared to plots without snow retention. This proves the extreme need for snow "reclamation", regardless of the year, accumulating almost all the transported snow. Long-term research by the North Kazakhstan Agricultural Experimental Station in this area shows that in the open steppe, on untouched backgrounds, no more than 50-60% of the total snowfall is retained by grain stubble and 30-40% by corn residues. In terms of moisture content, the black fallow exceeds the black fallow without snow retention by 56.5%, and the fallow with snow retention by 19.7-28.6%, which, based on 3 years of data, makes this type of fallow highly efficient in accumulating solid precipitation, both in winters with little snow (season 2022) and winters with medium and high precipitation (seasons 2023, 2024).

The results of the three-year monitoring of snow accumulation dynamics showed that the use of snow retention technologies provides a significant increase in soil moisture reserves by the time of spring thaw. The highest level of solid precipitation accumulation was recorded on the background of the winged plough, where the snow cover reached 30.3 cm and moisture reserves were 85.7 mm, which was 56.5% higher than on the flat-cutting plough without snow retention. These data emphasise the critical role of effective snow accumulation for water resources formation, which correlates with the conclusions of D. Molden *et al.* (2022), emphasising the importance of snowfall as the main source of water supply for water systems in Asian steppes and mountainous regions. Similarly, the study by G. Mezősi (2022) noted that disruptions in snow cover structure due to climate change significantly increase the risk of water shortages during spring vegetation growth, which is consistent with the trend identified in this study of the need for targeted management of winter precipitation.

Comparative assessment of agrotechnical backgrounds showed that systematic snow retention increases the efficiency of moisture accumulation not only on fallow plots, but also on stubble backgrounds. The water reserves in the snow cover on variants with snow retention exceeded the control values by 16.5-45.8%, depending on the agro-background and winter conditions. These results correlate with the findings of A. Canet-Martí *et al.* (2023) determined that minimum tillage methods and the preservation of crop residues contribute to improving the water balance in agroecosystems by increasing the water-holding capacity of the field. Similar trends were also identified by R. Amami *et al.* (2021), where the effectiveness of soil surface management techniques was directly correlated with an increase in water permeability and moisture accumulation in the profile, which confirms the validity of using snow retention as an element of adaptive farming technology in Northern Kazakhstan.

Additionally, the tendency for earlier snowmelt in areas without snow retention identified in the study correlates with the Q data. According to Q. Fu *et al.* (2015), the thermal interaction of snow and soil in conditions of insufficient snow accumulation leads to accelerated evaporation processes and reduced soil moisture recharge in the transitional winter-spring period. This further emphasises the importance of not only accumulating but also retaining snowfall to maintain the stability of the water regime of agricultural land in a changing climate. Thus, according to the results of the summary assessment of snow accumulation over the 3-year observation period, the highest amount of precipitation during the winter period, as well as its uniform accumulation, was noted for wing steam 85.7 mm, with a snow depth of 30.3 cm, wheat stubble over peas 76.2 mm, with a height of 25.8 cm, and pea stubble over wheat 73.5 mm, with a height of 23.1 cm (Fig. 1).

The minimum effect of snow accumulation was recorded on the pair of flat-cutting and fallow backgrounds without snow retention, where moisture reserves amounted to 37.3-46.4 mm (snow depth 9.5-14.3 cm), with most of the accumulated precipitation formed in early winter, by the time of the first accounting, up to 86-90%, and further had a weak accumulative effect by the end of the winter period. The monitoring results showed that the use of snow retention technologies provides a significant increase in soil moisture reserves regardless of variations in winter conditions. The highest efficiency in accumulating solid precipitation was demonstrated by the wing steam and stubble backgrounds with snow retention, which is confirmed by both quantitative indicators of snow cover and water equivalent and their stable dynamics during the winter period. The identified patterns emphasise the need for widespread implementation of snow retention measures to stabilise the water balance of arable land in the face of climate instability and the growing risk of spring moisture deficit.

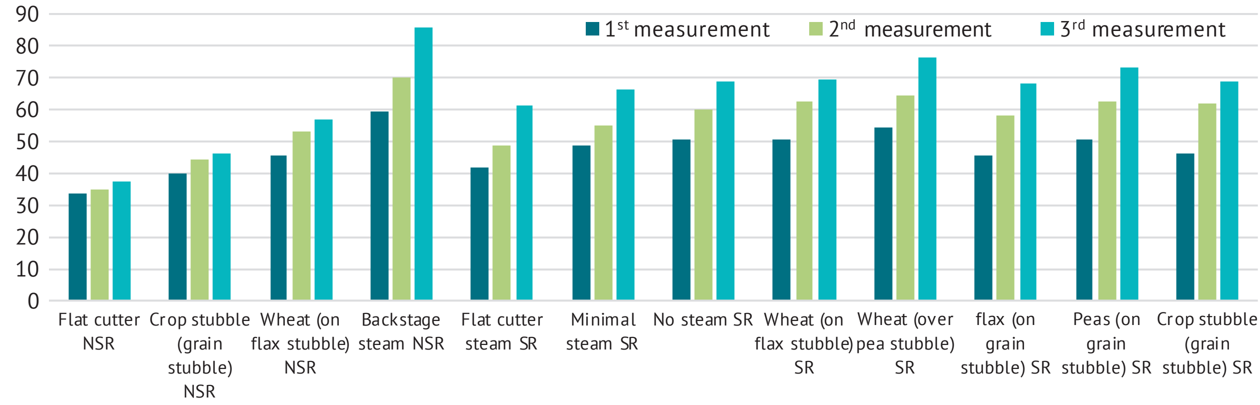

***Figure 1**. Dynamics of accumulation of moisture reserves in snow on different agrotechnical backgrounds based on the results of 3 measurements*

***Note:** NSR – no snow retention; SR – snow retention*

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

Impact of winter precipitation on soil moisture reserves. The main reasons for the difference in rainfall absorption, both by year and by crop rotation predecessors, are significant differences in the initial soil moisture reserves and the amount of precipitation during the period under consideration. The moisture content of the soil has a significant impact on the absorption of precipitation by the soil. In most cases, fields with lower moisture reserves in autumn experience more intensive moisture absorption and accumulation during snowmelt. In October-April, the average absorption of precipitation by the one-metre layer of soil for different predecessors in crop rotations ranged from 43.6 to 53.5%. According to the results of observations, the content of pre-winter moisture reserves in the soil was high and ranged from 74.2 mm (flax stubble) to 148.7 mm (zero fallow). At the same time, the maximum moisture content was recorded in the fallow plots at 117.2-148.7 mm, exceeding the stubble background by 36.7-41.4% (Table 3).

***Table 3**. Soil moisture balance by the sowing period, incorporating pre-winter moisture and moisture reserves in snow, average 2022-2024*

No.	Agricultural context	Snow retention	Pre-winter soil moisture reserves, mm	Moisture reserves in snow (by the time of melting), mm	+/- to control conditions, %	Moisture reserves in the soil before sowing, mm	Utilisation of winter precipitation, %
1	Flat cutter steam (control)	-	134.1	37.3	-	103.4	0
2	Wheat stubble (control)	-	79.7	57	-	88.7	10.2
3	Crop stubble (grain stubble) (control)	-	86	46.4	-	72.9	0
4	Backstage steam	-	117.2	85.7	+130	145.2	19.3
5	Flat cutter steam	+	134.1	61.2	+64	141.9	5.5
6	Minimal steam	+	141.1	66.1	+77	148.3	5
7	No steam	+	148.7	68.8	+84	151.3	2
8	Peas (on grain stubble)	+	87.2	73.5	+28	113.7	23.3
9	Wheat (over pea stubble)	+	79.7	76.2	+34	127.5	37.5
10	Wheat (on flax stubble)	+	83.2	69.5	+18	106.4	21.8
11	flax (on grain stubble)	+	74.2	68.3	+20	109.6	32.3
12	Crop stubble (grain stubble)	+	86	68.8	+48	106.3	19.1
	$LSD_{0.95}$			3.28			

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

In addition, to assess the soil moisture balance, the table shows data on the moisture reserves in snow at the time of melting (actual accumulated precipitation in snow over the winter period). Thus, on average, the variants of snow accumulation technology accumulated 20-130% more moisture on different backgrounds compared to the control variants. For steam backgrounds, the maximum effect was noted for the backstage steam +130% compared to the control (flat-cutting steam without snow retention), and for the zero steam +84% compared to the control (flat-cutting steam without snow retention). For stubble backgrounds, the difference is much lower, given the relatively high moisture reserves in the wheat stubble control without snow retention. At the same time, the maximum effect of snow retention was observed for stubble of wheat after peas +34%, and stubble of peas after grain +28% compared to the control. The effectiveness of snow retention on the background of early winter stubble was expressed by an increase in snow moisture of +48% compared to the control (winter stubble without snow retention).

The use of snow accumulation measures, such as snow retention, leaving high stubble, sowing wings, etc., achieved a snow layer thickness of up to 35-40 cm. As a result of better snow accumulation, soil moisture reserves increase by 30-50 mm by the beginning of sowing, and spring wheat yields increase by 1.9-2.2 c/ha. Thus, according to this study, the moisture reserves before sowing were in the range of 103.4-151.3 mm on fallow plots, with the excess of fallow plots with snow retention (flat-cut, minimal, zero) being 38.5-47.9 mm (+27.1-31.6%), and the excess of wing fallow by 41.8 mm (+28.8%) compared to the control (flat-cut fallow without snow retention). On stubble backgrounds, the increase in moisture reserves for sowing is much lower, with an indicator of 88.7 mm on the control (wheat stubble without snow retention), 17.7-38.8 mm (16-30%) on grain stubble with snow retention, and 20.9-25 mm (19-22%) on oilseeds and legumes. In the context of early winter with snow retention, the increase was 33.4 mm, or 31%, compared to the control (winter without snow retention).

Incorporating the content of pre-winter moisture reserves in the soil, as well as the actual moisture content in the soil by the time of sowing, it is possible to calculate the proportion of winter precipitation absorption, depending on the agrotechnical background. According to the results obtained, a zero or even negative balance was observed on the backgrounds of stubble-free flat-cut, winter tillage pairs without snow retention. At the same time, the stubble background without snow retention has a certain increase, within 10.2%, provided by the accumulation of snow to the height of the stubble left in autumn. The minimum effect was observed in the follow-up plots, with snow retention not exceeding 2-5.5%, mainly due to high pre-winter moisture. The exception is the wing follow, with a level of winter precipitation absorption of 19.3%, obtained due to higher moisture reserves in snow and lower pre-winter moisture. Thus, according to the results of average annual observations, this type of steam provides equal moisture reserves for the sowing period, with zero and minimal steam having a stubble background during the entire period of moisture accumulation, and additional snow retention in winter. The maximum efficiency of winter precipitation assimilation was observed on stubble backgrounds with snow retention, for stubble of cereals 21.8-37.5%, legumes and oilseeds 23.3-32.3%, and early winter crops 19.1%, which indicates the urgent need for annual snow accumulation measures on these backgrounds.

Determination of correlations between pre-winter soil moisture reserves, snow moisture reserves at the time of melting and winter precipitation assimilation established distinct patterns of water regime. The high direct correlation coefficient between the moisture reserves in snow and the level of precipitation absorption ($r = 0.67$) indicates the leading role of winter precipitation in replenishing productive moisture, with insufficient autumn moisture. At the same time, an inverse relationship was found between the initial soil moisture in autumn and the absorption of snow water ($r = -0.65$), which reflects a decrease in the water absorption capacity of waterlogged soils. These results are consistent with the hydrophysical features of the soil profile structure, where saturation of the upper horizons limits further moisture penetration during snowmelt. Assessment of the degree of influence of both factors on the final water balance by the sowing period showed the presence of significant correlations of medium and high strength ($r = 0.57$ - 0.66), which emphasises the complex nature of moisture accumulation processes. Thus, improving snow retention efficiency is only possible with an integrated approach that takes into account the initial level of pre-winter soil moisture. In the steppe zone of Northern Kazakhstan, optimisation of agrotechnical measures to regulate the water regime, including both snow accumulation and control of autumn moisture reserves, is a necessary condition for stabilising crop productivity in the context of changing climatic conditions.

The analysis of the data obtained showed that the effect of winter precipitation on the water regime of arable land varied significantly depending on the agronomic background and pre-winter moisture reserves. According to the observations, on backgrounds with high pre-winter moisture (vapour), the absorption of winter precipitation was minimal (2-5.5%), while on stubble plots with snow retention, the absorption efficiency reached 21.8-37.5%. These results correlate with the findings of W. Yan *et al.* (2021), determining that under conditions of different soil cover and crop residue structure, the soil response to winter precipitation varies significantly, with surfaces with crop residues providing more efficient moisture accumulation. The role of pre-winter moisture reserves in determining the efficiency of precipitation absorption was indicated by the study by J. Martínez-Fernández *et al.* (2021), which emphasises the effect of soil "memory": the higher the moisture content before the start of winter, the lower the subsequent absorption of precipitation. This pattern was reflected in the present study, which found an inverse correlation between the level of autumn moisture and winter moisture uptake ($r = -0.65$), which is consistent with the concept of reducing the water absorption potential of waterlogged horizons. The role of winter precipitation accumulation in the water balance is confirmed by F. Avanzi *et al.* (2021), demonstrating that an accurate assessment of the winter precipitation regime (especially snow characteristics) is critical for predicting water storage. The present study revealed a similar trend: fields with effective snow retention accumulated up to 130% more moisture in the snow cover compared to control plots.

The results of the comparative analysis of agronomic practices showed that the wagon steam and stubble backgrounds with snow retention provided the highest moisture reserves by the sowing period. These results correlate with the data of A. Rucins *et al.* (2024), where long-term studies on chornozems confirmed the effectiveness of mulching and minimal tillage in stabilising spring moisture reserves. A significant increase in moisture by 30-50 mm, provided by snow retention measures, is critically important for agroecosystems in arid regions. A comprehensive analysis of the dynamics of snow accumulation and moisture uptake presented by B. Dafflon *et al.* (2023) confirmed that the structure of the vegetation cover determines both the rate of snowmelt and the amount of available soil moisture in spring. Incorporating the identified patterns, optimisation of agrotechnical measures to manage winter precipitation, including the introduction of snow retention and preservation of plant residues, is considered a priority area for adaptation of agriculture to climate risks, which correlates with the findings of A. Demo and G. Asefa Bogale (2024) on the need to integrate water-saving technologies.

The analysis of the impact of agronomic measures on the dynamics of winter precipitation and soil moisture reserves showed the high efficiency of snow retention technologies on different backgrounds. The use of mechanised snow retention on fallow and stubble plots provided a significant increase in spring moisture reserves, which confirms the critical role of snow management in stabilising the soil water regime. The established correlation between the structure of plant residues and the efficiency of precipitation absorption underlines the need to integrate snow cover preservation technologies into adaptive farming practices. The results demonstrate that optimisation of winter water management methods is one of the keyways to increase the resilience of agroecosystems in the context of increasing climate risks. The data presented form the basis for further improvement of agrotechnical solutions aimed at stabilising the water balance of arable land in the steppe regions.

Influence of water regime on spring wheat productivity. The determining effect of moisture accumulation in winter is its impact on the final productivity of crops. According to the research results, the yield of spring wheat on backgrounds without snow accumulation was in the range of 1.74-2.29 t/ha, while snow accumulation measures increased productivity to 1.95-2.76 t/ha, with an increase of 0.15-0.47 t/ha on backgrounds (or +11-17%). The maximum yield increase was obtained in the fallow plots, within the range of 0.28 (zero fallow) to 0.47 t/ha (backstage fallow), as well as in the autumn tillage +0.38 t/ha (Table 4).

***Table 4**. Influence of water regime on spring wheat productivity depending on agronomic backgrounds, average for 2022-2024*

No.	Agricultural context	Snow retention	Moisture reserves in the soil before sowing, mm	Moisture reserves before cleaning, mm	Moisture consumption during the growing season, mm*	Spring wheat yield, t/ha	Increase in control, t/ha
1	Flat cutter steam (control)	-	103.4	55	256.4	2.29	-
2	Autumn tillage (control)	-	72.9	47.5	233.4	1.74	-
3	Backstage steam	-	145.2	61.8	291.4	2.76	0.47
4	Flat cutter steam	+	141.9	56.2	293.7	2.62	0.33
5	Minimal steam	+	148.3	67.5	288.8	2.68	0.39
6	No steam	+	151.3	71.6	287.7	2.57	0.28
7	Autumn tillage	+	106.3	53.6	260.7	2.12	0.38

Note: *moisture consumption during the growing season is calculated covering the total precipitation in May-August (average 208 mm in 2022-2024)*

Source: *compiled by the authors*

The average yield increase was significantly influenced by high precipitation during the growing season of 2022-2024, and it is logical to assume that with a decrease in the supply of precipitation during the growing season, the effectiveness of snow storage measures will increase by a multiple. The average moisture consumption during the growing season required for the formation of spring wheat yields was in the range of 233.4-293.7 mm. According to studies of winter precipitation conservation on the Great Plains, economically viable spring wheat production required an annual withdrawal of about 250-400 mm of water from the soil. At the same time, high moisture consumption rates were observed on steamy plots of 287.7-293.7 mm, which naturally affects the maximum yield in these areas. The increase in moisture consumption on the backgrounds with snow retention is in the range of 31.3-37.3 mm (+12.2-14.5%) on fallow plots, by 17.5-33.1 mm (+7.2-13.6%) on stubble plots, compared to plots without snow accumulation measures.

Assessment of the influence of the factors of the amount of moisture in the snow during the winter period and moisture consumption during the growing season on the final yield of spring wheat shows that the total moisture consumption during the growing season directly affects the formation of yield, while the amount of water in the snow correlates with the yield to a lesser extent, especially for stubble backgrounds (variants 8-12), where high water content in the snow has little effect on increasing productivity (Fig. 2).

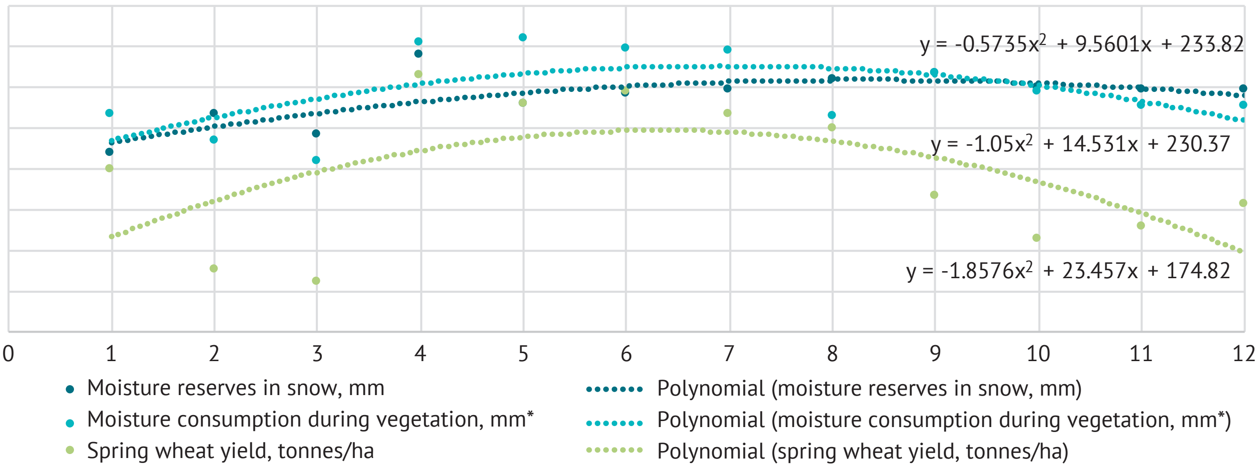

***Figure 2**. Relationship of spring wheat yield with the amount of moisture in snow and total moisture consumption during the growing season*
***Source:** compiled by the authors*

The correlation assessment of the data also confirms the obtained dynamics. Thus, the closeness of the correlation between the total moisture consumption during the growing season and productivity is 0.83, which, according to the Chaddock scale, corresponds to a high level of dependence, while the closeness of the relationship between the amount of water in the snow and productivity is 0.42, which corresponds to a moderate level of dependence. The assessment of the impact of water regime on spring wheat yield is consistent with the results of other studies. Thus, according to L. Kiewiet *et al.* (2022), the spatial and temporal variability of moisture supply has a decisive impact on the efficiency of water balance formation and the productivity of agricultural landscapes in the transitional rain-snow zone, which confirms the need to optimise agronomic measures for the accumulation of winter precipitation. The study by M. Khan *et al.* (2020) determined that agrometeorological drought events, assessed through standardised soil moisture and precipitation indices, significantly affect grain yields, especially when effective moisture reserves decrease during critical phases of the growing season, which is fully consistent with the observed decrease in productivity in variants with low snow retention.

Additionally, as shown by K. Gavahi *et al.* (2020), effective moisture management in agricultural systems requires integrated monitoring of soil moisture and transpiration flows, as underestimation of latent moisture losses can lead to underestimation of yield-limiting factors. This concept is in line with the high dependence of productivity on total moisture consumption during the growing season ($r = 0.83$), in contrast to the moderate influence of winter precipitation. In turn, according to R.P. Allan *et al.* (2020), changes in the global water cycle, including the redistribution of precipitation and increased aridity in some regions, require the adaptation of agricultural technologies to new water supply conditions, which emphasises the relevance of snow retention to stabilise production performance in the steppe zone of Northern Kazakhstan. The study confirmed that an increase in pre-season moisture reserves due to snow retention provides a significant increase in spring wheat yields in the steppe zone of Northern

Kazakhstan. The highest productivity was achieved on fallow plots with an optimised water regime. The high correlation between total moisture consumption and yield underlines the need for integrated water management in the face of climate instability. The results obtained substantiate the prospects of using snow retention and water conservation technologies for sustainable agriculture.

CONCLUSIONS

The study comprehensively assessed the impact of winter precipitation and snow retention measures on the formation of the water regime and spring wheat productivity in the steppe zone of Northern Kazakhstan. It was found that in the conditions of high interannual variability of winter precipitation (from -25.2 mm to +82.9 mm from the norm) and an increase in the average winter temperature by +1.6°C, the effectiveness of water regime regulation is critical for the stability of agriculture. The use of snow retention provided an increase in snow cover height by 26.6-32% and an increase in precipitation water equivalent by 26-33.4% compared to the control variants. The maximum moisture reserves in the snow cover were achieved on the background of wedge steam (85.7 mm), which is 56.5% higher than the steam flat-cutting background without snow retention. This indicates the high efficiency of structured surfaces in the accumulation of solid precipitation.

The soil moisture balance showed that the use of snow retention technologies increased moisture reserves by the time of sowing by 27.1-31.6% on fallow plots and by 16-30% on stubble plots. The most efficient absorption of winter precipitation was recorded on stubble plots, ranging from 21.8 to 37.5%. The correlation analysis revealed a high positive correlation between the moisture reserves in snow and the level of its absorption by the soil ($r = 0.67$) and an inverse relationship between the autumn level of soil moisture and the absorption of precipitation ($r = -0.65$). This emphasises the need to account for the initial soil moisture conditions to optimise water-saving measures.

Assessment of the influence of water regime on productivity showed that snow retention provided an increase in spring wheat yield by 0.15-0.47 t/ha, which corresponded to an increase of 11-17% depending on the agrotechnical background. The maximum yield (2.76 t/ha) was obtained on the wraparound fallow. The correlation between the total moisture consumption during the growing season and the yield was 0.83, indicating the crucial role of the total water balance in the formation of productivity. The influence of the amount of moisture accumulated in winter on yield was moderate ($r = 0.42$), especially on stubble plots, which confirms the importance of integrated water management throughout the growing season. The results reflect the peculiarities of soil and climatic conditions in the steppe zone of Northern Kazakhstan, which limits the possibility of their direct transfer to other agricultural landscapes with different natural characteristics. It is advisable to expand the research to include different climatic regions and soil types, as well as to address the projected changes in hydrothermal conditions in the context of global climate change.

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CONFLICT OF INTEREST

None.

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Ефективність заходів щодо накопичення опадів зимового періоду в кліматичних умовах Північно-Казахстанської області

Жанна Лутченко
Завідувач лабораторії селекції зернових культур
Північно-Казахстанська сільськогосподарська дослідна станція
150311, вул. Центральна, 19, с. Шагалали, Республіка Казахстан
https://orcid.org/0000-0002-0431-5398

Олег Соловйов
Завідувач лабораторії землеробства
Північно-Казахстанська сільськогосподарська дослідна станція
150311, вул. Центральна, 19, с. Шагалали, Республіка Казахстан
https://orcid.org/0000-0002-7341-5851

Віталій Заїка
Магістр, керівник організації
Північно-Казахстанська сільськогосподарська дослідна станція
150311, вул. Центральна, 19, с. Шагалали, Республіка Казахстан
https://orcid.org/0000-0002-2023-3755

Володимир Швидченко
Кандидат сільськогосподарських наук, науковий співробітник
Північно-Казахстанська сільськогосподарська дослідна станція
150311, вул. Центральна, 19, с. Шагалали, Республіка Казахстан
https://orcid.org/0000-0001-7426-9115

Анжеліка Артис
Магістр, науковий співробітник
Північно-Казахстанська сільськогосподарська дослідна станція
150311, вул. Центральна, 19, с. Шагалали, Республіка Казахстан
https://orcid.org/0000-0002-1945-0787

Анотація. Мета даного дослідження полягала у встановленні закономірностей формування водних ресурсів ґрунту за рахунок зимових опадів за використання різних агротехнічних прийомів в умовах степової зони. Методологія дослідження включала польові випробування різних агротехнічних фонів зі снігозатриманням і без нього з подальшим аналізом накопичення зимових опадів, зміни водного режиму ґрунту та продуктивність ярої пшениці. Середня висота снігового покриву на варіантах із застосуванням снігозатримання збільшувалася на 26,6-32 % порівняно з контролем без снігозатримання. Запаси вологи в ґрунті перед сівбою зростали на 27,1-31,6 % на парових фонах і на 16-30 % на стерньових ділянках. Засвоєння зимових опадів найефективніше відбувалося на стерньових фонах, де приріст вологи становив від 21,8 до 37,5 % відносно вихідних значень. Урожайність ярої пшениці на ділянках зі снігозатриманням перевищувала контрольні показники на 0,15-0,47 т/га, досягаючи максимальних значень до 2,76 т/га на кулісних парах. Коефіцієнт кореляції між загальним водоспоживанням за вегетаційний період і врожайністю становив 0,83, що свідчить про високий вплив водного режиму на продуктивність. Встановлена залежність між об'ємом вологи в снігу та врожайністю виявилася помірною, з коефіцієнтом 0,42, особливо на стерньових ділянках. Отримані результати підтверджують високу ефективність застосування технологій снігозатримання для підвищення водозабезпеченості посівів і стійкості врожайності в степових умовах Північного Казахстану. Їх використання рекомендується для оптимізації системи агротехнічних заходів в умовах посилення кліматичної нестабільності, що посилюється

Ключові слова: снігонакопичення; вологість ґрунту; снігозатримання; кулісний пар; зяблевий обробіток; урожайність

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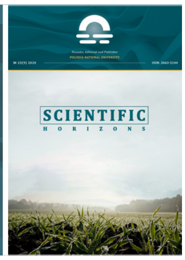

Radioecological state of the environment in the area of the former Semipalatinsk Nuclear Test Site

Ainur Serikova
PhD in Veterinary Sciences, Associate Professor
Shakarim University
071412, 20A Glinka Str., Semey, Republic of Kazakhstan
https://orcid.org/0000-0002-8707-5878

Sergazy Dyussembayev*
Doctor of Veterinary Sciences, Professor
Shakarim University
071412, 20A Glinka Str., Semey, Republic of Kazakhstan
https://orcid.org/0000-0001-6259-2871

Shyngys Suleimenov
Doctor of Philosophy, Professor
Shakarim University
071412, 20A Glinka Str., Semey, Republic of Kazakhstan
https://orcid.org/0000-0002-6164-9407

Zhaxylyk Serikov
Master of Science, Researcher
Shakarim University
071412, 20A Glinka Str., Semey, Republic of Kazakhstan
https://orcid.org/0000-0002-6895-8392

Shynar Abdykarimova
Doctoral Student
Shakarim University
071412, 20A Glinka Str., Semey, Republic of Kazakhstan
https://orcid.org/0009-0003-2893-2053

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Abstract. Radioactive contamination of the environment in the former Semipalatinsk nuclear test site (Kazakhstan) is caused by the deposition and long-term retention of long-lived radionuclides in soil, water and vegetation, which poses potential risks to ecosystems and public health. The study aimed to assess the levels of contamination of soil, water and vegetation with americium-241, cesium-137 and plutonium-239/240 radionuclides in areas of different radiation risk in the former Semipalatinsk nuclear

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**Corresponding author*

test site. Radiation and environmental monitoring were conducted at 12 control points using spectrometric analysis to determine the specific activity of the specified radionuclides in environmental samples. The study revealed pronounced differences in the content of radionuclides in soil, water and vegetation in areas with different levels of radiation risk. The maximum concentrations of americium-241 (0.55 ± 0.03 Bq/kg), cesium-137 (1.83 ± 0.15 Bq/kg) and plutonium-239/240 (0.012 ± 0.0015 Bq/kg) were recorded in the extreme radiation risk zone, while in the least contaminated areas, their levels were 4-7 times lower. In water bodies, the highest activity was recorded for cesium-137, with a concentration of 5.22 ± 0.2 Bq/l, which significantly exceeds the permissible limits. Significant accumulation of all three radionuclides was detected in the vegetation: Am-241 to 1.6 ± 0.3 Bq/kg, Cs-137 to 2.2 ± 0.1 Bq/kg, Pu-239/240 to 0.9 ± 0.1 Bq/kg. The highest levels were recorded in areas of extreme and maximum risk, mainly in pasture cereals. The analysis of the vertical distribution of radionuclides showed their differentiation by depth: Cs-137 and Am-241 were concentrated in the upper soil layer (0-10 cm), while Pu-239/240 partially migrated to 15-20 cm, which confirmed the risk of their inclusion in the trophic chains and the need for further monitoring. The data obtained can be used to plan measures for the environmental remediation of contaminated areas, regulate the agricultural use of pastures and ensure the radiation safety of the population

Keywords: radiation contamination; americium-241; cesium-137; plutonium-239/240; soil; water; vegetation

INTRODUCTION

Radioactive contamination of the environment in the former Semipalatinsk nuclear test site is a long-term environmental problem associated with a high level of accumulation of artificial radionuclides in soil, water bodies and vegetation. As a result of more than 450 nuclear tests conducted between 1949 and 1989, the site released long-lived radionuclides such as cesium-137, strontium-90, and plutonium-239 into the environment (Akhmetova *et al.*, 2024). These substances persist in ecosystems for decades, exerting radiotoxic effects and participating in migration processes in natural environments. The ability of radionuclides to penetrate ground and surface waters, accumulate in plant tissues and enter the food chain is of particular danger, as when they enter the human or animal body with drinking water or food, they are absorbed through the gastrointestinal tract, accumulate in tissues (especially in bone, muscle and parenchymal organs) and have chronic radiotoxic effects at the cellular and genetic levels, which may pose a threat to the biota and health of the population of nearby regions (Ongayev *et al.*, 2024).

Research in the field of radiation ecology, supported by international organisations, has contributed to the creation of radioactive contamination monitoring systems in the affected regions. The International Atomic Energy Agency (2014) and the European Commission (n.d.) have repeatedly initiated projects to assess the consequences of nuclear tests and develop methods for decontamination of contaminated areas. The contribution of the United Nations (2015) and World Health Organization (n.d.) programmes was to conduct epidemiological studies aimed at investigating the impact of radiation on public health. The analysis of the radioecological situation in the Semipalatinsk nuclear test site area covers a wide range of studies aimed at investigating the consequences of nuclear tests and their impact on the environment and public health. The impact of nuclear tests on the ecosystem of the region is manifested in the significant accumulation of radionuclides in soil and water, which was revealed by R. Akhmetova *et al.* (2024) in the absence of data on the transformation of radionuclides in food chains and mechanisms of their biological absorption. Historical changes in the radioecological situation, including the dynamics of radionuclide migration and distribution in natural environments, are considered in A. Mamyrbekov *et al.* (2024) without a comprehensive assessment of the current radiation background and interaction with agricultural ecosystems.

A generalised analysis of radioactive contamination management methods in different natural environments was presented in a review by A. Adeola *et al.* (2023). The review did not highlight the need for technological optimisation of monitoring and remediation. At the same time, they did not study the regional specifics of post-nuclear territories and did not consider the behaviour of americium-241, cesium-137 and plutonium-239/240 in agricultural landscapes with localised sources of contamination. D. Tchorz-Trzeciakiewicz *et al.* (2023) described seasonal fluctuations in the natural radiation background and concentrations of natural radionuclides in different ecosystems. However, the study did not compare the results of the study with man-made contamination sites and did not consider scenarios of interaction between natural and artificial radionuclides typical of nuclear test areas.

The impact of radioactive contamination on the health of the population living near the landfill is correlated with the nature of migration and accumulation of radionuclides in the natural environment (Işık *et al.*, 2024). S. Abd El-Azeem and H. Mansour (2021) analysed the content of natural radionuclides in soil samples with a focus on mineral composition and geochemical characteristics. However, the study does not cover anthropogenic radionuclides such as Cs-137 and Pu-239/240 and does not consider their environmental behaviour under conditions of nuclear contamination, which limits the applicability of the results in the context of assessing the radioecological state of former landfills. A. Panitskiy *et al.* (2022) highlighted the vertical distribution of radionuclides in the soil of the Semipalatinsk test site and provided relevant quantitative data. However, the authors do not consider the bioavailability of radionuclides, incorporation into food chains and transfer to aquatic and vegetation components of ecosystems. Furthermore, S.Zh. Sapanov *et al.* (2021) described soil contamination with radionuclides and heavy metals, but there is no analysis of the impact of this contamination on crops and livestock products, which limits the ecological and agricultural interpretation of the results.

The accumulation of radionuclides in vegetation was confirmed by N. Larionova *et al.* (2024), recording high concentrations of tritium in the landfill ecosystems, while other radionuclides with high radiotoxicity, such as Cs-137 and Pu-239/240, were not addressed, which reduced the accuracy of the environmental assessment. Similar results were reported by Y. Polivkina *et al.* (2024), describing the uptake of tritium by crops against the background of atmospheric pollution, although aspects of food safety and the physiological state of plants under chronic radiation exposure were not considered. The results of a study by D. Feng *et al.* (2022) on a comparison of the distribution of plutonium isotopes in soils from the Semipalatinsk test site and the Chinese Lob Nor site characterised migration processes in a geochemical context, but the biological behaviour of isotopes and their participation in trophic relationships remained outside the scope of the analysis.

Despite a considerable amount of research, several aspects of the radioecological state of the Semipalatinsk nuclear test site remain insufficiently studied. A detailed analysis of radionuclide migration in soil and water systems, their accumulation in vegetation and their impact on crops, as well as an assessment of the impact of contamination on the hydrological regime and bioremediation potential, is required. The study aimed to assess the radioecological state of the environment in the former Semipalatinsk nuclear test site with a focus on the contamination of soil, water sources and vegetation.

MATERIALS AND METHODS

The study was conducted in the laboratory of the Veterinary Department and the Agrotechnopark of Shakarim University (Kazakhstan) in July 2024, which addressed the seasonal features of radionuclide migration and accumulation in natural environments. To assess the radioecological situation, the territories adjacent to the Semipalatinsk nuclear test site were selected incorporating differences in radiation risk levels. The selection criteria were based on radiation mapping data for the region, the spatial distribution of gamma background, and historical information on nuclear test zones. The selection of sites was based on radiation risk levels, natural and landscape conditions, population density and logistical accessibility of the facilities. In the Abai district, where the radiation risk was suspected to be high, samples were taken in the settlements of Yer Zhanybek, Kulzhan ata and Baishuak. In Zhanasemey district, the areas around Kainar, Abyraly and Akbulak were surveyed, with the highest level of risk. For Ayagoz district, which is a high-risk area, the villages of Rustem, Bayan and Zhanat were selected. In Urdzhar district, where radiation exposure is minimal, the villages of Akan, Adilet and Maksat were selected. A total of twelve stationary control points were operated within the study, three in each district. At these points, soil, water and vegetation samples were collected, followed by spectrometric analysis to assess the levels of radionuclide contamination.

The analysis was conducted to determine the spatial distribution of radionuclides and their migration in various natural environments. Particular attention was paid to the study of the content of americium-241 (Am-241), cesium-137 (Cs-137) and plutonium-239/240 (Pu-239/240) in the samples, which ensured an objective assessment of the radioecological state of the region. The results obtained were compared with the permissible values established following the recommendations of the International Atomic Energy Agency (2014), which are used in radiation practice in the Republic of Kazakhstan as a member state of the Convention on Nuclear Safety and the Basic Safety Standards. Maximum permissible levels of specific activity in soil are: 0.3 Bq/kg for Am-241, 0.6 Bq/kg for Cs-137 and 0.02 Bq/kg for Pu-239/240. In the water environment, the maximum permissible concentrations are 0.2, 2 and 0.005 Bq/l, respectively. For plant samples, the indicative standards are up to 1 Bq/kg for Am-241, up to 0.6 Bq/kg for Cs-137 and up to 0.1 Bq/kg for Pu-239/240. These values were used as thresholds for interpretation of the results and classification of the surveyed areas by radiation risk levels. To increase the reliability of measurements, each pooled sample was analysed in triplicate. Since the original repeat measurement protocols were not available, the standard deviation (SD) values were estimated a priori based on the acceptable range of variability of the atomic emission spectrometry method, incorporating the sensitivity of the instrument at low concentrations. Estimated SDs were used in the tables as approximate indicators of data scatter.

Soil sampling was conducted based on the "envelope" methodology, which involves combining samples from five points in each study area into one mixed sample. The soil layer was sampled from a depth of 0-10 cm from the surface, which corresponds to the upper horizon most susceptible to the accumulation of radionuclides such as Cs-137 and Am-241. To assess the migration behaviour of plutonium, additional samples were taken from a depth of 10-20 cm, which identified a tendency of Pu-239/240 to be distributed at a deeper level. The weight of one combined sample was about 1 kg. The preparation of soil samples included transferring samples to plastic trays, removing impurities, grinding to 1-2 mm particles in a porcelain mortar and bringing them to an air-dry state. The samples were then dried in an oven at 105°C for 3 hours and sieved through a 1-2 mm mesh sieve. Decomposition of the samples was carried out by adding 20 ml of 3% nitric acid solution and stirring on a LIOP LS120 shaker (Russia) for 60 minutes. The resulting filtrate was diluted 50 times with distilled water and analysed by atomic emission spectrometry using an EXPEC 6500 spectrometer (China) (International Atomic Energy Agency, 2010). The concentration of the element was calculated by the formula (1):

$$C = \frac{a \times 50}{2 \times 1{,}000}, \quad (1)$$

where C – concentration of the element, mg/g; a – value of the element concentration displayed by the device, mg/l; 50 – volume of the extract, ml; 2 – mass of the sample, g; 1,000 – conversion factor for converting mass from millilitres to litres.

Water samples were collected from open water bodies, wells and springs using plastic containers to prevent secondary contamination. The samples were taken from the surface water layer (1-10 cm) in a volume of 1,000 ml, with all data recorded in a field passport. Before analysis, the samples were filtered through a paper filter and then diluted 50 times with distilled water. To avoid contamination of the samples, glass and polyethene containers were prepared and washed with Komarovsky's mixture and deionised water acidified with extra pure nitric acid ("ос. ч"). After preparation, the samples were analysed by atomic emission and mass spectrometry EXPEC 6500. The concentration of the element in the water sample was calculated using formula (2):

$$C = \frac{a \times 50}{1 \times 1{,}000}, \quad (2)$$

where 1 – mass of the attachment.

Vegetation and forage samples were collected in triplicate on 1×1 m plots. All vegetation was cut off with scissors within the plot boundaries, with the bottom cut left at least 3 cm from the soil surface. In the pastures, the mowing method was used to simulate grass eating by cattle, cutting short grasses at a height of 10-15 cm and tall grasses at 20-25 cm. Samples weighing 1.5-2 kg were packed in thick paper, plastic bags or paper bags. Before analysis, the samples were dried at 60-65°C in an oven, chopped with scissors (5-8 mm sections) and additionally ground in an electric grinder (2-5 minutes). A 2 g sample was isolated in a muffle furnace at 650°C for 3 hours, then the ash residue was decomposed with 2 ml of concentrated extra pure nitric acid, diluted 50 times with distilled water, and analysed using an EXPEC 6500 spectrometer. The element concentration was determined using formula (1).

The gamma radiation dose rate, as well as beta and alpha particle flux density, were determined following the Order of the Minister of Finance of the Republic of Kazakhstan No. 121 (2018) and Order of the Minister of Health of the Republic of Kazakhstan No. KR DSM-71 (2022). Measurements of gamma radiation exposure dose rate (EDR) were conducted in an open area at a height of 1 m from the soil surface using an RKS-01-SOLO radiometer (Russia), which ensured an objective assessment of the external radiation background of the studied areas. The flux density of alpha and beta particles was determined by the contact method on the soil surface using the Manufacturer: ATOMTEX, with a probe area of 1 cm^2, which provided a reliable assessment of the degree of soil contamination. To measure the volumetric activity of radon and thoron, a radon monitor Manufacturer: SOLO LLP (Republic of Kazakhstan)was used, which is used for sanitary and hygienic surveys of premises and territories.

To analyse the differences between groups of samples taken in areas with different levels of radiation risk, the methods of analysis of variance for multiple comparisons and Student's t-test for pairwise comparisons were used. In cases of non-normality of the data distribution, the non-parametric Mann-Whitney test was used. The level of statistical significance for comparisons between zones was set at $p < 0.05$. Statistical data processing was performed using IBM SPSS Statistics 26.0 software, which ensured the accuracy of calculations and the ability to visualise data. The study was conducted following international standards of bioethics and radiation safety (International Atomic Energy Agency, n.d.), as well as in compliance with the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1975). In the course of the work, measures were taken to minimise environmental impact and ensure personnel safety.

RESULTS

Radiometric monitoring of the surveyed areas. The analysis of gamma radiation EDR demonstrated a significant variation in the radiation background depending on the studied areas. The maximum values were observed in extreme radiation risk (Yer Zhanybek, Kulzhan ata, Baishuak), where the EDR reached 0.32-0.33 μSv/h. This was significantly higher than the natural radiation background typical for uncontaminated areas, which averages 0.07-0.15 μSv/h. In the zone of maximum radiation risk (Kainar, Abyraly, Akbulak), the EDR level was in the range of 0.15-0.2 μSv/h, which also exceeded the upper limit of the background range, although it was lower than in the extreme risk zone. In the areas with increased and minimal risk (Rustem, Bayan, Zhanat, Akan, Adilet, Maksat), the EDR ranged from 0.07 to 0.15 µSv/h, which corresponded to the natural radiation background. The results are shown in Figure 1.

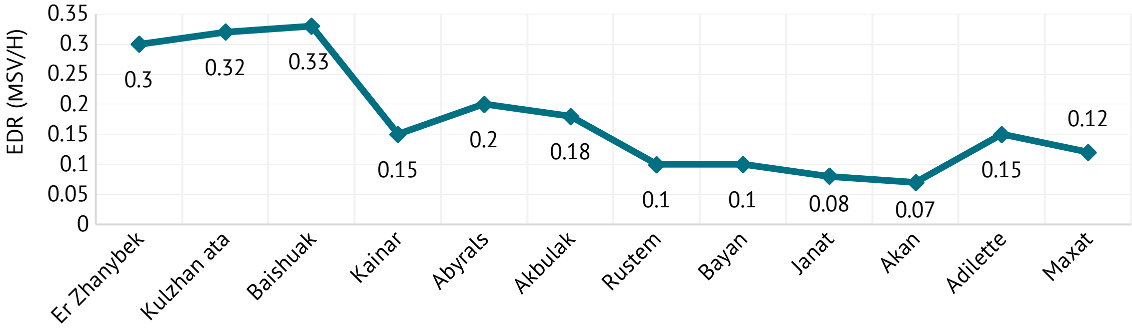

***Figure 1**. Gamma radiation EDR at a height of 1 m from the soil surface at the studied points*
***Source:** compiled by the authors*

The spatial distribution of EDR demonstrates pronounced fluctuations in the radiation background between areas with different degrees of contamination. The maximum values are recorded in areas historically exposed to the most intense radioactive impact, which confirms the presence of residual contamination. At the same time, a decrease in EDR levels at certain points may indicate the processes of natural decay of radionuclides and their migration deep into the soil profile. The flux density of alpha particles in the studied locations ranged from 0.2 to 2.2 ppm*cm^2. The highest values were registered in the extreme radiation risk zone (Er Zhanybek, Kulzhan ata, Baishuak), where the indicator reached 2.1-2.2 ppm*cm^2. High levels of alpha radiation may indicate the presence of transuranic elements, such as plutonium-239/240. In the zone of maximum radiation risk (Kainar, Abyraly, Akbulak), a sharp decrease to 0.2 ppm*cm^2 is observed, which may be due to the heterogeneity of alpha-emitting radionuclides in the soil. In the zone of increased radiation risk (Rustem, Bayan, Zhanat), the alpha particle flux density varies between 0.4-1.5 ppm*cm^2, while in the zone of minimal radiation risk (Akan, Adilet, Maksat) the lowest values are observed, not exceeding 0.3 ppm*cm^2. These values are significantly higher than the natural radiation background for uncontaminated areas, which is 0.1-0.2 ppm*cm^2 (Fig. 2).

