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The influence of an optimised system of mineral nutrition and biological products on the formation of winter wheat productivity in the conditions of southern Ukraine

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Abstract. In Ukraine, one of the key tasks of agriculture is to ensure stable production of high-quality grain, which is of great importance for food security and the national economy, particularly through wheat exports. Intensification of grain production is closely associated with the introduction of modern biopreparations that significantly affect the growth and development of agricultural crops. The aim of the study was to determine the effect of mineral fertilisers and pre-sowing seed treatment with biopreparations on the productivity of winter wheat. The article presented data from research conducted at the educational, scientific and practical centre of Mykolaiv National Agrarian University during 2020-2022 on winter wheat of the variety duma odeska. The study employed generally accepted methods, including analysis and synthesis, laboratory and field experiments. It was found that yield levels were strongly influenced by the biopreparations used for pre-sowing seed treatment, the level of mineral nutrition, and the impact of climatic conditions during the growing season. Similarly, changes in grain yield under the influence of cultivation factors were reflected in the elements of yield structure. The use of biopreparations affected the yield level of winter wheat. The greatest yield increase was obtained with the biopreparation Azotofit-r, while the lowest was recorded with Phytocid-r. Grain yield significantly increased with the application of mineral fertilisers at a rate of $N_{30}P_3O_{30} + N_{30}$ as early spring topdressing. The highest yield was obtained with

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seed treatment using the biopreparation Azotofit-r – 4.15 t/ha, while the lowest yield was formed in the control variant – 3.34 t/ha. The research confirmed the feasibility of pre-sowing seed treatment with biopreparations that optimise the nutrition of winter wheat for the formation of high grain yields. The obtained scientific results will contribute to wider application of biopreparations for seed treatment, ensuring rapid and full plant growth and development of winter wheat, as well as further increases in productivity and gross grain yield

Keywords: number of productive stems; 1,000-kernel weight; mineral fertilisers; grain weight per spike; yield increase

INTRODUCTION

The yield and quality of winter wheat depend on environmental conditions, farming practices, and the type and cultivar of the plants. Modern agricultural systems are aimed at minimising the costs of soil cultivation and using specialised crop rotation, which includes 2-3 types of plants that have similar cultivation technologies. However, sometimes such decisions prove to be unsuccessful, leading to a decrease in crop productivity. Research by V. Pichura *et al.* (2024) has shown that growing global demand for food is forcing agricultural producers to switch to more intensive land use, increasing the chemical load on the environment, which, in the context of climate change, can lead to depletion and deterioration of food quality, requiring a rethinking of fertiliser use and methods of justifying crop fertilisation systems. Studies by M. Korkhova *et al.* (2023) have established that wheat is the main agricultural crop in many countries around the world and the main food crop in steppe regions, so agrotechnical systems should be aimed at creating optimal conditions for high yields of this crop. Due to the growth of the world's population and the reduction of cultivated land due to military actions, there is an urgent need to find innovative approaches to increase crop productivity, which, in turn, will contribute to an increase in global food supplies. Annual fluctuations in wheat yields depend on factors such as moisture levels during the growing season, crop rotation structure, agrotechnical measures, and the type and dose of nutrients applied, which determine the effectiveness of plant growth and development.

Research by W. Jarecki (2023) has established that winter wheat is one of the most productive crops in terms of biological characteristics. It is the highest-yielding crop in the cereal group, making the most use of photosynthetically active radiation. However, its yield potential can only be achieved under certain conditions, such as normal overwintering of crops, good field preparation, moisture accumulation, and the use of agricultural practices that ensure sufficient fertilisation and the use of plant protection products against pests. S. Shahini *et al.* (2023) found that increasing yield is the main goal, but excessive fertiliser application causes environmental problems, with about 70%