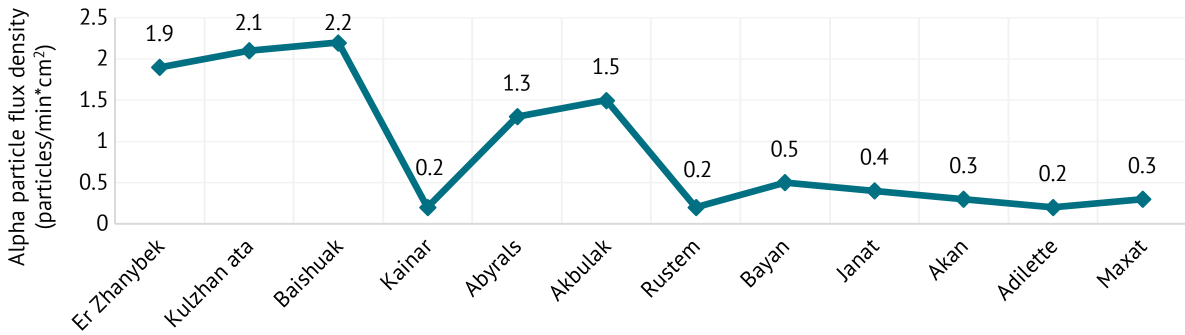

***Figure 2**. Alpha particle flux density was measured on the soil surface at the studied points*
***Source:** compiled by the authors based on International Atomic Energy Agency (n.d.)*

The analysis results show that alpha radiation levels are unevenly distributed over the territory, which may be due to different degrees of transuranic element migration in the soil profile. High values at certain points may indicate local areas of radioactive particle accumulation, which requires additional study of the geochemical features of the soil. In the settlements of Akan, Adilet, Maksat (Urdzhar district), Rustem (Ayagoz district) and Kaynar (Abay district), the flux density of alpha particles was 0.2-0.3 particles/min*cm^2, which corresponded to or only slightly exceeded the estimated values of the natural radiation background for uncontaminated areas.

According to radiation and hygiene standards, the flux density of beta particles in uncontaminated areas is no more than 2-2.5 ppm*cm^2, therefore the values can be used as a conditional background for assessing the man-made load. The range of 3.5-8.2 ppm/min*cm^2 was recorded in the studied areas, which reflects the presence of artificial radionuclides, in particular Cs-137 and Sr-90. The highest values were recorded in the zone of maximum radiation risk (Akbulak, Abyraly), where the flux density reaches 8-8.2 ppm*cm^2. In the extreme radiation risk zone (Er Zhanybek, Kulzhan ata, Baishuak), moderately high values (4.2-5.2 ppm*cm^2) are observed, indicating the presence of residual contamination. In the zone of increased radiation risk (Rustem, Bayan, Zhanat), the values decrease to 3.5-4 ppm*cm^2, while in the zone of minimal radiation risk (Akan, Adilet, Maksat), the beta particle flux density increases to 5.6 ppm*cm^2, which may be due to local redistribution of radionuclides due to natural and anthropogenic factors (Fig. 3).

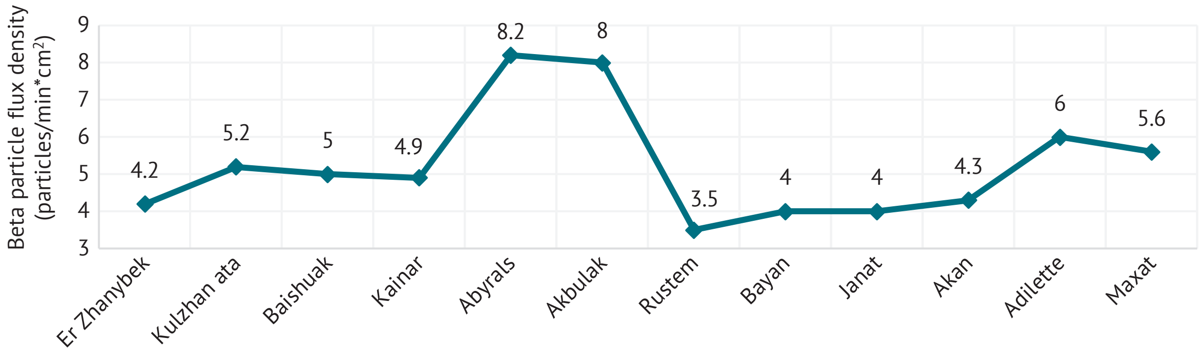

***Figure 3**. Beta-particle flux density at the studied points*

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

The graph demonstrates a significant variation in the beta particle flux density in the studied areas, which may indicate heterogeneity of radionuclide distribution in the soil. In some areas with low overall background radiation levels, such as the Ayagoz region (Rustem – 3.5 ppm*cm^2; Bayan and Zhanat – 4 ppm*cm^2 each), local increases in beta radiation density were observed compared to alpha background, which may indicate migration of radionuclides or their fixation in certain types of soil sediments. In addition, the identified differences may be due to natural processes of pollutant redistribution, such as wind and water erosion.

The obtained radiometric monitoring data confirm the heterogeneity of radioactive contamination in the studied areas, which is associated with historical nuclear tests and subsequent radionuclide migration processes. Maximum levels of gamma radiation, as well as increased density of alpha and beta particle fluxes, were recorded in the areas of emergency and maximum radiation risk (Abay and Zhanasemey districts), which indicates high residual activity of radionuclides. At the same time, local deviations detected in the areas classified as zones of relatively minimal radiation risk (Urdzhar district), according to radiation mapping data, background measurements of EDR and radionuclide activity, may be related to natural processes of redistribution of pollutants and require additional study.

Radioactive contamination of soil and spatial distribution of radionuclides. The study of radioactive contamination of soil in the Semipalatinsk nuclear test site made it possible to determine the content and spatial distribution of radionuclides with different lifetimes, including long-lived (Am-241, Pu-239/240) and intermediate-lived Cs-137. The values of these isotopes were determined by alpha and gamma spectrometry using an EXPEC 6500 analyser (sampling was carried out at a depth of 0-10 cm). The concentrations of radionuclides in soil samples varied depending on the level of radiation risk in the study areas. The highest levels of specific activity of radionuclides were observed in the Abay and Zhanasemey districts, which were classified as zones of high and extreme radioactive contamination based on radiation mapping and exceeding the thresholds set by the International Atomic Energy Agency. This is probably due to their primary deposition during nuclear tests and subsequent migration in the soil profile.

The results of alpha and gamma spectrometric analysis of the soil showed that in extreme radiation risk (Yer Zhanybek, Kulzhan ata, Baishuak), Am-241 concentrations were in the range of 0.52-0.55 Bq/kg, Cs-137 1.78-1.83 Bq/kg, and Pu-239/240 0.011-0.012 Bq/kg. Comparison of these values with the permissible levels set by the International Atomic Energy Agency, according to which the maximum permissible specific activity in soil is 0.3 Bq/kg for Am-241, 0.6 Bq/kg for Cs-137, and 0.02 Bq/kg for Pu-239/240, highlighted the following. The concentrations of Am-241 exceed the normative values by 1.7-1.8 times, Cs-137 by 3-3.1 times, while Pu-239/240 remains within the permissible range (Table 1). The data were calculated according to formula (1).

***Table 1**. Specific activity of radionuclides in soil (Bq/kg)*

Settlement	Am-241	Cs-137	Pu-239/240
Er Zhanybek	0.55 ± 0.03	1.83 ± 0.15	0.012 ± 0.0015
Kulzhan ata	0.52 ± 0.03	1.78 ± 0.12	0.012 ± 0.001
Baishuak	0.53 ± 0.04	1.8 ± 0.1	0.011 ± 0.0012

Table 1. Continued

Settlement	Am-241	Cs-137	Pu-239/240
Kainar	0.48 ± 0.03	0.8 ± 0.06	0.009 ± 0.001
Abyrals	0.49 ± 0.04	0.85 ± 0.07	0.008 ± 0.001
Akbulak	0.5 ± 0.04	0.87 ± 0.06	0.009 ± 0.001
Rustem	0.3 ± 0.02	0.5 ± 0.04	0.005 ± 0.001
Bayan	0.3 ± 0.02	0.4 ± 0.03	0.005 ± 0.001
Janat	0.3 ± 0.02	0.5 ± 0.04	0.005 ± 0.001
Akan	0.25 ± 0.02	0.22 ± 0.02	0.001 ± 0.0005
Adilette	0.24 ± 0.01	0.2 ± 0.02	0.001 ± 0.0005
Maxat	0.25 ± 0.02	0.19 ± 0.02	0.001 ± 0.0005

Note: *values are given as arithmetic means ± SD estimates calculated based on triplicate analysis of each pooled sample. SDs are estimated within the typical accuracy limits of the atomic emission spectrometry method (EXPEC 6500)*
Source: *compiled by the authors*

The spatial distribution of radionuclides in the soil of the studied areas demonstrates regularities caused by the history of nuclear tests and subsequent geochemical processes. In the most contaminated areas, a stable retention of Am-241 is observed, which confirms its low migration capacity in the soil profile. Cs-137, on the contrary, shows more pronounced concentration variations, which may be due to its tendency to secondary redistribution and partial leaching. Pu-239/240 was detected in trace amounts in all areas studied, which corresponds to its low mobility and high sorption capacity for soil particles. These features indicate the need for continued monitoring to identify potential risks of long-term contamination and assess the dynamics of radionuclide migration.

To assess the spatial distribution of radionuclides, an analysis of the vertical soil profile was also conducted. The data show that most of the Cs-137 and Am-241 are concentrated in the upper soil layers (0-10 cm), while Pu-239/240 tends to migrate deeper, with concentrations detected at depths of up to 15-20 cm. This is explained by its high affinity for soil particles, its ability to be sorbed by organo-mineral complexes, and its low solubility in water. In areas with low levels of radiation contamination (Akan, Adilet, Maksat), radionuclide concentrations are significantly lower: Am-241 0.24-0.25 Bq/kg, Cs-137 0.19-0.22 Bq/kg, Pu-239/240 0.001 Bq/kg. The results of the soil sample analysis confirm a significant accumulation of radionuclides in the study areas, especially in the areas of emergency and maximum radiation risk. The bulk of radionuclides is concentrated in the upper soil layer, but some Cs-137 demonstrates the ability to migrate, which requires further monitoring.

Radionuclide content in water bodies. Radioactive contamination of water bodies reflects the migration of radionuclides into the environment. Water contributes to the transport of radioactive particles, which can lead to their accumulation in hydrosystems and further spread in ecosystems. During the study, water samples were collected and analysed from various sources, including open water bodies, wells and springs located in areas with different levels of radiation risk. Radionuclide concentrations in the water environment were analysed using an EXPEC 6500 atomic emission and mass spectrometer, which provides high sensitivity in determining trace amounts of Am-241, Cs-137 and Pu-239/240. The study determined that the levels of these radionuclides differed significantly depending on the location of water sources and the degree of radiation risk in the respective territories. The maximum concentrations of radionuclides were recorded in the extreme radiation risk zone, which may indicate the continued intake of pollutants from the soil layer. In the zone of maximum radiation risk, a slight decrease in radionuclide content was noted, which may be due to the processes of dilution and self-purification of water bodies. In the zones of increased and minimum radiation risk, radionuclide concentrations are reduced, indicating lower mobility and natural sorption processes on bottom sediments (Table 2). The data were calculated according to formula (2).

Table 2*. Radionuclide content in water samples (Bq/l)*

Settlement	Am-241	Cs-137	Pu-239/240
Er Zhanybek	0.5 ± 0.04	5.22 ± 0.2	0.1 ± 0.01
Kulzhan ata	0.3 ± 0.03	4.92 ± 0.12	0.09 ± 0.008
Baishuak	0.4 ± 0.03	5.1 ± 0.08	0.1 ± 0.009
Kainar	0.45 ± 0.04	4.88 ± 0.1	0.09 ± 0.01
Abyrals	0.44 ± 0.04	4.72 ± 0.15	0.07 ± 0.006
Akbulak	0.45 ± 0.04	4.85 ± 0.13	0.09 ± 0.009
Rustem	0.38 ± 0.03	3.76 ± 0.08	0.08 ± 0.009

Table 2. Continued

Settlement	Am-241	Cs-137	Pu-239/240
Bayan	0.34 ± 0.03	3.58 ± 0.09	0.07 ± 0.007
Janat	0.28 ± 0.03	3.49 ± 0.08	0.08 ± 0.009
Akan	0.2 ± 0.02	1 ± 0.04	0.001 ± 0.001
Adilette	0.18 ± 0.02	0.9 ± 0.05	0.001 ± 0.001
Maxat	0.19 ± 0.02	0.8 ± 0.04	0.001 ± 0.001

Note: *values are given as arithmetic means ± SD estimates calculated based on triplicate analysis of each pooled sample. SDs are estimated within the typical accuracy limits of the atomic emission spectrometry method (EXPEC 6500)*
Source: *compiled by the authors*

A comparison of the data obtained with the maximum permissible concentrations established by the International Atomic Energy Agency (2014) showed that the normative values were exceeded in most of the samples studied. According to these standards, the permissible levels of radionuclides in the aquatic environment are as follows: Cs-137 2 Bq/l, Am-241 0.2 Bq/l, Pu-239/240 0.005 Bq/l. The analysis revealed that the concentration of Cs-137 in water bodies reached 5.22 Bq/l, which is 2.6 times higher than the established limit. Am-241 also exceeded the permissible levels, reaching 0.5 Bq/l, especially in the areas of emergency and maximum radiation risk. Pu-239/240 was recorded in the range of 0.07-0.1 Bq/l, which is significantly higher than the limit value set by the International Atomic Energy Agency.

The largest exceedance of permissible concentrations of radionuclides in the water environment was recorded in the settlements of Yer Zhanybek, Baishuak, Akbulak and Abyraly, where the content of Cs-137 and Am-241 significantly exceeded the background level. These settlements are located near the epicentres of ground and atmospheric nuclear tests, which led to the formation of foci of migration of radionuclides from soil to water. Accounting for the registered concentrations, it is necessary to strengthen control of water resources and organise systematic radiation monitoring to assess environmental and sanitary risks. Of particular concern is the high mobility of Cs-137, which is manifested in its ability to desorb and spread with surface and groundwater runoff. This is confirmed by its maximum concentrations in areas of extreme radiation risk. While Pu-239/240 remains predominantly fixed in the soil profile due to its low solubility and high sorption capacity, its presence in water samples indicates the possibility of local mobilisation (Hussain *et al.*, 2022). Despite the absence of critical levels of contamination, the recorded exceedances of thresholds for Cs-137, Am-241 and Pu-239/240 require consideration in the environmental zoning of the territory, planning of agricultural use and water supply. Continuous radiation and hygiene monitoring are necessary to prevent the chronicity of radiation's impact on ecosystems and the population.

Accumulation of radionuclides in vegetation and feed. Vegetation cover participates in the redistribution of radionuclides in the ecosystem and their transfer through food chains. In the area of the Semipalatinsk nuclear test site, the main flora species are fescue-wormwood and forb communities, in particular *Stipa lessingiana*, *Festuca valesiasa*, *Artemisia sublessingiana*, and *A. albida*. Plants growing in conditions of radioactive contamination are capable of accumulating radionuclides, which poses a potential hazard to farm animals and humans (Filss *et al.*, 1998). The process of radionuclide accumulation is determined by several factors, including the chemical form of the element, soil acidity and particle size distribution, depth of the root system, growing season and plant species. Cs-137 proved to be the most mobile of the studied radionuclides, as it is actively absorbed by plant roots, translocated to aboveground organs and can be involved in cellular metabolic processes. At the same time, Pu-239/240 is characterised by low solubility and strong sorption on soil particles, which limits its bioavailability. Am-241 demonstrates an intermediate degree of mobility and accumulation in biomass.

The analysis of plant samples taken in areas with different levels of radiation risk showed pronounced spatial differences in radionuclide content. In the extreme radiation risk zone, covering the settlements of Yer Zhanybek, Kulzhan ata and Baishuak, maximum concentrations of Am-241 were recorded at 1.55-1.6 Bq/kg, Cs-137 1.97-2.2 Bq/kg, Pu-239/240 0.8-0.9 Bq/kg. These values significantly exceed the natural background levels accepted in international practice: for Cs-137 no more than 0.1 Bq/kg, for Am-241 1 Bq/kg, for Pu-239/240 0.1-0.3 Bq/kg. In the zone of maximum radiation risk, including Kainar, Abyraly and Akbulak, the concentrations of the studied radionuclides were lower, but still exceeded the permissible levels established for plant samples: for Cs-137 (1.6-1.9 Bq/kg) 16-20 times higher than the background (0.1 Bq/kg), Pu-239/240 (0.6-0.7 Bq/kg) 2-6 times higher than the upper limit of the norm (0.3 Bq/kg), while Am-241 (0.85-1 Bq/kg) was close to the indicative threshold of 1 Bq/kg. Plants predominant in these areas were cereals and sagebrush species, which could contribute to the intensive accumulation of radionuclides from the upper soil horizons (Table 3). The values of radionuclide concentrations in plant samples were calculated using formula (1).

Table 3. *Radionuclide content in crop samples (Bq/kg)*

Settlement	Am-241	Cs-137	Pu-239/240
Er Zhanybek	1.6±0.3	2.2±0.1	0.9±0.1
Kulzhan ata	1.55±0.1	1.97±0.3	0.8±0.2
Baishuak	1.56±0.3	2±0.2	0.9±0.1
Kainar	1±0.3	1.9±0.3	0.7±0.2
Abyrals	0.85±0.3	1.6±0.1	0.6±0.2
Akbulak	0.9±0.3	1.8±0.2	0.7±0.2
Rustem	0.5±0.2	0.8±0.2	0.4±0.1
Bayan	0.5±0.2	0.75±0.2	0.2±0.1
Janat	0.4±0.1	0.8±0.2	0.4±0.1
Akan	0.3±0.1	0.3±0.1	0.09±0.03
Adilette	0.2±0.1	0.2±0.1	0.08±0.03
Maxat	0.3±0.1	0.3±0.1	0.09±0.03

Note: *values are given as arithmetic means ± SD estimates calculated based on triplicate analysis of each pooled sample. SDs are estimated within the typical accuracy limits of the atomic emission spectrometry method (EXPEC 6500)*
Source: *compiled by the authors*

Comparison with the data on soil and water confirms the close relationship between the level of radioactive contamination of the environment and the content of radionuclides in plants. In the areas where Cs-137 concentrations in soil reached 1.83 Bq/kg and in water 5.22 Bq/l, the highest content of Cs-137 in plant biomass was observed. This confirms the active migration of the radionuclide through ecosystem components. In contrast, Pu-239/240, despite its soil stability, accumulated in plants in much smaller amounts due to its chemical and physicochemical properties. The concentrations of Am-241 in vegetation correlated with its levels in soil, but varied within a wider range, which may indicate differences in the ability of plants to absorb it. Given that the region's agriculture is based on pasture-based livestock farming, the detected concentrations of radionuclides in feed pose a potential threat. One cow consuming vegetation from an area of up to 160 m^2 daily can accumulate significant doses of Cs-137, which is then transmitted with milk and meat (Levchuk *et al.*, 2025). This is especially true in areas with the highest levels of contamination. The accumulation of Pu-239/240 in animals is slower, but its radiotoxicity is much higher, which increases sanitary and hygienic risks.

The results obtained indicate persistent contamination of the ecosystem with long-lived radionuclides that continue to circulate in biogeochemical cycles decades after the cessation of nuclear testing. Despite the relative decrease in concentrations in several settlements, the presence of Cs-137, Am-241 and Pu-239/240 in the fodder base requires constant monitoring, especially in the context of seasonal migration of radionuclides and possible climate change. Monitoring the content of radionuclides in vegetation should be a priority task when developing strategies for sustainable agricultural development in the Semipalatinsk landfill area.

Mechanisms of accumulation and redistribution of radionuclides in the region's ecosystems. The study of radioactive contamination in the Semipalatinsk nuclear test site area has revealed the key mechanisms of accumulation and redistribution of long-lived radionuclides (Am-241, Cs-137 and Pu-239/240) in various natural environments. The migration processes of these elements are determined by the geochemical conditions of the region, soil type, hydrological characteristics and biological features of the local flora and fauna. The analysis of soil samples showed that the main factors affecting the content of radionuclides are the level of radioactive exposure, properties of the soil horizon, depth of occurrence, as well as local landscape features affecting the migration of radionuclides. Cs-137 was characterised by high adsorption by clay minerals and organic compounds, which resulted in its more uniform distribution in the soil profile. At the same time, Pu-239/240, which has extremely low solubility, was predominantly fixed in the upper horizon. This is confirmed by both the high content of the isotope in the soil (up to 0.012 Bq/kg) and its minimum concentration in water (up to 0.001 Bq/l). Am-241 was found in smaller quantities but showed local accumulation, probably related to leaching processes and the physical and chemical composition of the soil. The vertical distribution of radionuclides confirms their limited migration: Cs-137 and Am-241 were concentrated at a depth of 0-10 cm, while Pu-239/240 was detected at 15-20 cm.

The content of radionuclides in water samples also varied depending on the radiation risk category. The maximum values of Cs-137 in water reached 5.22 Bq/l (Er Zhanybek), which exceeds the maximum permissible level set by the International Atomic Energy Agency (2014) (2 Bq/l) by more than 2.6 times. Am-241 concentrations in some locations were 0.5 Bq/l, which is also 2.5 times higher than the permissible level (0.2 Bq/l). The situation is similar with Pu-239/240, where the recorded values (0.1 Bq/l) exceed the recommended limit (0.005 Bq/l) by a factor of 20. The permissible levels of Cs-137, Am-241 and Pu-239/240 in water are 11, 0.69 and 0.55 Bq/l, respectively, and exceedances were recorded only for Cs-137 in the emergency risk zone, but the data remain below the national limit.

Plants sampled from the studied pastures showed that the levels of Am-241 (up to 1.6 Bq/kg) and Cs-137 (up to 2.2 Bq/kg) exceeded the estimated background levels of uncontaminated areas (0.1-0.3 Bq/kg according to the International Atomic Energy Agency) by 7-20 times. This indicates the bioavailability of radiocaesium and americium and their active assimilation by grass vegetation. The concentrations of Pu-239/240 in plants (up to 0.9 Bq/kg) also significantly exceed the natural level (usually <0.01 Bq/kg), indicating its participation in the biological cycle under conditions of intensive contamination. A comparison of the radionuclide content in the three media showed that in the emergency risk zone, Cs-137 levels in the soil are on average 1.5 times higher than in plants and 3.5 times higher than in water, while Pu-239/240 demonstrates maximum retention in soil and minimum retention in water.

Fodder grown on pastures in contaminated areas represents a potential pathway for radionuclides to enter the body of animals and, consequently, livestock products (Lazarev & Klepko, 2023). Studies show that cattle consume vegetation mass from an area of up to 160 m^2 per day, which increases the likelihood of radionuclide accumulation in animal tissues. The greatest danger is posed by Cs-137, which is actively involved in metabolic processes and can accumulate in muscle tissue and milk. Pu-239/240 and Am-241, having low bioavailability, accumulate in bone tissue and internal organs, which requires special control over the safety of meat and offal. The accumulation of radionuclides in feed confirms the need for systematic monitoring of agricultural land and the development of measures to reduce the radiation load (Shaforost *et al.*, 2024).

The concentrations of radionuclides in the soil in the extreme risk zone (Er Zhanybek, Kulzhan ata, Baishuak) are as follows: Am-241 up to 0.55 Bq/kg, Cs-137 up to 1.83 Bq/kg, Pu-239/240 up to 0.012 Bq/kg. These values also exceed the indicative maximum permissible levels (0.3 Bq/kg for Am-241, 0.6 Bq/kg for Cs-137 and 0.02 Bq/kg for Pu-239/240) by 1.8-3 times for Cs-137 and Am-241. Consequently, soil remains the main depot of radionuclide contamination, with the level of accumulation exceeding similar values in water and vegetation by an average of 3-5 times. Periodic radiation monitoring of soil and vegetation is recommended, especially on agricultural land. The use of potassium fertilisers can reduce the uptake of Cs-137 by plants, and the reclamation of pastureland will minimise the risk of radionuclides entering livestock products. In addition, it is necessary to develop a strategy for remediation of contaminated areas to reduce their radiation hazard. Thus, the study confirmed that the mechanisms of accumulation and redistribution of radionuclides in the region's ecosystems are determined by several natural and anthropogenic factors. Continued monitoring studies and the implementation of appropriate protective measures will minimise environmental and radiation risks in the former Semipalatinsk nuclear test site.

DISCUSSION

The results of the study showed that the content of Am-241, Cs-137 and Pu-239/240 in soil, water and vegetation varies depending on the level of radiation risk in the studied areas. The identified differences in radionuclide concentrations indicate complex processes of migration and accumulation caused by natural and anthropogenic factors. Comparative analysis will help to clarify the patterns of radionuclide migration and provide a more accurate assessment of long-term environmental impacts.

A comparison of the data obtained with the results of other authors confirmed the complexity and multiethiological nature of radioecological processes in the region. The results of the present study, in which Cs-137 and Am-241 concentrations above background values were recorded in soil and water samples in the settlements of Akan, Adilet and Maksat, are consistent with the findings of A. Lipikhina *et al.* (2025), found that radioactive contamination of the southeast of the Abay region may be caused not only by the impact of the Semipalatinsk nuclear test site but also by transboundary transfer of radionuclides from the Chinese Lob Nor test site. The obtained values of Pu-239/240 accumulation in soil (up to 0.012 Bq/kg) and in plants (up to 0.9 Bq/kg) correspond to the observations of S. Arynova *et al.* (2024), who found a significant accumulation of actinides, including uranium and thorium, in natural components of the surrounding areas, indicating a complex composition of the radiation background.

S. Duyssembaev *et al.* (2018) emphasised the high mosaic nature of the radionuclide distribution, and the data of the present study confirmed this conclusion: the spatial distribution of alpha and beta radiation varied widely even within the same risk zone. In addition, K. Hanaček and J. Martinez-Alier (2024) noted that the unevenness of contamination in post-Soviet countries is exacerbated by the lack of availability of environmental remediation. The Cs-137 concentrations exceeding the maximum permissible concentration in water bodies (up to 5.22 Bq/l) recorded in Yer Zhanybek and Baishuak demonstrate the relevance of these findings and the need to expand monitoring and radiation safety measures in remote areas. The results of the water sample analysis, in which Pu-239/240 concentrations did not exceed 0.001 Bq/l, confirmed the extremely low solubility of this radionuclide and its low mobility, which limits its participation in water migration. At the same time, the recorded concentration of Cs-137 in the range of 0.8-5.22 Bq/l significantly exceeded the regulatory values of the International Atomic Energy Agency (2 Bq/l), especially in Yer Zhanibek, Bayshuak and Akbulak, indicating its high migratory capacity. These data are consistent with the results of D.K. Gupta and C. Walther (2025), where Cs-137 is characterised as the most mobile radionuclide, actively circulating in ecosystems and capable of desorption and transfer to the water phase. The values identified are also consistent with the observations of D. Dasher *et al.* (2002), highlighting cases of radionuclide leakage from underground nuclear test sites into surface waters, which is similar to the possible scenario for the Semipalatinsk test site.

The results obtained for radionuclide accumulation in vegetation, which recorded maximum concentrations of Am-241 (1.55-1.6 Bq/kg), Cs-137 (1.97-2.2 Bq/kg) and Pu-239/240 (0.8-0.9 Bq/kg) in areas with high levels of soil contamination (Er Zhanibek, Kulzhan Ata, Bayshuak) confirmed the close relationship between radionuclide content in soil and their uptake into plant biomass. These data were consistent with the conclusions of M. Gerzabek *et al.* (2024), which emphasised that the physical and chemical characteristics of the soil determine the sorption capacity and bioavailability of radionuclides to plants. The results of feed sample analysis, which showed exceedances of natural background levels, also confirmed the potential risks to livestock farming, which is consistent with the data of T. Ponomaryova *et al.* (2022), which found accumulation of Cs-137 and Sr-90 in crops grown on contaminated soils. In addition, a study by A. Yankauskas *et al.* (2024) recorded morphological and anatomical changes in plants exposed to radioactive contamination, which may explain the physiological response of vegetation to radionuclide accumulation, similar to that observed in the present study. N. Akhtaeva *et al.* (2022) demonstrated the adaptive mechanisms of plants under conditions of technogenic pollution, which is consistent with the facts of active absorption of Cs-137 and Pu-239/240 by forage plant samples, especially in areas of maximum radiation risk.

The revealed results emphasised the need for further study of the processes of radionuclide transfer to plant biomass and their subsequent inclusion in food chains. The recorded concentrations of Cs-137, Am-241, and Pu-239/240 in plant samples from areas of varying degrees of contamination confirmed the high dependence of radionuclide accumulation on the level of soil contamination. These observations coincided with the results of J. Guillén *et al.* (2022), who proposed using stable isotopes of Cs and Sr as indicators of the migration of radioactive analogues in the soil-plant system for monitoring in contaminated areas. The concentrations of radionuclides in plant biomass recorded in the studied areas in some cases exceeded the background level, which is consistent with the findings of S. Endo *et al.* (2008), where it was shown that vegetation in the vicinity of nuclear test zones can actively accumulate radionuclides in amounts that can have a long-term impact on ecosystems. Differences in the levels of radionuclide accumulation in the studied samples were explained by both textural and chemical characteristics of the soil and peculiarities of the morphology and physiology of the plants themselves.

The results of spectrometric analysis of soil samples showed that radionuclide levels in most of the studied areas did not exceed the maximum permissible values, but in the extreme radiation risk zone (Yer Zhanybek, Kulzhan ata, Baishuak) local zones with increased content of Cs-137 (up to 1.83 Bq/kg at a norm of 0.6 Bq/kg) and Am-241 (up to 0.55 Bq/kg at a norm of 0.3 Bq/kg), indicating residual contamination of the upper soil horizon. These observations confirmed the position of B. Penati (2019), according to which the scale of radioactive contamination on the territory of the former Semipalatinsk test site may be significantly underestimated. The data obtained showed the persistence of radionuclides in the soil decades after the completion of nuclear tests. In contrast to soil, in water samples, Pu-239/240 concentrations in several settlements significantly exceeded the maximum permissible value set by the International Atomic Energy Agency (0.005 Bq/l), reaching 0.1 Bq/l, which is 18-20 times the permissible level. This contradicts the results of X. Zhao *et al.* (2020), who recorded low plutonium mobility in natural waters. The reason for the discrepancies may be the specific geohydrological conditions of the studied areas or local leaching zones in the upper soil horizons containing residual amounts of Pu-239/240.

The highest levels of radiation contamination were recorded near the epicentres of nuclear explosions, where increased concentrations were observed in both soil and vegetation. Similar patterns were described by S. Duyssembaev *et al.* (2014), who, based on a comprehensive analysis of the components of the soil-plant-animal system, showed that even decades after the tests were completed, radioactive contamination pockets remain in the region, which can affect biogeochemical cycles. The data obtained confirmed the presence of such zones, especially in areas of extreme and maximum radiation risk, which requires continued monitoring and corrective measures.

The analysis of the spatial distribution of Pu-239/240 in soil and water showed significant differences in its behaviour in different natural environments. In soil samples, Pu-239/240 concentrations in most of the studied areas remained within the permissible limits, indicating its limited mobility and high sorption capacity. However, in water samples collected in areas of extreme radiation risk, Pu-239/240 concentrations reached 0.1 Bq/l. These data are consistent with the observations of C. Re (2024), who noted the transformation of soil and plant ecosystems under conditions of post-nuclear impact and the long-term persistence of residual radionuclides. The recorded low mobility of Pu-239/240 in soil and its minimal presence in the aquatic environment confirm the conclusions of E. Harrell and D. Hoffman (2013), according to which a significant portion of plutonium at the site is retained in isolated forms that are not involved in migration processes. The results obtained suggest that Pu-239/240 may participate in migration processes under certain hydrogeochemical conditions at the Semipalatinsk landfill.

The analysis of the data obtained revealed that in the areas with the maximum content of radionuclides, especially Cs-137 in water and Am-241 in plants, a high level of radioecological risk remains, which requires an assessment of the possibilities for local environmental remediation. The results showed that in the Yer Zhanybek zone, Cs-137 concentrations in water reached 5.22 Bq/l, while the norm is 2 Bq/l, and Am-241 content in plant biomass was 1.6 Bq/kg, while the permissible level is 1 Bq/kg. These indicators indicated a potential threat of biological transfer of radionuclides and the need for targeted remediation of contaminated areas. Such conclusions are consistent with the position of C. Evans (2022), who emphasises the limitations of current international efforts to address the consequences of nuclear testing. P. Högselius and A. Klüppelberg (2024) emphasised that the consequences of the Soviet nuclear legacy remain unresolved in several post-Soviet regions, which is consistent with the local areas of exceedance of permissible levels of radionuclides recorded in the present study. The presence in some areas of concentrations many times higher than the standards requires expanded monitoring and the development of localised strategies to reduce the radiation burden. The results confirm the presence of localised radioactive contamination on the territory of the former Semipalatinsk nuclear test site, with differential distribution of radionuclides in soil, water and vegetation. Comparison with other studies shows similarities in Cs-137 migration processes and Pu-239/240 persistence, which requires further monitoring to assess the long-term impact on the ecosystem and potential risks to public health.

CONCLUSIONS

A study of the radioecological situation in the former Semipalatinsk nuclear test site revealed varying degrees of contamination of soil, water, vegetation and fodder with long-lived radionuclides Am-241, Cs-137 and Pu-239/240. The data analysis confirmed the complexity of the spatial distribution of radionuclides due to the peculiarities of the soil profile, hydrogeochemical processes, biological migration and natural factors. The study of soil samples showed that the maximum levels of specific activity of radionuclides were recorded in the Yer Zhanybek zone, where the concentrations of Cs-137 were 1.83 ± 0.15 Bq/kg, Am-241 0.55 ± 0.03 Bq/kg, and Pu-239/240 0.012 ± 0.0015 Bq/kg. In most other locations studied, the concentrations did not exceed the maximum permissible values, but local areas with exceeding values were identified, which required additional studies. The distribution of Pu-239/240 was limited to the upper soil horizons (0-15 cm), which confirmed its low migration capacity. Cs-137 and Am-241 were localised mainly in the 0-10 cm layer, showing limited vertical movement.

The results of the water sample analysis confirmed the presence of radionuclides in surface and groundwater sources, indicating possible migration pathways. The highest concentrations of Cs-137 were recorded in the Yer Zhanybek area (5.22 ± 0.2 Bq/l), which was more than twice the permissible level according to the International Atomic Energy Agency (2 Bq/l). Am-241 concentrations in water ranged from 0.18 to 0.5 ± 0.4 Bq/l, which also exceeded the standard of 0.2 Bq/l. The concentrations of Pu-239/240 in the water environment at several points (up to 0.1 ± 0.3 Bq/l) exceeded the threshold of 0.005 Bq/l by a factor of 20, which indicated possible instability of its fixation in the soil. The vegetation cover confirmed its role in the biological migration of radionuclides. In the areas of maximum and extreme radiation risk, concentrations significantly exceeding the permissible levels were recorded: the content of Cs-137 in plants reached 2 ± 0.1 Bq/kg, which is 16-20 times higher than the background level (0.1 Bq/kg), Pu-239/240 up to 0.9 ± 0.1 Bq/kg, which is 3-9 times higher than the upper limit of the norm (0.3 Bq/kg). Am-241 concentrations ranged from 0.85 to 1.6 Bq/kg, approaching or exceeding the guideline value of 1 Bq/kg recommended for plant samples. These results indicate the active participation of herbaceous vegetation in the accumulation of radionuclides and confirm the risks of their entry into food chains.

The results of the study show that the radiation situation in the studied areas remains stable but requires regular monitoring. Radioactive elements, especially Cs-137, continue to persist in the environment, which poses a potential threat to ecosystems and the population. In the future, it is recommended to introduce additional measures to reduce the radioactive load, including phytoremediation, the use of sorbents to bind radionuclides in the soil, and restriction of agricultural use of pastures in areas of increased radiation risk. A comparative analysis of soil, water and vegetation samples showed that the level of radioactive contamination of water with Cs-137 and Am-241 exceeded that of soil by a factor of 3-10. This indicated the redistribution of radionuclides from the soil horizon to the water environment. Despite the overall low mobility of Pu-239/240, its concentrations in some water samples exceeded the permissible values by 15-20 times, indicating local migration processes. Cs-137 showed the highest mobility in natural environments, actively transferring from soil to water and vegetation. On the contrary, Pu-239/240 was retained mainly in soil, which limited its participation in biogeochemical cycles, but did not exclude occasional release to other environmental components. It is advisable to conduct further studies considering seasonal fluctuations in contamination and expanding the network of control points to improve the accuracy of radioecological assessment. It is important to study in more detail the processes of biological remediation and the impact of radionuclides on agricultural ecosystems.

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Радіоекологічний стан довкілля в зоні колишнього Семипалатинського ядерного полігону

Айнур Серікова
Кандидат ветеринарних наук, доцент
Університет Шакарім
071412, вул. Глінки, 20А, м. Семей, Республіка Казахстан
https://orcid.org/0000-0002-8707-5878

Сергази Дюсембаєв
Доктор ветеринарних наук, професор
Університет Шакарім
071412, вул. Глінки, 20А, м. Семей, Республіка Казахстан
https://orcid.org/0000-0001-6259-2871

Шингис Сулейменов
Доктор філософії, професор
Університет Шакарім
071412, вул. Глінки, 20А, м. Семей, Республіка Казахстан
https://orcid.org/0000-0002-6164-9407

Жаксилик Серіков
Магістр, науковий співробітник
Університет Шакарім
071412, вул. Глінки, 20А, м. Семей, Республіка Казахстан
https://orcid.org/0000-0002-6895-8392

Шинар Абдикарімова
Докторант
Університет Шакарім
071412, вул. Глінки, 20А, м. Семей, Республіка Казахстан
https://orcid.org/0009-0003-2893-2053

Анотація. Радіоактивне забруднення довкілля в районі колишнього Семипалатинського ядерного полігону (Казахстан) зумовлене осадженням і тривалим збереженням у ґрунті, воді та рослинності довгоживучих радіонуклідів, що створює потенційні ризики для екосистем і здоров'я населення. Мета дослідження полягала в оцінці рівнів забруднення ґрунту, води та рослинності радіонуклідами америцій-241, цезій-137 і плутоній-239/240 на територіях різного радіаційного ризику в районі колишнього Семипалатинського ядерного полігону. Радіаційно-екологічний моніторинг проведено на дванадцяти контрольних пунктах з використанням спектрометричного аналізу для визначення питомої активності зазначених радіонуклідів у пробах навколишнього середовища. У результаті дослідження було встановлено виражені відмінності у вмісті радіонуклідів у ґрунті, воді та рослинності на територіях із різним рівнем радіаційного ризику. Максимальні концентрації америцію-241 (0,55 ± 0,03Х Бк/кг), цезію-137 (1,83 ± 0,15 Бк/кг) і плутонію-239/240 (0,012 ± 0,0015 Бк/кг) зареєстровано в зоні надзвичайного радіаційного ризику, тоді як у найменш забруднених районах їхні рівні були нижчими в 4-7 разів. У водних об'єктах найбільшу активність відмічено у цезію-137, концентрація якого сягала 5,22 ± 0,2 Бк/л, що істотно перевищує допустимі нормативи. У рослинності виявлено значне накопичення всіх трьох радіонуклідів: Am-241 – до 1,6 ± 0,3 Бк/кг, Cs-137 – до 2,2v± 0,1 Бк/кг, Pu-239/240 – до 0,9 ± 0,1 Бк/кг. Найбільші рівні зафіксовано в зонах надзвичайного та максимального ризику, переважно в пасовищних злакових культурах. Проведений аналіз вертикального розподілу радіонуклідів засвідчив їх диференціацію за глибиною: Cs-137 та Am-241 зосереджені у верхньому шарі ґрунту (0-10 см), тоді як Pu-239/240 частково мігрував до 15-20 см, що підтверджувало ризик їхнього включення до трофічних ланцюгів та необхідність подальшого моніторингу. Отримані дані можуть бути використані при плануванні заходів з екологічної реабілітації забруднених територій, регулюванні сільськогосподарського використання пасовищ і забезпеченні радіаційної безпеки населення

Ключові слова: радіаційне забруднення; америцій-241; цезій-137; плутоній-239/240; ґрунт; вода; рослинність

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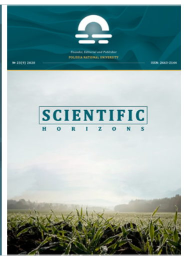

Economic models of smart farming integration into urban ecosystems

Vyacheslav Shebanin*

Doctor of Technical Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-0391-396X

Iryna Kormyshkina

Doctor of Philosophy
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0009-0002-9670-2295

Antonina Drobitko

Doctor of Agricultural Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-6492-4558

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Abstract. The aim of the study was to analyse the economic models of smart farming integration into urban ecosystems and their impact on the recovery of territorial communities in Ukraine and the European Union. In the process, a detailed review of modern smart farming technologies and models, such as hydroponics, aquaponics, vertical farms, as well as Internet of Things systems for agricultural management, rooftop farms and agro-industrial parks, was carried out. The main results included a comparative analysis of the productivity of traditional and vertical farming. It showed that vertical farms outperform traditional agriculture in terms of yield (150.23 kg/m^2 versus 4), water consumption (20 l/kg versus 250), and land use efficiency (0.0066 m^2/kg versus 0.25). In turn, the forecast for the IoT market in Europe showed a steady increase from USD 196.85 billion in 2025 to USD 284.26 billion in 2029, representing a compound annual growth rate of 9.62%. The results also indicated that investments in agricultural projects in the EU exceeded EUR 150 billion between 2015 and 2024, with Poland, the Czech Republic and Romania receiving the most funding, indicating a great potential for smart farming in these countries. Additionally, it was determined that regions in Ukraine with a high gross regional product (GRP), such as Kyiv (USD 9,268.5 million), Dnipro (USD 16,550.2 million) and Kharkiv (USD 10,494.4 million), have a greater potential for the introduction of smart farming technologies due to their high economic potential and infrastructure development. The practical significance of the study is to substantiate the effectiveness of the

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**Corresponding author*

introduction of smart farming technologies to increase agricultural productivity, optimise resource use and promote the economic development of urban agro-systems

Keywords: agricultural innovation; sustainable development; digitalisation of agriculture; hydroponics and aquaponics; Internet of things

INTRODUCTION

The modern development of agriculture is increasingly focused on innovative solutions that allow for increased efficiency in the use of natural resources, a reduction in negative environmental impact, and the ensuring of food security in the face of growing urbanisation. One promising avenue is the implementation of smart farming, which involves the use of digital technologies, automated management systems, hydroponic and aquaponic setups, vertical farming, and other innovative solutions to boost the productivity of the agricultural sector. Despite the active development of this trend in developed countries, in Ukraine, its integration into urban ecosystems remains at an initial stage due to a number of economic, technological, and institutional barriers. The main problem is the insufficient development of economic models that justify the feasibility of implementing such technologies in urban environments and their impact on the socio-economic development of local communities (Malik *et al.*, 2023).

For example, a study by A. Berxolli *et al.* (2023) discusses the necessity of innovative approaches to enhance the efficiency of Ukraine's agricultural sector amidst the war. The authors emphasise the importance of innovation and a comprehensive approach in the agricultural sector, which is relevant when considering the integration of smart farming into urban ecosystems. The integration of artificial intelligence (AI) in land resource management allows for increased efficiency in agricultural production through automated data analysis, yield forecasting, and the optimisation of fertiliser and water use (Wrzecińska *et al.*, 2023; Shebanina *et al.*, 2025).