of the total amount of mineral fertilisers being nitrogen-containing. This pattern is observed for most soil types in the steppe regions of southern Ukraine. The first minimum is nitrogen nutrition of plants. It is recommended to partially satisfy the need for nitrogen by including legumes in the structure of cultivated areas, which tend to accumulate biological nitrogen, because it does not pollute the soil and is not lost, but is 100% utilised by plants. According to the results of research by S. Kulkarni & A. Goswami (2019), it has been established that high crop yields can only be achieved under optimal mineral nutrition conditions. The use of excessive doses of fertilisers not only fails to increase productivity, but also hinders plant growth and development. In addition, exceeding these norms has negative environmental consequences, including the accumulation of heavy metals in the soil, eutrophication of water bodies, and increased nitrate content in products. At the same time, the increase in the cost of mineral fertilisers in recent years has contributed to increased interest in the use of biological products and the expansion of areas used for organic farming. A study by Y. Domarat-skyi *et al.* (2020) showed that stable crop yields can be achieved by deliberately creating optimal conditions for their growth and development throughout the growing season. It has been established that the level of soil nutrients plays an important role in the formation of wheat plants, which can be effectively adjusted by applying different doses and fertilisation schemes.

Research by G. Olkhovskiy *et al.* (2019) has shown that grain yield is determined by two main parameters: the density of productive stems and the weight of grain per ear, the structure of which depends on many components. Research by D. Jodaugiene *et al.* (2022) conducted at the experimental station of the Academy of Agriculture in 2019-2020 (Lithuania) determined that the use of biological products did not have a significant effect on seed germination, but led to an increase in the number of productive stems and tillering. The use of biological products had a positive effect on the formation of the leaf surface of winter wheat, contributed to an increase in the weight of 1,000 grains, an increase in the number of grains in the ear, and the weight of grain

from one ear. As a result, a significant increase in crop yield was recorded compared to the control variant. Research by V. Shebanin *et al.* (2025) has established that the use of biological products in the fertilisation system of grain crops enhances the effectiveness of mineral nutrition, stimulates the development of the root system, and has a positive effect on the formation of productivity elements, which is especially important for the conditions of the southern steppe of Ukraine. Research by V. Bazalii *et al.* (2020) showed that the formation of productivity and yield traits in winter wheat varieties largely depends on growing conditions. The authors note that various agronomic and environmental factors, such as nutrition, moisture, and climatic conditions, affect the morphophysiological characteristics of plants and potential yield. Scientists M. Mostipan *et al.* (2019) concluded that the productivity of winter wheat significantly depends on the weather conditions of the growing season, namely on overwintering and moisture supply to plants during the growing season.

According to the findings of A. Panfilova & A. Mohlynyska (2019) conducted in the soil and climatic conditions of the Southern Steppe of Ukraine, it was established that the application of mineral fertilisers at a rate of $N_{30}P_{30}$ before pre-sowing soil cultivation, combined with foliar feeding of winter wheat crops at the beginning of spring vegetation renewal with Escort -bio and Organic D₂ at the beginning of spring vegetation renewal contributes to the formation of the best crop structure indicators and an increase in their productive potential. Biological products stimulate the development of roots and above-ground vegetative biomass of agricultural crops, increase plant stress resistance, yield, and quality. Biological products increase the availability and speed of plant nutrient uptake by converting insoluble compounds into available forms with the help of live bacteria, providing nitrogen nutrition and protecting plants from diseases. The aim of the study was to evaluate the productivity of the Duma Odessa winter wheat variety depending on the application of different rates of mineral fertilisers and the use of biological products for pre-sowing seed treatment.

MATERIALS AND METHODS

The research was conducted during 2020-2022 at the experimental field of the Educational, Scientific, and Practical Centre of Mykolaiv National Agrarian University, located in the southern soil and climatic zone of Ukraine. The studies used the soft winter wheat variety Duma Odeska, which was included in the State Register of Plant Varieties... (2024). The integration of an optimised mineral nutrition system with biological products is in line with international approaches to preserving

agrobiodiversity and greening agriculture, as defined by The Convention on Biological Diversity (1992). The recommendations for agriculture in the southern steppe zone of Ukraine were used to conduct the research, with the exception of the factors mentioned in the study. Winter wheat was sown on October 10 with a sowing rate of 4.0 million seeds per hectare.