For their part, S.K. Sharma *et al.* (2024) investigated the economic aspects of implementing smart farming technologies, including the internet of things (IoT), AI, and data analysis, in urban agro-ecosystems. The authors highlighted that precision agriculture, vertical farms, and hydroponics contribute to resource optimisation, increased productivity, and the adaptation of agriculture to urbanisation and climate change. Researchers H. Shahab *et al.* (2025) considered the implementation of IoT in smart farming as a tool for achieving sustainable development goals. They demonstrated the effectiveness of an IoT system for monitoring soil parameters and using AI to optimise crop management, which contributes to increased productivity and the sustainability of agricultural production. Furthermore, M. Dhanaraju *et al.* (2022) explored the impact of smart farming on traditional agricultural practices through the use of IoT, wireless sensors, and cloud technologies. The authors highlighted the challenges of integrating new technologies into agriculture, particularly during the period from sowing to harvesting, as well as in packaging and transportation. Additionally, the findings of the work by H. Chawla *et al.* (2025) underscored the important role of IoT technologies in enhancing water efficiency and reducing carbon emissions in horticulture. Researchers N. Khan *et al.* (2023) analysed the role of social entrepreneurship and the factors influencing the adoption of smart farming technologies among older people. They determined that a positive attitude and social impact promote the implementation of smart farming, and also emphasised the importance of social entrepreneurs in improving older people's knowledge of these technologies.

In turn, O.B. Akintuyi (2024) emphasised that vertical farming is a promising solution for ensuring food security in the context of urbanisation. The author highlighted the importance of the architectural integration of vertical farms into the urban environment to optimise space utilisation, energy efficiency, and sustainable development, as well as the role of technologies in enhancing the efficiency and resilience of food systems. The results of the work by A. Mishra (2023) indicated the advantages of smart urban farming, including the possibility of growing nutritious crops in urban conditions using AI and IoT. The use of these technologies helps to reduce resource costs, improve product quality, and decrease environmental impact, which contributes to the creation of a clean and green urban environment. Additionally, G. Orbelyan (2024) developed a theoretical model, the "Comprehensive Model of Smart Tourism and Infrastructure", which focuses on the integration of engineering, transport, and tourism to create a sustainable urban ecosystem that promotes sustainable economic growth and inclusivity through intelligent technologies.

The aim of this research was to identify economic models for the integration of smart farming into the urban ecosystems of Ukraine and the EU, as well as their impact on the recovery of local communities, which has not been detailed in previous works. The research objectives included analysing existing smart farming technologies, their effectiveness and economic potential in the context of urbanisation, and comparing smart farming models in Ukraine and the EU to identify opportunities for their implementation.

MATERIALS AND METHODS

To achieve the research objective, the economic models of smart farming integration into urban ecosystems were analysed and their impact on the recovery of territorial communities in Ukraine and the EU countries was considered. Initially, the study considered such models and technologies as hydroponics and aquaponics, vertical farms, IoT systems for agricultural management, rooftop farms, and agro-industrial parks. This made it possible to trace the main stages of their implementation and interaction with other elements of the urban environment. Reference productivity indicators for traditional and vertical farming were also considered, which allowed to assess the competitiveness of smart farming technologies compared to traditional agricultural production methods (Moghimi & Asiabanpour, 2021). These indicators included the following parameters: benchmark production per year; the number of hours one person spends producing 1 kg of product; energy and water consumption, yield, and land ratio for producing 1 kg per year.

An example is the Green Future company, which is one of the largest vertical farms in Ukraine (One of the largest vertical farms in Ukraine..., 2024). On the other hand, to determine the prospects for the use of digital technologies in the agricultural sector, an analysis of the projected development of the IoT market in European countries in US dollars for 2025-2029 was carried out (Statista, n.d.). The data obtained on the main models of smart farming were systematised in the form of a comparative analysis covering their advantages and limitations. For this purpose, the expert evaluation method was used to identify the key success factors for each model. Further, to assess the effectiveness of the introduction of smart farming technologies, the economic effect assessment formula (Kosinska, 2019) was applied, which took into account changes in production levels, investment costs, and resource savings (1):

$$E = \frac{(Y_s - Y_b) \times (C + I + T)}{C} \times 100\%, \qquad (1)$$

where E – efficiency of technology adoption, %; Y_s – production level after technology adoption; Y_b – production level before technology adoption; C – costs of technology adoption; I – investments in staff training and technical support; T – savings from reduced use of resources (water, fertilisers, etc.).

Based on this formula, the efficiency of smart farming implementation was calculated, which allowed to estimate the potential increase in productivity and profitability of public initiatives. Additionally, the schedule of regional production and international trade of Ukraine in 2019 was considered, which allowed to analyse the economic preconditions for the development of smart farming in different regions of the country (National Bank of Ukraine, n.d.). For this purpose, the gross regional product (GRP), exports and imports, as well as the level of economic activity of the regions were estimated, which made it possible to identify opportunities for the integration of smart farming technologies. Moreover, the total amount of funding for projects in EU countries for 2015-2024 was studied, which made it possible to identify possible mechanisms for financial support for such initiatives (European Commission, 2025). The analysis considers the specifics of the distribution of funds from the EU Cohesion Fund, as well as the level of investment in the development of smart farming technologies in different countries.

RESULTS

Analysis of economic models for integrating smart farming into urban ecosystems. Smart farming is an emerging trend in the agricultural sector that uses innovative technologies to increase the efficiency and sustainability of agronomic activities. In the context of urban ecosystems, smart farming is particularly important as it can meet the needs of urban areas for the production of environmentally friendly products, reducing dependence on agricultural products supplied from rural areas. In the context of urban ecosystems, smart farming can be represented by several economic models that are adapted to the specific conditions of the urban environment and can meet the food security needs of urban communities. For example, hydroponics and aquaponics are soilless methods of growing plants that use aqueous solutions for nutrition. Hydroponics involves growing plants in special systems where the roots of the plants are in water with dissolved nutrients. Aquaponics combines hydroponics with fish farming, creating a closed ecosystem where fish waste is used as fertiliser for plants and plants filter water for fish. Consider integrating hydroponics and aquaponics in urban ecosystems (Fig. 1).

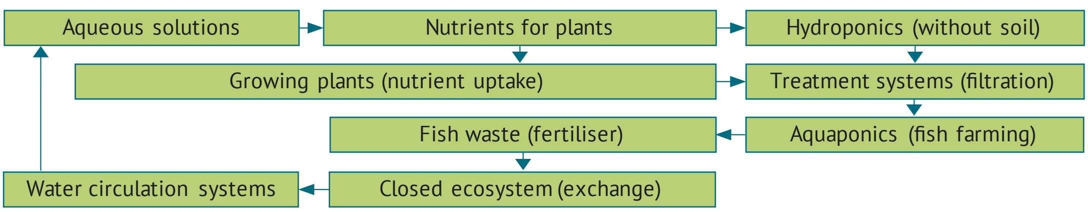

***Figure 1**. Integrating hydroponics and aquaponics in urban ecosystems*

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

This diagram shows the relationships between the different components of hydroponic and aquaponic systems, emphasising their integration into a closed ecosystem for efficient plant and fish production in urban environments. Generally speaking, hydroponics is a system of growing leafy vegetables such as lettuce and spinach in special pipes or containers where the roots of the plants are immersed in a water solution with the necessary nutrients. Such systems typically use networked solution flow technologies or a grid system. Aquaponics is implemented, for example, in urban greenhouses, where fish, such as tilapia, are grown in containers and their waste is used to fertilise plants, such as tomatoes or cucumbers, grown in the same conditions. The water in such systems circulates between the fish and plants, creating an efficient closed ecosystem that reduces water and fertiliser consumption.

Vertical farms, on the other hand, are another innovative model of smart farming that is being actively integrated into urban ecosystems (Kunakh *et al.*, 2021). They involve the use of vertical structures on which multi-tiered systems for growing plants are placed. This allows for significant space savings, which is an important factor in urban environments where land is limited. Such farms use effective growing methods such as aeroponics (a soilless method of growing plants in which the roots of plants are suspended in the air and regularly moistened with a water solution containing nutrients), ensuring maximum productivity in a minimum area. Vertical farms are capable of producing a wide range of crops, from vegetables to fruits, and help reduce the cost of transporting products by localising production. For a better understanding, it is worth comparing productivity indicators for traditional and vertical farming (Table 1).

***Table 1**. Reference productivity indicators for traditional and vertical farming*

Option	Traditional farming (field cultivation)	Vertical farming
Reference production per year (kg)	907,184.7	907,184.74
Labour per kg (man-hours/kg)	0.014	0.066666667
Energy consumption per kg (kWh/kg)	0.575	5.75
Water consumption per kg (l/kg)	250	20
Yield (kg/m^2/year)	4	150.23
Land ratio for production of 1 kg per year (m^2/kg)	0.25	0.006656307

***Note:** man-hours – the number of hours that one person spends on the production of one kilogram of product*
***Source:** F. Moghimi and B. Asiabanpour (2021)*

In other words, vertical farms outperform conventional agriculture in terms of yields, water consumption and land use efficiency. However, they require more energy, which is also an important factor in their economic and environmental assessment. For example, entrepreneur Viktor Shuleshko, founder of Green Future, created one of the largest vertical farms in a bomb shelter in the city of Dnipro (One of the largest vertical farms in Ukraine…, 2024). After losing his previous farm to a rocket attack, he built a new one, 7 times larger, which enables to grow up to 3 kg of greenery per m^2.

In turn, IoT systems for agricultural management are becoming an important element for optimising and automating processes in smart farming. IoT helps to integrate various devices and sensors that collect data on environmental conditions (temperature, humidity, light, soil pH and other parameters), as well as on the condition of plants and animals. This data is used to monitor, forecast and manage agricultural processes in real time, which helps to increase production efficiency and reduce the cost of resources such as water, energy and fertilisers. An important factor in the development of such technologies is the overall growth of the IoT market, which reflects the level of investment and innovation in various industries. In this context, it is useful to consider the projected growth of the IoT market in Europe, as it directly affects the implementation of such solutions in the agricultural sector (Fig. 2).

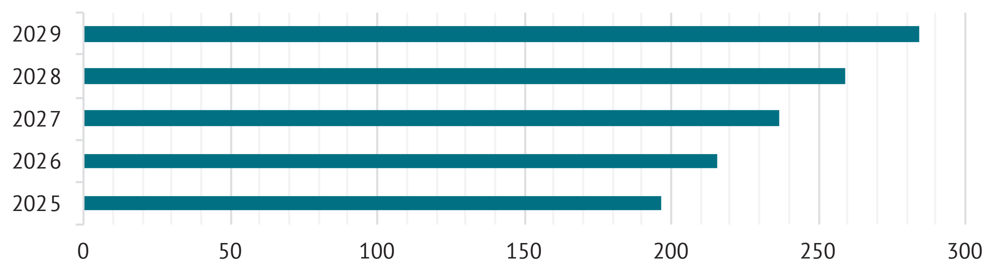

***Figure 2**. Forecasted size of the IoT market in Europe for 2025-2029*

***Source:** Statista (n.d.)*

The forecast shows a steady growth of the IoT market in Europe. It is expected to increase from USD 196.85 billion in 2025 to USD 284.26 billion in 2029, representing a compound annual growth rate of approximately 9.62%. This indicates the active integration of IoT into various industries, including the agricultural sector, where these technologies contribute to increased production efficiency. In general, in urban ecosystems, the use of IoT in smart farming allows for maximum adaptation of agricultural systems to the limited conditions of urban space. IoT can be used to automate watering, temperature and light control in vertical farms or hydroponic systems, making the process of growing plants much more efficient. For example, IoT-based technologies can automatically adjust water and energy consumption depending on environmental conditions, reducing the environmental footprint of agricultural production. The integration of IoT into agricultural management also opens up new opportunities for processing large amounts of data, allowing for crop forecasting, optimising logistics and reducing risks. With the help of IoT systems, farmers can receive analytical reports that allow them to respond quickly to changing conditions and make informed decisions aimed at improving production results and the sustainability of agricultural systems. One of the most promising models is the use of rooftop farms, which allow for the most efficient use of urban spaces. Such farms can be located on the roofs of residential and commercial buildings, as well as on industrial facilities. Not only do they provide access to fresh local produce, but they also help to improve the microclimate, reduce the heat load on buildings, reduce noise and increase air humidity. They can also be integrated with rainwater harvesting systems and solar panels, making them more energy efficient.

In addition, there are urban models of innovative agricultural clusters, such as agro-industrial parks. These are special agricultural parks that combine high-tech greenhouses, agricultural processing centres, crop research laboratories, educational parks and sales markets. Such clusters help to create new jobs, reduce logistics costs, develop small and medium-sized enterprises, and intensify cooperation between the agricultural sector, research institutions and municipal authorities. Thus, the considered smart farming models have their advantages and limitations (Table 2). Each of them adapts to the urban environment in different ways, taking into account factors such as spatial constraints, resource consumption and cost-effectiveness. The choice of the appropriate model depends on specific conditions, including resource availability, local community needs, environmental requirements and economic opportunities.

***Table 2**. Benefits and limitations of smart farming models in urban ecosystems*

Model	Benefits	Limitations
Hydroponics and aquaponics	Reduced water consumption	High cost of system installation
	Fast cultivation	The need for energy resources
	High space efficiency	Difficulty in balancing the ecosystem
	Sustainable process with minimal environmental footprint	
Vertical farms	High yields on small areas	High initial cost
	Reduced transport costs	High energy costs
	Conservation of resources (water, land)	
IoT systems for agricultural management	Increased efficiency through monitoring and automation	Data security issues
	Reduced resource costs	High cost of implementation
	Precise management of agricultural processes in real time	
Rooftop farms	Efficient use of urban space	Limitation of space for placement
	Improving the microclimate	Dependence on building design features
	Access to fresh products	
Agro-industrial parks	Creation of new jobs	High initial investment
	Development of high technologies	Need for government support
	Reduction of logistics costs	Difficulty in coordination between different actors
	Stimulation of the local economy	

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

Thus, the optimal choice of model depends on the specific conditions of the urban environment. Hydroponics and aquaponics models are best suited for confined spaces where production speed and efficient water use are important. Vertical farms are effective in tall cities with limited land space, particularly for growing vegetables and herbs. IoT systems are useful in the context of large farms or innovative agri-parks, where automation and monitoring are required. Rooftop farms are most appropriate for use in highly urbanised cities, where it is important to maximise the use of available space and ensure sustainable development. In addition, agro-industrial parks are promising for regions with a high level of technological development, where it is necessary to create jobs and reduce logistics costs.

The impact of smart farming models on the restoration of territorial communities in Ukraine and the EU. In the modern world, there is an active implementation of smart farming technologies aimed at addressing the problems of growing demand for food, climate change, lack of natural resources and the need to ensure the sustainability of agriculture. The use of technologies such as vertical farms, hydroponics and aquaponics allows crops to be grown in limited space and with minimal water use. Moreover, smart farming plays a key role in increasing the efficiency of the agricultural sector by automating processes, reducing resource use and improving product quality. In particular, IoT technologies allow for precise monitoring of soil conditions, moisture, temperature and other parameters, which contributes to more efficient management of agricultural processes. Another important aspect is the use of AI for crop forecasting and production management, which helps to reduce losses and increase the profitability of agricultural enterprises (Yerzhanova *et al.*, 2021).

In other words, the introduction of smart farming technologies in the agricultural sector is a key factor in increasing production efficiency. To quantify the impact of such technologies on agricultural productivity, an extended model can be used that takes into account various aspects of innovation (Kosinska, 2019). For example, before the introduction of smart farming technologies, the level of production was 100 units. After the introduction of the technology, production increased to 120 units. Implementation costs amounted to 50 units, investment in training – 10 units, and savings from reduced resource use - 5 units. The efficiency is then calculated as follows (1):

$$\mathrm{E} = \frac{(120-100)\times(50+10+5)}{50} \times 100\% = 260\%. \qquad (2)$$

Thus, the effectiveness of the introduction of smart farming technologies can be assessed by increasing productivity per unit of inputs. In the example above, each unit of inputs brought an additional 2.6 units of output, which indicates the high efficiency of such technologies in the agricultural sector. This means that the introduction of smart farming technologies has a significant potential to increase agricultural productivity and also has the potential to have a significant impact on the recovery of local communities. By reducing inputs, improving product quality and creating new jobs, these technologies contribute to economic growth and infrastructure rehabilitation in regions affected by conflict or economic hardship. As a result, smart farming is not only a factor in increasing productivity, but also in stabilising local economies in various countries and regions, such as Ukraine and the EU.

Ukraine has significant potential for the development of smart farming, but the pace of adoption of new technologies can vary significantly depending on the region and level of economic development. In recent years (2020-2025), there has been a trend towards more active adoption of innovations such as vertical farms, hydroponics, aquaponics and rooftop agriculture, especially in economically developed regions. At the same time, a number of regions face low levels of investment, limited resources and a lack of infrastructure, which slows down the pace of smart farming adoption. To better understand the spread of innovations in different regions of Ukraine and their impact on economic development, it is worth considering data on regional economic activity, such as GRP, exports and imports (Fig. 3). This helps to determine which regions have the greatest potential for the development of smart farming technologies and where additional efforts should be focused to improve the efficiency of innovation.

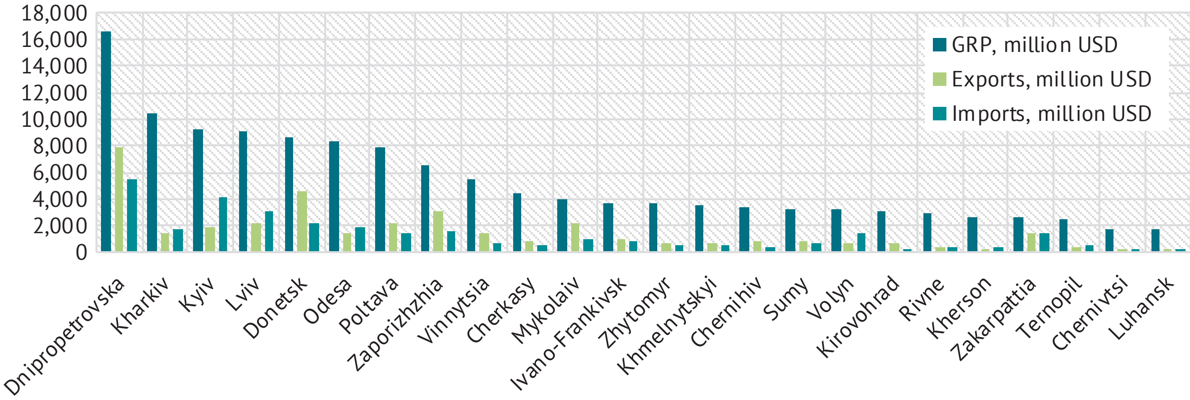

Figure 3. *Regional production and international trade in Ukraine in 2019*
Source: *National Bank of Ukraine (n.d.)*

According to the data provided, the highest GRP values are observed in Kyiv (USD 9,268.5 million), Dnipro (USD 16,550.2 million) and Kharkiv (USD 10,494.4 million) regions. This indicates the high economic potential of these regions, which have developed infrastructure and significant production. Higher GRP also indicates a greater potential for the integration of smart farming technologies, as these regions have more resources for innovation and the development of new agricultural models. At the same time, the highest exports are observed in Dnipropetrovska region (USD 7,907.2 million), which may indicate the importance of this region for foreign trade. In terms of smart farming, high exports in these regions may provide an additional opportunity for the development of agricultural technologies, as the demand for innovative agricultural products abroad may stimulate the development of new technologies.

In addition, in the most economically developed regions, such as Kyiv and Dnipro, imports are much higher (USD 4,112.3 million and USD 5,522.2 million accordingly), which may indicate a dependence on external suppliers to meet the needs for technology, equipment and raw materials. For smart farming, it is important to understand these flows, as imports of technology and innovations can be a key factor for their adoption in Ukraine. Thus, regions with high GRP and exports, such as Kyiv, Dnipro and Kharkiv, have a greater potential for integrating smart farming models, as their economic activity and foreign trade support the development of new technologies. In contrast, less developed regions, such as Chernivtsi or Luhansk regions, may face challenges in adopting such technologies due to limited resources. This also highlights the need to concentrate resources on supporting innovation in less economically developed regions to ensure sustainable development and recovery of communities throughout Ukraine.

On the other hand, the EU is witnessing an active adoption of smart farming technologies, including hydroponics, vertical farms, integration of IoT into agriculture, and the use of drones and AI to optimise agricultural production. Countries such as the Netherlands, Germany and France are leading the way in introducing innovative technologies that can significantly increase production efficiency and reduce the environmental impact of the agricultural sector. The importance of understanding the financing of smart farming technologies in the EU is that it enables to assess the extent to which countries are actively investing in the development and implementation of innovative agricultural practices. The financing system that supports such projects is a key factor for the development of smart farming, particularly in countries that are leading the way. Therefore, the total amount of investment allocated to various areas of agro-innovation, including hydroponics, vertical farms and IoT technologies, should be demonstrated (Fig. 4).

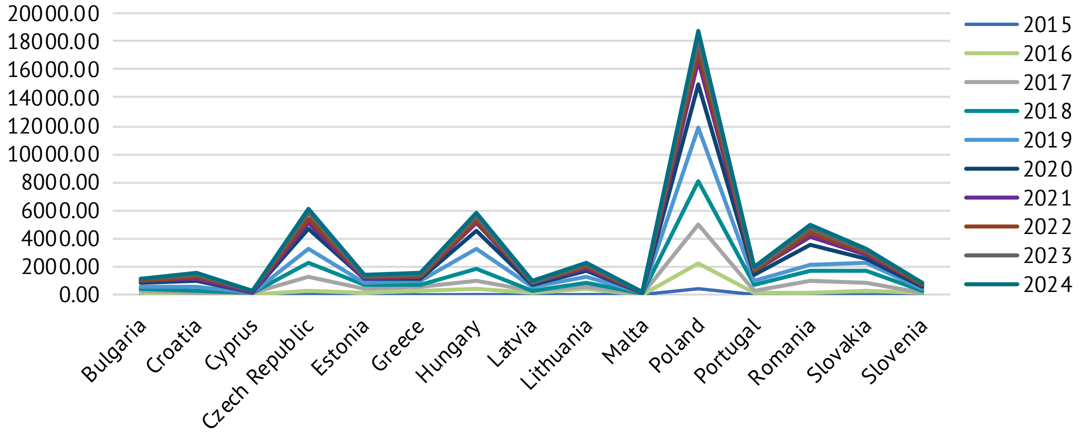

Figure 4. *Total funding from the EU Cohesion Fund for projects in EU countries (2015-2024)*
Source: *European Commission (2025)*

Although these data cover different types of projects, they are important for the introduction of innovative technologies, including smart farming, in the agricultural sector. For example, Cohesion Fund funding grew between 2015 and 2024, exceeding EUR 150 billion in 2024. This indicates sustainable funding for infrastructure and technology development, including smart farming initiatives. It is important to note that it was in the period from 2015 to 2024 that many EU countries increased their investments in innovation, particularly in the agricultural sector. Poland, the Czech Republic, and Romania received the most funding. This may indicate that these countries have significant potential for the development of smart farming projects, as the funding received can be used for innovations in the agricultural sector. For Poland, for example, a significant increase in funding for agricultural projects could facilitate the widespread adoption of smart farming.

Countries such as Malta or Cyprus received much less funding, which may indicate their limited economic potential for large-scale adoption of smart farming technologies. However, even these countries can use the funds to develop small and medium-sized projects in the agricultural sector. Overall, funding from the EU Cohesion Fund plays an important role in the development of innovations, including smart farming technologies. Given the large sums allocated to projects in Poland and the Czech Republic, it can be noted that these countries are actively integrating the latest technologies, including agricultural ones, to support sustainable development. This contributes to the restoration of regional communities and improves economic stability in rural areas, and the inclusion of EU funding can be important for the recovery of local communities.

It is worth noting that smart farm technologies are being actively implemented not only in Ukraine and the EU, but also in many other regions of the world, contributing to the recovery and development of local communities. For example, in Africa, there is a growing interest in implementing innovative agricultural practices. Due to limited water resources and the need to improve food security, the continent is actively developing hydroponics and vertical farms. These technologies make it possible to use limited resources efficiently and provide the population with the necessary products. In turn, Asia, in particular in countries such as Japan, South Korea and Singapore, is witnessing rapid adoption of smart farming technologies. High population density and limited land resources encourage the use of vertical farms and hydroponics. These methods allow for efficient food production in urbanised areas, reducing dependence on imports and improving food security. For their part, South American countries such as Brazil and Argentina are seeing the integration of IoT and drones into agriculture. These technologies help farmers monitor the condition of crops, optimise the use of resources and increase yields. As a result, there is an increase in productivity and an improvement in the economic situation of rural communities.

Overall, the adoption of smart farming technologies has the potential to significantly improve the agricultural sector in various regions of the world, contributing to economic development and the recovery of communities. However, successful implementation depends on access to finance, technological infrastructure and training of local farmers.

DISCUSSION

The results obtained confirm that the integration of IoT into smart farming helps to increase crop yields, reduce water consumption, and optimise the use of land resources, making agriculture more sustainable and efficient. The study by M.K. Pasupuleti (2024) considered the overall impact of IoT on precision agriculture, urban infrastructure, and digital security, with a focus on real-time monitoring and the cybersecurity of IoT ecosystems. That is to say, the results are consistent, as both studies confirm the importance of IoT in the development of the agricultural sector, but the research conducted here specifically focuses on the economic efficiency of smart farming models in urban ecosystems. Similarly, the study by K. Bakirov *et al.* (2024) examined the implementation of IoT in hydroponic vertical farming, demonstrating the effectiveness of dynamic management of water and energy resources based on sensor data, which led to a 50% increase in yield thanks to the integration of smart irrigation and solar photovoltaic panels. In this regard, the current results confirm that IoT is a key factor in increasing the productivity of smart farming, reducing water consumption, and improving energy efficiency. Consequently, the current work emphasises a comprehensive economic analysis of the implementation of technologies in urban ecosystems, whereas the reviewed work focused on the mathematical modelling of resource optimisation.

This research focuses on the economic efficiency of implementing smart farming technologies in urban ecosystems, such as vertical farms and agro-industrial parks, which allows for increased productivity and reduced resource costs. At the same time, the study by A.A. Zhahir *et al.* (2024), in developing a conceptual model for the adoption of technologies in smart urban farming, focuses on the social and economic factors influencing the implementation of innovations in urban agriculture, without considering the technological aspects in detail. In turn, the results of the work by M. Abbas *et al.* (2025) are focused on the application of IoT and cloud technologies to optimise dairy farm management, which shows the effectiveness of sensor technologies in reducing costs and increasing productivity. This aligns with the current results, as in both studies, IoT plays an important role in enhancing the efficiency of agricultural processes, although the research conducted here emphasises the application of technologies in urban agro-systems, while the mentioned study focuses on dairy farming.

This research focuses on the economic models of smart farming, such as hydroponics, aquaponics, vertical farms, and IoT for agricultural management, and has revealed the high efficiency of these technologies compared to traditional agriculture in terms of yield, water consumption, and land use efficiency. The study by A.M. Rosário and A.C. Boechat (2024) confirms the significance of smart technologies for the sustainable development of urban ecosystems, particularly the use of IoT and AI to optimise resources, which corresponds to the main aspects of the current research. On the other hand, the work by J. Procházka and A. Kubacova (2024) analyses the implementation of IoT solutions in the Czech Republic through Smart Post Boxes, which also highlights the effectiveness of technologies for sustainable development, but the research conducted here examines smart farming in the context of various EU countries, and not just the Czech Republic.

The analysis carried out showed that vertical farms demonstrate a yield of 150.23 kg/m² compared to 4 kg/m² in traditional farming, and water consumption was reduced to 20 litres/kg compared to 250 litres/kg in conventional agricultural production. In contrast to the study by C. Pereira de Sá *et al.* (2025), which considers organic farming and strategies for product certification through transparent governance and public procurement, the current research focuses on comparing smart farming models in agro-systems, where the main goal is to increase efficiency and reduce resource costs, rather than certification strategies. Furthermore, according to the results of the current analysis, the integration of smart farming technologies into urban agro-systems contributes to a significant reduction in energy and water consumption, which are key aspects of the sustainable development of urban ecosystems. Whereas the study by G.M. Ostanaqulova (2025) uses regression models and the analytic hierarchy process to assess technological innovations in smart cities, the research conducted here applies economic models to assess the effectiveness of technologies in the agriculture of urban ecosystems, specifically to compare different smart farming models and determine their economic feasibility in the context of different regions of the EU and Ukraine.

The research conducted has shown that the integration of smart farming into urban ecosystems contributes to increased resource efficiency, optimised food security, and the recovery of local communities, particularly through the implementation of IoT technologies and vertical farms. In turn, G.R. Pradyumna and R. Hegde (2024) emphasise the role of smart sensors and devices in improving the monitoring of urban ecosystems within blue-green infrastructures, while also drawing attention to cybersecurity risks and the need to use digital twins for real-time optimisation of urban processes. While the current work focuses on the integration of smart farming into urban ecosystems, the study by X. Kuai *et al.* (2024) highlighted the importance of combining urban data through the development of a Smart City Ontology Framework. This framework provides semantic compatibility for IoT, Building Information Modeling, and Geographic Information Systems in urban management. In this regard, the current research considers the need for data standardisation for the effective implementation of smart farming models, which contributes to increasing the productivity of urban agriculture and the sustainable use of resources.

The results obtained also showed that vertical farms significantly outperform traditional agriculture in terms of land use efficiency – 0.0066 m^2/kg compared to 0.25 m^2/kg, which confirms their competitiveness in urban conditions. This is consistent with the study by M.T. Abdelfatah (2025), which demonstrates that the Vertical Urban Oasis model helps to optimise land resources, ensure sustainable food supply, and promote economic development, although high initial costs and social barriers remain the main challenges. Additionally, the analysis of hydroponics in the current research showed its advantages in urban agricultural production due to minimal water use, automated parameter control, and increased yields. This is confirmed by the work of K. Kueh Yung Shin *et al.* (2023), which presented Smart Grow – an IoT-oriented hydroponic system that provides efficient management of plant water balance. However, unlike the mentioned work, the current research focuses on the economic analysis of the large-scale implementation of hydroponics in urban ecosystems.

The efficiency of using smart farming technologies significantly exceeds traditional agricultural methods; in particular, yields in hydroponic and aquaponic models reach 120 kg/m^2, which is several times higher than under traditional conditions (Poloviy *et al.*, 2024). This indicates the high productivity and economic benefit of such technologies. However, compared to the study by S. Raj *et al.* (2023), which focuses on data integration for smart cities and the optimisation of agricultural services, it should be noted that while these technologies contribute to sustainable development, the issues of efficient use of digital resources and ensuring confidentiality are important for further development. The research conducted also showed that investments in agricultural projects in the EU exceeded EUR 150 billion between 2015 and 2024, with Poland, the Czech Republic, and Romania receiving the most funding. This indicates a significant potential for the development of smart farming in these countries. At the same time, the study by P.-A. Langendahl (2021) noted that in Sweden, the implementation of smart farming promises to reduce costs and increase food security. However, its real effect is often limited, and in the EU, despite large investments, the effectiveness of agricultural initiatives often remains limited and in many cases does not lead to radical changes in traditional production methods (Shahini *et al.*, 2023).

Overall, this research compared the economic indicators of traditional agriculture and smart farming technologies, and the results showed significant advantages of such technologies, particularly in increasing yields, reducing water consumption, and improving land use efficiency. At the same time, the study by N. Khan *et al.* (2024) obtained similar results regarding the high efficiency of smart farming in conditions of urbanisation and limited resources. However, unlike the provided research, the current results analyse in more detail the economic prerequisites for the implementation of such technologies in different regions, particularly in Ukraine. The study by M. Bakhar and E. Evanita (2021) also confirms the benefits of agricultural innovations, particularly in the context of reducing the use of natural resources and increasing productivity. However, unlike their analysis, the current results emphasise the importance of factors such as infrastructure support and the level of investment for the effective implementation of smart farming at the level of urban ecosystems.

Thus, the research results confirm that the implementation of smart farming technologies and models, such as hydroponics, aquaponics, vertical farms, and IoT, significantly increases the efficiency of agricultural production, reduces resource costs, particularly water consumption, and optimises the use of land resources, which are key to the sustainable development of urban ecosystems. Moreover, smart farming is capable of significantly enhancing food security and supporting the recovery of local communities through the integration of modern technologies into the urban environment.

CONCLUSIONS

An analysis of economic models for integrating smart farming into urban ecosystems has confirmed the high efficiency of technologies such as hydroponics, aquaponics, vertical farms, IoT systems, rooftop farms and agro-industrial parks. Vertical farms have shown yields of up to 150.23 kg/m^2, which is higher than traditional farming, where yields are only 4 kg/m^2. Water consumption in vertical farms is 20 litres/kg of production, which is significantly less than the 250 litres/kg in conventional farming. In addition, they occupy only 0.0066 m^2 per 1 kg of produce, which is more efficient than conventional methods that use 0.25 m^2 per 1 kg. Hydroponics and aquaponics also contribute to a significant reduction in water consumption compared to traditional agriculture, ensuring more efficient use of water resources. In addition, IoT systems that optimise agricultural management can reduce energy and water costs, providing better control and efficiency. Rooftop farms make use of limited urban land resources, reducing the need for additional land for agricultural production, and agro-industrial parks provide an opportunity to integrate different agricultural technologies and enterprises in an urban environment. These technologies help to increase productivity, reduce water and energy costs, which are important factors for urban agricultural systems.

The results of the implementation of smart farming technologies in the agricultural systems of Ukraine and the EU have highlighted that this contributes to a significant recovery of local economies, as such technologies reduce resource costs and increase agricultural production. In particular, the comparative analysis showed that in developed regions such as Kyiv, Dnipro and Kharkiv, the introduction of smart farming models such as vertical farms and IoT systems can significantly increase the efficiency of agricultural production. In EU countries such as the Netherlands and Germany, innovative agricultural technologies are being actively used to increase not only productivity but also reduce environmental impact. Investments in smart farming projects in the EU, including through the Cohesion Fund, exceeded 150 billion euros in 2024, which demonstrates support for innovation in the agricultural sector. This demonstrates the high potential for the development of smart farming, which is an important element for ensuring food security and sustainable development of urban agricultural systems in Ukraine and the EU.

The main constraints to the introduction of smart farming technologies and models are high initial costs for infrastructure and equipment, as well as the lack of sufficient technical training among farmers, which can slow down the process of adopting innovations. In addition, the legal and regulatory frameworks to support such technologies need to be modernised, especially in Ukraine. To overcome these barriers, it is recommended to develop state support programmes and subsidies for farmers, increase investments in education and training, and strengthen cooperation between the government, research institutions and business to stimulate innovation in the agricultural sector.

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CONFLICT OF INTEREST

None.

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Економічні моделі інтеграції смарт-фермерства у міські екосистеми

В'ячеслав Шебанін
Доктор технічних наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-0391-396X

Ірина Кормишкіна
Доктор філософії
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0009-0002-9670-2295

Антоніна Дробітько
Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-6492-4558

Анотація. Метою дослідження був аналіз економічних моделей інтеграції розумного землеробства в міські екосистеми та їх вплив на відновлення територіальних громад в Україні та Європейському Союзі. У процесі було проведено детальний огляд сучасних технологій та моделей розумного землеробства, таких як гідропоніка, аквапоніка, вертикальні ферми, а також системи Інтернету речей для управління сільським господарством, дахові ферми та агропромислові парки. Основні результати включали порівняльний аналіз продуктивності традиційного та вертикального землеробства. Він показав, що вертикальні ферми перевершують традиційне сільське господарство за врожайністю (150,23 кг/м^2 проти 4), споживанням води (20 л/кг проти 250) та ефективністю використання землі (0,0066 кг/м^2 проти 0,25). У свою чергу, прогноз ринку IoT в Європі показав стабільне зростання з 196,85 млрд доларів США у 2025 році до 284,26 млрд доларів США у 2029 році, що становить сукупний річний темп зростання 9,62 %. Результати також показали, що інвестиції в сільськогосподарські проекти в ЄС перевищили 150 мільярдів євро між 2015 і 2024 роками, причому Польща, Чехія та Румунія отримали найбільше фінансування, що свідчить про великий потенціал для розумного землеробства в цих країнах. Крім того, визначено, що регіони України з високим валовим регіональним продуктом (ВРП), такі як Київ (9,268,5 млн доларів США), Дніпро (16,550,2 млн доларів США) та Харків (10,494,4 млн доларів США), мають більший потенціал для впровадження технологій розумного землеробства завдяки своєму високому економічному потенціалу та розвитку інфраструктури. Практичне значення дослідження полягає в обґрунтуванні ефективності впровадження технологій розумного землеробства для підвищення продуктивності сільського господарства, оптимізації використання ресурсів та сприяння економічному розвитку міських агросистем

Ключові слова: аграрні інновації; сталий розвиток; цифровізація сільського господарства; гідропоніка та аквапоніка; Інтернет речей

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The role of digital platforms in regulating the cyclicality of agricultural markets in Kazakhstan

Saule Ibraimova*

PhD in Economic Sciences, Professor

Kazakh University of Technology and Business named after K. Kulazhanov

010011, 37A Kaiym Mukhamedkhanov Str., Astana, Republic of Kazakhstan

https://orcid.org/0000-0001-6506-2446

Arhkat Assainov

Master of Science, Senior Lecturer

Kazakh University of Technology and Business named after K. Kulazhanov

010011, 37A Kaiym Mukhamedkhanov Str., Astana, Republic of Kazakhstan

https://orcid.org/0000-0003-3816-8039

Bakyt Bayadilova

PhD, Assistant

Kazakh University of Technology and Business named after K. Kulazhanov

010011, 37A Kaiym Mukhamedkhanov Str., Astana, Republic of Kazakhstan

https://orcid.org/0000-0002-4972-3408

Meiram Begentayev

Doctor of Economic Sciences, Professor

Toraighyrov University

140008, 64 Lomov Str., Pavlodar, Republic of Kazakhstan

https://orcid.org/0000-0001-9688-4370

Saule Kunyazova

PhD in Economic Sciences, Professor

Toraighyrov University

140008, 64 Lomov Str., Pavlodar, Republic of Kazakhstan

https://orcid.org/0000-0002-5538-5839

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Abstract. The purpose of this study was to substantiate the potential of using digital platforms to reduce the cyclicality of agricultural markets in Kazakhstan in the context of the modern transformation of agricultural production. The study used an applied analytical approach covering the period 2020-2024. The economic essence of the cyclical nature of agricultural markets was analysed, the regulatory framework for the management of the agro-industrial complex was investigated, and an empirical

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*Corresponding author

study of the East Kazakhstan and Akmola regions was conducted. In particular, in 2022, the gross volume of agricultural production in the Akmola region reached KZT 976.6 billion, which is 18.6% more than the previous year. In 2024, crop production dominated the region (up to 75% of production), while animal husbandry prevailed in East Kazakhstan (up to 60%). Investment programs were analysed, including the implementation of more than 670 projects with a total value of KZT 3.3 trillion by 2027, as well as the implementation of microcredit under the "Auyl Amanaty" program in the amount of KZT 100.5 billion. Particular attention was paid to the assessment of key digital platforms: Ger Inspector, Qoldau.kz, GeoPard, AgriSupp, which contributed to the reduction of information asymmetry, automation of subsidies, climate risk analysis, and production planning. The practical significance of the study lies in the possibility of using its results to develop regional strategies for the digital transformation of the agricultural sector in order to stabilise markets and strengthen food security

Keywords: sustainable development; technologies; farming; prices; market fluctuation

INTRODUCTION

In the current conditions of agricultural development in Kazakhstan, the search for effective mechanisms for stabilising agricultural markets prone to cyclical fluctuations is of particular importance. Price disparities, uneven production, and limited access to market information pose threats to the economic security of farms and the food system as a whole. At the same time, digitalisation opens up new opportunities for operational data analysis, forecasting supply and demand, and forming transparent product sales channels. Kazakhstan's agriculture remained vulnerable to seasonal and market fluctuations, which made it difficult to maintain stable production and income. R. Gabdualiyeva *et al.* (2024) investigated the potential of digital technologies – Global Positioning System (GPS) navigation, drones, online platforms, and monitoring systems – to increase the efficiency of agricultural production. The authors identified a number of barriers, including unstable internet coverage, a shortage of qualified personnel, a lack of standards, and a low level of digital literacy among farmers. At the same time, the study did not sufficiently reveal the role of digital platforms in smoothing fluctuations in agricultural markets, which required further study.

A low share of digital solutions in Kazakhstan's agriculture constrained its economic efficiency due to outdated technologies and uneven resource use. O. Ryskeldi *et al.* (2024) analysed the impact of six digital tools – including livestock monitoring, cow tracking, drones, parallel driving, telematics, and soil sensors – on over 130 farms. Their findings showed increased productivity, reduced costs, and high returns on investment (up to 400%). However, the study did not explore the influence of these technologies on regulating market fluctuations, stabilising farm incomes, or mitigating seasonal volatility. A low level of digital integration in Kazakhstan's agricultural machinery industry has limited its modernization and competitiveness. M. Sarsembayev *et al.* (2023) examined legal aspects of digitalisation, highlighting the need to update regulations on document management, cybersecurity, the Internet of Things, robotics, and smart systems. However, the study did not assess how such transformation could help mitigate seasonal and market instability in agricultural production. The weak level of investment activity and technical modernization has long restrained the growth of the competitiveness of agricultural production in Kazakhstan.

Limited use of digital technologies, weak infrastructure, and low levels of digital literacy have hindered the development of agricultural production in Kazakhstan (Akhmet *et al.*, 2025). D. Kulanova *et al.* (2025) examined the institutional conditions for digitalisation, analysed state programs, and found that less than 10% of farmers use digital solutions, and support remains patchy. However, the impact of digital platforms on reducing market volatility was not considered, which requires further analysis. Insufficient integration of production participants, weak infrastructure, and limited access to financing have hindered the effective development of cluster models in agriculture in Kazakhstan. A. Tkacheva *et al.* (2024) investigated the potential of agroclusters using the example of the Pavlodar region, confirming the effectiveness of vertical integration and state support. The authors identified the prospects of grain, meat, and dairy clusters, emphasising the role of investment and training. At the same time, they did not consider how digital solutions can affect the reduction of market volatility, which requires further study.

The low level of digitalisation of irrigation systems and the deterioration of infrastructure have hindered the efficient use of water resources in agricultural production in Kazakhstan. Z. Imanbayeva *et al.* (2024) examined the role of state regulation in the implementation of digital technologies and substantiated the effectiveness of "smart irrigation" and agricultural notes, proving that increasing digitalisation by 75% can reduce water consumption by 18%. However, the authors did not consider the impact of digital platforms on mitigating market fluctuations, which requires further analysis. Limited use of financial technologies and low investment activity have hindered the innovative development of agricultural production in Kazakhstan. P. Buzaubayeva *et al.* (2023) analysed the possibilities of using FinTech tools, agricultural lending, and state support to finance digitalisation. The authors noted their ability to increase the efficiency and attractiveness of the sector. However, the impact of these tools on smoothing market fluctuations was not considered, which requires further study.

The purpose of this study was to substantiate the possibilities of using digital tools to reduce fluctuations in demand, supply, and prices for agricultural sector products in the context of modern transformations of the agricultural market of Kazakhstan.

MATERIALS AND METHODS

In the process of the study, an applied analytical approach was used involving qualitative methods of analysis, covering the time period 2020-2024. A theoretical review was conducted on agricultural markets' cyclical nature, its manifestations, and its impact on price stability and food security. Particular attention was paid to the analysis of theoretical approaches to the application of digital platforms in the agricultural sector, with a focus on institutional economics, transaction cost theory, and the paradigm of sustainable development. The research involved content analysis of academic and policy literature, as well as comparative analysis of economic theories relevant to digitalisation in agriculture. The methodology combined qualitative synthesis and structural analysis to identify the key conceptual foundations for the integration of digital platforms in agricultural market stabilisation.

At the empirical level, the agro-industrial complexes of East Kazakhstan – Aitas KZ (n.d.) and the Akmola-Atameken Agro regions – were studied. These companies were selected as the largest and most innovative agro-industrial complexes in their respective regions, which are actively implementing digital technologies and are of strategic importance for the development of the agro-industrial complex. Their socio-economic structure, specialisation in agricultural production, and export level were analysed. For spatial comparison, indicators of the estimated distribution of agricultural production in 2024 were used (Satubaldina, 2024; United States Department of Agriculture, 2025). The analysis revealed differences in the ratio of crop and livestock production, which made it possible to use regional parameters of digital transformation. The study also included an assessment of investment activity in the digital infrastructure of the agricultural sector, in particular within the framework of the implementation of the Agro-Industrial Complex Development Program for 2022-2026 (Food and Agriculture Organisation, 2023). As part of the methodological framework, the study involved an analytical review of six companies from the food industry sector listed on the Kazakhstan Stock Exchange (n.d.). These companies were selected based on official exchange data and examined for structural characteristics relevant to the overall dynamics of the sector. The analysis included a review of corporate documentation, regional affiliation, and stock exchange performance. The selected enterprises included Rakhat JSC (n.d.), Bacchus JSC (n.d.), and Kostanay Flour Company (n.d.). In addition, Tsesna-Astyk Concern JSC (Kazakhstan Stock Exchange, n.d.), Kainar-AKB JSC (n.d.), and Aksaynan JSC (n.d.) were also examined.

Information was systematised on key digital platforms operating in the agricultural sector of Kazakhstan. These include the Unified State Subsidy Information System (Kazakhstan intensively introducing..., 2025) and e-Agriculture. Also analysed were Auyl Amanaty and the Crop Traceability Information System. Additional attention was given to the E-farming Platform and artificial intelligence-driven solutions. The data was collected on the basis of official statistical and analytical materials. Data analysis allowed us to determine the level of their integration into production processes, the impact on reducing information asymmetry, optimising management decisions, and stabilising the market. Based on the results obtained, recommendations were formulated to strengthen the investment attractiveness of digital solutions, and proposals were developed to enhance food security through the formation of regional digital policy.

RESULTS AND DISCUSSION

The cyclical nature of agricultural markets is one of the key characteristics that determines the behaviour of prices, production volumes, and incomes of agricultural producers in the medium and long term. Its essence lies in the periodic repetition of growth and recession phases that arise under the influence of a number of objective and subjective factors – from climatic conditions, seasonality of demand and supply, and fluctuations in resource costs to changes in public policy, prices on world markets, and the availability of technologies. Agricultural products are characterised by high sensitivity to external and internal disturbances, since most of their types have a limited shelf life, significant dependence on weather conditions, and a specific cost structure.

In practice, the cyclical nature of agricultural markets is manifested in price volatility, unevenness of farmers' incomes, and instability of food supply. In years of overproduction, a sharp decline in prices is observed, which reduces the profitability of agricultural production and discourages further investment. On the contrary, in years of deficit, prices increase, which exacerbates social tensions, especially in conditions of limited access to imports or underdeveloped logistics infrastructure. Such unevenness is especially dangerous for countries with a strong agricultural component of the economy, such as Kazakhstan, where the agro-industrial complex plays an important role in ensuring employment, foreign exchange earnings, and food security (Jumabayeva *et al.*, 2023). The economic significance of the cyclicality of agricultural markets lies not only in the impact on producers' profits but also in the broader macroeconomic context. First, the instability of agricultural production complicates the formation of a strategy for the development of the sector, as financial risks increase and incentives for modernization decrease. Second, price volatility affects the availability of food for consumers, especially vulnerable social groups, which is directly related to the level of food security of the state. Thirdly, cyclicality makes it difficult to attract investment in the agribusiness sector, as private capital is focused on predictability and stability of income.

Another feature of agrarian markets is their tendency to so-called "price scissors," when the growth rate of the cost of means of production (fuel, fertilisers, seeds) outpaces the growth of prices for agricultural products (Palamarchuk *et al.*, 2023). This exacerbates imbalances in the agribusiness sector and creates conditions for structural instability. In such conditions, it becomes necessary to find tools to smooth out cyclicality, among which digital platforms are playing an increasingly important role. Their ability to provide prompt access to market information, perform analytics, forecasting, and regional coordination of supply and demand makes it possible to increase the adaptability of market participants to fluctuations (Digital Platforms for Farmers..., 2025). Thus, the cyclicality of agrarian markets is a complex economic phenomenon that has multi-level consequences at both the micro and macro levels. Overcoming it requires not only improving state regulatory instruments but also actively implementing digital solutions that can increase market transparency, reduce risks, and support food security. These aspects are important in further analysing the effectiveness of digital platforms in a regional context.

In modern economic science, digital platforms are considered as a tool capable of transforming the agricultural sector by creating new models of interaction between producers, consumers, government agencies, and investors (Makhazhanova *et al.*, 2024). Theoretical approaches to their application in agricultural production are based on a combination of institutional theory, transaction cost theory, innovative development, and digital economy. They are united by a common understanding that digital solutions are not just a technological update – they change the rules of market functioning, reduce information asymmetry, simplify access to resources, and increase the efficiency of management decisions. According to the theory of transaction costs, digital platforms reduce the costs of searching for information, concluding agreements, and monitoring the fulfilment of obligations. In agriculture, this is manifested through the rapid exchange of data on prices, product quality, weather conditions, logistics, the availability of subsidies, and insurance programs. Such platforms allow agricultural producers to act proactively, rather than reactively, which is especially important in conditions of market instability and climate risks (Rindfleisch, 2019). Examples of such solutions are the AgriTech Farm Management Software, Cropio, and Climate FieldView. Other widely used systems include EOSDA Crop Monitoring. In Kazakhstan, Digital Village also provides tailored technological support for farmers. They provide the opportunity to monitor soil conditions in real time, forecast yields, plan irrigation, optimise fertiliser use, and choose the best time for harvesting, taking into account market trends. Based on this concept, digitalisation reduces risks and increases the efficiency of resource use, allowing for prompt adjustment of production behaviour.

From the standpoint of an institutional approach, digital platforms act as a new type of infrastructure institution that provides conditions for transparent, open, and predictable interaction of all market participants (Matskiv *et al.*, 2025). They create a new ecosystem where transactions take place in the digital space, rather than through traditional chains of intermediaries, which reduces costs and reduces price volatility. These processes are of particular importance in the agro-industrial complex of Kazakhstan, where the territorial fragmentation of producers and the underdevelopment of logistics channels create high barriers to effective communication between market participants. The innovative paradigm considers digital platforms as drivers of technological development that integrate big data, cloud computing, remote monitoring, the Internet of Things, and decision-making systems based on artificial intelligence. In the context of the agricultural sector, this makes it possible to automate the processes of sowing, irrigation, harvesting, yield forecasting, and monitoring the condition of soil and plants. In addition, digital solutions allow the creation of financial support platforms – electronic lending systems, digital agricultural receipts, insurance, and grant support (Acs *et al.*, 2021).

Within the framework of the approach to sustainable development, digital platforms are considered as a tool not only for increasing economic efficiency but also for ensuring social justice and environmental balance. Through access to knowledge, government services, investment resources, and new markets, small farmers are able to compete on a par with large agricultural holdings. This helps reduce regional disparities and ensure food security (Robertsone & Lapiņa, 2023). Thus, digital platforms in the agricultural sector act as a complex multifunctional system that embodies economic, organisational, and technological approaches to increasing the efficiency of agricultural production. Their implementation is not only applied but also strategic for stabilising agricultural markets, minimising cyclicality, and creating sustainable agro-economic models. This study and M.-H. Ehlers *et al.* (2021) started from the same position regarding the importance of digitalisation for the agricultural sector but differed in their emphases. In M.-H. Ehlers *et al.*'s work, digitalisation was considered as a factor in the transformation of agricultural policy, with an analysis of nine policy dimensions, including spatial specificity, cost distribution, and flexibility over time. The authors emphasised the change in policy instruments under the influence of digital technologies. This study focused on the practical aspect of reducing the cyclicality of agricultural markets in Kazakhstan. Digital platforms were considered as a tool for stabilising prices, coordinating supply and demand, and supporting farmers' incomes. The work also took into account barriers to implementation: weak infrastructure, lack of investment, and low levels of digital literacy. While M.-H. Ehlers *et al.*'s study focused on policy transformation, this study focused on market stability.

The approach proposed by R. Abiri *et al.* (2023) was based on a systemic vision of digital agriculture as a set of interconnected technologies (Internet of Things, artificial intelligence, blockchain, and robotics) capable of ensuring productivity and sustainability of production. While the emphasis was on the technological framework and its potential for global application, this study paid more attention to a specific task – reducing price volatility and stabilising the agricultural market in Kazakhstan. Thus, these approaches complement each other: the first from a technological perspective, the second from the point of view of local market risk management. In J. MacPherson *et al.* (2022), digital agriculture was considered through the prism of global policy, legal regulation, and sustainable development goals. The authors structured the analysis in five areas: climate, biodiversity, soils, nutrition, and biomass, supplementing it with future development scenarios. The study had a comprehensive, multidisciplinary nature. In contrast, this study was focused on solving a specific economic problem – stabilising price dynamics in the agricultural market in Kazakhstan. Thus, the work of J. MacPherson *et al.* served as an example of a global policy-analytical review, while this study presented an example of the local application of digital solutions for market adaptation.

The agro-industrial complexes of the East Kazakhstan and Akmola regions play a crucial role in Kazakhstan's agriculture, serving both the domestic market and exports. In 2022, the gross output of agriculture, forestry, and fisheries in the Akmola region reached KZT 976.6 billion (USD 2.09 billion), which marked an 18.6% increase compared to the previous year. Of this amount, 708.09 billion KZT came from crop production (mainly grains), while 264.2 billion KZT came from livestock production, representing 72.5% and 27% of agricultural output, respectively (Azernews, 2023). Akmola is part of Kazakhstan's "grain belt" and is one of the country's leading exporters of wheat, barley, and oilseeds, with up to 50% of production exported (Satubaldina, 2024). In contrast, East Kazakhstan has a more balanced agricultural structure, with a stronger focus on livestock production, especially cattle farming and dairy. Although exact figures for total output in recent years are not available, the region is among the leaders in livestock production and is home to major meat processing and vegetable oil facilities, with 88 active oilseed processing plants. Approximately 30-40% of the region's production is exported, while the rest is consumed domestically (APK-Inform, 2025). The structure of agricultural production in both regions in 2024 is presented in Table 1.

***Table 1**. Estimated distribution of agricultural output by region in 2024*

Region	Crop production	Livestock production	Notes
Akmola Region	70-75%	25-30%	Dominated by grain and oilseed cultivation
East Kazakhstan Region	40-50%	50-60%	Leading in livestock production; well-developed oil industry

***Source:** created by the authors based on A. Satubaldina (2024), United States Department of Agriculture (2025)*

Both regions are actively involved in state support programs, including machinery leasing at 5% annual interest, microcredits at 2.5%, subsidies for imported equipment, loan guarantees of up to 85%, and initiatives in partnership with the Food and Agriculture Organisation. These programs cover tens of thousands of farms, while hundreds of agricultural cooperatives benefit from better access to land and resources. Under the "Auyl Amanaty" program alone, 15,500 microcredits worth KZT 100.5 billion were issued, including to 442 cooperatives, many of which are located in Akmola and East Kazakhstan (Agroberichten Buitenland, 2025a). Thus, regional features of the agro-industrial complex demonstrate the dominance of grain farming in Akmola and livestock in East Kazakhstan. Both regions are deeply integrated into Kazakhstan's agricultural policy and continue to develop through a combination of modernization, export orientation, and active state support.

One of the largest agro-industrial complexes of the East Kazakhstan region in 2020-2024 is the Aitas KZ holding, which includes Aitas Agro. The company is a national leader in poultry farming and occupies key positions in the region both in terms of production volumes and the scale of innovation implementation. The main production facilities are located in Ust-Kamenogorsk, where a large poultry farm operates with an annual capacity of up to 160 thousand tonnes of poultry meat, which provides more than a third of the country's domestic market. The subsidiary Aitas Agro specialises in crop production and cultivates more than 30 thousand hectares of arable land. The main crops are spring and winter wheat, sunflower, and barley. The company is actively implementing digital technologies – in particular, precision farming systems based on yield mapping, modified fertiliser application rates, and GPS navigation. They use the Cropwise and OneSoil platforms to build a map of field productivity, which allows for differentiating approaches to sowing and improvement, taking into account the peculiarities of substantiation and relief. The initiative to introduce precision agriculture was launched by the company's management after completing international business education, which testifies to Aitas KZ's strategic orientation towards innovation (OneSoil, 2023). The company also participates in state programs for the digitalisation of the agricultural sector, in particular within the framework of the National Project for the Development of the Agro-Industrial Complex of Kazakhstan for 2021-2025 (Food and Agriculture Organisation, 2021), which includes subsidising innovations, research and development, and the introduction of "smart" farms. free activities in the field of animal husbandry and crop production, the company has its own meat processing infrastructure: the subsidiary Aytas-MP Limited Liability Partnership provides red meat processing with an annual capacity of 12 thousand tonnes, as well as a separate line for processing poultry meat (25 thousand tonnes/year) (Deloitte, 2021). Thus, Aitas KZ demonstrates an appropriate vertically integrated agribusiness structure with a high level of digitalisation, which to a large extent shapes the agricultural profile of Eastern Kazakhstan and increases the food security of the region and the country as a whole.

And one of the most powerful agro-industrial complexes of the Akmola region, which deserves special attention, is Atameken Agro (n.d.). The company is one of the largest agro-holdings in the region and plays a key role in the grain sector of Kazakhstan. The main production facilities are located within the Akmola and North Kazakhstan regions. The total land bank of Atameken Agro is about 321 thousand hectares of arable land, a significant part of which falls on the Akmola region. Atameken Agro specialises in growing grain and industrial crops, such as soft and durum wheat, barley, rapeseed, flax, mustard, peas, lentils, chickpeas, and buckwheat. Thanks to the introduction of modern agricultural technologies, the company managed to achieve high yield indicators; in particular, in 2024 an increase in barley yield was recorded to 17.3 quintals per hectare, which allowed reducing the cost of production to USD 90 per tonne, while previously this figure was USD 120. The company is actively implementing elements of precision agriculture, in particular variable crop rationing, automated fertiliser application, and the use of satellite monitoring to manage field productivity. To store the harvest, Atameken Agro uses modern elevator complexes and grain drying plants, which allow for effective organisation of storage and further logistics of grain (APK-Inform, 2023). This is especially important, given the company's active export activities. Atameken Agro participates in state support programs, such as Ken Dala and initiatives of the Baiterek holding, receiving preferential financing for updating the technical park and implementing investment projects. The company also joins regional initiatives to modernise the agricultural industry, in particular in the field of implementing digital platforms for agricultural production.

The food industry of Kazakhstan is one of the basic industries that ensure food security, domestic demand, and export potential of the country (Tungyshbayeva *et al.*, 2021; Tleubayev *et al.*, 2024). In the context of economic instability in early 2020, caused by the global pandemic and devaluation fluctuations, this industry has maintained relative stability and demonstrated positive dynamics. Analytical data from the Kazakhstan Stock Exchange and state statistics allow us to assess the key economic indicators of food industry enterprises and outline the main trends in their development. In the first quarter of 2020, the index of physical volume of food industry production was 113.4%, which indicates a real growth in production. The largest increase was recorded in the production of flour (605 thousand tonnes, +7.8%), sunflower oil (66.1 thousand tonnes, +33.3%), and mineral water (104.7 million litres, +13.5%). The Kazakhstan Stock Exchange (2020) listed 6 companies from the food industry sector, with a total market capitalisation of KZT 67.8 billion, representing 0.31% of the total exchange market. The largest share belongs to Rakhat JSC (Almaty), a leading confectionery manufacturer, which accounts for over 91% of the sector's capitalisation and demonstrates strong financial sustainability.

Other listed companies include Bacchus JSC (Almaty), specialising in alcoholic beverages, and Kostanay Flour Mill JSC (Kostanay region), focused on grain processing and flour production. Tsesna-Astyk Concern JSC (Akmola region) (Kazakhstan Stock Exchange, n.d.) is one of the major players in grain storage and trading, while Kainar-AKB JSC (Pavlodar region) manufactures battery components with food industry applications. Another example is Aksaynan JSC (West Kazakhstan region), engaged in bakery and pasta production. However, all companies aside from Rakhat JSC exhibit low trading liquidity and limited capitalisation, which constrains their influence on the broader food industry stock segment. Other issuers, such as Bacchus and Kostanay Flour Mill, had limited liquidity. Financial results indicate stability: the average profitability on net profit is 11.5%. Profits grew due to increased demand for long-term storage products, in particular under quarantine restrictions. At the same time, costs for imported components increased due to the fall in the KZT exchange rate and logistical difficulties. Despite this, the industry maintained its development pace thanks to state support programs, access to financing, and active participation in modernization projects. The food industry is expected to continue to be a stable sector with high demand and potential for export expansion, especially in the value-added processing and distribution segment.

Kazakhstan's agro-industrial sector is undergoing a dynamic transformation driven by the national strategy for digital modernization (Chykurkova *et al.*, 2025). As of 2024, the Ministry of Agriculture provides 93 public services, with 98% of them available online. More than 2.6 million electronic service transactions were completed in the agricultural sector in that year alone, reflecting a high degree of digital integration among farms and agribusinesses (Agroberichten Buitenland, 2025b). A key component of this transformation is the development and implementation of digital platforms and systems that automate subsidy applications, monitor land use, manage livestock, and provide farmers with access to credit and decision-making tools. These systems are helping to reduce bureaucratic barriers, increase transparency, and improve production efficiency. Table 2 below presents the core platforms used in Kazakhstan's agricultural digital ecosystem.

Table 2*. Key digital platforms in Kazakhstan's agricultural sector*

Platform/system	Purpose/function
Unified State Subsidy Information System	Subsidy management and application automation
e-Agriculture	Integrated agro-industrial management system
Auyl Amanaty	Credit and microcredit services for farmers and cooperatives
Crop Traceability Information System	Crop production traceability (under development)
E-farming Platform	Unified digital ecosystem for agro-industrial complex (planned)
Artificial Intelligence-Driven Solutions	Automation and optimisation via artificial intelligence (chatbots, drones, soil analysis)

Source: *created by the authors based on Kazakhstan intends to increase yields in agriculture by introducing digital technologies (2025), Agroberichten Buitenland (2025b)*

Over 200 digital farms across Kazakhstan – including in Akmola and East Kazakhstan – are currently using artificial intelligence-powered drones, GPS-guided machinery, and soil analysis sensors to improve productivity. The government has also outlined ambitious plans for artificial intelligence integration between 2025 and 2026. Projects include chatbots for subsidy automation (reducing human error from 30% to 5%), intelligent soil diagnostics that cut manual labour by up to 80%, and drones capable of reducing crop losses by 25-30% through precision pest control (Kazakhstan intends to..., 2025). Despite this progress, key challenges remain. Limited internet access in rural areas, low levels of digital literacy, and insufficient localisation of digital tools slow adoption. However, the Digital Acceleration for an Inclusive Economy initiative, supported by the World Bank, aims to expand broadband coverage and increase digital access across rural Kazakhstan. Support from the private sector and startup community is also growing. The Astana Hub startup ecosystem has contributed around KZT 4.7 billion (~USD 9.3 million) in agri-tech innovations, driving digital development and job creation in rural areas (Agroberichten Buitenland, 2025b).

This study and that of M.J. Bustamante (2023) are similar in recognising the importance of digital platforms for the agricultural sector but differ in focus. M.J. Bustamante's emphasis was on the process of forming the "value" of the platform in its initial phase – how economic and social orientations are aligned between participants. The study showed how economic arguments dominate in attracting investors. In contrast, this study focused on the practical use of platforms to reduce market volatility in Kazakhstan. The first is about assessing the potential, and the second is about actual impact. The publication by M.T. Morepje *et al.* (2024) examined e-commerce as a mechanism for increasing the sustainability of agriculture in sub-Saharan Africa. It was about access to markets, financial inclusion, and reducing losses. The research was structured around the socio-ecological dimension. Instead, the focus of this study was economic stabilisation – digital platforms here act as a means of regulating supply and demand in the agricultural market of Kazakhstan. A comparison of these two works demonstrates a shift in emphasis from inclusion to regulatory efficiency.

M. Vahdanjoo *et al.* (2025) described how the digitalisation of agriculture emerged as a strategic transformation at the macro level – the integration of technologies along the entire chain "from field to fork" with an emphasis on circularity, sustainable development, and system interoperability. The authors proposed a systemic, interdisciplinary view. In contrast, this study is based on a regional analysis and demonstrates how digital platforms can be used to address a specific problem – the instability of the agricultural market in a particular country. In the work of R. Birner *et al.* (2021), the research interest focused on digital solution providers, their business models, potential market concentration, and challenges for small farmers. The authors applied a theoretical framework, in particular the concept of club goods. This study operates at a different level of analysis – considering the platform as a practical tool for reducing price volatility and levelling the agricultural situation in Kazakhstan. This study and the study by A.S. Suali *et al.* (2024) agreed in recognising digital platforms as a tool for increasing the resilience of agricultural systems but differed in context. In A.S. Suali *et* *al.*, digital solutions were analysed in the context of the COVID-19 pandemic in the United Kingdom as a means of logistical adaptation. This study focused on the long-term stabilisation of agricultural markets in Kazakhstan through the reduction of seasonal and price volatility. The first study is about crisis flexibility; the second is about market stability.

The work of A. Cimino *et al.* (2024) addressed the behavioural factors of the adoption of digital technologies – the authors studied the intentions of farmers even before the implementation of the platform, taking into account the impact of environmental uncertainty and the role of social ties. This study is predictive in nature. In turn, this work captures the already realised effect: digital tools integrated into the agricultural sector have reduced volatility and improved access to information. A.K. Sanders (2022) approached the topic from the legal perspective – the main attention was paid to the risks of monopolisation, data control, intellectual property, and the need to update the regulatory framework. This study, on the other hand, appeals to the economic mechanisms of the influence of platforms – market transparency, access to forecasts, and price stabilisation. If A.K. Sanders's key issues are the regulatory challenges of the digital age, then in this case, practical solutions for agricultural stability. The analysis demonstrates that the cyclical instability of Kazakhstan's agricultural markets remains a significant challenge, influencing both food security and producer sustainability. While regulatory frameworks and strategic programs have aimed to strengthen self-sufficiency since 2014, dependency on imports for key food groups has persisted. The increasing integration of digital platforms – such as subsidy systems, satellite land monitoring, and artificial intelligence-based solutions – has shown clear potential to reduce volatility and enhance transparency in agricultural management (Wrzecińska *et al.*, 2023). Therefore, the expansion of digital tools, particularly in regions like Akmola and East Kazakhstan, is a critical step toward long-term market stabilisation and improved food system resilience.

In the current conditions of market instability in the agricultural sector of Kazakhstan, digital platforms with price forecasting and agricultural analytics functions are becoming one of the key stabilisation tools. They provide agricultural producers with operational data, demand forecasts, climate risks, and price dynamics, which allows reducing the impact of seasonal fluctuations, information asymmetry, and financial losses. One of the most functional platforms in this direction is AgriSupp – an analytical system developed by UkrAgroConsult. It covers grain and oilseed markets, including Kazakhstan, and provides daily operational information, analytical reports, historical databases, trend visualisation, and integration via Application Programming Interface. Thus, farmers, traders, and agricultural companies are able to make informed decisions, relying not only on current prices but also on a forecast model. Another important platform is APK-Inform (n.d.), which provides up-to-date market prices, expert reviews, and analytical materials, which are especially valuable for market participants in the Commonwealth of Independent States countries, in particular Kazakhstan. It acts as a source of timely information for agricultural producers and traders focused on domestic and foreign demand.

Among precision agriculture solutions, the GeoPard Agriculture platform stands out, which, in partnership with Eurasia Group Kazakhstan, provides comprehensive analytics based on satellite images, agrochemical soil analysis, and vegetation indices. It allows you to create task maps for differentiated fertiliser and seed application, which optimises costs and increases yields. Another example is EOSDA Crop Monitoring, a system with artificial intelligence elements that provides analytics on the condition of fields, soil moisture, and weather risks. The platform supports Application Programming Interface integration with other agricultural programs and is aimed at both farmers and traders. It is worth noting the national platform of Kazakhstan – Qoldau.kz, which carries out digital satellite monitoring of 116 million hectares of agricultural land, contributing to land use control, restoration of uncultivated lands, and justification of credit decisions.

A feature of the listed solutions is the availability of application programming interfaces – AgriSupp, GeoPard, and EOSDA provide the ability to connect market and satellite data to farm management systems or regional platforms. State services of the Ministry of Agriculture also cover key areas – subsidies, land registration, and animal identification – but there is less specific information about public integration via Application Programming Interface. Platforms such as the Unified Subsidy System, Qoldau.kz, and Ger Inspector contribute to transparent resource management, reduce administrative burden, and stabilise financial flows. In the B2B solutions market, the most active are UkrAgroConsult, GeoPard, EOS Data Analytics, and national digital operators. In addition to them, start-ups in the field of agro-innovation are developing within the Astana Hub ecosystem, in particular in the areas of blockchain logistics, digital exchanges, and electronic contracts. Although the exact names are not detailed, their presence is confirmed in reports on venture financing. An example of the effective action of digital solutions is the result of the work of Qoldau.kz, which contributed to the return to cultivation of millions of hectares of land, reducing disputes between farms and ensuring predictability in financing. Also, thanks to the Unified Subsidy System, in 2023 the level of abuse in the provision of subsidies was significantly reduced, and the management of funds became more transparent (Arystanbek, 2021).

Regarding investments, in 2025 the volume of financing for the agricultural sector of Kazakhstan amounted to USD 880 million, which is many times higher than the figures for 2024 (USD 262 million). The plan for 2025-2027 provides for the implementation of 677 projects with a total value of KZT 3.3 trillion (~USD 7.1 billion), most of which involve the use of digital technologies. International organisations are also involved in this process (Kazakhstan steps up..., 2025). The Food and Agriculture Organisation supports the implementation of digital solutions through the 2022-2026 Agro-Industrial Complex Development Program. The United States Agency for International Development (USAID) finances projects to increase productivity and inclusion that contain digital components. The European Bank for Reconstruction and Development has traditionally supported the digitalisation of logistics and the modernization of food chains. Together, these tools form an ecosystem of partnerships between the state, business, and international institutions (Food and Agriculture Organisation, 2023).

Official statistics also confirm the dynamism of the digital transition. In the first four months of 2025, KZT 213 billion (~USD 440 million) was invested in the agro-industrial complex, which is 118% more than in 2024 (Temirgaliyeva, 2025). Of the 93 services of the Ministry of Agriculture, 98% are already provided online, and the number of electronic applications in 2024 exceeded 2.6 million (Agroberichten Buitenland, 2025a). This indicates a deep digital integration of the agricultural environment. In addition, the total amount of venture investments in start-ups in 2024 amounted to USD 157 million, part of which was directed at agrotechnology (Omarova, 2025). It is also worth noting the tax and customs incentives that the state provides to accelerate the introduction of modern agricultural equipment. These include leasing at 5% per annum, subsidies from 15 to 40% for the purchase of imported equipment (including drones and robotic complexes), privileges for importing equipment, and participation in special economic zones (Agroberichten Buitenland, 2025b). Astana Hub, as an innovation centre, offers tax benefits to agrotechnology start-ups, including zero Value Added Tax and income tax. At the regional level, initiatives to introduce digital tools are being implemented in the North Kazakhstan, Akmola, Kostanay, and Karaganda regions (Farmonaut, n.d.). Given all of the above, authors can conclude that Kazakhstan is gradually forming an effective digital infrastructure for the agricultural sector. Platforms with analytics, monitoring, and price forecasting functions not only increase production efficiency but also serve as levers of market stabilisation. Thanks to state support, the involvement of international partners, and the development of private initiatives, agricultural digitalisation is becoming the basis of a new model of sustainable agricultural development.

In the work of E.N. Sadjadi and R. Fernández (2023), the digitalisation of the agricultural sector appeared through the prism of systemic challenges in Spain – infrastructural inequality, low digital literacy, and legal restrictions became the main barriers. The authors focused on the need for political will and long-term reforms. Instead, this study demonstrated how digital solutions are already functioning in Kazakhstan as a practical tool for market stabilisation – based on the provided analytics, monitoring, and forecasting. That is, while the first work describes the prerequisites for changes, the second – their implementation in action. In the publication of V. Nianko *et al.* (2021), the classical vision of state support for the agricultural sector prevails – through subsidies, infrastructure projects, and direct participation in regulation. The authors rely on traditional intervention mechanisms. The study under consideration demonstrates a departure from such approaches – through the integration of digital platforms that independently ensure a balance between demand and supply. This shows a shift from administrative to technological support tools.

The experience presented in the work of K. Kosior and P. Młodawska (2024) focuses on building trust in agri-food chains through digital food passports in Poland. The main emphasis is on transparency, data exchange, and product traceability. This study also illustrates the use of platforms in Kazakhstan for the purpose of economic stability – through volatility management and forecasting. That is, platforms act in different roles: in one case, as a communication tool; in the other, as an anti-crisis response mechanism. In the work of V. Borsellino *et al.* (2020), agri-food markets are considered in the context of global megatrends: from trade liberalisation to urbanisation. The authors analyse the impact of global structures, transnational corporations, and political strategies on the transformation of the sector. Against this background, this study looks like an example of a local solution within one country, where transformation is carried out not through macroeconomic reforms, but through the implementation of digital tools in everyday agricultural practice. Summarising the results, it can be stated that Kazakhstan is confidently moving towards creating a sustainable digital infrastructure in the agricultural sector. Digital platforms with analytics, monitoring, and price forecasting functions have become an important tool for stabilising the market and reducing its volatility. The synergy of state support, international financing, and business activity creates a favourable environment for technological change. It is digitalisation, as the study showed, that is becoming the basis of a new model of agricultural development with a long-term effect.

CONCLUSIONS

The study found that digital platforms play a key role in stabilising Kazakhstan's agricultural markets, reducing price and seasonal volatility, increasing the efficiency of agricultural production, and ensuring food security. Empirical analysis, in particular on the example of the East

Kazakhstan and Akmola regions, showed significant regional shifts, accompanied by an increase in production and exports. Thus, in 2022, gross agricultural output in the Akmola region amounted to KZT 976.6 billion (over USD 2 billion), which is 18.6% more than in the previous year. Of this amount, 72.5% was accounted for by crop production, which indicates the leading role of the region in grain production. At the same time, East Kazakhstan is distinguished by developed livestock farming and a significant export share (30-40%), which determines the need for digital solutions for coordinating logistics and pricing. In general, in the first quarter of 2020, the physical volume index of Kazakhstan's food industry production amounted to 113.4%, and in 2025, investments in the agro-industrial complex reached KZT 213 billion, which is 118% more than in 2024. This increase is associated with the implementation of more than 670 projects worth KZT 3.3 trillion by 2027, most of which have a digital component. At the same time, more than 98% of 93 state services in agriculture are already provided online, and the number of electronic applications has exceeded 2.6 million, which indicates a deep digital integration of the agricultural environment.

Digital platforms such as AgriSupp, EOSDA Crop Monitoring, GeoPard, and Qoldau.kz have demonstrated the ability to reduce information asymmetry, predict fluctuations in demand and supply, and increase the accuracy of agronomic decisions. For example, Qoldau.kz provides satellite monitoring of 116 million hectares, facilitating control over land use and financial decision-making. The GER Inspector system helps prevent subsidy abuse, which increases transparency and reduces financial risks. Despite progress, there are barriers – limited internet coverage, low digital literacy, and lack of localized solutions. However, initiatives such as the Auyl Amanaty program (KZT 100.5 billion of microloans for 15,500 applicants) and the activities of the Astana Hub (KZT 4.7 billion of investments in agro-tech start-ups) are creating a favourable innovation climate. The involvement of international partners – the Food and Agriculture Organisation, USAID, and the European Bank for Reconstruction and Development – has strengthened the investment and institutional base for digitalisation. Thus, the results obtained indicate that digital platforms in the agricultural sector of Kazakhstan not only contribute to increasing productivity but also play a stabilising role in counteracting market cyclicality. Their implementation ensures a balance between state regulation and market mechanisms of self-regulation, strengthens food security, and creates the foundation for the long-term sustainability of the country's agri-food system. Prospects for further research include expanding the geography of analysis and conducting a quantitative assessment of the effectiveness of digital platforms using econometric models.

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Роль цифрових платформ у регулюванні циклічності аграрних ринків в Казахстані

Сауле Ібраїмова
Кандидат економічних наук, професор
Казахський університет технологій і бізнесу ім. К. Кулажанова
010011, вул. Кайима Мухамедханова, 37А, м. Астана, Республіка Казахстан
https://orcid.org/0000-0001-6506-2446

Архкат Асаінов
Магістр, старший викладач
Казахський університет технологій і бізнесу ім. К. Кулажанова
010011, вул. Кайима Мухамедханова, 37А, м. Астана, Республіка Казахстан
https://orcid.org/0000-0003-3816-8039

Бакит Баяділова
Доктор філософії, асистент
Казахський університет технологій і бізнесу ім. К. Кулажанова
010011, вул. Кайима Мухамедханова, 37А, м. Астана, Республіка Казахстан
https://orcid.org/0000-0002-4972-3408

Мейрам Бегентаєв
Доктор економічних наук, професор
Університет Торайгирова
140008, вул. Ломова, 64, м. Павлодар, Республіка Казахстан
https://orcid.org/0000-0001-9688-4370

Сауле Кунязова
Доктор економічних наук, професор
Університет Торайгирова
140008, вул. Ломова, 64, м. Павлодар, Республіка Казахстан
https://orcid.org/0000-0002-5538-5839

Анотація. Метою даного дослідження було обґрунтування потенціалу використання цифрових платформ для зменшення циклічності сільськогосподарських ринків Казахстану в контексті сучасних трансформацій сільськогосподарського виробництва. У дослідженні використовувався прикладний аналітичний підхід, що охоплював період 2020-2024 років. Було проаналізовано економічну суть циклічності сільськогосподарських ринків, досліджено нормативно-правову базу управління агропромисловим комплексом та проведено емпіричне дослідження Східно-Казахстанської та Акмолинської областей. Зокрема, у 2022 році валовий обсяг сільськогосподарського виробництва в Акмолинській області досяг 976,6 млрд тенге, що на 18,6 % більше, ніж у попередньому році. У 2024 році в регіоні переважало рослинництво (до 75 % виробництва), тоді як у Східному Казахстані переважало тваринництво (до 60 %). Було проаналізовано інвестиційні програми, включаючи реалізацію понад 670 проектів загальною вартістю 3,3 трлн тенге до 2027 року, а також реалізацію мікрокредитування в рамках програми «Ауйл Аманата» на суму 100,5 млрд тенге. Особлива увага приділялася оцінці ключових цифрових платформ: Ger Inspector, Qoldau.kz, GeoPard, AgriSupp, які сприяли зменшенню інформаційної асиметрії, автоматизації субсидій, аналізу кліматичних ризиків та плануванню виробництва. Практичне значення дослідження полягає в можливості використання його результатів для розробки регіональних стратегій цифрової трансформації сільськогосподарського сектору з метою стабілізації ринків та зміцнення продовольчої безпеки

Ключові слова: сталий розвиток; технології; сільське господарство; ціни; ринкові коливання

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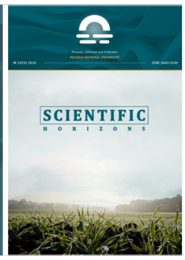

Internal control and cost management systems in agricultural enterprises: A case study of enterprises in the Karaganda region

Rakymzhan Yelshibayev

PhD in Economic Sciences, Professor
Narxoz University
050035, 55 Zhandosov Str., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0001-7119-7400

Maxat Kulubekov*

PhD in Economic Sciences, Associate Professor
Kostanay Engineering and Economics University named after M. Dulatov
110007, 59 Chernyshevsky Str., Kostanay, Republic of Kazakhstan
https://orcid.org/0000-0003-1123-1085

Zulfiya Arynova

PhD in Economic Sciences, Professor
Toraighyrov University
140008, 64 Lomov Str., Pavlodar, Republic of Kazakhstan
https://orcid.org/0000-0003-0123-6667

Svetlana Zolotareva

PhD in Economic Sciences, Associate Professor
Toraighyrov University
140008, 64 Lomov Str., Pavlodar, Republic of Kazakhstan
https://orcid.org/0000-0001-8784-6153

Alfiya Baktiyarova

Master of Sciences, Senior Lecturer
Narxoz University
050035, 55 Zhandosov Str., Almaty, Republic of Kazakhstan
https://orcid.org/0000-0001-5170-9536

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Abstract. The aim of the conducted study was to examine the features of internal cost control and management in agricultural enterprises in the Karaganda region, Republic of Kazakhstan. The set objective was achieved through a contextual and comparative analysis of three (N = 3) agricultural enterprises in the Karaganda region, selected through stratified sampling: "Agrofirma Zhanibek", "Karaganda Agro Invest-T", and "Shakhtyorskoe". The calculation of the point-biserial Pearson correlation coefficient

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**Corresponding author*

(r = 0.43) revealed a moderate positive correlation between the size of an agricultural enterprise and its readiness for digitalisation of internal cost control and management. A strong negative correlation (r≈-0.98) was also identified between the level of enterprise digitalisation and the speed of report preparation. The comparative analysis of the systems at the agricultural enterprises revealed a positive impact of digitalisation of internal cost control and management on production efficiency, expressed through a 25-30% reduction in labour costs for manual auditing and repeated checks, a 40-50% acceleration in report generation, and a reduction in the likelihood of errors and penalty charges by 1-2% of the enterprise's total budget. According to Kurt Lewin's theoretical model, the enterprises were at different stages of transformation: while "Karaganda Agro Invest-T" was at the preparatory stage, "Agrofirma Zhanibek" and "Shakhtyorskoe" had made the transition to using digital cost control and management tools but required consolidation of the achieved results. The enterprises were advised to plan cost control and management considering regional specifics, to assess the current cost status in order to evaluate the efficiency of available resources, and to implement a multi-component management accounting system. The obtained data could be used for the modernisation of the cost control and management system, which would increase the competitiveness of agricultural enterprises in the Karaganda region

Keywords: government subsidies; sustainable development; agroclimatic modelling; information technology; modernisation

INTRODUCTION

Given the high resource intensity of agricultural enterprises, there arose a need to improve the efficiency. One of the key ways to achieve this goal was the development of an effective internal cost control and management system. The absence of such a system indicated that the chosen topic was relevant, and the results obtained could be used to improve the productivity and performance of agricultural enterprises. I. Yatsiv and S. Yatsiv (2024), in the study, stated that cost control and management was a prerequisite for the effective development of agricultural enterprises. The cited experts, in particular, emphasised that the relationship between cost management and the productivity of agricultural enterprises was moderated by the reduction in the cost of individual production operations, improvement in the quality, and subsequent enhancement of competitiveness. W.F. Abobatta and F.W. Fouad (2024) pointed out the link between cost management and the sustainable development of agricultural enterprises. According to these authors, the connection existed because internal control helped optimise expenses, thus bringing agricultural enterprises closer to the rational use of available resources. H. Abdelrady (2024) noted that internal control and cost management increased the attractiveness of agricultural enterprises for both national and international investors. The investment attractiveness of agricultural enterprises was enhanced due to the fact that cost control and management fostered an atmosphere of trust between parties, who then received complete and objective information for making effective strategic decisions. A similar idea was expressed by C. Khadka *et al.* (2024), who studied the role of cost control in the management system of an agricultural enterprise. The researchers put forward the idea that such control created a system of economic security for the enterprise, improving its reputation among potential investors.

N.L. Khomiuk *et al.* (2022) emphasised that cost control should be carried out at all management levels, including at the enterprises and at the points of cost origin. Based on this concept, the cited authors proposed a multi-level model in which the choice of control tools and methods depended on the objectives and expected outcomes of management, enterprise resources, management functions, and other factors. O. Pavelko *et al.* (2024) used a linear regression model to confirm a statistically significant correlation between the discount rate and the volume of bank investments in the agricultural sector. The existence of such a correlation highlighted the importance of streamlining the internal expenditure control system as a source of information about the financial status of an agricultural enterprise. E. Raji *et al.* (2024) also insisted on the need to develop a new cost control and management system for agricultural enterprises that would incorporate previously unaccounted climate, technological, or market factors. The researcher emphasised that the importance of such a model was due to the rapid development of the agricultural sector of the economy, which, if effectively integrated into the international economic system, produced more products than needed for domestic consumption. Thus, several conceptual models and approaches to cost management were proposed, taking into account the contextual realities of agricultural enterprise development.

According to S. Suieubayeva *et al.* (2022), the development of the agricultural sector was one of the strategic priorities of the Republic of Kazakhstan. The mentioned authors pointed out that this development involved, in particular, the rational use of available resources, which was fully aligned with the country's "Sustainable Development Agenda". G. Abdikerimova *et al.* (2024), in the comparative analysis, emphasised the growing demand for cattle and poultry meat as one of the drivers of the development of Kazakhstan's agricultural sector. Such demand indicated the need for a systematic approach to accounting and controlling the resources of agricultural enterprises. D. Kangalakova *et al.* (2025) proposed the idea that the introduction of a universal accounting system could be effective in controlling not only material but also intangible resources, such as human capital. Such a control system would provide a systematic approach to resource accounting and planning with the aim of ensuring the sustainable development of agricultural sector enterprises.

Based on the data analysed, there was no unified conceptual model of internal cost control and management in academic sources that could ensure the sustainable development of agricultural enterprises. The absence of such a model underscored the relevance of research aimed at studying the specifics of cost control and management in the national sector. Possessing significant agricultural potential, the Republic of Kazakhstan could benefit from the development and implementation of a multi-component accounting and analysis system. Thus, the objective of this study was to analyse the features of cost control and management systems in the agricultural sector of the Republic of Kazakhstan. The study's tasks included examining case studies of individual agricultural enterprises in the Karaganda region, identifying the factors influencing cost accounting and control strategies, and developing recommendations to improve the effectiveness.

MATERIALS AND METHODS

The study, conducted between January and June 2024, included the use of several analytical methods, including the case study method. Using this method, a sample was compiled, containing three (N = 3) agricultural enterprises of the Republic of Kazakhstan: Limited Liability Partnership (LLP) "Agrofirma Zhanibek", LLP "Karaganda Agro Invest-T", and LLP "Shakhtyorskoe". Given the weak information and communication component in the strategies of the selected enterprises, data on the listed enterprises were taken from sources such as State Procurement of the Republic of Kazakhstan (2024), the National Information and Analytical Centre (n.d.), and Statsnet (n.d.). The use of stratified sampling implied the inclusion of cases that met the following selection criteria: the agricultural enterprise was registered or operated in the Karaganda region of the Republic of Kazakhstan; the enterprise had an internal cost control and management system; and information on the cost control and management system of the enterprise was publicly available. Non-compliance with one or more of these criteria served as the exclusion criterion from further analysis. To examine the cases, a multi-structured analytical framework was developed, including such key components as enterprise profile, cost management, and internal control. The analysis also took into account the obstacles faced by the selected enterprises in implementing cost control and management.

A COSO analysis was carried out to identify the enterprises' readiness to implement information technologies (IT) in cost control and management. Readiness was assessed based on the following parameters: Control environment – reflected in the availability of job descriptions, the number of IT-related training sessions conducted, and the existence of internal IT security policies; Risk assessment – seen in the existence of procedures for regular IT audit checks and the use of vulnerability analysis tools for IT-based cost control systems; Control activities – expressed in the number of implemented automated cost control procedures, the level of document workflow automation, and the availability of electronic access rights and data access control systems; Information and communication – reflected in the presence of an integrated IT system for interdepartmental data exchange and the regularity of automated report distribution; Monitoring – in the form of the frequency and completeness of internal audits using IT systems, the presence of automatic alerts for inconsistencies or deviations from budget limits, and reports on IT implementation monitoring results in cost control. During the comparative analysis, attention was paid to which elements of cost control and management had already been implemented at the selected enterprises, and which required further implementation or refinement. During the analysis, the point-biserial Pearson correlation coefficient was also calculated using formula (1):

$$r_{pb} = (M_1 - M_o)/s \times \sqrt{\frac{pq}{n}}, \qquad (1)$$

where M_1 – mean value of the quantitative variable in the group with $Y = 1$; M_0 – mean value of the quantitative variable in the group with $Y = 0$; s – standard deviation of the quantitative variable X across the entire sample; p – proportion of observations with $Y = 1$; q – proportion of observations with $Y = 0$, i.e., $q = 1 - p$; n – total number of observations.