The experimental plots were located on southern-type chernozem soils with a neutral soil solution reaction. The arable layer is characterised by a humus content of 3.3%, which provides sufficient fertility for the growth and development of winter wheat. The area of each sowing plot was 70 m², and the accounting area was 48 m²; the experiment was set up with three repetitions of the variants and sequential arrangement, which minimised the influence of soil and microclimatic variability on the results of the experiment. The experimental design included the following variants: Factor A – mineral fertiliser doses: no fertiliser (control), application of $N_{30}P_{30}K_{30}$, application of $N_{30}P_{30}K_{30} + N_{30}$ in early spring fertilisation; Factor B – pre-sowing seed treatment: control (treatment with water), Phytocide-r, Azotofit-r. The influence of the biological products Azotofit-r and Phytocide-r was studied on the variety under investigation. Azotofit-r is a natural biostimulant that promotes the fixation of molecular nitrogen in the atmosphere, creates substances that promote growth, improve seed germination, enhance root system development, increase crop yield, and promote the fixation of other nutrients. Phytocide-r is a biological fungicide for the elimination of fungal and bacterial diseases, increasing resistance to adverse environmental conditions, and improving the quality of plant products. Biological preparations for pre-sowing seed treatment are used at a dose of 0.8 and 1.0 l/t, respectively.

The average number of grains in an ear was determined as the ratio of the total number of grains after threshing 25 ears to the number of ears in the analytical sample (25 pcs.). The average weight of grain per ear was calculated by dividing the weight of grain in the sheaf sample by the number of productive stems in this sample. The weight of 1,000 grains was determined in accordance with DSTU ISO 520:2015 (2016). The winter wheat harvest was recorded using a SAMPO-500 combine harvester (Finland). The experimental data obtained were processed using statistical and mathematical methods with the help of the Agrostat computer program. To assess the impact of the factors under study, analysis of variance (ANOVA) was used, and the statistical significance of the differences between the mean values of the variants was determined at a significance level of $p \leq 0.05$. The reliability of the differences between the variants was assessed by the least significant difference (LSD05).

RESULTS AND DISCUSSION

The yield of winter wheat is mainly determined by the interaction of such productivity components as the number of stems, the number of grains per ear, the weight of grain per ear, and the weight of 1,000 grains, which vary significantly depending on the fertilisation schemes used. Thus, the most productive stems were formed by plants on fertilised plots, which exceeded this indicator by 1.2 times on plots without fertilisers (Fig. 1).

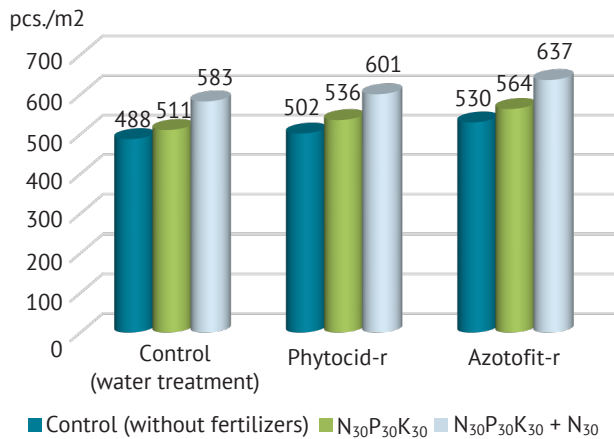


Figure 1. Effect of mineral fertilisers and biological products on the number of productive stems in winter wheat plants (average for 2020-2022), pcs/m²
Source: developed by the authors

On average, for 2020-2022, the maximum density of productive winter wheat stems was observed with pre-sowing treatment of seeds with the Azotofit-r biological product against the background of fertiliser application at the rate of N₃₀P₃₀K₃₀ + N₃₀, reaching 637 pcs/m². When only N₃₀P₃₀K₃₀ was applied, the number of productive stems was slightly lower – 601 stems/m². Pre-sowing treatment of seeds with the biological product Phytocid-r also had a positive effect on the formation of productive stems, but its effect was slightly weaker compared to Azotofit-r. These results indicate that the combination of optimal mineral nutrition with the use of biological products contributes to the intensification of growth processes and an increase in the potential yield of winter wheat. The lowest indicator when using this biological product was obtained in the control variant without fertilisers – 502 pcs/m², which is 19.7% less compared to the fertilised variant at a dose of N₃₀P₃₀K₃₀ + N₃₀ in early spring feeding. The studies have shown that the nutrient background also affected the grain weight per ear (Fig. 2). Winter wheat plants placed on fertilised plots had the highest grain weight per year.