The Pearson correlation coefficient, calculated using Microsoft Excel, was used to determine the potential relationship between the size of the agricultural enterprise and its readiness to implement IT in internal cost control and management, as well as between the use of such technologies and the effectiveness of internal control and management, expressed in the speed of enterprise activity reporting. The recommendations proposed in the study were considered within the paradigm of Kurt Lewin's model, which assumes that the transition to a new cost control and management system is a multi-stage process. The study identified the transformation stages at which the selected enterprises were positioned and proposed strategies for progressing to a higher level.

RESULTS

Features of control and management of costs of agricultural enterprises in Kazakhstan. As one of the cases, LLP "Karaganda Agro Invest-T" was examined – a small enterprise registered in 2020, whose main activity is the processing and preservation of meat. The study of data on "Karaganda Agro Invest-T" made it possible to conclude that the main factors influencing the enterprise's cost management were its relatively small size – up to 5 employees – as well as financial risks in the form of tax arrears and property seizures (National Information and Analytical Centre, n.d.). The case indicated that the selected agricultural enterprise needed the implementation of basic accounting systems and optimisation of production processes. The proposed changes would help optimise the enterprise's expenditures, thereby increasing its efficiency and competitiveness.

The main areas of activity of LLP "Zhanibek-Aidos" are crop production and animal husbandry, which imply the presence of numerous factors influencing production cost management (State Procurement of the Republic of Kazakhstan, 2024). Among these factors, in particular, were seasonal and price fluctuations in raw materials. The identified types of fluctuations suggested that the agricultural enterprise in question should plan its expenses more carefully so that seasonal profits could at least partially offset off-season losses. The activity analysis made it possible to conclude that, as of 2025, LLP "Zhanibek-Aidos" also needed supplier diversification to reduce seasonal and other risks. A diversified supplier network required revision of the existing cost control and management system to achieve optimisation and ensure sustainable development in the context of economic uncertainty.

Registered in 2001, the agricultural enterprise "Shakhtyorskoe" is engaged in the production and sale of agricultural seed crops, the cultivation of potatoes, as well as cereals, legumes, and oilseeds. As of 2025, the area of cultivated land amounted to 35 thousand hectares, and the total number of employees was 250 (Statsnet, n.d.). Similar to LLP "Zhanibek-Aidos", the main challenges for LLP "Shakhtyorskoe" were a strong dependence on weather conditions and the need for modern equipment and machinery to reduce costs. Given these specifics, it was concluded that the agricultural enterprise in question required the implementation of monitoring systems, including technologies for forecasting weather conditions and planning agricultural work in the context of cost reduction. It was also established that LLP "Shakhtyorskoe" required regular maintenance of machinery, which could reduce unplanned expenses. The COSO analytical tool helped identify the elements that determined the selection and application of internal control and resource management tools for agricultural enterprises in the Karaganda region. In the study of digital tools for cost control and management, emphasis was placed on the progress already achieved, as well as on the elements requiring further strengthening. The results of the comparative analysis are presented in Table 1.

***Table 1**. COSO analysis of digitalisation of internal control systems and cost management of individual agricultural enterprises of the Karaganda region*

Component	Examples
1. Control environment	Zhanibek Aidos: Presence of an internal audit department; a policy for segregation of duties; regular training sessions for the accounting and IT departments. Karaganda Agro Invest-T: Documented instructions for expenditure and procurement checks; an approved regulation for contract verification; the head of the finance department is responsible for budget execution. Shakhtyorskoe: All decisions are made by the director; the control policy is not formally documented; no internal auditor.
2. Risk assessment	Zhanibek Aidos: Annual analysis of budget overrun risks is conducted; stress scenarios are planned in case of fluctuations in fuel and lubricants prices. Karaganda Agro Invest-T: Risk assessment is conducted informally; relies on the experience of the chief accountant. Shakhtyorskoe: Risk assessment is not carried out as a separate procedure.
3. Control activities	Zhanibek Aidos: Dual verification of all invoices through ERP and automatic control of limit overruns. Karaganda Agro Invest-T: Paper-based dual verification + director's approval; transition to BAS: Agro is planned. Shakhtyorskoe: Only visual document verification by the accountant.
4. Information and communication	Zhanibek Aidos: SAP ERP integration with cloud storage; employee access to reports via a mobile app; regular distribution of instructions. Karaganda Agro Invest-T: Reports are prepared manually in 1C and Excel; as data volume increases, the risk of errors also rises. Shakhtyorskoe: Reports are prepared only on paper or in Word.
5. Monitoring	Zhanibek Aidos: Ongoing internal audit, monthly monitoring of budget deviations. Karaganda Agro Invest-T: Expenditure monitoring is conducted quarterly; no automatic overspending alerts. Shakhtyorskoe: Monitoring is conducted only at the end of the year for reporting to the tax authority.

Source: *compiled by the authors based on N. Kamalova and L. Xu (2024), A. Bekbossinova and R. Doszhan (2025), National Information and Analytical Centre (n.d.)*

Based on Table 1, it was concluded that "Zhanibek Aidos" demonstrated high maturity of the control environment: there was internal auditing, segregation of duties, and a data protection policy. For "Karaganda Agro Invest-T", this environment was formed more through internal rules and the responsibility of the accounting department – without IT tools, the risks of the "human factor" remained. "Shakhtyorskoe" effectively had no formalised control environment: control was concentrated in the hands of a single person – the director – which increased the risk of errors and misconduct. In terms of risk management, "Zhanibek Aidos" carried out full analyses of overspending and budget violations – which allowed management actions to be taken in advance. "Karaganda Agro Invest-T" still did this intuitively, relying on the chief accountant's experience. "Shakhtyorskoe" did not formally assess risks and responded to deviations only after the fact. In the context of control activities, a clear difference between the selected enterprises was also observed. "Zhanibek Aidos" had automated key stages of control – spending limits and dual checks were performed within the ERP system, minimising manual data entry (National Information and Analytical Centre, n.d.).

In "Karaganda Agro Invest-T", control was still entirely paper-based, which created excessive administrative costs and increased the risk of errors. In "Shakhtyorskoe", control activities were minimal: the accountant checked everything manually, increasing the likelihood of undetected errors. In the information and communication domain, "Zhanibek Aidos" demonstrated high speed and transparency of data exchange – ERP was integrated with the cloud, and staff could monitor indicators online. "Karaganda Agro Invest-T" continued to use Excel and 1C without a unified interface – making it difficult to quickly prepare a consolidated report. LLP "Shakhtyorskoe" used paper-based reporting, reducing the speed of managerial decision-making. Significant differences were also noted in how monitoring was conducted in the selected agricultural enterprises. In "Zhanibek Aidos", regular internal audits and budget monitoring were organised every month, allowing for prompt deviation management. In "Karaganda Agro Invest-T", monitoring occurred once per quarter, without automatic alerts on overspending. In "Shakhtyorskoe", monitoring was nominally carried out once a year – only to comply with tax authority requirements.

Thus, agricultural enterprises in the Karaganda region demonstrated different approaches to internal control and cost management. These differences were also evident in the choice and intensity of use of digital platforms and tools. The existence of such distinctions suggested varying effectiveness in internal cost control and management among agricultural enterprises in the Karaganda region.

Internal control and cost management, using the example of individual agricultural enterprises in the Karaganda Region. The agricultural enterprises included in the sample differed significantly in terms of employee numbers, cultivated land areas, and other quantitative indicators. The identified differences suggested a potential correlation between certain quantitative enterprise indicators – particularly size – and the likelihood of implementing digital technologies for internal cost control and management. The point-biserial Pearson correlation coefficient was calculated for the selected agricultural enterprises. The resulting coefficient was $r = 0.43$, indicating a moderate positive relationship between enterprise size and its readiness to implement digital technologies for internal cost control and management. Compared to small enterprises, medium and large agricultural producers were more likely to implement digital solutions and platforms for internal cost control and management. A subsequent digital analysis was conducted to identify potential correlation between the level of digitalisation of the enterprise and the effectiveness of cost control, as reflected in the average time required to prepare operational reports. The results of the comparative analysis of the impact of digitalisation level on the duration of report preparation are presented in Table 2.

***Table 2**. Impact of the level of digitalisation on the duration of reporting in the period from January 1 to June 30, 2024*

No.	Enterprise	Level of digitalisation (index, 0-1)	Report preparation time (working days)
1	LLP "Zhanibek"	1	6
2	LLP "Karaganda Agro Invest-T"	0.5	10
3	Shakhtyorskoe LLP	0.2	11

***Note:** when determining the level of digitalisation of the enterprise, a progressive scale was used, on which "0" meant a complete absence of digitalisation, and "1"* meant *digitalisation of all processes of internal control and cost management of the enterprise*

***Source:** compiled by the authors based on A. Tkacheva et al. (2024)*

Based on the data in Table 2, the relationship between enterprise digitalisation and the effectiveness of cost control and management was confirmed. The quantitative expression of this relationship was determined by calculating the point-biserial Pearson correlation coefficient, which for the given sample amounted to -0.98 ($r \approx -0.98$). The identified negative correlation indicated that as the level of automation and implementation of dual control tools increased, the time required for report preparation decreased, thereby improving the efficiency of cost management. The highest level of automation and digitalisation was observed at the enterprise "Zhanibek": in 2023-2024, an SAP ERP system was implemented, electronic document management was established, and a payment calendar was introduced to automate treasury operations (State Procurement of the Republic of Kazakhstan, 2024). As a result, the average time for preparing management and financial reports was reduced from approximately 10 working days to 5-7 days, representing an acceleration of 40-50%. In addition, automation of invoice approvals reduced labour costs for manual checks and dual verification of documents by approximately 25-30%, calculated in person-days per month.

At the enterprise "Karaganda Agro Invest-T", according to the National Information and Analytical Centre (n.d.), a full-fledged ERP platform had not yet been implemented, although a transition to the BAS: Agro system was under discussion. Currently, cost control was carried out mainly manually using standard accounting software (1C). The lack of automation resulted in a longer reporting cycle – on average 9-10 working days – and a higher risk of errors and invoice approval delays compared to "Zhanibek". "Shakhtyorskoe" also had not yet implemented an integrated digital platform. Cost control and auditing were carried out through traditional dual document checks and periodic internal audits, but without the use of automated analytical tools (Statsnet, n.d.). Consequently, the longest duration of management report preparation was observed – on average 10-12 working days – along with a risk of cost duplication due to the shortcomings of paper-based accounting.

The comparative analysis helped identify the key advantages of using modern digital platforms, including SAP and BAS: Agro, for internal cost control in agricultural enterprises. The calculations indicated that automating cost control helped reduce labour costs for manual audits and repeated checks by 25-30%. Compared to manual data processing, the use of digital platforms helped accelerate report preparation by 40-50%. A decrease in the probability of errors and penalty accruals by 1-2% of the total enterprise budget was also observed. Thus, the conclusion was made regarding the economic feasibility of using digital platforms to ensure internal cost control in agricultural enterprises. A comparative analysis of the internal control systems of the enterprises was also carried out, taking into account the strengths and weaknesses. The comparison aimed primarily to identify key barriers to the use of modern internal control systems in the context of the selected agricultural enterprises. The result of the analysis is presented in Table 3.

***Table 3**. Comparative analysis of cost control and management systems at LLP "Karaganda Agro Invest-T", "Zhanibek-Aidos", and "Shakhtyorskoe", Karaganda Region, Republic of Kazakhstan*

Criterion	LLP "Karaganda Agro Invest-T"	LLP "Agrofirma Zhanibek"	Shakhtyorskoe LLP
Cost Management Approach	Mainly manual and accounting, no automation	Partially automated, seasonal budgeting	Management accounting system, technology orientation
Main challenges	Financial restrictions, arrests and debts, lack of investment	Fluctuations in fuel and seed prices, dependence on subsidies	Risks of weather conditions, equipment wear and tear, complex logistics
Total annual budget	120 million tenge	350 million tenge	500 million tenge
Total annual costs	100 million tenge (83% of the budget)	310 million tenge (89% of the budget)	420 million tenge (84% of the budget)
Cost structure			
Material resources	60 million tenge (60% of costs)	180 million tenge (58% of costs)	230 million tenge (55% of costs)
Fuel and lubricants	20 million tenge (20% of costs)	80 million tenge (26% of costs)	120 million tenge (29% of costs)
Remuneration	15 million tenge (15% of costs)	35 million tenge (11% of costs)	50 million tenge (12% of costs)
Other expenses (repairs, rent, taxes)	5 million tenge (5% of costs)	15 million tenge (5% of costs)	20 million tenge (4% of costs)
Type of cost control	Basic (accounting for direct and indirect costs, control of payments)	Seasonal plan-fact analysis, subsidies, financial statements	Planned analytical accounting, depreciation accounting, scheduled preventive maintenance of equipment
Financial planning	Minimal, no investment planning	Partial, taking into account seasonality and government support	Advanced, includes crop profitability analysis
Current solutions to reduce costs	Reducing fixed costs, seeking support	Use of state programs (Qoldau), change of suppliers	Implementation of agrotechnologies, digital field maps, agronomic planning
Recommended steps	Implementation of basic management accounting, digitalisation	Expansion of automation, staff training	Environmental, Social, and Governance reporting, crop profitability monitoring, digital farming

***Source:** compiled by the authors based on State Procurement of the Republic of Kazakhstan (2024), National Information and Analytical Centre (n.d.), Statsnet (n.d.)*

From Table 3 it is evident that the universal problems of cost control and management in agricultural enterprises include difficulties in accessing finance, lack of accounting automation, staffing shortages, rising prices for key resources, dependence on weather and climate conditions, and challenges in subsidy reporting. Understanding these universal challenges helps develop effective strategies for creating, implementing, and maintaining the efficient functioning of internal cost control and management systems in agricultural enterprises. A comparative analysis of agricultural enterprises LLP "Karaganda Agro Invest-T", LLP "Agrofirma Zhanibek", and LLP "Shakhtyorskoe" shows that the effectiveness of cost management directly depends on the scale of business, level of automation, and nature of production activities. Small enterprises generally use simplified accounting methods with minimal resources and limited opportunities to invest in digital solutions (Pylypenko *et al.*, 2025). In contrast, larger farms strive to implement seasonal budgeting, management accounting, monitoring systems, and digital field maps, which allow for more precise planning and optimisation of production costs (Zagurskiy *et al.*, 2024). All companies face common challenges – rising resource prices, staffing shortages, dependence on weather conditions, and complications in subsidy reporting. The most effective solutions include digitalisation, participation in state support programmes (e.g., Qoldau.kz), development of financial control systems, and staff training in cost planning and analysis. Thus, it was found that the intensity of digital technology implementation into internal cost control and management systems partly depends on the size and turnover of an agricultural enterprise. Active use of IT should be considered a long-term investment in improving enterprise management efficiency. Increased efficiency is reflected in reduced time spent on completing and verifying documentation, reduced organisational costs, and minimised risk of errors that lead to financial losses.

Recommendations for the implementation of a system for monitoring and managing the costs of agricultural enterprises in the context of the Karaganda region. Based on the analysis of individual agricultural enterprises in the Karaganda region, recommendations were developed for the implementation of internal cost control and management systems. One of the key recommendations is to take into account the specifics of the Karaganda region, characterised by an arid climate, which implies additional costs for irrigation and moisture retention. It is also proposed to consider the geographical remoteness of the region and related logistics costs. The remoteness of some agricultural enterprises also implies the need for local processing of agricultural products, the establishment of which requires short-term investments but could reduce future costs (Mukhamediyarova *et al.*, 2025). A distinctive feature of the studied region is the development of livestock farming, which requires constant control of the feed base and expenses for the maintenance of cattle. As with local processing, livestock development in the region implies substantial simultaneous investments, the effective planning of which can ensure the long-term profitability of enterprises. A detailed study of the region's specifics during cost planning and accounting can be conducted using tools such as ABC analysis, which categorises costs by the impact on total production costs, and XYZ analysis, which identifies predictability and stability of consumption or supplies, for example, seasonal fluctuations in feed. Another recommended analytical tool is agroclimatic modelling, which involves the use of meteorological station data, satellites, and geographic information systems to forecast yields and plan costs, including consideration of adverse climatic factors.

Agricultural enterprises in the region are also advised to analyse the current state of costs to determine the main categories. In the agricultural sector of the economy, the main expenses typically include costs for seed purchase; purchase, maintenance, and repair of machinery; rent of agricultural and production areas; employee salaries; and logistics operations (Zakharchuk *et al.*, 2019). Understanding the main costs enables agricultural enterprises to conduct strategic planning and maintain sustainable development even in conditions of economic uncertainty (Lupenko *et al.*, 2021). It is also recommended to analyse the current state to identify bottlenecks and inefficient links in the production and supply chain and remove or replace such elements where possible. Comparative analysis suggests that certain agricultural enterprises in the Karaganda region may benefit from the creation of a multi-component management accounting system. The proposed accounting system involves the implementation of responsibility centres, i.e., allocation of costs by departments and types of activity. In such a system, the normative method of cost accounting also plays a key role – that is, comparing planned and actual expenses. Comparative accounting helps identify sources of overspending and revise enterprise operations to avoid unnecessary costs. Thus, the proposed management accounting system is based on variance analysis – the regular identification of overspending causes and planning strategies for rational cost reduction.

In addition to the above recommendations, agricultural enterprises in the Karaganda region are encouraged to implement IT for more efficient cost control and management. The comparative analysis shows that due to a lack of funding, qualified personnel, and other reasons, some agricultural enterprises in the Karaganda region do not fully utilise IT potential, which may affect the quality of cost control and accounting. The use of automated accounting and reporting systems such as 1C: Agro, AgriBusiness ERP, and SAP Rural Sourcing Management ensures effective cost management through real-time registration (Kipkenei *et al.*, 2022; Ying, 2024). Agricultural enterprises may also integrate GIS systems to monitor crop, field, and equipment conditions for cost planning and accounting. The key objective of using such control systems is the rational use of available resources, avoidance of overspending, and continuous search for ways to optimise costs. In developing the recommendations, it was also taken into account that implementing improved cost control and management systems is impossible without the involvement of qualified personnel. Based on this, regional agricultural enterprises are advised to enhance staff qualifications by training accountants and economists in management accounting, preparing machine operators and agronomists to work with digital accounting systems, and encouraging initiatives for saving and cost optimisation. Based on the results of the conducted analysis, it was also concluded that investing in the training and retraining of staff can reduce the outflow of qualified personnel, thereby lowering the cost of hiring new employees.

Further application of the cost-benefit method allows the conclusion that the proposed recommendations are realistic and appropriate for effective cost control and ensuring the sustainable development of agricultural enterprises. The main costs of implementing the proposed recommendations include initial IT investments, staff training, and stakeholder consulting. These costs vary depending on company size, strategic objectives, service providers, and other factors. In a hypothetical scenario where USD 50,000 is invested in technical equipment and staff training at an agricultural enterprise with a discount rate of 10% and a 2-year implementation period, the investment would be cost-effective and generate annual cost savings of USD 30,000. High return on investment is possible due to direct and indirect benefits, including reduced production costs, increased yield and controllability, improved profitability, and the readiness of qualified staff for long-term cooperation. If the proposed recommendations are properly implemented and supported by state or private programmes, payback may be documented within 1.5 to 3 years. At the same time, enterprises should take into account existing risks, including a lack of qualified personnel, stakeholder resistance to change, and limited access to technology in certain regions of the country (Shahini & Shtal, 2023).

Some of these risks can be minimised if the proposed recommendations are implemented through Kurt Lewin's model. In the first stage – "unfreezing" – it is important to prepare agricultural enterprises for the upcoming changes. Such preparation involves analysing the current state of costs and processes, justifying the need for changes, creating change coalitions, conducting information and persuasion sessions, and launching pilot changes. At the "unfreezing" stage is LLP "Karaganda Agro Invest-T" – an enterprise where resource control and management are carried out mainly manually. In addition to the mentioned company, a hypothetical agricultural enterprise that found that 15% of fertilisers were being used inefficiently – leading to higher product cost and reduced competitiveness – may also illustrate the first transformation stage. Understanding the medium- and long-term consequences of inefficient fertiliser use motivates responsible parties to make changes to optimise costs.

The second stage is the implementation of transformation – that is, the introduction of new technologies, procedures, and skills to optimise costs. At this stage are "Agrofirma Zhanibek" and "Shakhtyorskoe", which are gradually transitioning to the intensive use of digital platforms and tools for cost control and management. At the change stage, a management accounting system will be introduced, appropriate software installed, personnel trained to use new systems, key performance indicators and reporting set up, and feedback and process adjustment ensured. In the proposed scenario, the change process would include training machine operators to log the hours and routes in a selected mobile application and providing agronomists with field productivity maps. In the "refreezing" stage, the main task is to consolidate the changes as the new norm and ensure the sustainable functioning. At this stage, strategies may include formalising new procedures, regular reporting and analysis, material and non-material staff incentives, training employees in new standards, and integration with state support programmes and external auditors. For an agricultural enterprise facing irrational fertiliser use, the "refreezing" stage may include submitting an annual report under the new accounting system to the local agricultural administration on the use of the provided subsidy.

Thus, the conditions for the functioning of internal cost control and management systems in agricultural enterprises of the Republic of Kazakhstan were considered. Comparative case analysis revealed that certain enterprises in the Karaganda region have underdeveloped accounting and reporting systems, which may reduce the efficiency of the management and competitiveness. Recommendations were made to improve the efficiency of the cost control and management systems of agricultural enterprises in the Karaganda region of the Republic of Kazakhstan.

DISCUSSION

The comparative analysis showed that certain enterprises in the Karaganda region, including LLP "Karaganda Agro Invest-T", had an outdated, manual accounting and reporting system, which reduced the quality of its operations. The idea presented in the study regarding the importance of a modernised cost control and management system was confirmed by earlier research, including M. Jakobsen (2024). According to M. Jakobsen, who studied the experience of seven financially successful Danish agricultural companies, business entities striving for sustainable development abandoned the official accounting system for making current decisions, preferring locally developed models and practical rules. M. Jakobsen emphasised that the transition to new forms of reporting helped agricultural enterprises to compensate for the illusion of cost control created by the formal reporting system. The present study offered precise figures characterising management efficiency, for example, a 25-30% reduction in the time spent on document verification and approval. Thus, the idea of revising the existing system of cost control and management in agricultural enterprises found confirmation in an international context.

According to B.R. Joshi (2024), cost management, including budgeting and delegation, made it possible to maintain operational efficiency and maximise profits. Using Agriculture Development Bank Limited, Nepal, as the research context, B.R. Joshi emphasised the importance of implementing robust cost control methods to improve financial stability and competitiveness in the agricultural sector. The findings presented by B.R. Joshi broadly coincided with the idea presented in this study that, compared to other economic sectors, the agricultural sector developed in significantly more unpredictable conditions, increasing the need for modernised control methods as levers to ensure stability and sustainable development.

The present study also paid significant attention to how exactly cost management in an agricultural enterprise improved various aspects of its efficiency. It was particularly proven that automated cost control and management reduced the risk of errors and helped to avoid penalty accruals amounting to 1-2% of the enterprise's total budget. Based on a comparative analysis of agricultural enterprises in the Karaganda region, it was concluded that revising the existing control and management system would help optimise resources and reduce the cost of production, making it more competitive at local or national levels. The idea of a correlation between cost control and management systems and enterprise profitability was also confirmed by previous studies, including M.N. Lestari *et al.* (2020). Using statistical data from individual Indonesian agricultural enterprises, M.N. Lestari *et al.* concluded that there was a positive correlation between cost control, production, and operating profit, with a coefficient of determination of 75.1%. The data obtained in the international context highlighted the relevance of research aimed at improving the internal cost control and management system of agricultural enterprises in Kazakhstan. Considering the certain similarity of the political, economic, and sociocultural contexts of Indonesia and the Republic of Kazakhstan, it was concluded that the changes that took place in one country could be successfully implemented in the other.

The study emphasised that a modernised cost control and management system ensured the sustainable development of the enterprise even in unfavourable conditions. As an example, certain agricultural enterprises in the Karaganda region were used, which had an arid climate and complex logistics. The recommendation to implement modernised control and management systems as a risk minimisation tool was also confirmed by earlier studies, including the work of V. Kalisa and A. Aforabi (2024). Using maize cultivation in Kirehe, Rwanda, V. Kalisa and A. Aforabi concluded that there was a strong correlation ($r = 0.966$) between budget planning and the efficiency of irrigation projects in the arid region of the country. The data obtained were relevant to the Kazakhstani agricultural context, in which measures aimed at reducing the negative impact of the environment increased the cost of final products, making the production unprofitable. A comparative contextual analysis suggested that the implementation of a modernised cost control system contributed to the optimisation of costly resources, thereby increasing the competitiveness of an agricultural enterprise forced to operate in unfavourable climatic conditions.

This assumption was also partially confirmed by a systematic review of 136 relevant studies and 28 documents conducted by G. Papadopoulos *et al.* (2024). According to G. Papadopoulos *et al.*, the use of modern production technologies could reduce the use of pesticides by up to 60%, and fertilisers by up to 80%, thereby lowering the cost of production. G. Papadopoulos *et al.* also emphasised that such reductions required detailed accounting of available resources. The cited idea confirmed the one presented in this study about the interconnection between rational use of resources, the detailed accounting, and the competitiveness of an agricultural enterprise. The present study also paid considerable attention to the role of digital technologies in creating an effective cost control and management system for agricultural enterprises. A comparative analysis of three enterprises in Karaganda revealed a common issue – the episodic use of digital technologies for cost control and management, or a complete rejection of such technologies. The enterprises of the region were recommended to use innovative tools, as investments in modern cost management systems were found to be cost-effective in the medium and long term. The rationale for the use of modern digital tools for cost accounting was also confirmed by earlier research, including W. Geng *et al.* (2024). Based on the results of structural equation modelling, the authors concluded that digital capabilities, digital orientation, and digital transformation of enterprises had a positive and significant impact on the financial indicators of a company. From the point of view of the cited findings, investing in digital tools for cost control and management enhanced the company's resources.

The systematic review by G. Crispim *et al.* (2024) confirmed the advisability of investing in the development of digital control tools even under conditions of limited financial resources. This recommendation could be particularly useful for small agricultural enterprises such as LLP "Karaganda Agro Invest-T", striving to find the place among larger and technically better-equipped competitors. According to H.F. Liang (2025), one of the key roles of digital technologies was that these technologies served as a source of diverse information required for decision-making in resource accounting and cost management. Such information could also be processed through artificial intelligence capabilities, enabling enterprises to optimise expenses on data analyst services. And although all sources cited in this paragraph pointed to the feasibility of using digital tools for cost control and management, no specific economic sector was mentioned in relation to this feasibility. From this point of view, the conducted study was unique and made a significant contribution to the current discourse by examining the digitalisation of the agricultural sector for cost optimisation.

The key idea of the proposed study also included the notion that the implementation of an updated cost control and management system required the involvement of qualified specialists. The validity of this idea was studied, for example, in the context of LLP "Karaganda Agro Invest-T", whose small staff did not contribute to the implementation of transformational processes and led to most cost control and management operations being carried out manually. A different situation was observed in LLP "Zhanibek-Aidos", which had sufficient human resources to implement the updated cost accounting system. The idea of the importance of human resources for the transition to digital cost management was also confirmed in earlier literature, including the work of D. Qorri *et al.* (2024). After analysing 149 studies in the field, D. Qorri *et al.* concluded that human resources were the driving force behind organisational changes, including the use of artificial intelligence capabilities for processing enterprise cost data. Similar conclusions were drawn in the study by O. Opoku (2024), whose relevance to the proposed discourse was due to its focus on the agricultural sector. According to O. Opoku, there was a statistically significant positive correlation between human resource management methods and the economic efficiency of the poultry sector. It should be noted, however, that unlike studies examining the relationship between human resource management strategies and the economic efficiency of various sectors, this study had a narrower focus. The presented study focused on the impact of human capital management practices on the implementation of a modernised cost control and management system. A narrower focus reduced the risk of bias in the conducted research, thereby increasing its value to the current discourse. Based on the conducted comparative analysis, it can be stated that most of the ideas proposed in this study were confirmed by earlier research. The uniqueness of the present study lay in its narrower research focus, with an emphasis on the implementation of a modernised cost control and management system in agricultural enterprises of the Karaganda region.

CONCLUSIONS

The conducted study confirmed that the level of effectiveness of internal control systems and cost management in agricultural enterprises of the Karaganda region of the Republic of Kazakhstan varied significantly and was largely determined by business scale, degree of automation, and human resource capacity. Using the example of three enterprises – "Karaganda Agro Invest-T", "Agrofirma Zhanibek", and "Shakhtyorskoe" – a comparative analysis was conducted, which revealed that the enterprise "Zhanibek" demonstrated the highest level of maturity of the control system, including the presence of internal audit, automated planning, and budget deviation monitoring. At the same time, "Karaganda Agro Invest-T" and "Shakhtyorskoe" mainly relied on manual or weakly formalised approaches, which increased the risk of errors, delayed reporting preparation, and raised the cost of management control. Quantitative data are significant: the Pearson coefficient calculated for the relationship between enterprise size and readiness for digitalisation amounted to $r = 0.43$, indicating a moderate positive correlation. A more pronounced inverse correlation of $r \approx -0.98$ was identified between the level of digitalisation and the duration of reporting preparation: the higher the level of automation, the less time is spent on the formation of management documents – from 6 working days at the fully digitalised "Zhanibek" to 10-11 days at "Shakhtyorskoe". In addition, calculations showed that investments of USD 50,000 could annually save the enterprise up to USD 30,000, with a payback period of 1.5 to 3 years, which demonstrates the economic feasibility of cost control automation.

Among the developed practical recommendations were the implementation of responsibility centres and the normative accounting method for plan-fact cost analysis; the use of ABC/XYZ methods and agro-climatic modelling for more accurate planning of expenses taking into account seasonality and climate risks; transition to modern ERP systems (SAP, BAS: Agro) and integration of geographic information platforms for field and machinery monitoring. Particular emphasis was placed on the need to invest in the training and retraining of personnel, as it is precisely the qualified human resource that ensures the successful implementation of digital and managerial innovations. For further research, it is recommended to expand the empirical base by including enterprises from other regions of Kazakhstan, as well as to conduct a longitudinal analysis of the impact of the implementation of digital platforms and responsibility centres on the dynamics of operating profit and profitability of agribusiness under conditions of climate change and raw material price fluctuations.

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CONFLICT OF INTEREST

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Системи внутрішнього контролю та управління витратами в агропідприємствах: кейс підприємств Карагандинської області

Ракимжан Єлшибаєв
Кандидат економічних наук, професор
Університет Нархоз
050035, вул. Жандосова, 55, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0001-7119-7400

Максат Кулубеков
Кандидат економічних наук, доцент
Костанайський інженерно-економічний університет ім. М. Дулатова
110007, вул. Чернишевського, 59, м. Костанай, Республіка Казахстан
https://orcid.org/0000-0003-1123-1085

Зульфія Аринова
Кандидат економічних наук, професор
Університет Торайгирова
140008, вул. Ломова, 64, м. Павлодар, Республіка Казахстан
https://orcid.org/0000-0003-0123-6667

Світлана Золотарьова
Кандидат економічних наук, доцент
Університет Торайгирова
140008, вул. Ломова, 64, м. Павлодар, Республіка Казахстан
https://orcid.org/0000-0001-8784-6153

Альфія Бактіярова
Магістр, старший викладач
Університет Нархоз
050035, вул. Жандосова, 55, м. Алмати, Республіка Казахстан
https://orcid.org/0000-0001-5170-9536

Анотація. Метою проведеного дослідження було вивчити особливості функціонування внутрішнього контролю та управління витратами на агропідприємствах Карагандинської області, Республіки Казахстан. Поставленої мети було досягнуто за допомогою проведення контекстуального і порівняльного аналізу трьох (N = 3) аграрних підприємств Карагандинської області, обраних за допомогою стратифікованого відбору: «Агрофірма Жанібек», «Караганда Агро Інвест-Т» і «Шахтарське». Підрахунок точкового бісеріального коефіцієнта Пірсона (r = 0,43) виявив середню позитивну кореляцію між розміром аграрного підприємства і його готовністю до цифровізації внутрішнього контролю та управління витратами. Було також виявлено високу зворотну кореляцію (r≈-0,98) між рівнем цифровізації підприємства та швидкістю підготовки звітності. Порівняльний аналіз систем аграрних підприємств виявив позитивний вплив цифровізації внутрішньої системи контролю та управління витратами на ефективність виробництва, що виявляється через скорочення на 25-30 % трудовитрат на ручний аудит і повторні перевірки, прискорення на 40-50 % формування звітності та зниження ймовірності помилок і штрафних донарахувань на 1-2 % від загального бюджету підприємства. З погляду теоретичної моделі Курта Левіна, підприємства перебувають на різних етапах трансформації: в той час як «Караганда Агро Інвест-Т» перебуває на підготовчому етапі, «Агрофірма Жанібек» і «Шахтарське» здійснили перехід до використання цифрових інструментів контролю та управління витратами, однак, потребують закріплення отриманого результату. Підприємствам було рекомендовано планувати контроль та управління витрат з урахуванням специфіки регіону, проведення поточного стану витрат для оцінювання ефективності використання наявних коштів та впровадження багатокомпонентної системи управлінського обліку. Отримані дані можуть бути використані для модернізації системи контролю та управління витратами, що підвищити конкурентоспроможність аграрних підприємств Карагандинської області

Ключові слова: державні субсидії; сталий розвиток; агрокліматичне моделювання; інформаційні технології; модернізація

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Analysis of tobacco production in Indonesia: A deterministic approach

Norida Canda Sakti*

Doctor of Economics Education, Associate Professor
Universitas Negeri Surabaya
60231, Ketintang Str., Surabaya, Indonesia
https://orcid.org/0000-0002-5805-2466

Muhlisin

Doctoral Candidate in Economics Education
Universitas Negeri Surabaya
60231, Ketintang Str., Surabaya, Indonesia
https://orcid.org/0009-0003-0979-3211

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Abstract. Improving production input efficiency is crucial for enhancing productivity and sustainability in Indonesia's tobacco farming. This study examined the effects of land area, number of seeds, fertiliser use, pesticide application, and labour on tobacco production using multiple linear regression with natural logarithm transformation. Data were collected from tobacco farmers in East Java, Central Java, and West Nusa Tenggara through purposive sampling. The results showed that land area negatively affected tobacco production ($\beta = -0.242$, $p = 0.0001$), indicating inefficiency on larger land areas, possibly due to uneven land quality or problems in land management. In contrast, number of seeds ($\beta = 0.512$, $p < 0.0001$), fertiliser use ($\beta = 0.206$, $p < 0.0001$), and pesticide application ($\beta = 0.139$, $p < 0.0001$) had a positive and significant effect on yield. Labor had no significant effect ($\beta = 0.0003$, $p = 0.9819$), although it made a small contribution to production efficiency. Most farmers manage small to medium scale land (10.5% own 0.30 ha), plant 8,500 seedlings (8.4%), and use 600 kg of fertiliser (8.1%) and 400 ml of pesticide (11.7%). This emphasises the significance of efficient input allocation to support greater productivity. Additionally, the findings reflect farmers' tendency to manage resources conservatively due to cost or knowledge constraints. Overall, these findings confirmed the need to optimise the use of inputs, especially quality seeds, and efficient use of fertilisers and pesticides, to increase productivity while reducing adverse environmental impact and supporting the implementation of sustainable agricultural practices. The present study recommended adopting agricultural technology, farmer training, and crop diversification to improve productivity

Keywords: land area; number of seeds; number of fertilisers; pesticides; labour

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*Corresponding author

INTRODUCTION

Tobacco production in Indonesia plays a crucial role in the national economy, supporting millions of farmers and contributing significantly to government revenue. However, the industry faces challenges in balancing economic benefits with public health concerns and environmental sustainability. The present study employed a deterministic approach to analyse tobacco production, aiming to improve agricultural practices, improve farmers' welfare, and support sustainable policies. B. Prasetya *et al.* (2025) stated that tobacco cultivation is a primary source of income for many farmers, contributing between 40-80% of their total earnings. As the key raw material for cigarette manufacturing, tobacco is essential for the industry, making it a focal point for both economic stakeholders and tobacco control advocates. The Indonesian government has designated the tobacco industry as a national priority sector due to its economic impact. A 45% increase in tobacco taxes since 2019 is projected to boost economic output by USD 5.11 bn, increase household income by USD 1.46 bn, and create approximately 400,300 jobs (Bella *et al.*, 2024). As an agrarian nation, the economy and livelihood heavily depend on agriculture, with natural processes at its core to meet both food and economic needs.

Indonesia, with its rich natural resources, depends on agriculture as the foundation of its economy. Globally, eleven countries – China, Brazil, India, the United States, Turkey, Zimbabwe, Indonesia, Italy, Greece, Malawi, and Argentina – produce nearly 80% of the world's tobacco, with China alone accounting for 33% of global production (World Bank, n.d.). D. Nuryunarsih *et al.* (2021) noted that tobacco, derived from the *Nicotiana* genus, is widely used in clove cigarettes, filter cigarettes, cigars, and other tobacco products. The economic significance of tobacco is clear in its impact on agricultural productivity and export earnings. J. Smith and J. Fang (2020) also noted its role in job creation and economic benefits. Countries like China, India, and Indonesia dominate global production, contributing significantly to rural employment and government revenue through excise taxes. According to E. Fukase and W. Martin (2020), government investment in agriculture enhances productivity, enables efficient resource allocation, and promotes poverty reduction. Despite these benefits, the sector faces challenges such as declining employment, income instability, and opportunity costs linked to unpaid family labour and health risks, as emphasised by D. Samaan *et al.* (2023). Indonesia's diverse agricultural landscape, characterised by varying land conditions across provinces, influences tobacco production strategies and yields. A. Chikowore and A. Chawarika (2024) highlighted that land types markedly affect production outcomes, emphasising the need for tailored development strategies. Land transfer and improved accessibility can enhance economic value and farming systems.

M. Naeem *et al.* (2020) suggested that sustainable agricultural practices, including intensive land management, seed selection, and organic fertiliser use, help maintain productivity, especially in hilly areas. While pesticides are essential for pest control, E. López Dávila *et al.* (2020) warned that their excessive use poses environmental and health risks. To enhance resilience in tobacco farming, M. Shammi *et al.* (2020) proposed implementing crop diversification as an effective adaptation strategy. Labour is another critical factor in tobacco production. M.Z. Rahman *et al.* (2020) emphasised that labour-intensive cultivation provides employment opportunities, benefiting both the government and the market. Z.N. Kebede (2021) highlighted the significance of working capital in enhancing agricultural profitability, particularly for smallholder farmers. Considering these challenges and opportunities, understanding the determinants of tobacco production is essential for improving efficiency, addressing climate challenges, and reducing agricultural poverty.

The purpose of the present study was to identify key determinants of tobacco production in Indonesia and develop a framework for optimising agricultural practices, enhancing farmers' welfare, and promoting sustainable policies in the tobacco sector. By examining variables such as seed quantity, land area, fertiliser use, and labour, the research sought to improve production yields sustainably while balancing economic and environmental considerations.

LITERATURE REVIEW

Tobacco production is increasing in low- and middle-income countries, which creates complications for tobacco control efforts. A. Appau *et al.* (2020) emphasised the need to understand and address global tobacco leaf supply as a means to reduce tobacco consumption and improved farmers' livelihoods. The expansion of tobacco land has significantly affected the land distribution of urban construction as the continued growth of tobacco market demand has driven increased land use for tobacco farming. D.C. Midamba *et al.* (2024) explored the impact of tobacco cultivation on land use and the livelihoods of smallholder farmers in Uganda, indicating that land area influences total tobacco production. The relationship between land area and total tobacco production is evident, considering that most of tobacco is grown by smallholders on small plots of land, where small land area is the principal characteristic of tobacco cultivation. Nevertheless, Indonesia continues to be one of the world's major tobacco producers due to the high intensity of manual labour and local adaptation to agronomic conditions.

However, this needs to be considered as the research findings by J. Shao *et al.* (2024) on tobacco farming in Yunnan Province, China, indicated that the expansion of tobacco land can seriously threaten biodiversity. This finding emphasises the relevance of regulation to maintain a balance between tobacco farming expansion and environmental conservation. This is also relevant for Indonesia, where the expansion of tobacco growing can have analogous impacts on biodiversity and soil quality. The number of seedlings planted has a direct relationship with the yield of tobacco production. Increasing the number of seeds can increase yields, but it needs to be adjusted to land conditions and the availability of other resources. Tobacco seeds were separated into three weight groups of 76 mg, 65 mg, and 50 mg/1,000 seeds. Germination was tested at 20°C in light and in darkness without disturbance. Adoption of the latest technologies and the use of recommended tobacco varieties can markedly increase yields and farmers' income. T.M. Yola *et al.* (2023) indicated that the adoption of innovative technologies and the use of superior seed selection in tobacco varieties can reduce production costs and increase farmers' profits compared to the use of non-superior seeds.

Tobacco plants require high amounts of pesticides, insecticides, and fertilisers. The role of fertiliser application in tobacco is known to be key for efficient nutrient uptake in application in poor sandy soils as this will result in increased yield and quality of tobacco leaves (Lisuma *et al.,* 2023). Pesticides are chemicals and other materials used to control pests, diseases, and weeds in plants. Their function also includes regulating and stimulating plant growth, but not as fertilisers. According to G.M.V. Lengai *et al.* (2020), pesticides reduce crop yield losses before and after harvest enhancing agricultural productivity their use increases yields and profits but involves costs and potential risks a cost-benefit analysis is essential to optimise their effectiveness. However, in other studies, intensive use of fertilisers and pesticides gradually reduces soil fertility (Sultana *et al.*, 2020).

M.Y. Ali *et al.* (2023) highlighted that while tobacco farmers contribute economic benefits, there are major social and environmental impacts in Bangladesh. This suggests that the government's role in tobacco regulation should involve strategic steps that balance economic benefits with social and environmental considerations. A comparable situation exists in Indonesia, where tobacco is primarily cultivated by smallholders with limited land, relying heavily on family labour and restricting mechanisation. G.A. Sahadewo *et al.* (2020) further observed that in Indonesia, Kenya, and Zambia, household labour costs exceed those of hired labour for both tobacco and non-tobacco farming, with tobacco farming incurring significantly greater household labour costs compared to non-tobacco farming.

By adopting the latest systems and technologies, Indonesia can increase tobacco productivity while addressing labour-related constraints. This step is crucial to ensure the sustainability and efficiency of tobacco production in the future. Current tobacco farmers typically allocate more labour – both from household members and hired workers – for crop cultivation compared to former tobacco farmers. Tobacco farming employs millions of small-scale tobacco farmers worldwide, most of whom are casual farmers dependent on the tobacco industry (Martins-da-Silva *et al.*, 2022). Tobacco farming usually involves various labour-intensive activities, such as planting and harvesting tobacco leaves, drying the leaves, and packaging and transporting the finished product. According to R. MacKenzie *et al.* (2021), tobacco production causes deforestation, soil erosion, and water pollution due to intensive farming practices, while the curing process also contributes to greenhouse gas emissions. These environmental impacts are most evident in Indonesia's major tobacco-producing regions, where deforestation continues to rise alongside the expansion of tobacco farmland.

This plant can thrive in various types of climates, ranging from tropical to sub-tropical regions, and is utilised to produce a variety of products, such as cigarettes, cigars, and snuff (Ndlangamandla *et al.*, 2024). The average productivity of tobacco is still relatively low. Virginia tobacco productivity only reaches 1.3 tonnes per hectare, lower than its optimal potential of 2 tonnes per hectare. This low production is thought to be related to the lack of pure superior varieties used, suboptimal land management, and the absence of the application of pruning technology (World Bank, n.d.). Technological innovations that combine the use of high-yielding varieties, proper fertilisation, and balanced pruning have been proven to increase the productivity and quality of Virginia tobacco in several regions, such as Bojonegoro and Bondowoso (East Java), and East Lombok (West Nusa Tenggara). Commercially viable quality tobacco is only produced in certain regions. Some of the principal areas producing local Virginia tobacco include West Nusa Tenggara (NTB) and East Java. Local Virginia tobacco notably contributes to the regional and national economy, such as being one of the sources of state revenue through cigarette excise. Time trends reflecting technological improvements are expected to positively influence the amount of tobacco production.