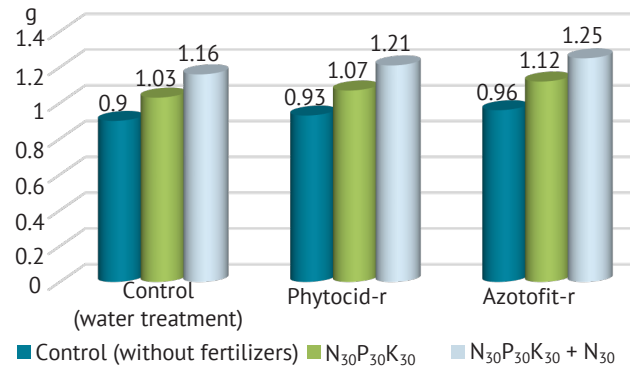


Figure 2. The effect of nutrition and seed treatment on the weight of grain from 1 ear of winter wheat (average for 2020-2022), g
Source: developed by the authors

On average, in 2020-2022, when sowing winter wheat on fertilised plots, the weight of grain per ear, depending on the use of the Azotofit-r biological product, ranged from 1.12 to 1.25 g. The effect of Azotofit-r on the grain weight per ear was also quite significant. On average, over the years of research, the most productive ears were those of plants treated with the Azotofit-r; without this agricultural measure, their weight decreased by 6.7-8.7% depending on the nutrient background. The indicator characterising grain size, i.e., the weight of 1,000 grains, also varied depending on the agricultural measures studied (Fig. 3).

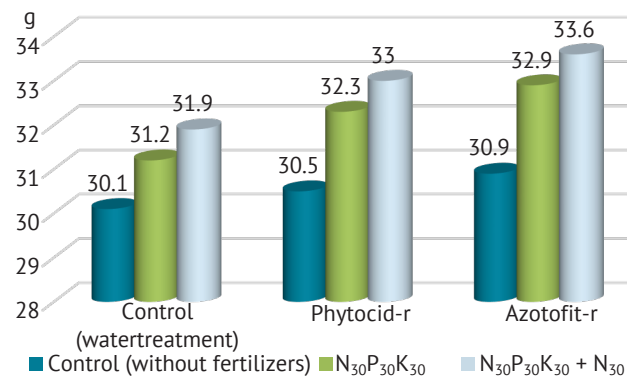


Figure 3. The importance of nutrition and seed treatment for the weight of 1,000 grains of winter wheat (average for 2020-2022), g
Source: developed by the authors

On average, for 2020-2022, when sowing winter wheat, the weight of 1,000 grains on fertilised plots exceeded this indicator compared to the plot without fertilisers, respectively, without seed inoculation by 0.4 and 0.8 g; with the use of Phytocid-r – by 1.8 and 2.5 g, and with the use of the Azotofit-r – by 2.0 and 2.7 g. The

grain density of the ear, which depends on weather conditions and agrotechnical cultivation methods, plays an important role in the formation of the yield. The results of the studies show that the number of grains in the ear of winter wheat varied depending on fertilisation – from 26.2 to 27.1 grains without seed inoculation and from 27.8 to 29.4 grains with seed inoculation, depending on the biological product studied (Fig. 4).

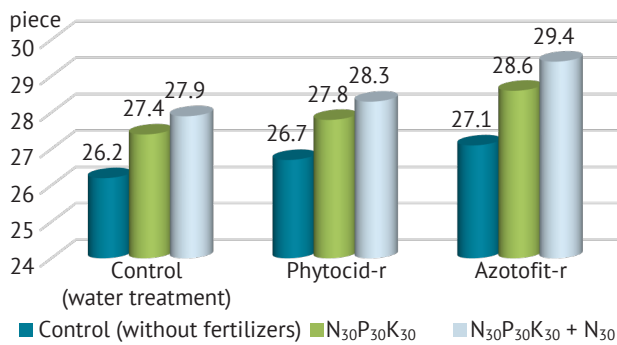


Figure 4. Number of grains in a winter wheat ear depending on the factors studied

Source: developed by the authors

The highest grain yield was observed in areas that received mineral fertilisers, with the maximum number of grains formed by plants when N₃₀P₃₀K₃₀ + N₃₀ was applied in combination with pre-sowing treatment of

seeds with the Azotofit-r. This indicator exceeded the control group without fertilisers and seed treatment with biological products by 12.2%, which emphasises the effectiveness of the combined use of mineral nutrition and biological products to increase the productivity of winter wheat. The yield of winter wheat is the final stage of plant development and fully reflects the effectiveness of the agricultural techniques used to grow it during the growing season. The interaction of plant productivity factors was shaped by a complex combination of biotic and abiotic factors affecting wheat in close interaction with the studied agricultural techniques, which led to the formation of yields of varying productivity during the study period. The analysis of the impact of the studied factors on winter wheat plants reveals patterns in crop yield formation depending on the level of nutrition and pre-sowing treatment of seeds with biological products. This approach makes it possible to evaluate the effectiveness of various fertilisation schemes and biological stimulants in ensuring high productivity and grain quality (Table 1). The data show that the average yield of winter wheat in all variants with the use of fertilisers during the years of research was 0.11-0.38 t/ha higher than in the variant without fertilisers. The greatest increase from the use of Azotofit-r was 0.43-0.50 t/ha. An increase was also observed from the use of the biological product Phytocid-r – 0.29-0.33 t/ha, which is 3.4-4.7% less than with the Azotofit-r.

Table 1. The effect of fertiliser application and seed treatment with biological products on the yield of winter wheat variety Duma Odeska (average for 2020-2022), t/ha

Seed treatment (factor B)	Nutritional background (factor A)	Yield, t/ra	Increase from the use of biological products	
			t/ra	%
Control (water treatment)	Control (no fertilisers)	3.34	-	-
	N ₃₀ P ₃₀ K ₃₀	3.45	-	-
	N ₃₀ P ₃₀ K ₃₀ + N ₃₀	3.72	-	-
Phytocid-r	Control (no fertilisers)	3.65	0.31	9.3
	N ₃₀ P ₃₀ K ₃₀	3.78	0.33	9.6
	N ₃₀ P ₃₀ K ₃₀ + N ₃₀	4.01	0.29	7.8
Azotofit-r	Control (no fertilisers)	3.83	0.49	14.7
	N ₃₀ P ₃₀ K ₃₀	3.95	0.50	14.5
	N ₃₀ P ₃₀ K ₃₀ + N ₃₀	4.15	0.43	11.6
LSD ₀₅ , t/ha: A – 0.24; B – 0.29; AB – 0.42				

Source: developed by the authors

Analysis of experimental data shows that the use of mineral fertilisers and biological products significantly affected the yield of winter wheat. The highest yield indicators (3.72-4.15 t/ha) were obtained in variants with the application of N₃₀P₃₀K₃₀ in combination with early spring feeding with N₃₀, which significantly ($p \leq 0.05$) exceeded both the control without fertilisers and the variants with basic fertilisation without feeding, since the difference between the variants exceeded

the LSD₀₅ value for factors A, B, and their interaction. A separate analysis of the factors showed that the use of only mineral fertilisers without pre-sowing seed treatment provided an increase in yield compared to the control, but the maximum effect was achieved with the combined use of fertilisers and biological products. Pre-sowing seed treatment with the biological products Phytocid-r and Azotofit-r contributed to an additional yield increase of 7.8-14.7%, with the greatest

effect observed in the variants with the use of Azotofit-r. The advantage of the Azotofit-r biological product is explained by its ability to activate associative nitrogen fixation, improve the supply of available forms of nitrogen to plants in the early stages of organogenesis, and stimulate the development of the root system. This, in turn, increases the efficiency of mineral nutrition, as confirmed by the maximum yield of 4.15 t/ha in the $N_{30}P_{30}K_{30} + N_{30}$ variant in combination with pre-sowing treatment of seeds with Azotofit-r.