MATERIALS AND METHODS

Data collection. This study employed a quantitative approach to analyse the factors that influence Virginia tobacco production in Indonesia (Fig. 2). The variables used in this study included the amount of tobacco production, land area, number of tobacco seeds, amount of fertiliser, pesticides, and the number of workers. Despite their influence on the level of production, some variables that can affect production were omitted, namely, rainfall, land conditions, plant age, season, because this study was conducted in three provinces and the timing of the season could not be predicted. Therefore, that these variables were assumed to be homogeneous for all respondents. Three provinces in Indonesia such as East Java, Central Java, and West Nusa Tenggara were selected for this study as they are among the most significant areas with Virginia tobacco cultivation capacity and are the largest contributing areas in the tobacco sector in Indonesia.

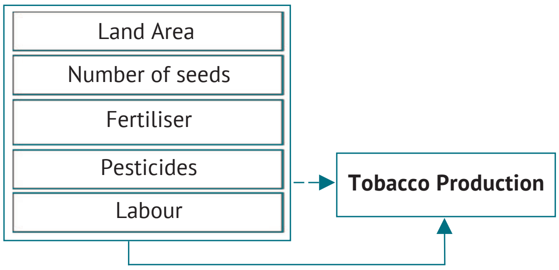


***Figure 1**. Research design*
***Source:** created by authors of this study based on (World Bank, n.d.)*

Sampling. This study was conducted from April to August 2024, following the planting and harvesting seasons among tobacco farmers, labourers, and entrepreneurs in Indonesia. Research participants were selected from three provinces with the largest tobacco production over five consecutive years and significant contributions to the national economy, based on data from the Directorate General of Estates, as presented in Table 1. A purposive sampling method was employed to select participants, with the most respondents coming from East Java, West Nusa Tenggara, and Central Java. To qualify as research participants, individuals had to be actively involved in the tobacco sector, whether as full-time workers, part-time workers, or entrepreneurs. An offline survey was distributed, containing an explanation of the research objectives and a questionnaire, to 418 selected respondents. Participation was conducted anonymously, and all respondents provided informed consent before taking part. This study strictly followed the ethical standards for research involving human subjects (The Declaration of Helsinki, 2013), ensuring that participation was voluntary and free from coercion. To validate the questionnaire used, three experts in the fields of tobacco farming and economics were involved. These experts had over 10 years of experience in their respective fields at the time of study and provided input to ensure the research tools aligned with the study's context and objectives.

The questionnaire was designed to collect information on tobacco farming practices, covering aspects of production and challenges faced by farmers. Respondents provided personal data, land ownership status, as well as the size and number of plots used. The questions covered the type and quantity of seedlings planted, seedling mortality rates, and replanting methods. The use of fertilisers and pesticides was also examined, including their types, quantities, and application during production. Additionally, the questionnaire highlighted labour requirements at each stage of cultivation, harvest yields, sales methods, agricultural equipment, as well as obstacles and efforts made by farmers to improve production outcomes.

Table 2 outlines the distribution of 418 respondents across three provinces: East Java, Central Java, and West Nusa Tenggara (NTB). East Java had the greatest number of respondents (200), followed by NTB (118), and Central Java (100). The selection of these provinces aligned with their status as the top tobacco-producing regions in Indonesia, as evidenced by the production data in Table 1. The distribution reflected the study's focus on areas with pronounced tobacco farming activities, ensuring that the research captures insights from key stakeholders in the industry. The total number of respondents (418) provided a robust sample size for analysing tobacco farming practices and challenges in these regions.

***Table 1**. Distribution of respondents in three provinces in Indonesia*

No.	Province	Number
1	Jawa Timur	200
2	Jawa Tengah	100
3	Nusa Tenggara Barat	118
Total		**418**

***Source:** created by authors of this study based on data from the Directorate General of Estates (2021, 2022, 2023)*

Table 2 presents a detailed breakdown of respondents by subdistrict within the three provinces. In East Java, respondents were evenly distributed across four subdistricts: Bojonegoro, Jember, Pamekasan, and Sumenep, with 50 respondents in each. In Central Java, Temanggung had the largest number of respondents (50), followed by Rembang (30), and Boyolali (20). In West Nusa Tenggara, respondents were concentrated in Lombok Tengah (50) and Lombok Timur (68). This distribution ensured representation from various subdistricts known for tobacco farming, enabling a comprehensive analysis of regional differences in farming practices, challenges, and outcomes. The focus on specific subdistricts highlighted the localised nature of tobacco cultivation and its economic significance in these areas.

Table 2*. Distribution of respondents in three provinces in Indonesia (by Subdistrict)*

Province	Municipality	N
East Java	Bojonegoro	50
	Jember	50
	Pamekasan	50
	Sumenep	50
Central Java	Temanggung	50
	Rembang	30
	Boyolali	20
West Nusa Tenggara	Lombok Tengah	50
	Lombok Timur	68

Source: *created by authors of this study based on data from the Directorate General of Estates (2021, 2022, 2023) and World Bank (n.d.)*

Data analysis. To analyse the magnitude of the influence between variables, an econometric estimation model was employed. Regression analysis was applied to predict the causal relationship between variables. Additionally, tobacco farmers differed in the amount of input used in managing their farms. To estimate the regression coefficient, it is necessary to calculate the natural logarithm (Ln) of each variable that has an unequal unit of measure when entered into the model. This process will result in the following equation being obtained:

$$Ln\_TProduction_i = \alpha + \beta_1 Ln\_LA_i + \beta_2 Ln\_NS_i + \\ + \beta_3 Ln\_NF_i + \beta_4 Ln\_Pest_i + \beta_5 Ln\_Labour_i + \mu, \quad (1)$$

where Ln is the natural logarithm (e = 2.718); TProduction is the total production of tobacco (kg); LA is the land area (ha); NS is the tobacco seedlings (pcs); NF is the fertiliser requirement (kg); Pest is the pesticide (ml); Labour is the total labour (person). The subscript i denotes the cross-sectional unit of observation, referring to each individual farmer included in the sample. The term α represents the intercept of the regression equation, indicating the expected log of tobacco production when all explanatory variables are at their base levels. Coefficients β_1 to β_5 represent output elasticities, measuring the percentage change in output due to a 1% change in each input. The error term μ accounts for unobserved factors influencing production.

Impact assessment framework. Figure 2 illustrates various factors influencing tobacco production in Indonesia, where each factor has sub-factors contributing to production efficiency. The horizontal axis in the diagram represents the primary production factors, namely land area, number of seedlings, amount of fertiliser, pesticide use, and labour. The vertical axis shows the derivative elements of each primary factor that determine the success of tobacco production.

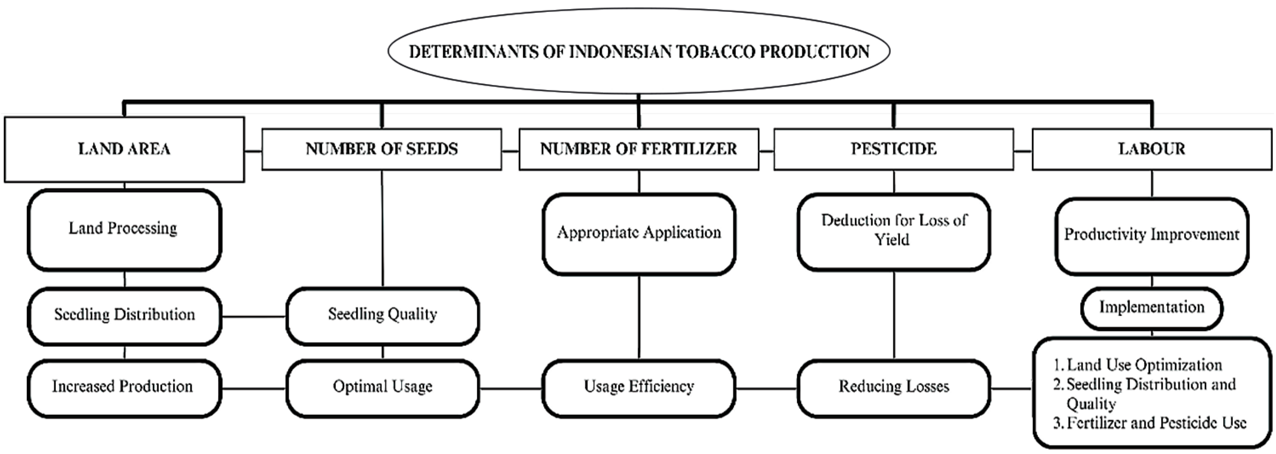
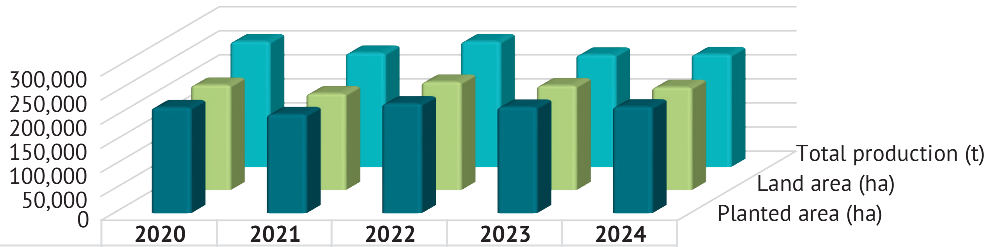


Figure 2*. Framework of determinants of tobacco production in Indonesia*
Source: *compiled by authors of this study based on N.N. Sultana et al. (2020), G.A. Sahadewo et al. (2020), M. Yahui et al. (2021), R. MacKenzie et al. (2021), T.M. Yola et al. (2023), World Bank (n.d.)*

This study was conducted following the ethical principles outlined in the Declaration of Helsinki (2013). Although this study was not funded by any institution or agency and therefore did not involve formal ethical approval documents from an ethics committee, the authors of this study ensured that all research procedures were designed to protect participants' rights, privacy, and well-being. Participation in this study was voluntary, with all respondents providing consent upon receiving sufficient information regarding the objectives, procedures, and their right to withdraw from participation at any time without any negative consequences. The authors of the present study emphasise that no coercion or pressure was applied to participants during the research process. The authors are strongly committed to confidentiality and data protection. All collected data were anonymised when necessary to prevent participant identification, and strict measures were implemented to secure sensitive information. The identities of all respondents were strictly safeguarded, with access to personal data restricted only to authorised researchers and solely for the purposes of this study.

RESULTS AND DISCUSSION

Overview of tobacco production. Indonesia's tobacco production has fluctuated in recent years due to weather, technology, and policy factors. As presented in Figure 1, output peaked at 261,018 tonnes in 2020 but declined to 234,138 tonnes by 2024. East Java, the top producer, saw a drop from 128,919 tonnes (2020) to 109,539 tonnes (2024) due to climate change, soil degradation, and land access challenges.



	2020	2021	2022	2023	2024
Planted area (ha)	219,774	205,406	227,673	220,830	221,290
Land area (ha)	218,476	200,626	224,905	217,275	213,883
Total production (t)	261,018	237,116	261,208	233,255	234,138

***Figure 3**. Planted area, land area, and tobacco production in Indonesia*
***Source:** created by authors of this study based on data Directorate General of Estates (2021, 2022, 2023)*

Table 3 presents tobacco production data (in tonnes) across various provinces in Indonesia from 2020 to 2024. The data reveals significant variations in production levels among provinces. East Java consistently dominates tobacco production, with figures ranging from 128,919 tonnes in 2020 to 109,539 tonnes in 2024, despite a gradual decline. Central Java and West Nusa Tenggara (NTB) also contribute substantially, with Central Java producing between 57,643 tonnes (2020) and 50,439 tonnes (2024), and NTB ranging from 57,065 tonnes (2020) to 56,667 tonnes (2024). Other provinces, such as North Sumatra, Lampung, and South Sulawesi, show fluctuating but relatively lower production levels. Notably, provinces like South Sumatra and Central Sulawesi have minimal contributions, with production below 100 tonnes in some years. This data highlights the concentration of tobacco production in specific regions, particularly Java and NTB, which are key contributors to Indonesia's national tobacco output.

***Table 3**. Tobacco production data by province in Indonesia*

Provinces	Production (tonnes)				
	2020	2021	2022	2023	2024
Aceh	2.255	2.110	2.273	2.244	2.339
Sumatera Utara	1.740	1.754	1.754	1.613	1.807
Sumatera Barat	245	123	247	250	314
Jambi	166	177	167	159	180
Sumatera Selatan	61	114	61	38	30
Lampung	910	812	916	700	497
Jawa Barat	8.035	7.435	8.096	7.773	8.721
Jawa Tengah	57.643	57.645	58.082	52.151	50.439
D.I Yogyakarta	744	835	750	671	471
Jawa Timur	128.919	110.814	129.901	114.013	109.539
Bali	350	307	353	323	307
Nusa Tenggara Barat	57.065	53.122	57.500	50.718	56.667
Nusa Tenggara Timur	830	749	836	714	754
Sulawesi Tengah	107	107	107	79	65
Sulawesi Selatan	1.948	1.012	165	1.809	2.008

***Source:** created by authors of this study based on data Directorate General of Estates (2021, 2022, 2023)*

The Figure 4 illustrates the concentration of tobacco production in three key provinces of Indonesia: East Java, Central Java, and West Nusa Tenggara (NTB). East Java recorded the largest production at 109,539 tonnes, solidifying its position as the national hub for tobacco production. Central Java contributed 50,439 tonnes, while NTB produced 56,667 tonnes, making both regions major players in the tobacco industry. This data indicates that tobacco production in Indonesia is concentrated in these three provinces, with East Java leading the way. This concentration reflects the crucial role of the tobacco sector in the regional and national economy, supported by geographical, climatic, and agricultural traditions that favour tobacco cultivation in these areas.

Figure 4. *Distribution of tobacco production in Indonesia (top three largest provinces)*
Source: *created by authors of this study based on Directorate General of Estates (2021, 2022, 2023) and World Bank (n.d.)*

Tobacco variants in Indonesia are remarkably diverse, which can be identified from their morphology or characteristics. This is related to the long adaptation of tobacco in various agroecologies of plantation areas spread across 15 provinces, from dryland to irrigated and from lowland to upland. Tobacco was introduced in Indonesia more than four centuries ago and is mostly used for cigarettes. The significance of research into production determinants cannot be underestimated, considering its valuable contribution to the national economy (Sahadewo, 2023). The survey involved 418 active tobacco farmer households located in the key tobacco producing provinces of East Java, Central Java, and West Nusa Tenggara. In the next stage of the study, various key selected sub-districts in Indonesia were randomly sampled for farmers based on the amount of tobacco production (Table 3). The graph below (Fig. 5) presents the data of tobacco land area and a brief explanation of the distribution of land area owned (in hectares).

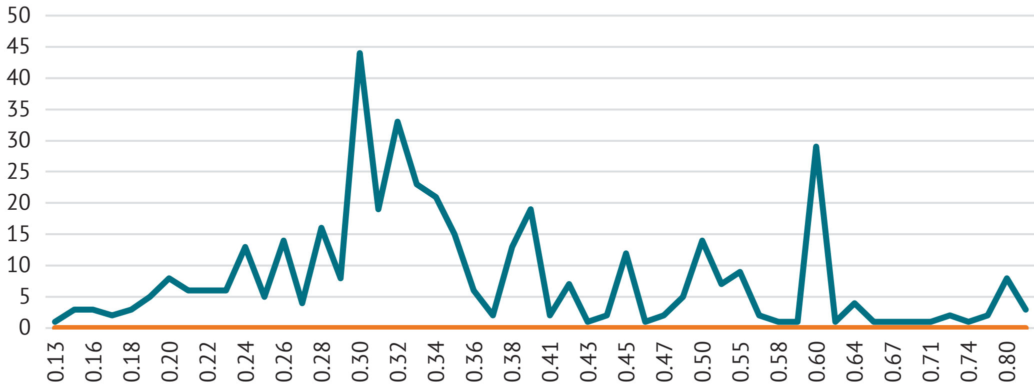


Figure 5. *Distribution of tobacco land area (Ha) based on respondent data*
Source: *created by authors of this study*

The distribution of the size of land owned by the 418 respondents shows that the majority owns relatively small plots of land, with the most widespread land size being 0.30 ha, owned by 44 respondents (10.5%). The other dominant groups included landholders with 0.32 ha (33 respondents or 7.9%) and 0.60 ha (29 respondents or 6.9%). Most respondents owned land that ranged within 0.20-0.40 ha, indicating that land distribution was concentrated in this category. In contrast, certain land sizes such as 0.13 ha, 0.43 ha, 0.46 ha, 0.58 ha, and a few others were owned by only 1 respondent (0.2%), indicating the rarity of land ownership at these sizes. This reflects that most farmers own small to medium-sized landholdings, which was relevant for analysing tobacco production in Indonesia.

Data on the distribution of the number of tobacco seedlings planted (Fig. 6) shows that most farmers plant within 7,000-8,500 seedlings. The most dominant number of seedlings was 8,500 pcs, which is planted by 35 farmers (8.4%), followed by 8,000 pcs with 34 farmers (8.1%). Additionally, 7,000 and 7,500 seedlings also showed a strong number, with 24 farmers (5.7%) and 31 farmers (7.4%) respectively. In contrast, the number of seedlings under 6,000 pcs or over 10,000 pcs tended to have a lower frequency. Only 1 farmer (0.2%) planted 3,000 seedlings, while only 10 farmers (2.4%) planted 15,000 seedlings.

At exceedingly high numbers, such as 25,000 seedlings, there was only 1 farmer (0.2%). This pattern reflected that most farmers choose an intermediate seedling quantity between 7,000 pcs and 8,500 pcs, which may reflect farming practices that are compatible with land capacity or yield optimisation strategies. Farmers with exceedingly small or large seedling numbers reflect the diversity of tobacco farming scale, which may be influenced by factors such as land size, resource availability, or financial capability. The distribution data of the amount of fertiliser used by tobacco farmers in kilograms (Fig. 7) shows that most farmers use fertiliser within 500-600 kg. The largest amount of fertiliser used was 600 kg with a frequency of 34 farmers (8.1%), followed by 590 kg with a frequency of 27 farmers (6.5%). Additionally, 750 kg of fertiliser was also used by 19 farmers (4.5%).

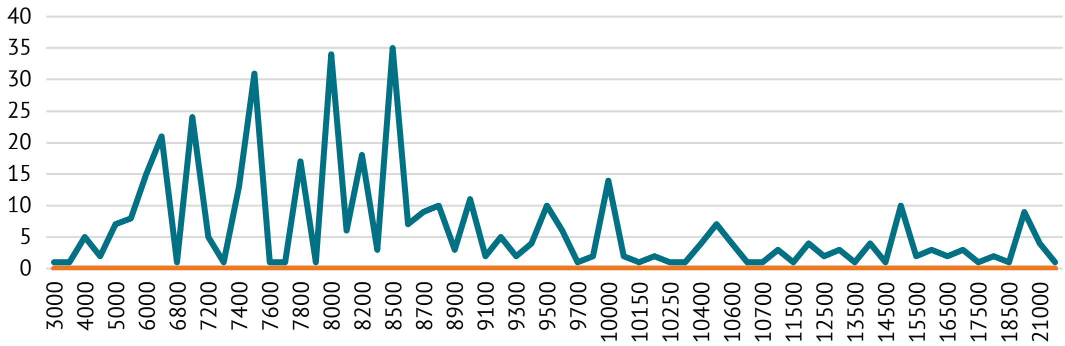


***Figure 6**. Distribution of quantity of tobacco seedlings (pcs) based on respondent data*
***Source:** created by the authors of this study*

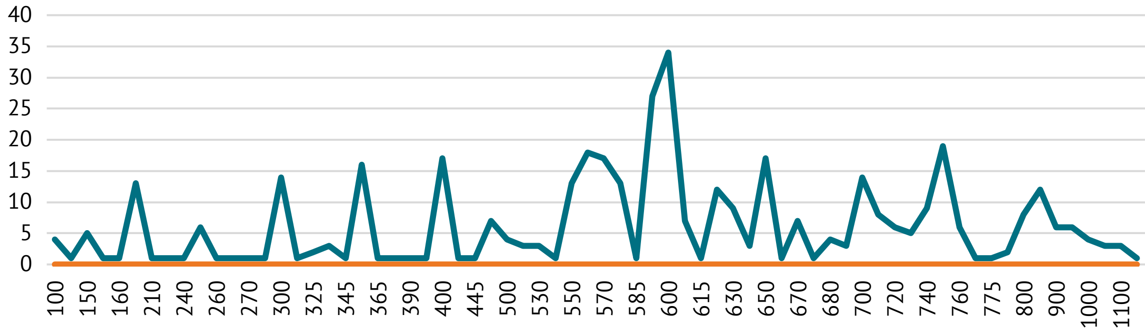


***Figure 7**. Distribution of fertiliser amount (kg) based on respondent data*
***Source:** created by the authors of this study*

Fertiliser usage below 200 kg or above 800 kg had a lower frequency, indicating that most farmers are in the moderate fertiliser usage category. For example, only 1 farmer (0.2%) used 120 kg or over 1,000 kg of fertiliser, respectively. This trend illustrates a relatively concentrated pattern of fertiliser use around the optimal number that supports tobacco yields. Fertiliser usage within 400-750 kg shows a significant pattern, such as the use of 400 kg by 17 farmers (4.1%) and 650 kg by 17 farmers (4.1%). This data reflects farmers' efforts to balance the nutritional needs of the plants with the capacity of their land. Additionally, variations in fertiliser use may be explained by differences in farming practices, land type, and accessibility to fertilisers.

Based on the data on the use of pesticides in millilitres (ml) in Figure 8, there are variations in the frequency of use with concentrations at certain amounts. The most frequently used amount of pesticide was 400 ml with a frequency of 49 respondents (11.7%), indicating that most farmers chose this amount as the main dose.

Additionally, the use of 200 ml was also significant with a frequency of 41 respondents (9.8%). The frequency of pesticide use in the 300-600 ml range was fairly evenly distributed, with frequently used amounts such as 500 ml (24 farmers or 5.7%), 350 ml and 370 ml (19 farmers or 4.5% each), and 340 ml and 600 ml (18 and 19 farmers, respectively, about 4.3-4.5%). In contrast, the use of pesticides at under 100 ml or over 800 ml was extremely low. For example, only 1 farmer (0.2%) used 900 ml or 1,000 ml of pesticides, reflecting that extreme use is rare. This could be explained by the efficient use of pesticides tailored to crop needs or awareness of environmental impacts. This distribution shows that most farmers tend to use moderate amounts of pesticides (200-500 ml). This pattern indicates a consistency in pesticide application methods. However, there are also small variations that may be influenced by land conditions, crop type, or accessibility to pesticides.

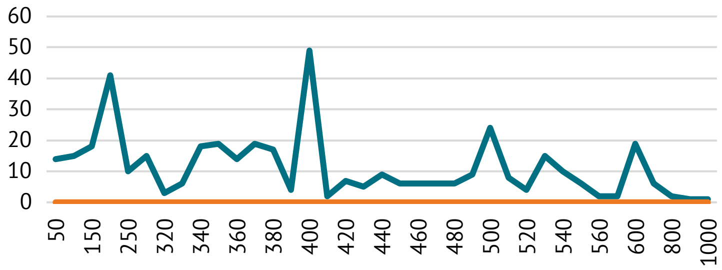


Figure 8. *Distribution of pesticides (ml) based on respondent data*
Source: *created by the authors of this study (2024)*

Data on the distribution of labour use (Fig. 9) showed that most tobacco farmers employed labour in the range of 8 to 15 people, with 9 people being the most dominant (14.8%), followed by 8 people (12.7%). This reflects the tendency of small to medium-scale enterprises to maximise labour efficiency in this range. Additionally, the use of a workforce of 10 people (7.9%) and 14 and 15 people (7.2% each) was also quite significant, indicating that operations were centred on a moderate number of workers. In contrast, labour numbers below 6 people or above 30 people were rare, involving only a handful of businesses. A small number of workers (5 to 7 people) was only used by around 5.5% of businesses, while the use of a large number of workers such as 72 to 97 people was exceedingly rare. This pattern indicated that most farmers operated with an efficient labour structure suitable for the needs of lower-middle-scale businesses.

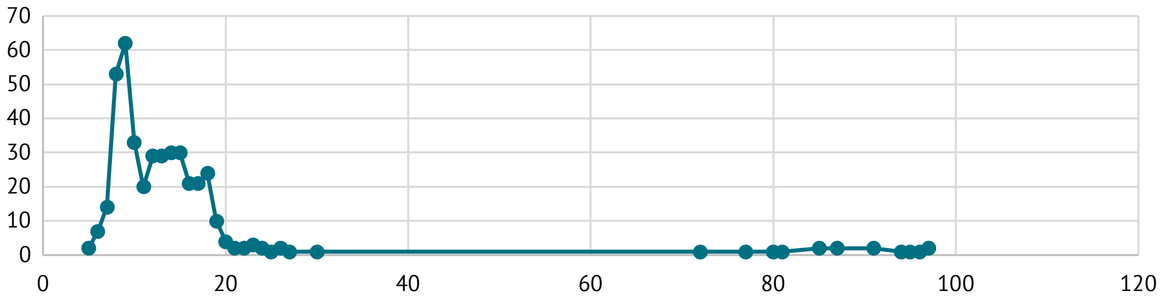


Figure 9. *Distribution of labour usage (person) based on respondent data*
Source: *created by the authors of this study (2024)*

The regression results (Table 4) indicate that land area (Ln_LA) had a significant negative effect on tobacco production, with a coefficient of -0.242433 and a probability of 0.0001. This implies that a 1% increase in land area reduces production by approximately 0.242%, potentially due to inefficiencies in land use or uneven land quality. This finding contrasts with the results presented by M. Yahui *et al.* (2021), who emphasised land suitability for yield improvement, and aligned with J. Shao *et al.* (2024), who warned against unregulated land expansion due to its environmental and productivity risks. The study highlighted that tobacco cultivation is often more effective on smaller plots, as larger areas may lead to inefficiencies. Despite these challenges, Indonesia continues to be a major global tobacco producer, supported by intensive manual labour and local adaptation to agronomic conditions.

Tobacco seeds (Ln_NS) significantly and positively affect production, with a coefficient of 0.512401 and a probability of 0.0000, indicating that a 1% increase in seed quantity can raise production by approximately 0.512%. This highlights the critical role of high-quality seedlings in boosting productivity. However, seed effectiveness depends on land conditions and the adoption of adequate technologies. Increasing the number of seeds can enhance yields, but this must be balanced with resource availability and sustainable practices. The adoption of superior seed varieties and the latest technologies can reduce production costs and increase farmers' income, as supported by T. Yola *et al.* (2023). Still, the expansion of tobacco farming must be carefully managed to avoid adverse environmental impacts, such as threats to biodiversity and soil quality, as highlighted by J. Shao *et al.* (2024). Sustainable practices are essential to balance production growth with environmental conservation.

Table 4. *Regression analysis results*

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-0.323571	0.625316	-0.517453	0.6051
Ln_LA	-0.242433	0.060379	-4.015215	0.0001
Ln_NS	0.512401	0.058356	8.780566	0.0000
Ln_NF	0.206108	0.036447	5.655008	0.0000
Ln_PEST	0.139687	0.025096	5.566184	0.0000
Ln_LABOUR	0.000311	0.013673	0.022735	0.9819

Source: *created by the authors of this study*

The amount of fertiliser (Ln_NF) also has a significant positive effect on production with a coefficient of 0.206108 and a probability of 0.0000. This means that a 1% increase in fertiliser use will increase production by about 0.206%. This result indicates the significance of fertiliser use in supporting the productivity of tobacco plants, so that the management of fertiliser needs must be considered optimally. Fertiliser usage shows a significant positive effect on tobacco production, consistent with the findings of J.B. Lisuma *et al.* (2023), who highlighted the relevance of fertiliser application in improving crop quality and yield. However, inadequate fertiliser use can adversely impact soil fertility in the long term, as warned by N.N. Sultana *et al.* (2020). Therefore, effective fertiliser management is necessary for sustainability. Pesticide (Ln_PEST) has a significant positive effect on production with a coefficient of 0.139687 and probability of 0.0000. A 1% increase in pesticide use can increase tobacco production by approximately 0.14%. Tobacco requires high pesticide and fertiliser use, with fertilisers improving yield and leaf quality, especially in poor soils. Pesticides reduce crop losses and increase productivity, according to G.M.W. Lengai *et al.* (2020), but excessive use can degrade soil fertility. Balancing their application with sustainable practices is crucial for long-term productivity and environmental health.

Total labour (Ln_LABOUR) showed no significant effect on production with a coefficient of 0.000311 and probability of 0.9819. This result indicates that changes in the amount of labour have no significant impact on tobacco production, which may suggest that labour input is less relevant than other input factors. Production optimisation is better focused on the use of significant inputs such as seeds, fertilisers, and pesticides. Tobacco farming provides economic benefits but also creates social and environmental challenges, as highlighted by M.Y. Ali *et al.* (2023). Analogous trends in Kenya and Zambia showed greater household labour costs than hired labour, especially in tobacco farming (Lencucha *et al.*, 2022). Strategic government action is needed to balance economic benefits with social and environmental sustainability. Various studies have consistently reported proportionally greater agricultural input costs for tobacco crops compared to non-tobacco crops grown in the same geographical area in the same season (Hussain *et al.*, 2020). Strong supply chains, such as in tobacco-producing countries, allow farmers to access essential inputs such as seeds, fertilisers, and pesticides. In this study, these inputs were shown to significantly affect production outcomes. For example, in Kenya, the government does not provide resources for research related to tobacco farming, and therefore information on tobacco cultivation depends entirely on the industry (Appau *et al.*, 2020). Through contractual arrangements, farmers can borrow essential inputs such as seeds, fertilisers, and pesticides, with repayment made after their tobacco crop is sold to the lender (Nguenha *et al.*, 2021).

The study revealed significant insights into the determinants of tobacco production in Indonesia, focusing on land area, seed quantity, fertiliser use, pesticide application, and labour input. The regression analysis indicated that land area has a significant negative effect on production, suggesting that larger landholdings may lead to inefficiencies. In contrast, the quantity of seeds and the use of fertilisers and pesticides have significant positive effects on production, highlighting their critical roles in enhancing yield. Specifically, a 1% increase in seed quantity, fertiliser use, and pesticide application can raise production by approximately 0.512%, 0.206%, and 0.14%, respectively. However, labour input does not significantly influence production, indicating that other factors such as seed quality and input management are more crucial for optimising yields. The obtained findings underscore the value of sustainable practices in tobacco farming, balancing productivity with environmental and social considerations. This aligns with global trends where efficient input management and technological adoption are key to improving agricultural outcomes.

CONCLUSIONS

The present study highlighted that tobacco production in Indonesia is significantly influenced by several key factors, including land area, the number of seeds, fertiliser use, pesticide application, and labour. The findings reflected a strong relationship between the efficient use of production inputs and the amount of output produced. Specifically, the regression analysis revealed that land area (Ln_LA) had a significant negative effect on production, with a 1% increase in land area reducing production by approximately 0.242%. In contrast, the number of seeds (Ln_NS), fertiliser usage (Ln_NF), and pesticide application (Ln_PEST) had significant positive effects, with a 1% increase in these inputs raising production by 0.512%, 0.206%, and 0.14%, respectively. Labor input (Ln_LABOUR), however, showed no significant impact on production, suggesting that other factors such as seed quality and input management are more critical for optimising yields.

As a strategic commodity, tobacco plays a vital role in the regional economy, particularly in key production areas such as East Java, Central Java, and West Nusa Tenggara, which have long been the centres of national tobacco production. The survey data revealed that most farmers own small to medium-sized landholdings, with 44 respondents (10.5%) owning 0.30 ha, the most widespread land size. Additionally, most farmers plant between 7.000-8.500 seedlings, use 500-600 kg of fertiliser, and apply moderate amounts of pesticides (200-500 ml). These findings align with the significance of quality seeds, as highlighted in previous studies, which found that seed weight affects germination rates and crop quality. Analogously, fertilisers and pesticides are crucial for increasing yields, although excessive use can have adverse environmental impacts, as noted in other studies. Labour, while not statistically significant in the regression analysis, continues to be an essential factor in production efficiency, particularly in Indonesia's labour-intensive tobacco sector. The findings emphasised the significance of optimised production input management and adequate policy support, such as improved access to agricultural technology, training for farmers, and sustainable farming practices. This not only enhances yields but also ensures the long-term sustainability of the tobacco sector in the face of economic and environmental challenges. For instance, adopting superior seed varieties, efficient fertiliser and pesticide management, and labour training can markedly improve productivity while minimising environmental degradation.

Future research should explore the long-term environmental impacts of tobacco farming, particularly the effects of intensive fertiliser and pesticide use on soil health and biodiversity. Additionally, studies could investigate the socio-economic implications of tobacco farming on rural communities, including labour conditions and income stability. Further analysis could also focus on the adoption of innovative technologies, such as precision agriculture, to optimise input use and reduce environmental footprints. Finally, comparative studies between tobacco and alternative crops could provide insights into diversifying agricultural practices in tobacco-producing regions, ensuring both economic viability and environmental sustainability.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Аналіз виробництва тютюну в Індонезії: Детерміністичний підхід

Норіда Канда Сакті
Докторант з економічної освіти, доцент
Державний університет Сурабаї
60231, вул. Кетінтанг, м. Сурабая, Індонезія
https://orcid.org/0000-0002-5805-2466

Мухлісін
Докторант з економічної освіти
Державний університет Сурабаї
60231, вул. Кетінтанг, м. Сурабая, Індонезія
https://orcid.org/0009-0003-0979-3211

Анотація. Підвищення ефективності виробничих ресурсів має вирішальне значення для підвищення продуктивності та стійкості тютюнового господарства в Індонезії. У цьому дослідженні було проаналізовано вплив площі земельних угідь, кількості насіння, використання добрив, застосування пестицидів та робочої сили на виробництво тютюну за допомогою множинної лінійної регресії з використанням натурального логарифмічного перетворення. Дані були зібрані від тютюнових фермерів у Східній Яві, Центральній Яві та Західній Нуса-Тенггара за допомогою цілеспрямованої вибірки. Результати показали, що площа земельних угідь негативно впливала на виробництво тютюну (β = -0,242, p = 0,0001), що вказує на неефективність на більших площах, можливо, через нерівномірну якість землі або проблеми в управлінні земельними ресурсами. Натомість кількість насіння (β = 0,512, p < 0,0001), використання добрив (β = 0,206, p < 0,0001) та застосування пестицидів (β = 0,139, p < 0,0001) мали позитивний і значний вплив на врожайність. Праця не мала значного впливу (β = 0,0003, p = 0,9819), хоча все ж мала невеликий внесок у ефективність виробництва. Більшість фермерів обробляють невеликі та середні ділянки землі (10,5 % володіють 0,30 га), висаджують 8500 саджанців (8,4 %) та використовують 600 кг добрив (8,1 %) і 400 мл пестицидів (11,7 %). Цей висновок підкреслює важливість ефективного розподілу ресурсів для підвищення продуктивності. Крім того, результати дослідження відображають тенденцію фермерів до консервативного управління ресурсами через обмеження у витратах або знаннях. Загалом, ці результати підтверджують необхідність оптимізації використання ресурсів, особливо якісного насіння та ефективного використання добрив і пестицидів, для підвищення продуктивності при одночасному зменшенні негативного впливу на навколишнє середовище та підтримці впровадження стійких сільськогосподарських практик. Це дослідження рекомендує впровадження сільськогосподарських технологій, навчання фермерів та диверсифікацію культур для підвищення продуктивності

Ключові слова: площа землі; кількість насіння; кількість добрив; пестициди; робоча сила

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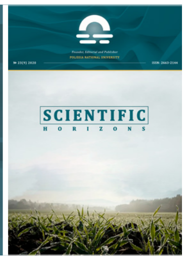

Ukraine's competitive position in international agricultural markets: Overcoming challenges and prospects

Tetyana Zinchuk*

Doctor of Economic Sciences, Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-5143-2394

Nataliia Kutsmus

Doctor of Economic Sciences, Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0001-9756-7019

Oksana Prokopchuk

PhD in Economic Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-0377-2693

Oleksandr Kovalchuk

PhD in Economic Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0002-7799-3157

Tetiana Usiuk

PhD in Economic Sciences, Associate Professor
Polissia National University
10008, 7 Staryi Blvd., Zhytomyr, Ukraine
https://orcid.org/0000-0003-1809-0502

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Abstract. The agricultural sector continues to be a leader in the global market as an exporter of agricultural products, but the large-scale war in Ukraine and geo-economic challenges have substantially changed the priorities for choosing trade partners in export-import activities in a competitive environment. The purpose of this study was to analyse the possibility of maintaining the competitive position of Ukrainian agri-food products in the world commodity markets and to identify strategic alternative market segments of the agricultural sector through the lens of structural transformations in commodity exports. The study employed economic and

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*Corresponding author

statistical methods of research (for analysing the dynamics and structure of agricultural exports), the index method (for assessing the level of market monopolisation), analysis and synthesis, induction and deduction (for substantiating conclusions and proposals). It was found that competitive positions were strengthened in the structural transformation process through the development of new market segments. The study analysed the commodity and geographical structure of exports and the nature of changes in the choice of priorities and market concentration and found that the impact of negative factors objectively reoriented producers and intermediaries to the European market, strengthening the role of Eastern European countries. The study identified changes in competitive positions in the markets of grain, oilseeds, vegetable and animal fats, which allowed assessing the prospects for the recovery and retention of target agricultural markets. The dynamics of changes in the positions of importing countries showed new leaders in the import of agri-food products, including the top 5 countries: Romania, Turkey, Poland, China, and Spain. The study found that the primary consumers in the vegetable and animal fats market are India, Poland, Spain, and Romania; in the oilseeds market – Germany, Belgium, the Netherlands, and Egypt. The value of the Herfindahl–Hirschman index indicates that Ukraine has partially lost its competitive advantages in China, Egypt, and Israel due to increased market concentration. The proposals for strengthening competitive positions in international agricultural markets in the face of global risks are of practical significance. The findings of this study are recommended to be used at the state and local levels in determining the strategic areas of competition policy, which can be effectively implemented under conditions of subsidies and regulation of agricultural markets, cost and price advantages, compliance with quality and safety standards, compliance with the spatial location of agri-food segments, the ecological ability of agriculture to withstand climate change, and information provision of producers

Keywords: agricultural sector; international trade; comparative advantage; geographical structure of exports; commodity structure of exports; market concentration; agricultural products

INTRODUCTION

Ukraine's agriculture sector is highly rated in terms of the interaction of the most favourable factors influencing agricultural production and the function of guaranteed food security. Specifically, it has the most fertile land in the world (32.7 million ha) used for agricultural production; it has excellent natural and climatic conditions for the dominance of major export crops (grain and industrial); it continues to be a priority sector of the economy in terms of its contribution to the country's budget in the post-war period and maintains a favourable investment climate and innovation capacity. A prominent role in contributing to the Sustainable Development Goals is ensured by the social significance of the industry (employment level is 14% of the total number of employed), a considerable share in the country's GDP (10.9%), environmentally friendly climate change adaptability, and a strong level of land capital use as a mechanism for the functioning of the economic system overall (Albaladejo, 2024). Despite the scale of losses due to the war, which experts estimate at USD 49 bn, the agricultural sector demonstrates not only high resilience and adaptability to risks but also prioritises maintaining the competitive advantages of agri-food products on global commodity markets (Report on direct infrastructure… 2023). Such a strategic perspective of Ukraine is in line with modern theoretical and methodological concepts of competitive assessment of the agricultural sector's capabilities and the postulates of the theory of classical competition by M.E. Porter (1990), according to which no nation can be uncompetitive.

From the standpoint of agricultural sector competitiveness policy, there is a wide variety of scientific opinions on the analysis of the impact of factors on competitiveness. The EU competitive markets, which are regulated under the Common Agricultural Policy (n.d.), are viewed and formed through the lens of policy schemes and price models due to the existing subsidy rules. In contrast to the conventional findings, M. Graubner and R. Sexton (2023), who considered the key feature that distinguishes agricultural markets from other industries to be their spatial location, argued that the regional dimension is fundamental to determining prices and production volumes, as well as market competitiveness. The spatial dimension encourages producers to locate in the centres of their market areas, avoiding intense competition and minimising price competition. Analogous opinions on the market effects of different countries are typical for other researchers, for example, E. Bulte *et al.* (2024) noted the lack of competition in remote commodity markets and the low quality of supply from small owners. Therewith, an effective method of increasing competition could be to improve the contracting system, as well as to use a relational contract that enables the negotiation of crop prices and quality.

Compared to international competitiveness, the concept of international competitive position is much narrower: it is the state and changes in the share of a particular country in international trade, as well as the evolution of this turnover, including the corresponding transformation of quality. For agriculture, according to a team of researchers, it is the skilful use of the natural comparative advantages of the respective countries (Jarosz-Angowska *et al.*, 2020). The topic of the correlation between competitive advantages and export performance is also developed by other researchers in their studies, coming to the general conclusion that export development is of great significance both at the macro and micro levels, as it contributes to the economic and social development of nations, increases productivity, creates jobs, and is an attractive way to enter international markets. According to O. Rua *et al.* (2018) and H. Keskin *et al.* (2021), export efficiency can be increased by the costs or benefits of differentiating competitive strategies and export opportunities. Accordingly, successful exports result from the efficient use of resources and capabilities, which ultimately creates a broad field for international competitiveness.

Thus, recognising that competitiveness in the trade flow is viewed as a clear position of a country in the global economy or the economy of a particular region, as well as its performance in foreign trade, and considering the specific features of Ukraine's integration into the single European market, the competitive position of Ukrainian agri-food producers requires constant monitoring and evaluation of opportunities and results in the light of both strengthening their positions and reorientation to more profitable export segments. According to Ł. Ambroziak *et al.* (2024), the evolution of the competitive advantages of manufacturers will largely depend on how long the war and the post-war reconstruction process will last. A major factor in shaping future comparative advantages will be the inflow of foreign capital and the pace of Ukraine's integration into the European single market. The purpose of this study was to substantiate the strategic areas of export commodity policy in the agricultural sector of Ukraine based on a comprehensive analysis of the impact of objective global factors and the consequences of the war on the change in geographical and commodity priorities in market conditions.

MATERIALS AND METHODS

The scientific hypothesis of the study assumed that structural transformations of agricultural exports and changes in Ukraine's competitive position in international agricultural markets are the product of the systemic impact of the consequences of military operations in the country (destruction of production potential, disruption of logistics chains and routes) and the competitive policy of the world's largest exporters. Confirmation of the hypothesis formed the analytical basis for identifying target regional and commodity segments of the agricultural market for Ukraine, key competitors, prospects, and risks for restoring and strengthening competitive positions in the global agricultural market. The research methodology was based on a two-stage analysis of Ukraine's agricultural exports (value dynamics – time series method; commodity and regional structure – structural grouping method) and national markets of the key importers of agricultural products from Ukraine in terms of key commodities (assessment of the level of market monopolisation by the Herfindahl-Hirschman index and concentration level). In assessing the level of monopolisation of markets in individual countries, the Herfindahl–Hirschman index was calculated using the following formula:

$$I_h = \Sigma x_i^2, \tag{1}$$

where I_h is the Herfindahl–Hirschman index; x_i is the is the share of the i^{th} importer in the total volume of imported products.

The index value below 1,000 reflects a low level of market monopolisation (high competition), from 1,000 to 1,800 – an average level of monopolisation (medium competition intensity), and above 1,800 – high market monopolisation. The analysis of market concentration was also based on the results of calculating the aggregate share of the largest importers – the level of concentration is optimal if one importer holds no more than 31% of the market; two importers – no more than 44% of the market; three importers – no more than 54% of the market; four importers – no more than 63% of the market. To achieve the objectives of the research, the study employed the following scientific methods: analysis and synthesis (to identify changes in Ukraine's competitive position in the international commodity markets of grains and oilseeds, vegetable and animal fats); induction and deduction (to identify Ukraine's key competitors in international markets, prospects for restoring and maintaining competitive positions). The systematic application of scientific methods helped to perform the research objectives, namely: to identify cost changes and structural transformations of agricultural exports from Ukraine; to assess Ukraine's competitive position in the target agricultural markets; to substantiate the prospects for their restoration and maintenance considering changes in the level of market concentration and the policies of major competitors.

The conclusions of the theoretical part of the study were based on a synthesis of the results of academic developments of Ukrainian scientists and researchers from Poland, Italy, Portugal, the USA, and China. The empirical research was conducted based on analytical data from the State Statistics Service of Ukraine (2024) and the State Customs Service of Ukraine (2024) (information on the value of exports of agricultural products from Ukraine by commodity groups and countries for 2013-2025) and the international database Trade Map (2024) (information on the value of imports of agricultural products to individual countries overall and by importers for 2019-2025, formed based on data provided by national statistics services). The use of analytical information from official sources proved the reliability of the study results.