The complex effect of fertilisers and biological products was probably achieved not only through an increase in overall productivity, but also through an improvement in the structural elements of the crop, in particular the formation of a greater number of productive stems and an increase in grain weight per ear. Research by L. Marcińska-Mazur & M. Mierzwa-Hersztek (2023) showed that both a deficiency and an excess of nutrients have a negative impact on soil condition. The rational use of fertilisers aimed at increasing crop yields replenishes nutrients in the soil, which stimulates plant growth and development and increases the quantity and quality of the harvest. At the same time, excessive fertilisation can lead to contamination of groundwater and surface water and loss of nutrients through leaching into deeper soil layers. Therefore, to ensure sustainable agricultural production and environmental protection, fertilisers should be applied in optimal doses. The effectiveness of Azotofit-r on southern black soil depends on its average fertility level. The highest effectiveness was recorded on plots without mineral fertilisers, where yield increases were minimal and ranged from 0.18 to 0.30 t/ha. When using an ineffective predecessor, even with minimal fertilisation rates, a slightly higher but still limited increase was observed – about 0.35 t/ha. At the same time, with the background application of $N_{64}P_{64}K_{64}$ fertilisers during the cultivation of the Knopa variety on black fallow, stable yield increases of 0.19-0.26 t/ha were noted, indicating a moderate but positive response of the crop to nutrition and a more favorable agricultural background. These results indicate a significant influence of the predecessor and the level of mineral nutrition on the productivity of the variety, as well as the need to optimise the fertilisation system depending on the growing conditions.

Based on the results of 14 years of research (2007-2020), S. Burykina *et al.* (2021) established the effectiveness of applying a fertilisation system for winter wheat in the southern regions of Ukraine. The application of fertilisers at a rate of $N_{180}P_{60}K_{60}$ led to an increase in grain yield by 2.24 t/ha compared to the variant without fertilisers, which emphasises the significant positive effect of optimal mineral nutrition on crop

productivity. The formation of winter wheat grain yield is determined by the interaction of various productivity factors, in particular the number of productive straws, the weight of 1,000 grains, their size and quality (Olkhovskiy *et al.*, 2019; Tsvey *et al.*, 2021). According to research by M. Lozinskiy *et al.* (2021), the weight of grain on a single ear, which reflects its productivity, directly depends on the effectiveness of that ear. Undoubtedly, the main ear is of key importance in determining the productivity and yield of wheat grain, as it is the result of the interaction of many genetic factors that determine its quality and quantity. The results of studies by N. Pinchuk *et al.* (2022) showed that treating Skagen winter wheat seeds with biological products before sowing led to an increase in stem density compared to the control variant. The use of the Azotofit-r biological product for pre-sowing treatment against the background of adding $N_{30}P_{30}K_{30} + N_{30}$ in spring fertilisation showed a stem density of 637 pcs/m², which is 20.2% higher than in experiments without fertiliser application.

The use of biological products significantly affects the weight of 1,000 grains and the yield of winter wheat. The highest weight of 1,000 grains (38.7 g) was recorded when treating seeds with the Organic Balance biological product for the Duma Odeska variety, which is 13.2% higher than the results of treatment with the Azotofit -r against the background of $N_{30}P_{30}K_{30} + N_{30}$ application in early spring fertilisation. The use of biological products also has a positive effect on the overall productivity of the crop: the maximum yield was obtained after black fallow treated with Organic Balance, and for the Duma Odessa variety it was 7.19 t/ha, which is 30.3% higher than the variant without fertilisers. These results highlight the effectiveness of the combined use of biological products and agrotechnical measures to increase the productivity of winter wheat. D. Jodaugiene *et al.* (2022) found that the use of biological products does not significantly affect seed germination, but contributes to an increase in tillering, leaf area, number of productive stems, weight of 1,000 grains, weight of grain from the ear, and grain yield compared to the control variant. Thus, the studied biological products for pre-sowing seed treatment significantly affect key indicators of winter wheat productivity, in particular the number of productive stems, grain weight per ear, yield, and weight of 1,000 grains, contributing to an increase in the overall efficiency of crop cultivation.

CONCLUSIONS

Studies conducted in the southern regions of Ukraine during 2020-2022 showed that winter wheat productivity directly depends on the availability of nutrients and the use of pre-sowing seed treatment with biological

products. The use of biological products had a significant impact on crop yields: among the products studied, Azotofit-r provided the highest yield increase, while Phytocide-r showed the least effect. In addition, a significant increase in grain yield was observed when mineral fertilisers were applied at a rate of $N_{30}P_{30}K_{30} + N_{30}$ in early spring fertilisation, which contributed to active growth and the formation of productive stems.

The yield of winter wheat was largely determined by the interaction of productivity components, such as the number of productive stems, the number of grains per ear, the weight of grain per ear, and the weight of 1,000 grains, which varied significantly depending on the type of fertiliser applied. Plants that received mineral fertilisers at a rate of $N_{30}P_{30}K_{30} + N_{30}$ in combination with pre-sowing treatment of seeds with the biological product Azotofit-r formed the maximum number of productive stems – 637 pcs/m². Pre-sowing treatment of seeds with the biological product Phytocide-r also had a positive effect on this indicator, providing 601 pcs/m², which is 23.2% higher than the control. The weight of grain from one ear varied from 1.07 to 1.25 g depending on the use of biological products and mineral nutrition. The highest grain yield was observed in areas with a combination of

fertilisation and pre-sowing treatment of seeds with biological products, where the number of grains per ear ranged from 27.8 to 29.4.

The results of the studies showed that the use of the Azotofit-r biological product during the cultivation of the Duma Odeska winter wheat variety ensures maximum yield – 4.15 t/ha, while in the control variant it was 3.34 t/ha. This emphasises the significant role of pre-sowing seed treatment with biological products in optimising plant nutrition and increasing grain yield. In the future, it is planned to study the combined effect of mineral fertilisers and biological products on pre-sowing seed treatment in order to assess their impact on grain quality characteristics, which will allow for a more detailed description of the productive and technological properties of winter wheat varieties.

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CONFLICT OF INTEREST

None.

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Вплив оптимізованої системи мінерального живлення та біопрепаратів на формування продуктивності пшениці озимої в умовах півдня України

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Анотація. В Україні одним із ключових завдань сільського господарства є забезпечення стабільного виробництва якісного зерна, що має важливе значення для продовольчої безпеки та економіки країни, зокрема через експорт пшениці. Інтенсифікація зерновиробництва тісно пов'язана із впровадженням сучасних біопрепаратів, які істотно впливають на ріст і розвиток сільськогосподарських культур. Метою роботи було встановити дію мінеральних добрив та обробки насіння перед сівбою біопрепаратами на продуктивність пшениці озимої. В статті наведено дані результатів досліджень, проведених в умовах Навчально-науково-практичного центру Миколаївського національного аграрного університету впродовж 2020-2022 рр. з пшеницею озимою сорту Дума одеська. При проведенні дослідження використані загальноприйняті методи: аналіз і синтез, лабораторний та польовий. Було виявлено, що на рівень врожайності сильно впливали біопрепарати, які використовувалися для обробки насіння перед сівбою, рівень мінерального живлення та вплив кліматичних умов вегетаційного періоду. Аналогічно, зміни врожайності зерна під впливом факторів вирощування також змінювали елементи структури врожаю. Використання біопрепаратів вплинуло на рівень урожайності пшениці озимої. Найбільший приріст урожаю отримано під дією біопрепарату Азотофіт-р, а найнижчу – Фітоцид-р. Рівень урожаю зерна суттєво підвищився за внесення мінеральних добрив у дозі $N_{30}P_{30}K_{30} + N_{30}$ у ранньовесняне підживлення. Найбільшу врожайність отримано за обробки біопрепаратом Азотофіт-р – 4,15 т/га, а найменшу врожайність було сформовано у контрольному варіанті – 3,34 т/га. Дослідження підтвердили доцільність обробки насіння біопрепаратами перед сівбою, які оптимізують живлення пшениці озимої для формування високих врожаїв зерна. Отримані наукові результати сприятимуть більш широкому застосуванню біопрепаратів для обробки насіння, що забезпечить швидкий і повноцінний ріст та розвиток рослин озимої пшениці, подальше збільшення продуктивності та валового збору зерна