RESULTS AND DISCUSSION

In the geo-economic system, Ukraine has always been positioned as a country with an agrarian economy. Extensive resource capacities and favourable agricultural land areas determined the need and potential for the development of the agricultural sector, which grew by 5-6% annually (Draft recovery plan for Ukraine, 2022). This growth was achieved through increased volumes and intensive technological upgrades. Ukraine's gradual integration into international economic integration processes contributed to its position in the global agricultural market. The military events in the east and south of Ukraine in 2014 also strengthened the agricultural vector of economic development and the country's foreign economic potential, which led to changes in the sectoral structure of exports. The share of agricultural products in the value of national exports increased from 26.8% in 2013 to 45% in 2020 (Fig. 1). Even despite the crisis in the national and global economy, agricultural exports grew positively, reaching a peak in 2019 and 2021 (19.0% and 24.9%, respectively).

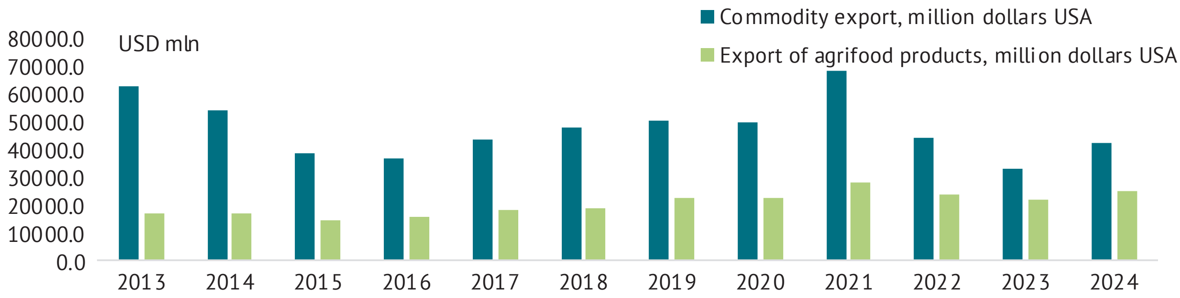

***Figure 1**. Dynamics of the value of Ukraine's exports of agricultural products, USD million*
***Source:** calculated by the authors of this study according to data from the State Statistics Service of Ukraine (2024)*

A critical factor for the development of the agricultural sector of the economy was the outbreak of full-scale military operations in Ukraine. The destruction of production facilities, occupation and mining of territories, and blocking of logistics corridors led to a decrease in the value of agricultural exports in 2022 to USD 23,390 mn (84.4% of 2021) (State Customs Service of Ukraine, 2024). In 2023, the rate of decline in the value of agricultural exports slowed down, with USD 22 bn worth of agri-food being supplied to the global market. This is a lower figure compared to 2021, although it is one of the largest in the last 30 years. Notably, the decline in global food prices was a major factor behind the decline in the value of agricultural exports from Ukraine, as exports of certain commodities increased markedly in physical terms (Pugachov, 2024). In 2024, the increase in the value of agricultural exports was already positive (12% compared to the previous year). Despite the negative trends in the value of agricultural exports, in 2022 the trend towards an increase in its share in national exports resumed. In 2023, it reached a record high of 60.8%.

The systemic effect of negative factors, with the most prominent impact of blocking international logistics routes, led to structural changes in agricultural exports from Ukraine. Specifically, the closure of access to the use of sea corridors, which were the primary channel for selling products to the south and east, forced producers and agro-traders to reorient themselves towards the European market. This led to considerable changes in the geographical structure of exports in favour of the EU countries (Fig. 2).

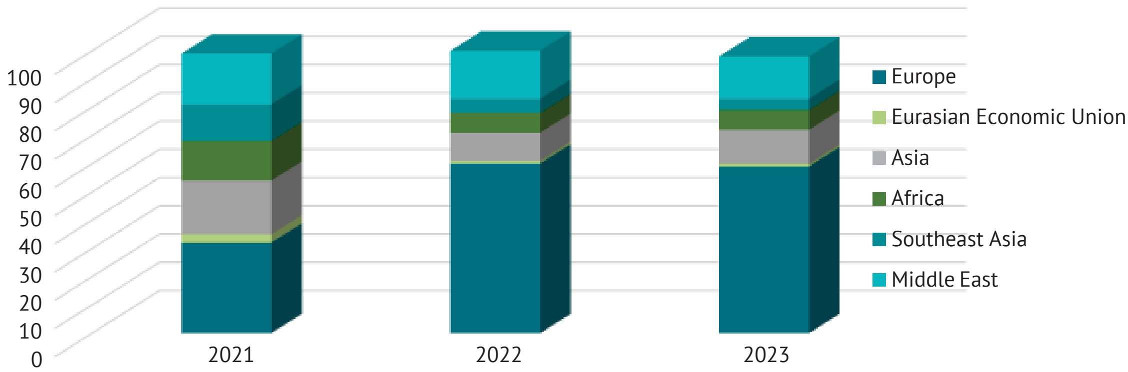

***Figure 2**. Regional structure of Ukraine's agricultural exports, %*
***Source:** calculated by the authors of this study according to data from the State Customs Service of Ukraine (2024)*

In terms of countries, Romania, Turkey, Poland, China, and Spain were the leaders in terms of the value of agricultural imports from Ukraine in 2022-2023 marketing year (Table 1). Within the EU, the vector of agricultural exports shifted towards Eastern European countries. The increase in the volume and share of exports to the EU in 2022 was made possible by the introduction of a 'trade visa-free regime' for agricultural products by the European Commission within the framework of its support for the Ukrainian economy. In 2023, to reduce further competitive pressure on the internal market and protect European farmers, the preferences were extended to limit imports of wheat, maize, soybeans, and sunflower to five EU countries. At the same time, the European Council developed mechanisms for close monitoring of the market situation and 'emergency braking' of imports, under which customs tariffs will be imposed on poultry, eggs, sugar, oats, cereals, maize, and honey within two weeks if imports of these products exceed the average imports recorded in the second half of 2021, as well as during 2022 and 2023 (Zanuda, 2024). The increase in the European market share came at the expense of a substantial reduction in supplies to the South and East in 2022: in the next marketing year, Ukraine's diplomatic efforts with the support of the EU managed to curb the rate of decline in exports to these regions. Accordingly, the geographical structure of agricultural exports has relatively stabilised. Changes in the geographical structure of agricultural exports from Ukraine, in line with the specifics of regional market demand, led to minor changes in the commodity structure of exports. The bulk of agricultural exports comprises cereals, vegetable and animal fats, oilseeds, and residues and waste from the food industry (Fig. 3).

***Table 1**. Dynamics of changes in the position of countries importing agricultural products from Ukraine*

Country	2020/21 marketing year		2022/23 marketing year	
	Cost, USD bn	Ranking	Cost, USD bn	Ranking
China	3.5	1	2.0	4
India	1.9	2	–	–
Netherlands	1.7	3	0.9	6
Egypt	1.6	4	–	–
Turkey	1.4	5	2.9	2
Spain	1.17	6	1.3	5
Poland	1.07	7	2.3	3
Germany	0.8	8	0.6	10
Indonesia	0.7	9	–	–
Romania	–	–	3.5	1
Bulgaria	–	–	0.8	8
Hungary	–	–	0.8	7
Italy	–	–	0.7	9

***Source:** calculated by the authors of this study according to data from Agricultural exports to the EU... (2024)*

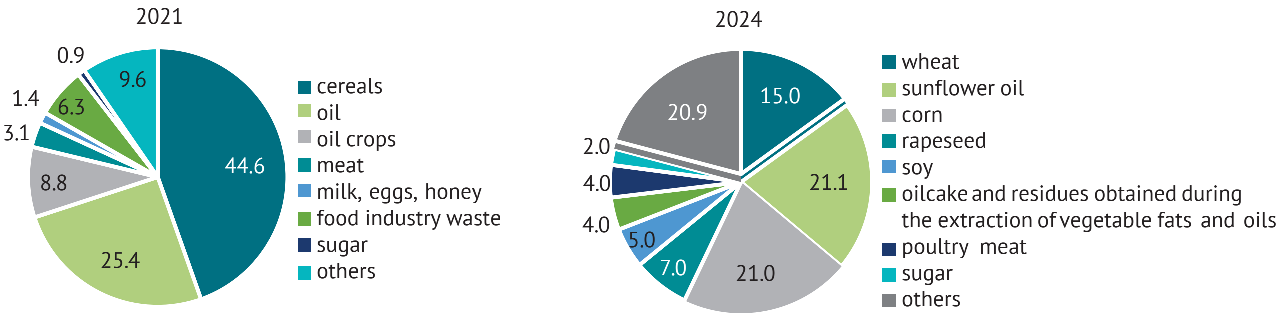

***Figure 3**. Commodity structure of Ukraine's agricultural exports, %*
***Source:** calculated by the authors of this study according to data from the State Customs Service of Ukraine (2024)*

It is the reorientation from the East and South to the European region that has led to a decrease in the share of grains to 37.8% and an increase in the share of oilseeds in the export structure. However, overall, the structure of exports to the EU is analogous to the national one, with 82% of exports of grains and oilseeds, oils and fats, and residues of the processing industry. In 2023, the European market stayed the primary market for a series of Ukrainian products: poultry meat (USD 407 mn, 51% of total exports of this type of agricultural product); eggs (USD 39 mn, 64%); egg products (USD 36 mn, 92%); wheat flour (USD 25 mn, 60%); starch (USD 19 mn, 51%); sugar, sugar confectionery (USD 487 mn, 82%); dough products (USD

43 mn, 81%); bakery products (USD 122 mn, 57%), etc. (In 2023, the volume of exports of Ukrainian agricultural products..., 2024).

To determine the vectors of further transformations of Ukraine's agricultural exports, the study analysed its subject structure and diagnosed the national markets of the key importers of agricultural products in terms of key commodities. Over 40% of Ukraine's agricultural exports in the pre-war period were accounted for by grain crops, which was driven by high demand and well-established logistics routes to the countries of the South (Egypt, China, Indonesia, Bangladesh, etc.). A significant share of grain was supplied to the European market (Table 2).

***Table 2**. Top 10 countries importing grain from Ukraine*

2019			2024			Change in the country's position in the ranking, 2024/2019, +/-
Ranking	Country	Cost, USD thsd	Ranking	Country	Cost, USD thsd	
1	Egypt	1,310,267	1	Spain	1,917,837	+2
2	China	858,653	2	Egypt	904,481	-1
3	Spain	764,825	3	China	765,175	-1
4	Turkey	718,407	4	Turkey	745,884	–
5	Netherlands	623,587	5	Italy	627,578	+5
6	Indonesia	537,479	6	Netherlands	543,000	-1
7	Bangladesh	420,308	7	Indonesia	480,194	-1
8	Israel	316,075	8	Tunisia	293,261	+1
9	Tunisia	292,515	9	Algeria	283,627	+5
10	Italy	282,683	10	Israel	250,015	-2

***Source:** calculated by the authors of this study according to data from Trade map (2024)*

The military invasion of Ukraine resulted in a substantial increase in the European market share. Specifically, in 2023, Romania (from 68th to 3rd position), Poland (from 41st to 8th position), and Hungary (from 57th to 9th position) entered the top 10 largest importers. In 2024, these countries decreased the volume of grain imports from Ukraine, while the share of Spain and Italy increased. In the markets of the Eastern countries, Ukraine lost some of its competitive advantage. The key reasons for this trend were the negative consequences of the military invasion of the country and the active and rather aggressive behaviour of competitors. The assessment of Ukraine's competitive position was based on the monitoring of the level of concentration (monopolisation) of the national commodity markets of the major importers of agricultural products from Ukraine. China has been one of the target grain markets for Ukraine in recent years. In 2019-2024, the country's grain market capacity increased by 4 times, which opened considerable prospects for agricultural importers. In 2024, the value of grain exports from Ukraine to China also increased (by 37.7%) to USD 1,495.4 mn but did not reach the pre-war level. According to the Herfindahl-Hirschman index, the Chinese grain market has an average concentration (the index is within 1,000-1,800) and did not undergo substantial changes in 2019-2024. The intensity of competition was medium – the total share of the 3 major importers was 54%. At the same time, the competitive ratio of the major grain importers changed. In 2024, Australia and Brazil, which had not been among the top 10 largest suppliers until present, moved into the top three in terms of import value. This led to a decline in Ukraine's position from 1st to 4th (Table 3).

***Table 3**. Concentration level of the Chinese grain market according to the Herfindahl-Hirschman index*

2019				2024			
Exporting country	Cost, USD thsd	x_i^*, %	$(x_i)^2$	Exporting country	Cost, USD thsd	x_i^*, %	$(x_i)^2$
Ukraine	1,085,913	21.48	461.50	Australia	3,211,665	21.68	469.94
Canada	904,516	17.89	320.19	USA	2,893,861	19.53	381.54
Australia	799,565	15.82	250.20	Brazil	1,887,665	12.74	162.34
France	413,520	8.18	66.92	Ukraine	1,495,405	10.09	101.88
Thailand	345,452	6.83	46.70	Canada	1,446,838	9.77	95.37
USA	274,826	5.44	29.56	France	1,266,756	8.55	73.11
Vietnam	240,743	4.76	22.68	Argentina	730,088	4.93	24.28
Myanmar	236,984	4.69	21.98	Russia	434,146	2.93	8.59
Pakistan	234,869	4.65	21.59	Myanmar	321,726	2.17	4.72

Table 3. Continued

2019				2024			
Exporting country	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**	**Exporting country**	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**
Cambodia	171,535	3.39	11.52	Kazakhstan	300,613	2.03	4.12
Others	346,964	6.87	–	Others	826,514	5.58	–
Total	5,054,887	100	***1,252.84***	Total	14,815,277	100	***1,325.88***

Note: *x_i is the share of i-country in the total value of imported products, %*
Source: *calculated by the authors of this study according to data from Trade map (2024)*

Egypt is the target market for Ukraine's grain crops. Its capacity has been growing over the years, but the volume of supplies from Ukraine has stayed virtually unchanged. At the same time, the value of the Egyptian market for Ukraine has declined. Calculations of the Herfindahl-Hirschman index show that the level of monopolisation of the Egyptian grain market in 2019-2023 is changing from high to medium. However, the level of market concentration by weight of the largest importers in 2023 is high – the share of two in the market capacity is 48.2% (the critical limit is 44%), three – 56.9% (with the limit of 54%), four – 64% (64%) (Table 4). The entity structure of imports did not change markedly during the study period. As a result of the externalities of the military invasion of Ukraine and certain geo-economic events, Ukraine is losing its competitive position in the markets of Indonesia, Israel, Bangladesh, and Tunisia, which were among the top 10 grain importers. According to the official statistics of Indonesia, the value of grain imports from Ukraine in 2019-2023 decreased threefold, which led to a decline in its place in the structure of major importers from the 3rd to the 9th position. However, in 2024, a major increase in the value of grain imports from Ukraine was recorded (to the level of 2019), and the country ranked 4th in terms of significance. Ukraine's market niche was partially replaced by supplies from Vietnam, Thailand, and Brazil. The level of concentration of the Indonesian grain market is low (994.17 in 2024), which indicates prospects for restoring Ukraine's competitive position.

Table 4. *Concentration level of the Egyptian grain market according to the Herfindahl-Hirschman index*

2019				2024			
Exporting country	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**	**Exporting country**	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**
Russia	1,435,472	27.39	750.10	Russia	2,554,686	30.76	945.88
Ukraine	1,362,523	26.00	675.80	Ukraine	1,448,293	17.44	304.00
Brazil	629,608	12.01	144.30	Brazil	726,095	8.74	76.41
Argentina	561,851	10.72	114.91	Romania	590,609	7.11	50.55
Romania	410,242	7.83	61.26	Argentina	522,675	6.29	39.59
USA	263,670	5.03	25.31	France	123,889	1.49	2.22
France	171,778	3.28	10.74	India	119,137	1.43	2.06
China	156,229	2.98	8.88	USA	60,368	0.73	0.53
India	95,731	1.83	3.34	Bulgaria	58,984	0.71	0.50
Poland	32,341	0.62	0.38	Turkey	54,051	0.65	0.42
Others	121,725	2.32	–	Others	2,047,746	4.65	–
Total	5,241,240	100	***1,795.04***	Total	8,306,533	100	***1,422.17***

Note: **x_i is the share of i-country in the total value of imported products, %*
Source: *calculated by the authors of this study according to data from Trade map (2024)*

The Israeli grain market has a significantly lower capacity than China or Egypt and a prominent level of concentration (the Herfindahl-Hirschman index was 3,581.78 in 2024), which tends to grow dynamically. For a long time, Ukraine has been the primary supplier of grain to Israel (accounting for about 40% of imports). However, during the war period, the volume of grain supplies decreased by almost 40%, which led to a decline in the country's market share to 26.6%. Thailand, Australia, India, and Brazil became Ukraine's new competitors. Considering the situation, capacity, and level of monopolisation of the Israeli grain market, restoring and maintaining competitive positions for Ukraine will be a challenging task, which will become more problematic over the years. Tunisia is a promising market for Ukraine's grain exports, considering the dynamic growth of its capacity (by 2 times in 2019-2023). Grain supplies to this country stayed virtually unchanged in value terms during the period under study (about USD 300 mn). This ensured that Ukraine maintained its leading position in the structure of the largest importers. However, the positions of Ukraine's key competitors – Russia (from 4% to 17% of the market), Romania (from 5% to 9%), Canada (from 3.5% to 11%), and Bulgaria (from 2% to 9%) – have markedly strengthened in the Tunisian market. This led to a substantial decrease in the level of concentration of the grain market from high to insignificant (the Herfindahl–Hirschman index decreased from 2,077 in 2019 to 1,057 in 2023), which is a positive development for Tunisia and a negative factor in the growth of competitive pressure for Ukraine (Table 2).

The logical induction of the results of the analysis of target markets for grain exports from Ukraine suggests that the negative consequences of the destruction of Ukraine's production, logistics, and export potential have led to the loss of competitive positions in the markets of the countries of the Eastern and Southern regions and a reorientation to the European market. The most active competitors for Ukraine in the markets of the East (China, Egypt, Israel) were Brazil, Russia, and Australia. In the countries of the South, the loss of Ukraine's market position is conditioned by competitive pressure from Russia and European countries. Ukraine is also a powerful player in the global market of fats of vegetable and animal origin, exporting products worth over USD 5 bn annually. The maximum volume of fat exports reached USD 7.04 bn in 2021 (Trade map, 2024). Ukraine supplies its products to the countries of the South and Europe. Therewith, the regional structure of fat exports has changed in recent years in favour of the EU countries (Table 5). In the pre-war period, the major target markets for Ukraine's fat exports were India and China. The markets of these countries have a high capacity, and therefore are promising, but Ukraine lost its leadership due to the destruction of established logistics routes (Table 6). Currently, the largest volumes of fat exports go to European countries.

***Table 5**. Top 10 importing countries of vegetable and animal fats from Ukraine*

2019			2024			Change in the country's position in the ranking, 2024/2019, +/-
Ranking	**Country**	**Cost, USD thsd**	**Ranking**	**Country**	**Cost, USD thsd**	
1	India	1,446,846	1	India	720,388	–
2	China	741,274	2	Poland	646,462	+5
3	Netherlands	457,986	3	Spain	617,000	-1
4	Spain	313,066	4	Romania	476,211	+71
5	Iraq	265,443	5	Netherlands	466,509	-2
6	Italy	263,809	6	Italy	429,848	–
7	Poland	171,353	7	Turkey	361,577	+16
8	France	99,371	8	Bulgaria	232,004	+22
9	United Kingdom	80,857	9	France	176,431	-1
10	Malaysia	75,694	10	China	155,453	-8

***Source:** calculated by the authors of this study according to data from Trade map (2024)*

***Table 6**. Concentration level of the Indian fat market according to the Herfindahl-Hirschman index*

2019				2024			
Exporting country	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**	**Exporting country**	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**
Indonesia	2,690,051	27.36	748.80	Indonesia	4,356,903	25.62	656.43
Malaysia	2,313,648	23.54	553.91	Malaysia	2,806,267	16.50	272.33
Argentina	1,789,781	18.21	331.47	Argentina	2,713,272	15.96	254.58
Ukraine	1,551,024	15.78	248.93	Russia	2,163,383	12.72	161.85
Nepal	251,906	2.56	6.57	Ukraine	834,628	4.91	24.09
Singapore	250,966	2.55	6.52	Thailand	776,806	4.57	20.87
Brazil	226,175	2.30	5.29	Brazil	747,898	4.40	19.34
Switzerland	202,899	2.06	4.26	Singapore	630,007	3.70	13.73
Russia	157,498	1.60	2.57	Romania	393,626	2.31	5.36
Bangladesh	91,823	0.93	0.87	Netherlands	298,048	1.75	3.07
Others	304,780	3.11	–	Others	1,283,894	7.55	–
Total	9,830,551	100	***1,909.19***	Total	17,005,225	100	***1,431.64***

***Note:** $^*x_i$ is the share of i-country in the total value of imported products, %*
***Source:** calculated by the authors of this study according to data from Trade map (2024)*

The Indian fat market has an average level of concentration (according to the Herfindahl-Hirschman index), which tended to decline slightly in 2019-2024. Ukraine's share in the import structure decreased threefold to 4.91% due to internal events and growing competitive pressure. New powerful competitors for Ukraine are Russia, Thailand, and Brazil, which have extensively strengthened their market positions. The second most significant target market for Ukraine for vegetable and animal fats is China, which has a high level of monopolisation both in terms of the Herfindahl-Hirschman index and market shares of major importers that exceed critical values (Table 7). Ukraine's share in the Chinese market in 2019-2024 decreased by 5%, which was the result of a halving of the cost of supplies from Ukraine, increased competitive pressure from Russia, whose supplies increased 4 times, and India.

***Table 7**. Concentration level of the Chinese fat market according to the Herfindahl-Hirschman index*

2019				2024			
Exporting country	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**	**Exporting country**	**Cost, USD thsd**	**x_i^*, %**	**$(x_i)^2$**
Indonesia	3,951,225	39.78	1,582.29	Indonesia	5,207,932	41.27	1,702.84
Malaysia	1,500,675	15.11	228.24	Russia	1,907,865	15.12	228.53
Ukraine	806,591	8.12	65.94	Malaysia	1,590,034	12.60	158.73
Canada	796,383	8.02	64.28	India	867,914	6.88	47.29
Russia	494,314	4.98	24.76	Ukraine	398,886	3.16	9.99
India	407,056	4.10	16.79	United Arab Emirates	317,873	2.52	6.34
Argentina	355,817	3.58	12.83	Brazil	293,646	2.33	5.41
Brazil	291,931	2.94	8.64	Australia	251,121	1.99	3.96
Australia	214,348	2.16	4.66	Belarus	239,901	1.90	3.61
Spain	174,277	1.75	3.08	Spain	237,800	1.88	3.55
Others	940,585		–	Others	1,307,489	41.27	1,702.84
Total	9,933,202	100	***2,011.50***	Total	12,620,554	100	***2,170.26***

***Note:** *x_i is the share of i-country in the total value of imported products, %*
***Source:** calculated by the authors of this study according to data from Trade map (2024)*

Oilseeds occupy the third position in the commodity structure of Ukraine's agricultural exports, with high sales volumes even under challenging conditions of military influence (USD 3.36 bn in 2024). The primary consumers of Ukrainian products in this commodity group are invariably the EU countries, Turkey, and Egypt (Table 8). Among the EU countries, Romania's position in terms of imports of fats and oilseeds from Ukraine has strengthened the most. Pakistan entered the top ten importers for the first time.

***Table 8**. Top 10 countries importing oilseeds from Ukraine*

2019			2024			Change in the country's position in the ranking, 2023/2019, +/-
Ranking	**Country**	**Cost, USD thsd**	**Ranking**	**Country**	**Cost, USD thsd**	
1	Germany	483,620	1	Germany	789,072	-
2	Turkey	467,044	2	Belgium	483,737	+1
3	Belgium	340,603	3	Netherlands	426,351	+2
4	Egypt	229,732	4	Egypt	314,296	–
5	Netherlands	178,043	5	Turkey	262,577	-4
6	France	170,607	6	United Kingdom	172,189	+13
7	Belarus	138,906	7	France	157,382	-1
8	Poland	99,890	8	Pakistan	122,498	+116
9	Italy	69,900	9	Poland	77,033	+1
10	Greece	56,521	10	Greece	76,506	–

***Source:** calculated by the authors of this study according to data from Trade map (2024)*

The evolution of researchers' opinions and the results of studies by A. Jarosz-Angowska *et al.* (2020), M. Graubner and R. Sexton (2023) have been proving over many years that the place of the agricultural sector in international trade continues to be global and attractive for investment, and that competition policies vary by country. Therewith, for countries to take advantage of new opportunities in international trade, they must have knowledge of the regulatory framework of importing countries, follow agri-food standards and other rules of coordination with trading partners, which positively influences the development of an effective export policy and its increase in the future. Summarising the findings obtained, it can be argued that Ukraine has weakened its competitive position in the key segments of the global agricultural market. At the same time, there has been a reorientation of Ukrainian exports from the East and South to the West, particularly the EU. One of the major factors behind the preservation of Ukraine's agricultural export potential is the increase in supplies to EU member states due to the introduction of a preferential trade regime.

The loss of positions in the grain market is largely conditioned by competitive pressure from Brazil and Russia in the markets of the East (China, Egypt, Israel), Russia and Europe in the countries of the South. However, China and Egypt continue to be promising target markets for Ukraine as their capacity is growing dynamically. Competitive positions on the markets of Indonesia, Israel, Bangladesh, and Tunisia, which were among the top 10 grain importers from Ukraine, will be more challenging to restore, considering their low capacity and high concentration. Highly capacious markets for vegetable and animal fats (China, India) are highly concentrated, which, in the face of aggressive policies of competitors (Russia and Brazil), increases the risks of maintaining and restoring market positions for Ukraine.

To restore and maintain competitive positions in the global commodity market for agricultural products, Ukrainian producers should focus on quality and reorientation to products with higher added value. Analogous recommendations were outlined in the studies of some Ukrainian researchers who noted that a comprehensive approach to ensuring competitiveness in wartime requires rapid adaptation to changes in the global market, as military conflict disrupts the conventional environment, increases risks, and at the same time creates new opportunities (Volkova *et al.,* 2023). It is quality that is becoming the key factor that stabilises and increases the competitiveness of the agricultural sector and the national economy overall. Improving the quality of agricultural products, e.g., with a focus on organic production, is becoming a popular trend in the European and global markets, which strengthens competitive positions in agricultural segments. An example of the country's potential success in the struggle for better sales conditions may be the use of such a comparative advantage as the export of organic agri-food products. For instance, K. Boys *et al.* (2022) analysed and considered the organic agribusiness of the United States in terms of a promising trade tool and potential market opportunities for the country in a competitive market environment with many countries and a wide variety of products of organic origin. Furthermore, the organic farming model provides environmental benefits, stimulates sustainable agricultural development and economic growth without harming the environment and society, influences market demand, and regulates the clear definition of consumer demands based on continuous analysis of competitors or customer preferences (Dudar, 2019). As a complement to measures to strengthen competitive advantages in agriculture, it is proposed to factor in and implement international practices of effective public policy, develop cooperatives to reduce the monopolistic pressure of large enterprises, increase the product range, develop niche market segments, and apply processes to optimise production processes (Revenko *et al.,* 2024). The diversification contributes to strengthening the position of Ukrainian agricultural producers in global commodity markets, as the production of monocultures in agriculture and the maintenance of narrow specialisation has led to the decline of the livestock industry and other labour-intensive sectors, as well as critical social consequences, such as reduced employment of the rural population, increased migration, and depopulation of rural areas (Luzan *et al.,* 2025).

The generation of added value is directly reflected in the upward change in the export price of goods. Agricultural products of adequate quality and with a high degree of processing contribute significantly to employment and value added, thereby generating positive economic and social effects in terms of reputation, tourist attraction and environmental protection. Product quality is a motivating factor and a crucial element of a company's success in the international market. Improving the quality of exported products, according to Chinese researchers, is a prerequisite for economic growth, especially for developing countries, which often have a comparative advantage in the agri-food sector (Wang *et al.,* 2023). The key steps that will ensure the competitive position of Ukrainian agri-food products on the global market in the future should also include increasing the level of public investment in the development of the agricultural sector, integrating Ukraine's legislation into the EU in the context of quality standards for agricultural production, strengthening environmental requirements, etc. Other researchers also reached analogous conclusions (Kvasha *et al.,* 2024), arguing that these measures are significant both at the national and global levels and act as a certain guarantee of the country's food and national security in the context of a full-scale war.

CONCLUSIONS

The high productivity of agriculture shapes Ukraine's competitive position in the global agri-food market. The current trend in the development of Ukraine's agricultural sector is determined by the strengthening of its role in the integration into the global and European single market, as evidenced by the growing share of national exports, which reached 60% in 2023. The new format of international trade ties simultaneously serves as a driver for mitigating the consequences of the devastation and counteracting the challenges of globalisation. Despite the substantial externalities caused by the large-scale war, Ukraine's agricultural sector proved to be relatively resilient and showed strong results in food production and exports. Thus, in 2024, agricultural exports totalled USD 24.7 bn, supporting food security and the export potential of the national economy. Compensation for the loss of areas suitable for growing agricultural products by increasing production volumes, strengthening the export orientation of the agricultural sector, and the results of diplomatic efforts helped to maintain Ukraine's position in the global agri-food market. The identified changes in the commodity and geographical structure of agricultural exports are interdependent and resulted from internal factors and active competitive policy of agricultural exporting countries.

The export potential is based on the competitive advantages of conventional types of agri-food products (grains, oilseeds, vegetable, and animal fats). The commodity structure of agricultural exports is determined by the geography of export flows, which has been changing as a result of the large-scale war. Specifically, in the pre-war period, China, India, the Netherlands, and Egypt were the leading countries in terms of Ukrainian agricultural imports, while in 2023 the situation changed towards Romania, Turkey, Poland, and China. Accordingly, the markets of these countries will determine the future prospects for export orientation, but at the same time, the requirements for products will increase, especially in terms of quality and added value of agri-food products.

In 2019-2024, Ukraine demonstrated a weakening of its competitive position in the main segments of the global agricultural market, which is confirmed by the diagnostics of the national markets of the main importers of agricultural products in terms of key commodities. Thus, in the Chinese grain market, the country moved from 1st to 4th place with a change in share from 21.5% to 10.1%; in the Indian fat market, from 4th to 5th place with a change in share from 15.8% to 4.9%. Notably, in 2024 the situation improved slightly compared to 2023. The loss of positions in the grain market is largely driven by competitive pressure from Brazil and Russia in the markets of the East (China, Egypt, Israel), Russia, and Europe in the countries of the South. However, China and Egypt continue to be promising target markets for Ukraine, as their capacity is growing dynamically. The capacity of China's grain market increased almost 3 times, reaching USD 14.8 bn, and that of Egypt – 1.5 times, reaching USD 8.3 bn.

Competitive positions in the markets of Indonesia, Israel, Bangladesh, and Tunisia, which were among the top 10 grain importers from Ukraine, will be more difficult to regain, considering their low capacity and high concentration. High-capacity vegetable and animal fats markets (China, India) are highly concentrated. Specifically, the Indian fat market, with a capacity of USD 17 bn, is characterised by a concentration level of 1,431, which is greater than the average. In the context of aggressive policies of competitors (Russia and Brazil), the prominent level of market concentration creates further risks for Ukraine to maintain and restore its competitive position. Promising areas for further research will be transformational changes in the conjuncture of high-capacity foreign agri-food markets, the nature of which will increasingly be influenced not only by economic levers but also by political decisions of the world's leading countries. At the same time, a large-scale war gives Ukraine a chance and incentive to explore new product and geographical niches of the global agricultural market, which requires scientific support for relevant management decisions on possible international market expansion.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Конкурентні позиції України на міжнародних аграрних ринках: подолання викликів та перспективи

Тетяна Зінчук
Доктор економічних наук, професор
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-5143-2394

Наталія Куцмус
Доктор економічних наук, професор
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0001-9756-7019

Оксана Прокопчук
Кандидат економічних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-0377-2693

Олександр Ковальчук
Кандидат економічних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0002-7799-3157

Тетяна Усюк
Кандидат економічних наук, доцент
Поліський національний університет
10008, бульв. Старий, 7, м. Житомир, Україна
https://orcid.org/0000-0003-1809-0502

Анотація. Аграрний сектор залишається лідером на світовому ринку як експортер сільськогосподарської продукції, але широкомасштабна війна в Україні і геоекономічні виклики суттєво змінили пріоритети вибору торговельних партнерів в експортно-імпортній діяльності в конкурентному середовищі. Мета статті полягала в аналізі можливості утримання конкурентних позицій української агропродовольчої продукції на світових товарних ринках та визначити стратегічні альтернативні ринкові сегменти аграрного сектора через призму структурних трансформацій в товарному експорті. Використано економіко-статистичні методи дослідження (при аналізі динаміки та структури аграрного експорту), індексний метод (для оцінки рівня монополізації ринків), аналізу і синтезу, індукції і дедукції (обґрунтування висновків і пропозицій). Було досліджено, що в процесі структурних трансформацій, конкурентні позиції зміцнилися через освоєння нових сегментів ринків. Було проаналізовано товарну та географічну структуру експорту й характер змін у виборі пріоритетів та концентрації ринків та встановлено, що дії негативних чинників об'єктивно переорієнтували виробників та посередників на європейський ринок, посилюючи роль країн Східної Європи. Було проведено ідентифікацію змін конкурентних позицій на ринках зерна, олійних культур, жирів рослинного та тваринного походження, що дозволило оцінити перспективи відновлення та утримання цільових аграрних ринків. Динаміка у змінах позицій країн-імпортерів показала нових лідерів в імпорті агропродовольчої продукції, серед яких 5-ТОП країн: Румунія, Туреччина, Польща, Китай, Іспанія. Виявлено, що основними споживачами на ринку жирів рослинного і тваринного походження є Індія, Польща, Іспанія, Румунія; на ринку олійних культур – Німеччина, Бельгія, Нідерланди, Єгипет. Значення індексу Харфіндела-Хіршмана свідчить, що Україна частково втратила конкурентні переваги в Китаї, Єгипті, Ізраїлі внаслідок підвищення рівня концентрації ринків. Практичного значення набувають пропозиції щодо укріплення конкурентних позицій на міжнародних аграрних ринках в умовах глобальних ризиків. Результати дослідження рекомендовано використовувати на державному та локальному рівнях при визначенні стратегічних напрямів конкурентної політики, яка може ефективно реалізовуватися за умов субсидування та регулювання аграрних ринків, переваг у витратах і цінах, відповідності стандартам якості і безпеки, дотримання просторового розміщення сегментів агропродовольчого товару, екологічної здатності сільського господарства протистояти змінам клімату, інформаційної забезпеченості товаровиробників

Ключові слова: аграрний сектор; міжнародна торгівля; порівняльна перевага; географічна структура експорту; товарна структура експорту; концентрація ринку; сільськогосподарська продукція

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Improvement of financial mechanisms to support resource conservation in the agricultural sector of Ukraine

Rahib Kazimov

PhD in Economic Sciences, Associate Professor
Azerbaijan State University of Economics (UNEC)
AZ1001, 6 Istiglaliyyat Str., Baku, Azerbaijan
https://orcid.org/0000-0001-6141-2365

Vadim Levitsky*

Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0009-0004-8684-9896

Nataliia Verniuk

PhD in Economic Sciences, Associate Professor
Uman National University
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0001-9478-5088

Viktoriia Zhmudenko

PhD in Economic Sciences, Associate Professor
Uman National University
20300, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0002-6756-8288

Olga Varchenko

Doctor of Economic Sciences, Professor
Bila Tserkva National Agrarian University
09117, 8/1 Soborna Sq., Bila Tserkva, Ukraine
https://orcid.org/0000-0002-9090-0605

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Abstract. The purpose of this study was to assess the effectiveness of financial mechanisms for resource conservation in the agricultural sector of Ukraine, considering regional differences and barriers to innovation. The study presented a comprehensive analysis of the effectiveness of financial mechanisms to support resource conservation in the agricultural sector of Ukraine in 2020-2024. The structure of funding was analysed by the following categories: government programmes (UAH 480 mn in 2020), regional budgets (UAH 110 mn in 2021), banking instruments (UAH 135 mn in 2022), grant mechanisms (UAH 90 mn in 2023), and private investments (UAH 205 mn in 2024). The study covered 12 regions with the most active fundraising, including Vinnytsia, Poltava, Lviv, Khmelnytskyi, Dnipro, and Cherkasy. Examples of successful

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*Corresponding author

projects included: drip irrigation on an area of 80 ha (Farm Enterprise "Agro-Dar", Vinnytsia region), which reduced water consumption by 35%, strip-till on 150 ha (Peasant (Farm) Economy "Prometey", Poltava region), which reduced diesel fuel consumption by 18% and increased moisture storage by 20%, and the introduction of a 300 kW biogas plant (Limited Liability Company "Haysynbiolab"), which covered 60% of the farm's energy needs. In 2021, the application of biofertilisers reduced the use of mineral fertilisers by 30% without reducing yields. Pellet heating reduced energy costs by 25%, and the switch to biomass dryers reduced natural gas consumption by 40%. The average amount of funding per project in 2023 was UAH 1.73 mn, the highest in the five-year period. The need to expand access to innovative financial mechanisms for small and medium-sized producers, including agri-bonds, green loans, and digital subsidies, was emphasised. The expediency of creating a single digital platform with open information on all available forms of support was substantiated. The practical significance of the findings lies in their potential use to improve government programmes to support resource conservation in the agricultural sector

Keywords: energy efficiency; drip irrigation; grant funding; precision farming; environmental modernisation

INTRODUCTION

The relevance of the study is driven by the growing need to transform agro-industrial complex of Ukraine towards sustainable development, which includes the efficient use of natural resources, reducing environmental burden, and increasing energy efficiency. The problem of the study lies in the fragmentation of existing financial mechanisms, their limited accessibility for small and medium-sized farms, insufficient integration of support instruments with environmental criteria (ESG), and the lack of a systematic approach to assessing the effectiveness of funding by regional and technological characteristics. Despite the existence of government, grant and banking programmes, their practical implementation is often accompanied by administrative barriers, regional disparities, and a low level of local institutional support (Boiko *et al.*, 2025). Therefore, a comprehensive study of the sources, dynamics, efficiency, and barriers to funding resource-saving technologies in the agro-industrial complex allows substantiating the areas for improving financial policy in the sector and contributing to the ecological modernisation of Ukrainian agriculture.

As demonstrated in the thesis study by M.M. Gursky (2021), state financial support in the agricultural sector continued to be insufficiently flexible in stimulating environmentally friendly investments. The researcher emphasised the need to adapt subsidy programmes to the needs of small producers and resource-efficient technologies. According to I. Honcharuk and I. Tomashuk (2023), innovation processes in agriculture played a key role in increasing the competitiveness of enterprises. The researchers concluded that the effectiveness of funding depends on a combination of technological upgrades and access to financial instruments. According to O.V. Ostapovych (2023), the system of financial support in the agricultural sector was prone to fragmentation, and the mechanisms for allocating funds were not integrated. The researcher emphasised that regional disparities in funding were caused not only by economic but also by institutional barriers. L.C. Freitas *et al.* (2021) proved the effectiveness of agricultural waste reuse as part of a sustainable agro-industry. The study confirmed that investments in circular production models require special financial incentive mechanisms.

According to T. Sequeira *et al.* (2024), the productivity of the agricultural industry directly depended on the amount of targeted investment. The study emphasised that financial innovations contributed to reducing the technological gap between regions, subject to institutional support. According to R. Myniv and R. Batyuk (2023), the implementation of investment and innovation programmes required synchronisation of financial policy with the needs of environmental transformation of production. The researchers pointed out the significance of developing multi-instrument funding models with the inclusion of grant, leasing, and credit resources. Within the framework of an interdisciplinary approach, T. Crovella *et al.* (2024) focused on water conservation in the agricultural industry through the analysis of the water footprint and its alignment with the Sustainable Development Goals. The researchers substantiated the need to introduce comprehensive financial indicators to regulate water use in the agricultural sector. According to a review by S. Cosma *et al.* (2023), the current system of conservation finance is not sufficiently structured to effectively support nature-based solutions in agriculture. The researchers emphasised the lack of a coherent financial strategy that would cover both public and private sources.

Y. Jin *et al.* (2021) analysed the effectiveness of funding enterprises that implement energy saving and environmental protection technologies. The findings revealed that strong financial efficiency is achieved when a stable institutional environment for green investment is created. According to Y. Yang *et al.* (2021), the relationship between green financial policy, fintech, and high-quality economic growth is a key factor in promoting environmental modernisation. The researchers' empirical study proved that the introduction of financial innovations had the greatest effect in regions with developed digital infrastructure. According to D. Zhang (2023), although green finance is being actively implemented in the global economy, there are considerable risks of 'green hypocrisy' associated with the unfair positioning of ESG initiatives. The researcher demonstrated that without real transparency, funding does not ensure either sustainable development or increased public trust. Finally, Y. Tan and Z. Zhu (2022) showed that the environmental innovation activity of enterprises largely depends on ESG rating events and related financial constraints. The study confirmed that managers' environmental awareness and access to targeted funding are critical for the development of green technologies.

Regional disparities, the effectiveness of support for small farms, and barriers to financial innovation in the Ukrainian agro-industrial complex (AIC) continue to be understudied. The purpose of the present study was to assess the effectiveness of financial mechanisms for resource conservation in the Ukrainian agro-industrial complex, considering the specific regional features, support for small farms, and barriers to innovation.

MATERIALS AND METHODS

The timeframe of the study covered the period from 2020 to 2024, which ensured representative coverage of the transformation processes in resource conservation funding in the agro-industrial complex of Ukraine. The methodology was based on a combination of quantitative and qualitative analysis, structural-dynamic, and regional approaches, which helped to assess the effectiveness of financial mechanisms, regional disparities, sources of investment, and barriers to innovation.

Four regions were selected to analyse the funding of environmental programmes in agriculture: Vinnytsia (Strategy for balanced…, n.d.), Poltava (Ministry of Finance of Ukraine, n.d..), Dnipro (Concept of the Comprehensive…, 2015) and Lviv (Environmental Protection Programme…, n.d..). The selection criteria included the availability of implemented regional or interregional programmes to support the greening of production (United Nations Industrial Development Organisation, 2024). The basic data were obtained from the open budget reports of the Regional Military Administration, as well as from the financial reports of the enterprises that received support (Strategy for balanced…, n.d..; Ministry of Finance of Ukraine, n.d..; Concept of the Comprehensive…, 2015; Environmental Protection Programme…, n.d..). The amount of annual funding was analysed with a breakdown by the following areas: energy efficiency, water conservation, bioenergy, and reduction of mineral fertiliser use. Formula 1 was used for each year:

$$F_{i,t} = \sum_{j=1}^{n} C_{j,t}, \quad (1)$$

where $F_{i,t}$ is the total amount of funding in region i in year t, $C_{j,t}$ is the amount under programme j in this year, $\sum$ is the sum (aggregation) sign, j is the programme index, n is the number of programmes within the region.

The following enterprises were selected for the study of the annual distribution of sources of resource conservation funding in the agro-industrial complex: Limited Liability Company "Agrovin" (n.d.), Peasant (Farm) Economy "Prometey" (n.d.), Public Catering Enterprise in the Form of a Limited Liability Partnership "Zeleny Gay" (n.d.), Limited Liability Company "Aqua-Land" (n.d.), Limited Liability Company "Karpaty-Agro" (n.d.), Limited Liability Company "Haysynbiolab" (n.d.), Limited Liability Company "Dnipro Agro Group" (n.d.), Limited Liability Company "Agropostach" (n.d.), Farm Enterprise "Zelena Nyva" (n.d.), Limited Liability Company "Globus Agro" (n.d.). The selection was made based on the following criteria: availability of implemented resource-saving technologies, availability of annual financial reports or information from open sources, participation in government or grant funding programmes. The share of each source in the funding was determined according to the formula 2:

$$S_d = \left(\frac{I_d}{\sum_{i=1}^{n} I_i}\right) \times 100, \quad (2)$$

where S_d is the share of funding source d in percentage, I_d is the investment from the source, $\sum_{i=1}^{n} I_i$ total amount of all funding sources (sum of i from 1 to n)

To compare the efficiency of farms with and without state support, the following were selected: a farm from Khmelnytskyi region (a participant in the Ukragroleasing programme), farms from Poltava and Vinnytsia regions (recipients of compensation for strip-till and no-till), and enterprises from Odesa and Mykolaiv regions that did not attract funding. The level of resource saving was calculated as follows:

$$RE = \left(\frac{V_{\text{before}} - V_{\text{after}}}{V_{\text{before}}}\right) \times 100, \quad (3)$$

where RE is the percentage reduction in resource use (resource efficiency), V_{before} is the amount of resource use before the introduction of the tool (water, fertiliser, fuel), V_{after} is the volume of use after implementation. The return on investment was calculated using formula 4:

$$T_p = \frac{I}{\Delta P_{\text{yearly}}}, \quad (4)$$

where T_p is the investment payback period, I is the amount of investment in the project, ΔP_{yearly} is the annual cost savings (difference before/after).

The assessment of the regional distribution of fundraising covered 12 regions: Vinnytsia, Poltava, Khmelnytskyi, Dnipro, Cherkasy, Lviv, Odesa, Ternopil, Kyiv, Mykolaiv, Kherson, Zaporizhzhia, Chernihiv, Sumy, and Zhytomyr. In the study, the amount of funding for each region was calculated by adding up the financial receipts from different sources in each of the five years. The total amount was calculated as follows:

$$R_i = \sum_{t=2020}^{2024} F_{i,t}, \qquad (5)$$

where R_i is the total funding of region *i* for 2020-2024, $\Sigma_{t=2020}^{2024}$ is the amount by years from 2020 to 2024, is the amount of funding in region *i* in year *t*.

The study identified five main barriers to the introduction of financial innovations in the agricultural sector: distrust of new mechanisms (28%), high entry costs (26%), information silos (19%), lack of access to finance (15%), and regional inequality (12%). To determine the share of each barrier in the overall structure, the following formula 6 was used:

$$B_i = \left(\frac{W_i}{\sum_{i=1}^{n} W_i}\right) \times 100, \qquad (6)$$

where B_i is the share of influence of barrier *i* in the overall structure (%), W_i is the assessment of the weight of the barrier *i* (expressed as a conditional value, e.g., in points or impact on failure), $\sum_{i=1}^{n} W_i$ is the total weight of all barriers.

To ensure the accuracy of the analysis, the average deviation of factual funding from the planned budget figures was considered. The margin of statistical error was calculated using the formula for the relative deviation between planned and actual amounts and averaged ±7% for the years analysed. This parameter was factored into the interpretation of financial volumes at the regional and national levels, which helped to avoid distortions in the comparison between years. The total amount of funded activities was calculated by summing the annual funding for each region:

$$R_i = \sum_{t=2020}^{2024} F_{i,t}, \qquad (7)$$

where R_i – is the total amount of funding in region i, $F_{i,t}$ is the financed volume in year t.

The data sets were processed using Python (Pandas and Matplotlib libraries) and Excel. This comprehensive approach provided a reliable basis for interpreting the results of the study on the effectiveness of financial support for resource conservation in the Ukrainian agro-industrial complex.

RESULTS

In 2020, the most effective use of public funding was made in Vinnytsia and Lviv regions. In the village of Makhnivka, Kalynivka district, Vinnytsia region, Limited Liability Company "Agrovin" (n.d.) implemented a project to modernise the irrigation system. Within the framework of the project, the outdated pipelines were completely replaced with polyethylene ones, and automated controllers were introduced to regulate water supply depending on soil moisture. These measures resulted in a 28% reduction in water consumption and a 19% reduction in electricity consumption, demonstrating the effectiveness of the investment. In Zhovkva, Lviv region, Limited Liability Company "Karpaty-Agro" implemented a comprehensive thermal modernisation of livestock facilities, including insulation of roofs, facades, and floors, and installation of pellet boilers for heating. This helped reduce heating costs by 25% compared to previous years, providing added stability in the production process in the autumn and winter (Wartime state support..., 2025).

In 2021, robust performance was recorded in Poltava and Cherkasy regions. In the city of Myrhorod, Poltava region, Limited Liability Company "Agropostach (n.d.) reconstructed a grain drying complex by converting dryers to run on biomass, particularly sunflower husks. This reduced the amount of natural gas consumed by 40% and reduced overall carbon dioxide emissions, which was in line with the principles of low-carbon agriculture. In Kamianka, Cherkasy region, Farm Enterprise "Zelena Nyva" (n.d.) introduced a technology for applying liquid biofertilisers made from livestock products, which reduced the use of conventional mineral fertilisers by 30% without reducing yields. This approach combined environmental and economic feasibility, helping to reduce the anthropogenic burden on the soil environment (Development Strategy of..., 2020).

In 2022, the effectiveness of implementing financial instruments for resource conservation was demonstrated in Vinnytsia and Dnipro regions. In the village of Uladivka in Vinnytsia region, the Farm Enterprise "Agro-Dar" (n.d.) installed a drip irrigation system on an area of 80 hectares. According to the results of agronomic monitoring, the system reduced water consumption by 35% and ensured even distribution of moisture even in conditions of limited natural moisture. In the city of Pavlohrad, Dnipro region, the Public Catering Enterprise in the Form of a Limited Liability Partnership "Zeleny Gay" (n.d.) started operating a dryer that used sunflower husk waste as fuel. The company's economic calculations showed a 42% reduction in energy costs and a shorter grain drying period, which positively affected the organisation of the production cycle (Skydan *et al.,* 2022).

In 2023, Poltava and Ternopil regions were the leaders in terms of implementing resource conservation programmes. In the city of Lubny, Poltava region, the Peasant (Farm) Economy "Prometey" (n.d.) introduced strip-till technology, which combined elements of minimal tillage with fertilisation in narrow strips. This technology reduced diesel fuel consumption by 18%, reduced soil compaction, and improved moisture retention by 15-20% compared to conventional ploughing. In the city of Zbarazh, Ternopil region, Limited Liability Company "Aqua-Land" (n.d.) implemented a project to organise a rainwater harvesting system. The system involved the collection of water from the roofs of greenhouse premises into tanks for further use for irrigation, which completely eliminated centralised water supply in the summer, reducing water costs by 100% within the greenhouse sector (Rusan & Zhurakovska, 2024). In

2024, Vinnytsia and Poltava regions demonstrated the most active engagement in resource conservation programmes. In the city of Haysyn, Vinnytsia region, Limited Liability Company "Haysynbiolab" (n.d.) implemented a 300-kW biogas plant that operated on livestock waste. As a result, the farm received over 60% of its electricity and heat needs from an alternative source and reduced methane emissions. In the village of Velyki Sorochyntsi, Poltava region, Limited Liability Company "Globus Agro" (n.d.) equipped agricultural machinery with GPS navigation and variable fertiliser application systems, which reduced fertiliser use by 20%, while maintaining stable yields and reducing fertiliser losses due to precise dosing (Gusarova, 2025) (Table 1).

***Table 1**. Funding for environmental programmes in agriculture*

Year	Funding, UAH mn	Energy efficiency, UAH mn	Water conservation, UAH mn	Other, UAH mn	Concrete examples (places, enterprises)
2020	610	170.8	128.1	207.4 (organic production, reclamation)	Makhnivka village – Limited Liability Company "Agrovin"; Zhovkva city – Limited Liability Company "Karpaty-Agro"
2021	735	220.5	161.7	220.5 (soil monitoring, advisory services)	Myrhorod city – Limited Liability Company "Agropostach"; Kamianka city – Farm Enterprise "Zelena Nyva"
2022	690	220.8	158.7	179.4 (agroforestry reclamation, training)	Uladivka village – Farm Enterprise "Agro-Dar"; Pavlohrad city – Public Catering Enterprise in the Form of a Limited Liability Partnership "Zeleny Gay"
2023	810	283.5	194.4	170.1 (environmental audit, biocontrol)	Lubny city – Peasant (Farm) Economy "Prometey"; Zbarazh city – Limited Liability Company "Aqua-Land"
2024	865	311.4	216.3	155.7 (digitalisation of agroecology, innovative start-ups)	Haysyn city – Limited Liability Company "Haysynbiolab"; Velyki Sorochyntsi village – Limited Liability Company "Globus Agro"

***Source:** compiled by the authors of this study based on Development Strategy of Cherkasy Region 2021-2027 (2020), O. Skydan et al. (2022), V. Rusan and L. Zhurakovska (2024), A. Gusarova (2025), Wartime state support for agribusiness (2025)*

The concrete examples of the farms cited above confirmed the feasibility of further expanding such programmes, provided that a favourable institutional environment is created and farmers are better informed about available funding instruments. In 2020, state budget programmes continued to be a key source of funding. The total amount of support amounted to UAH 480 million, which enabled the implementation of 720 projects in regions such as Vinnytsia, Poltava, and Khmelnytskyi. Under these programmes, Limited Liability Company "Agrovin" (Makhnivka village, Vinnytsia region) and Peasant (Farm) Economy "Prometey" (Lubny city, Poltava region) successfully implemented the modernisation of irrigation systems and strip-till tillage technology, respectively. This was achieved through programmes to compensate for part of the cost of equipment to reduce water loss and energy consumption. The average amount of funding per project was UAH 667 thsd (Ministry of Agrarian Policy and Food of Ukraine, & Kyiv School of Economics, 2021).

In 2021, regional budget programmes intensified, providing funding of UAH 110 mn for 95 projects, with an average amount of approximately UAH 1.16 mn. Geographically, the largest support was observed in Poltava and Ternopil regions. A positive effect was demonstrated by the farms of Limited Liability Company "Aqua-Land" (n.d.) (Zbarazh city), which implemented a rainwater harvesting system for greenhouse irrigation, and Farm Enterprise "Zelena Nyva" (n.d.) (Kamianka city), which introduced biofertilisers based on organic waste. These examples confirm the high effectiveness of regional initiatives focused on concrete technologies, tailored to local needs. In 2022, banking instruments played a leading role in funding, with a total volume of UAH 135 mn and a total of 140 projects financed. The average cost of a supported project was UAH964 thsd. Kyiv and Khmelnytskyi regions were the most active, where Limited Liability Company "Ukragrokapital" (n.d.) and Farm Enterprise "Dovira" (n.d.) took advantage of preferential agricultural loans under the state programme "5-7-9%" to purchase precision fertiliser equipment and GPS navigation systems. Considering the absence of separate specialised bank lines for resource-saving technologies, obtaining funding required substantial preparation of business plans and external advisory support.

In 2023, grant programmes from international donors such as the United States Agency for International Development (USAID), the Global Environment Facility (GEF), and individual European Union (EU) projects dominated, providing 52 projects totalling UAH 90 mn. On average, funding per project amounted to about UAH 1.73 mn, which is the highest figure for the five-year period. The bulk of these programmes were implemented in Odesa and Lviv regions. Limited Liability Company "Karpaty-Agro" in Zhovkva city received support for the thermal modernisation of livestock facilities, while Agricultural Production Cooperative "Dobrobut" (n.d.) implemented a demonstration project on biocontrol of pests in the open field. The advantage of the grant programmes was their relative flexibility, but they were mainly open to those with project management experience and who could pass the complex selection procedures. In 2024, enterprises' private investments were the most active, providing 225 projects worth UAH 205 mn, resulting in an average investment of UAH 911 thsd per project. Investment activity was concentrated mainly in Vinnytsia and Dnipro regions. For example, Limited Liability Company "Haysynbiolab" (n.d.) installed a biogas plant, while Farm Enterprise "Agro-Dar" (n.d.) implemented drip irrigation on 80 hectares in the village of Uladivka. These examples illustrate that, given stable profits, enterprises are ready to invest in sustainable development technologies, even without external support, but this mechanism is still available mainly to large producers (Table 2).

***Table 2**. Annual distribution of sources of funding for resource conservation in the agricultural sector with examples of enterprises (2020-2024)*

Year	Funding, UAH million	Number of projects	Regions of implementation	Enterprises
2020	480	720	Vinnytsia, Poltava, Khmelnytskyi	Limited Liability Company "Agrovin", Peasant (Farm) Economy "Prometey"
2021	110	95	Poltava, Ternopil	Limited Liability Company "Aqua-Land", Farm Enterprise "Zelena Nyva"
2022	135	140	Kyiv, Khmelnytskyi	Limited Liability Company "Ukragrokapital", Farm Enterprise "Dovira"
2023	90	52	Odesa, Lviv	Limited Liability Company "Karpaty-Agro", Agricultural Production Cooperative "Dobrobut"
2024	205	225	Vinnytsia, Dnipro	Limited Liability Company "Haysynbiolab", Farm Enterprise "Agro-Dar"

***Source:** compiled by the authors of this study based on Limited Liability Company "Haysynbiolab" (n.d.), Limited Liability Company "Dnipro Agro Group" (n.d.), Limited Liability Company "Agropostach" (n.d.), Farm Enterprise "Zelena Nyva" (n.d.)*

The regional picture shows greater activity in Vinnytsia, Poltava, Khmelnytskyi, and Lviv regions, while the northern and south-eastern regions were less covered. Priority areas of funding included water conservation, bioenergy, precision agriculture, and infrastructure modernisation using local resources (Tokarchuk *et al.,* 2022). An illustrative example of the effective use of the financial instrument was a farm from Khmelnytskyi region, which in 2022, with the participation in a leasing programme implemented through the State Public Joint Stock Company "National Joint Stock Company "Ukragroleasing" (n.d.), managed to implement a drip irrigation system on an area of more than 50 hectares. As a result, in one growing season, water consumption was reduced by 30% compared to previous years, which reduced energy costs for water supply by 19%. The reduction in operating costs helped to reduce the payback period of the invested funds to 2.4 years, which is a high indicator for medium-sized agricultural production (Toryanyk, 2024).

A separate group of farms comprised those that benefited from the state programme "Financial support for agricultural producers by reducing the cost of purchased agricultural machinery and equipment". Specifically, this programme covered up to 30% of the cost of no-till and strip-till machines, which markedly reduced the cost of switching to conservation tillage. Such cultivation systems not only reduced fuel consumption by 25-30% but also increased soil moisture accumulation by 15-20% compared to conventional ploughing, which was crucial in the context of climate change. In Vinnytsia and Poltava regions, the introduction of strip-till was accompanied by such support, which encouraged farms to reduce deep mechanical intervention in the soil. A positive result of the implementation was a 12-15% increase in corn yields on some farms, while reducing cultivation costs. Furthermore, farms that took advantage of the "Affordable Loans 5-7-9%" programme managed to borrow money on favourable terms to invest in precision fertiliser technology, GPS navigation, micro-sprinkler systems, and other digital tools that reduce inputs. This programme, developed by the Ministry of Finance of Ukraine and the Entrepreneurship Development Fund, provided greater access to funding for innovation, especially in 2022–2023, when banks stepped up their cooperation with the agricultural sector (United Nations Industrial Development Organisation, 2024).

To compare the results, the study analysed 10 farms, including Limited Liability Company "Agrovin" (n.d.), Limited Liability Company "Karpaty-Agro" (n.d.), Peasant (Farm) Economy "Prometey" (n.d.), Farm Enterprise "Agro-Dar" (n.d.), Limited Liability Company "Aqua-Dar" (n.d.).), Limited Liability Company "Aqua-Land" (n.d.), Public Catering Enterprise in the Form of a Limited Liability Partnership "Zeleny Gay" (n.d.), Limited Liability Company "Agropostach" (n.d.), Farm Enterprise "Zelena Nyva" (n.d.), Limited Liability Company "Haysynbiolab" (n.d.), and Limited Liability Company "Globus Agro" (n.d.). The selection criteria for the farms included the use or absence of state financial support for the introduction of resource-saving technologies, while the division by production scale was not the main criterion. The sample included both medium and large-scale enterprises. The group with state support showed considerably better results in terms of reducing water consumption, fertiliser use and fuel costs. Specifically, the average reduction in water consumption reached 30%, while the average reduction in water consumption in farms without financial support did not exceed 12%. Analogous dynamics were observed in mineral nutrition: by introducing precision fertilisation technologies and using bio-organics, supported farms reduced their fertiliser use by 25%, while the control group reduced their fertiliser use by 10%.

An assessment of the payback periods for investments demonstrated another advantage of targeted funding. On average, the farms that received support had a payback period of 2.5 years, while without external assistance it exceeded 4 years. The reason for this was not only direct compensation of costs but also access to more modern technological solutions that provided greater efficiency per unit area (Fig. 1).

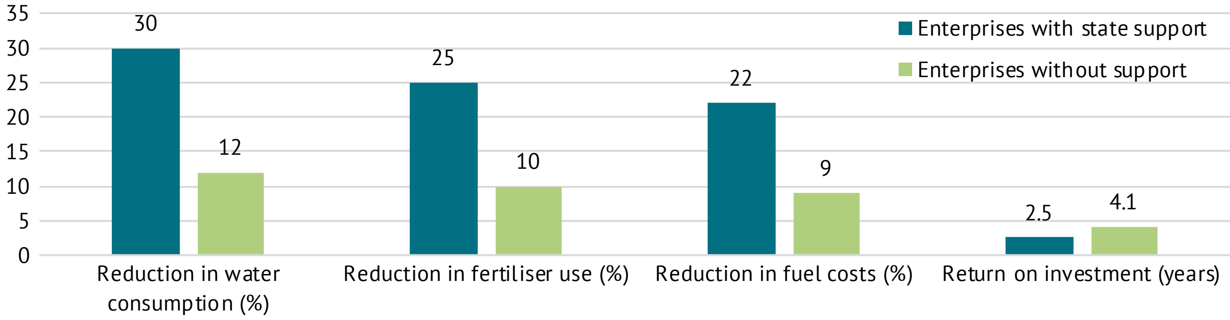

***Figure 1**. Comparison of the efficiency of farms with and without state support*
***Source:** compiled by the authors of this study based on United Nations Industrial Development Organization (2024)*

In 2020, the highest amounts of funding for resource conservation measures were concentrated in Vinnytsia region (over UAH 85 mn) and Poltava region (approximately UAH 78 mn). Regional programmes for modernising irrigation and compensating for the cost of precision farming equipment were active in these regions. The projects included drip systems in Makhnivka village and strip-till in Lubny city. At the same time, in Kherson, Zaporizhzhia, and Chernihiv regions, funding did not exceed UAH 10-12 mn, due to a lack of prepared projects and limited access to the mechanisms of the State Public Joint Stock Company "National Joint Stock Company "Ukragroleasing" (n.d.).

In 2021, Khmelnytskyi (about UAH 72 mn) and Cherkasy (about UAH 65 mn) regions joined the leaders, where more than 200 projects were financed against the backdrop of biofertiliser support programmes and the modernisation of grain dryers. In the Khmelnytskyi region, leasing mechanisms for organic aggregates were first applied through the state-owned State Public Joint Stock Company "National Joint Stock Company "Ukragroleasing" (n.d.), which allowed small farms to engage in resource conservation. Compared to 2020, the situation improved in Lviv region, but southern regions were left out of systemic participation in funding: Mykolaiv region attracted only UAH 15 mn (Peasant (Farm) Economy "Prometey", n.d..).

In 2022, the share of bank products (specifically, the "Affordable Loans 5-7-9%" programme) increased substantially, enabling Khmelnytskyi, Dnipro, and Kyiv regions to enter the top 5 in terms of attracted funding. For instance, over 180 projects to introduce biomass dryers and precision seeding were supported in the Dnipro region. The amount of funding in the region reached UAH 90 million. In 2022, Poltava region implemented a co-funding programme for strip-till technologies (with 30% compensation), which funded about 60 farms. In that year, a slight increase in activity was recorded in Sumy and Zhytomyr regions (approximately UAH 20-25 mn), but the unevenness was still significant (Public Catering Enterprise..., n.d..).

In 2023, grant programmes played a dominant role, intensifying in Lviv (about UAH 55 mn) and Odesa (over UAH 50 mn) regions. Demonstration projects on rainwater harvesting (Zbarazh city), thermal modernisation of livestock complexes (Zhovkva city), and biofertiliser production were implemented with international support from USAID and GEF. However, Chernihiv, Mykolaiv, and Kherson regions continued to fail to reach the threshold of UAH 20 mn per year. The reasons for this were related not only to infrastructure and security risks, but also to the poor coordination of local councils with line ministries and donor agencies (Limited Liability Company 'Aqua-Land', n.d..).

In 2024, Vinnytsia (over UAH 90 mn) and Poltava (about UAH 82 mn) regions remained the leaders, with projects of biogas plants ("Haysynbiolab"), precision farming systems (Globus-Agro), and autonomous water supply. This year was also marked by an increase in the engagement of Dnipro (UAH 70 mn) and Cherkasy (UAH 60 mn) regions, where the first elements of cluster funding appeared (Limited Liability Company "Karpaty-Agro", n.d..). However, in the northern regions, specifically, Chernihiv and Sumy, the amount of support did not exceed UAH 25 mn due to the lack of service centres for preparing applications and restrictions on the safety of field projects (Fig. 2).

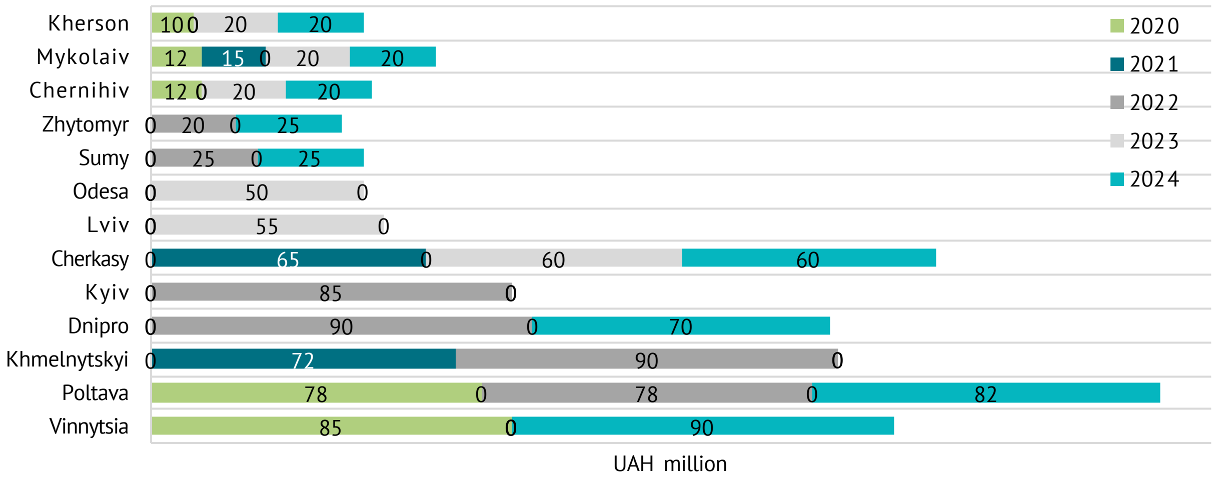

Figure 2. *Fundraising by region for 2020-2024*
Source: *compiled by the authors of this study based on Strategy for balanced regional development of Vinnytsia region for the period until 2027 (n.d.), Peasant (Farm) Economy "Prometey" (n.d.), Public Catering Enterprise in the Form of a Limited Liability Partnership "Zeleny Gay" (n.d.), Limited Liability Company "Aqua-Land" (n.d.), Limited Liability Company "Karpaty-Agro" (n.d.)*

Overall, in 2020-2024, a clear regional stratification of funding can be observed. The highest average annual level of support was recorded in Vinnytsia (UAH 73 mn/year), Poltava (UAH 68 mn/year), and Khmelnytskyi (UAH 59 mn/year) regions. These regions all had strong institutional capacities, access to advisory services, and a history of joint participation in national and regional programmes. In contrast, in such regions as Kherson, Zaporizhzhia, Mykolaiv, and Chernihiv, the average annual level of support did not exceed UAH 15-20 mn, indicating the need to reorient state support policy towards the development of technical infrastructure, digital services, and agricultural education hubs in these regions. The greatest obstacle was the lack of trust in new financial mechanisms, such as agri-bonds, climate loans, and green banking products. This barrier accounted for 28% of the total impact. The problem was the lack of a stable regulatory framework for the functioning of agri-bonds, the complexity of legal registration of issues, and unclear circulation mechanisms. Climate loans, despite support from international financial institutions, were applied exclusively at the level of individual pilot initiatives in Kyiv, Lviv, and Dnipro regions (Voloshchuk *et al.*, 2025). In other regions, the banking system did not offer adapted products linked to ESG indicators or reduced rates for eco-technologies, which reduced farmers' interest in using them (Koliada & Prozorov, 2022).

The second most influential barrier was the high entry cost of innovative projects and the lengthy payback period (26%). Technologies that required large-scale investments, such as biogas plants, solar power plants, autonomous micro-sprinkler systems, or precision agriculture, required initial investments of UAH 1.5-5 mn, while real payback periods ranged within 4-7 years (Hutorov *et al.*, 2021). In the absence of specialised loan programmes with reduced rates or the possibility of attracting donor co-funding, many farms, especially in the central and southern regions, postponed the implementation of such solutions or limited themselves to local upgrades (USAID AGRO Programme..., 2024). The third most influential barrier was the low level of transparency and information availability of financial instruments (19%). Until 2023, there was no integrated digital platform in Ukraine that would accumulate data on all existing government, banking, and international programmes (Shahini & Shtal, 2023). As a result, farmers often received information untimely or were unable to understand the requirements for participation, the list of required documents, or the deadlines for submitting applications. In many regions (specifically, Chernihiv, Sumy, and Kherson), access to such information was limited or entirely dependent on the initiative of local specialists in agricultural policy departments (Zenkin, 2024).

The fourth position in the structure of barriers was occupied by the lack of regional project infrastructure (15%). This primarily refers to the lack of specialised services that could provide technical support for the preparation of applications, financial efficiency modelling, and legal advice. A few regions did not have any accredited institution or independent advisory centre that could provide farmers with the necessary expertise. This made it impossible to submit projects even if they were ready to invest (Cabinet of Ministers of Ukraine Resolution No. 1163-2024-p, 2024). Limited access to funding for small producers (12%) rounded out the list of the main barriers. In practice, programmes such as "Affordable Loans 5-7-9%" often stayed inaccessible to small farms due to collateral requirements, tax history, or complicated banking procedures. It was also challenging for small businesses to meet the criteria of donor funding programmes, which often required co-funding capacity, electronic reporting, audits, and statutory documents (Solonyna, 2021; Shumka *et al.*, 2021). Thus, part of the sector remained excluded from the innovative financial environment, leading to a deepening technological gap between large and small producers (Fig. 3).

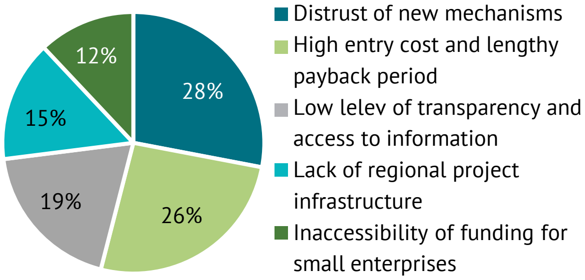

Figure 3*. Structure of barriers to financial innovation i n the agricultural sector of Ukraine*
Source: *compiled by the authors of this study based on E. Solonyna (2021), T.A. Koliada and Prozorov (2022), USAID AGRO Program will provide up to UAH 270 million in co-funding for the development of grain elevator facilities (2024), D. Zenkin (2024), Cabinet of Ministers of Ukraine Resolution No. 1163-2024-p (2024)*

To summarise, successful scaling of financial innovations in the Ukrainian agricultural sector in 2025 and beyond requires the creation of a comprehensive supportive ecosystem. This means a combination of regulatory reforms (e.g., simplifying the circulation of agri-bonds), development of regional agri-financial advisory infrastructure, digitalisation of support application processes, and a special focus on small and medium-sized enterprises. Only under these conditions is it possible to widely adapt environmentally friendly funding instruments at the level of all regions of Ukraine. In Vinnytsia region, the average deviation of the effective funding from the plan was ±5%, which indicated the stability of the implementation of the planned activities. Funding stayed stable throughout the period, with no reductions caused by the hostilities, and programmes to modernise irrigation and install biogas plants were fully implemented.

In Poltava region, the deviation rate was ±6%. Despite some delays in programme implementation, the overall funding for the activities was unchanged. The hostilities did not substantially affect the implementation of the projects, which enabled the successful introduction of strip-till technologies and modernisation of water supply systems. In Khmelnytskyi region, the deviation was recorded within ±7%. Financial activity was maintained at a strong level. The minor impact of external factors did not lead to a change in the priority areas of resource conservation, and the main drip irrigation and precision farming projects were completed on time. In Lviv region, the average deviation of effective funding was ±8%. Despite the overall stability, there was a slight decrease in grant activity in 2022-2023 due to the redistribution of international aid. Farm thermal modernisation programmes were partially adjusted. In Cherkasy region, the average deviation was recorded at ±7%. The impact of external factors was minimal, which ensured sustainable funding for projects to introduce biofertilisers and reconstruct irrigation systems.

In Dnipro region, the average deviation was ±6%. At the same time, there was a partial reduction in funding of 15% in 2022-2023 due to the deteriorating security situation. Despite this, the region maintained a high rate of implementation of bioenergy and precision agriculture projects. In Kyiv region, the deviation of the plan from the factual result stayed at ±5%. The war did not lead to a reduction in funding; conversely, the increased activity of international programmes contributed to the introduction of advanced technologies in water conservation and energy efficiency. In Odesa region, the average deviation reached ±9%, while the amount of funding decreased by 40% after 2022. Most grant and regional programmes were either frozen or adjusted to meet humanitarian needs. In Mykolaiv region, the average deviation was ±10%. Under the influence of the hostilities, funding cuts exceeded 65%, which led to the effective termination of most resource efficiency projects.

In Kherson region, the average deviation from the targets was ±12%, while funding decreased by over 80%. Due to the hostilities in the region, most water conservation and infrastructure modernisation projects were suspended. In Zaporizhzhia region, a deviation of ±11% was recorded with a corresponding reduction in funding by 75%. Implementation of new projects was hampered by high security risks, and only a few farms continued to operate on a limited basis. In Chernihiv region, the average deviation was ±10%. Due to shelling and destruction, funding was reduced by 55%. The resumption of programme implementation was slow, with a focus on minimal measures to restore production infrastructure. An average deviation of ±9% was recorded in Sumy region. The reduction in funding reached 35%. A considerable number of farms were forced to refuse to take part in modernisation programmes due to the danger of field work. In Zhytomyr region, the average deviation from the plan was ±8%. The hostilities had a limited impact on the implementation of measures, with funding cuts estimated at 25%, which allowed for continued activity in water conservation and energy efficiency (Table 3).

***Table 3**. Consideration of errors and external factors in the funding of resource saving measures*

Region	Average deviation from the plan, %	Nature of the war's impact
Vinnytsia	±5%	Impact not recorded
Poltava	±6%	Impact not recorded
Khmelnytskyi	±7%	Insignificant impact
Lviv	±8%	Local decrease in grant activity
Cherkasy	±7%	Insignificant impact
Dnipro	±6%	Partial reduction in funding
Kyiv	±5%	Increase in funding
Odesa	±9%	Major cuts to programmes
Mykolaiv	±10%	Massive cessation of project implementation
Kherson	±12%	Effective termination of funding
Zaporizhzhia	±11%	Major cuts to programmes
Chernihiv	±10%	Decreased activity in project implementation
Сумська	±9%	Partial reduction in funding
Zhytomyr	±8%	Insignificant impact

***Source:** compiled by the authors of this study based on Concept of the Comprehensive Regional Program (Strategy) for Environmental Safety and Climate Preservation of Dnipropetrovsk Region for 2016-2025 (2015), Strategy for balanced regional development of Vinnytsia region for the period until 2027 (n.d.), Ministry of Finance of Ukraine (n.d.), Environmental Protection Program for 2021-2027 (n.d.)*

Thus, the study found that in the context of the armed conflict, resource-saving programmes-maintained stability mainly in the central and western regions, while in the southern and eastern regions, project implementation was severely limited by external factors. At the same time, in those regions where institutional capacity continued to be high, funding adapted to the new conditions, confirming the flexibility of financial instruments for resource conservation in the agricultural sector.

DISCUSSION

The findings demonstrated the effectiveness of resource-saving technologies in Ukraine's agricultural sector with government support. In Vinnytsia and Poltava regions, irrigation projects were steadily implemented (reduction in water consumption by 28-35%), bioenergy (reduction in energy consumption by 40-42%), and precision agriculture (reduction in fertiliser use by 20-30%). Lviv and Cherkasy regions made progress in thermal modernisation (25% reduction in heating costs) and the use of biofertilisers (30% reduction in mineral fertilisers). Strip-till and rainwater harvesting technologies in Poltava and Ternopil regions reduced fuel consumption by 18% and water consumption by 100% in greenhouses.

According to M.-H. Nguyen and T.E. Jones (2022) and W. Haijun *et al.* (2023), the relevance of green financial instruments was considered mainly within the framework of corporate social responsibility and consumer culture. W. Haijun *et al.* proved that digitalisation contributes to the growth of the ESG index of companies, but the model did not account for agricultural specifics and did not assess the effectiveness of state support in rural areas. M.-H. Nguyen and T.E. Jones focused on the behavioural aspects of urban communities, highlighting the concept of "ecological surplus", but did not include agricultural practices, financial mechanisms, or regional differences in their study. In contrast, the present study was based on a systematic analysis of resource conservation funding in Ukrainian agriculture, covering more than 15 regions and 10 enterprises, and quantifying the effectiveness of state support with disaggregated data on water, fertiliser, and fuel consumption.

B. Gu *et al.* (2021) and C.-Y. Zhang and T. Oki (2023) focused on water resources and green funding policies, but in isolation from practical implementation at the level of small and medium-sized farms. C.-Y. Zhang and T. Oki focused on water pricing in the Chinese agricultural sector, but their approach did not include an analysis of funding sources or an assessment of effectiveness in terms of payback or resource savings. B. Gu *et al.* examined the policy impact of green finance on industrial transformation, but the study was limited to the macroeconomic level without territorial or economic disaggregation. In contrast, the present study not only analysed the structural sources of finance, but also empirically compared the efficiency of farms with and without support: water consumption reduced by 30% vs. 12%, fertiliser use by 25% vs. 10%, payback period of 2.5 vs. 4+ years. This provided an applied dimension that was missing in the cited studies.

As shown by X. Zhao *et al.* (2022) and M.C. Udeagha and E. Muchapondwa (2023a), the problem of green transformation was considered in the context of climate challenges and sustainable development strategies. X. Zhao *et al.* investigated China's national regulatory strategies for carbon neutrality, but the study did not assess the affordability or practical implementation of programmes at the farm level. M.C. Udeagha and E. Muchapondwa focused on the potential of fintech tools in green finance, but did not cover the specifics of the agricultural sector, the role of government participation, or the distribution of resources by region. In contrast to these studies, the present study is the first to quantify the structure of barriers to financial innovation: distrust (28%), high entry costs (26%), and information silos (19%). This approach allowed not only recording political strategies, but also establishing causal links between access to funding, investment efficiency, and regional policy in the Ukrainian agro-industrial complex (Sadovoy *et al.*, 2025).

According to W. Shiwei *et al.* (2022) and S. Liu and Y. Wang (2023), research on green innovations has mostly been undertaken within urbanised systems and pilot programmes. W. Shiwei *et al.* found that the digital economy contributed to the stimulation of green patenting in urban clusters, but the agricultural sector was left out of the analytical framework. S. Liu and Y. Wang assessed the effectiveness of pilot regions for green financial reform using a quasi-experimental approach, focusing on the overall effects of investment promotion, but did not address the specifics of local access to finance and did not analyse resource saving indicators. In contrast to these studies, the evaluation focused on concrete indicators of the effectiveness of funding in the agricultural sector, such as reduced water consumption (30% vs. 12%), reduced fertiliser use (25% vs. 10%), and differences in return on investment (2.5 vs. over 4 years), which allowed for an applied interpretation of the accessibility and effectiveness of support at the farm level.

According to H.M. Arslan *et al.* (2022) and X. Yin and Z. Xu (2022), green funding research has been conducted in the context of sustainable economic growth and policy coordination. H.M. Arslan *et al.* focused on the effects of natural rents and environmental policies on macroeconomic indicators in the long term, but the analysis did not cover the financial efficiency of resource conservation measures or the level of regional access to support. X. Yin and Z. Xu assessed the coordinated development of China's green financial system and economy, but did not consider the impact of government support on concrete agricultural practices. In contrast to these approaches, the present study examined the distribution of funding across 15 regions of Ukraine, identified key barriers (specifically, distrust 28%, high entry costs 26%) and compared the effectiveness of support instruments. This allowed expanding the study beyond strategic planning to focus on applied effects.

As demonstrated by C. Debrah *et al.* (2022) and M.C. Udeagha and N. Ngepah (2023b), research on green funding mainly focused on fintech potential and structural investment gaps. M.C. Udeagha and N. Ngepah studied the role of fintech infrastructure in ensuring environmental sustainability in Brazil, Russia, India, China, South Africa (BRICS), but the agricultural component was not considered, nor was regional availability of funding. C. Debrah *et al.* focused on the financial gap in the green building sector, pointing to the lack of systematic financial models, but without empirical verification in productive sectors, including agriculture. In contrast to these approaches, the present study not only assessed the amount of support, but also established a direct correlation between the funding structure and efficiency: enterprises with state support reduced their resource consumption by up to 30%, while the control group's figure was three times lower. This approach allowed for the first quantitative diagnosis of the relationship between funding sources and sustainable outcomes in the agricultural sector.

As shown by T.H.H. Nguyen *et al.* (2021) and A.G. Corrêa *et al.* (2025), research on financial-environmental interactions has focused on corporate governance in industry and digital inclusion. T.H.H. Nguyen *et al.* found a link between governance quality and environmental performance in highly polluting sectors, but the agricultural sector was not included in the analysis. A.G. Corrêa *et al.* proved the impact of digital financial technologies on growth and sustainability, but did not assess the effectiveness of funding eco-technologies at the farm level. In contrast to these approaches, the current study covered the agricultural sector and quantified the impact of various financial mechanisms on resource conservation, specifically, establishing a reduction in water consumption of up to 30% in cases of state support, while in the control group this figure did not exceed 12%.

According to S. Feng *et al.* (2022) and N.T. Hung (2023), environmental transformation was considered through the interaction of digital finance, decentralisation, and sustainability indices. S. Feng *et al.* investigated the impact of digital infrastructure on innovation in the context of environmental decentralisation, but without reference to agricultural production or analysis of financial sources. N.T. Hung, using quantitative methods, assessed the green development of Vietnam, but the study stayed within the macro-level without applied case studies of farms. In contrast to the above studies, the presented analysis assessed not only general trends but also concrete performance indicators of the implemented financial instruments, namely, a 25% reduction in fertiliser use and a 2.5-year payback period for supported farms.

As demonstrated by L.C. Belarmino *et al.* (2022) and C. Jiakui *et al.* (2023), resource conservation and green productivity have been explored mainly in the context of technological processes and macroeconomic regulation. C. Jiakui *et al.* linked green productivity to the development of the financial system, but without a detailed analysis of access to finance or applied regional comparisons. In contrast to these studies, the present analysis enabled not only the identification of dominant barriers such as distrust in financial innovation (28%) and high entry costs (26%), but also the assessment of the effectiveness of support by region and source, which provided the basis for practical conclusions on the modernisation of financial policy in the agricultural sector. The findings confirmed the relevance of a comprehensive approach to improving financial policy, considering regional and institutional specifics.

CONCLUSIONS

The study evaluated the effectiveness of financial mechanisms to support resource conservation in the Ukrainian agro-industrial complex in 2020-2024 – drip irrigation on 80 ha (Farm Enterprise "Agro-Dar", Vinnytsia region), which reduced water consumption by 30%; strip-till on 150 ha (Peasant (Farm) Economy "Prometey", Poltava region).), which reduced water consumption by 35%; strip-till on 150 ha (Peasant (Farm) Economy "Prometey", Poltava region), which reduced fuel consumption by 18% and increased soil moisture retention by 20%; 300 kW biogas plant (Limited Liability Company "Haysynbiolab"), which covered 60% of energy needs.

The regional dynamics of funding proved to be resilient to external factors: Vinnytsia, Poltava, Khmelnytskyi, Lviv, Cherkasy, and Kyiv regions implemented projects in the areas of precision agriculture, thermal modernisation, biofertilisers, and bioenergy. For example, Kyiv region received increased funding from international programmes, Cherkasy region steadily implemented biofertilisers, and Lviv region maintained thermal modernisation despite a decrease in grants. At the same time, the southern and eastern regions (Odesa, Mykolaiv, Kherson, Zaporizhzhia, and Chernihiv) experienced a reduction in funding of up to 80% due to the hostilities. The average results of the supported farms were as follows: water savings of 30-35%, fertiliser savings of 25-30%, and fuel savings of 18-22%; payback period of 2.5-3 years. In the Ternopil region, Limited Liability Company "Aqua-Land" completely switched to rainwater in greenhouses. Overall, financial support, extension services, and institutional mechanisms strengthened the sustainability of agricultural production, especially in the central and western regions.

The findings of the present study can be used to develop regional funding programmes aimed at supporting small farms, creating digital platforms for accessing grants and loans, and strengthening advisory services. The analysis was limited to medium and large farms, ignoring small farms due to lack of data. Future research should focus on assessing the involvement of small farms, analysing long-term environmental effects (e.g., CO_2 emissions), developing funding models for regions with low institutional capacity, and integrating digital tools to monitor project performance.

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CONFLICT OF INTEREST

None.

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Удосконалення фінансових механізмів підтримки ресурсозбереження в агропромисловому комплексі України

Рахіб Казимов
Кандидат економічних наук, доцент
Азербайджанський державний економічний університет (UNEC)
AZ1001, вул. Істиглаліят, 6, м. Баку, Азербайджан
https://orcid.org/0000-0001-6141-2365

Вадим Левитський
Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0009-0004-8684-9896

Наталія Вернюк
Кандидат економічних наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0001-9478-5088

Вікторія Жмуденко
Кандидат економічних наук, доцент
Уманський національний університет
20300, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0002-6756-8288

Ольга Варченко
Доктор економічних наук, професор
Білоцерківський національний аграрний університет
09117, пл. Соборна, 8/1, м. Біла Церква, Україна
https://orcid.org/0000-0002-9090-0605

Анотація. Метою дослідження була оцінка ефективності фінансових механізмів ресурсозбереження в аграрному секторі України з урахуванням регіональних відмінностей та бар'єрів впровадження інновацій. У статті здійснено комплексний аналіз ефективності фінансових механізмів підтримки ресурсозбереження в агропромисловому комплексі України в 2020-2024 роках. Проаналізовано структуру фінансування за категоріями: державні програми (480 млн грн у 2020 році), регіональні бюджети (110 млн грн у 2021), банківські інструменти (135 млн грн у 2022), грантові механізми (90 млн грн у 2023) та власні інвестиції (205 млн грн у 2024). Дослідження охоплювало 12 областей із найбільш активним залученням фінансування, зокрема Вінницьку, Полтавську, Львівську, Хмельницьку, Дніпропетровську та Черкаську. Наведено приклади успішних проектів: крапельне зрошення на площі 80 га (фермерське підприємство «Агро-Дар», Вінниччина), що дозволило скоротити водоспоживання на 35 %, strip-till на 150 га (селянське господарство «Прометей», Полтавщина), що знизив витрати дизельного пального на 18 % та підвищив вологонакопичення на 20 %, впровадження біогазової установки потужністю 300 кВт (Товариство з обмеженою відповідальністю «Гейсинбіолаб»), що покрило 60 % потреб господарства в енергії. У 2021 році внесення біодобрив дозволило скоротити використання мінеральних добрив на 30 % без зниження врожайності. Пелетне опалення знизило витрати на енергоносії на 25 %, а перехід на сушарки на біомасі скоротив споживання природного газу на 40 %. Середній розмір фінансування одного проєкту в 2023 році становив 1,73 млн грн, що є найвищим за п'ятирічний період. Акцентовано на необхідності розширення доступу малих та середніх виробників до інноваційних фінансових механізмів, зокрема агрооблігацій, зелених кредитів і цифрових субсидій. Обґрунтовано доцільність створення єдиної цифрової платформи з відкритою інформацією про всі доступні форми підтримки. Практична значимість результатів дослідження полягає в тому, що вони можуть бути використані для вдосконалення державних програм підтримки ресурсозбереження в аграрному секторі

Ключові слова: енергоефективність; крапельне зрошення; грантове фінансування; точне землеробство; екологічна модернізація

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10008, б-р Старий, 7, м. Житомир, Україна
Тел. (0412) 22-04-17
E-mail: info@sciencehorizon.com.ua
https://sciencehorizon.com.ua

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