Ключові слова: кількість продуктивних стебел; маса 1 000 зерен; мінеральні добрива; маса зерна з колоса; збільшення врожайності

Electrophysical indicators of typical chernozems under the influence of combat actions and technological loading

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Abstract. The article presents the results of a study of the electrophysical indicators of typical chernozems that have been affected by combat actions and technological loading, as well as agrogenic use. The aim of the work was to identify changes in electrical conductivity, total mineralisation, salinity and the content of water-soluble calcium, sodium and potassium cation salts by comparing areas with different types of technogenic, agrogenic and post-agrogenic loading. According to the methodology, samples were taken from 0 to 40 cm at 10 cm intervals. Electrophysical parameters were measured in a water-soil paste (1:1) using an EZODO-8200 M conductometer and HORIBA LAQUAtwin ion meters. Additionally, correlations were established between electrical conductivity, total mineralisation, salinity and water-soluble salt content. Combat impact caused a decrease in electrical conductivity with depth, uneven distribution and accumulation of sodium and potassium salts in the upper layers. On the burnt fallow land, electrical conductivity decreased from 258 to 185 $\mu\text{S}/\text{cm}$ and the potassium salt content from 55 to 7 ppm. In the road and equipment parking variants, an increase in electrical conductivity (up to 302 $\mu\text{S}/\text{cm}$) and accumulation of calcium salts up to 150 ppm and potassium up to 24 ppm were observed. In the arable land variant, electrical conductivity remained consistently high (up to 360 $\mu\text{S}/\text{cm}$), which was caused by agrogenic salt accumulation. On the ploughed section of the road, the indicators were moderate, indicating partial recovery. A strong correlation was found between electrical conductivity and calcium (+0.72) and sodium (+0.89), as well as a negative correlation with potassium (-0.35). The practical significance of the research results lies in the possibility of using electrical conductivity and water-soluble salt content as indicators of the degree of soil disturbance, which made it possible to quickly assess the degradation of agrogenic and technogenic disturbed areas of chernozems as a result of hostilities, as well as the possibility of formulating recommendations for the restoration of soil cover in the context of post-conflict land use.

Keywords: military degradation; electrical conductivity; water-soluble salts; post-conflict land use; agrogenic use; fallow use

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INTRODUCTION

In the current conditions of military conflict and intense technogenic pressure on Ukraine's agricultural landscapes, the ability to quickly assess the state of the soil environment, in particular its physical and chemical properties, is becoming particularly relevant. Typical chernozems, as the most fertile soils intensively used in agriculture, are subject to the complex effects of military operations, including mechanical compaction from the passage of military equipment, thermal damage from fires, and chemical contamination from fuel and lubricants spilled on the surface. These factors alter the water regime, structural condition, biological activity, and thus the soil's ability to self-regenerate and self-clean. At the same time, agricultural use also changes the ionic composition of the soil solution, which complicates the diagnosis of the degree of soil degradation. Under these conditions, electrophysical indicators (electrical conductivity, total mineralisation, salinity), supplemented with information on the content of water-soluble calcium, sodium and potassium, can serve as indicators of edaphic disturbance, allowing for a rapid assessment of the level of degradation and the formulation of scientifically sound recommendations for soil cover restoration.

Operational monitoring of the agrobiological condition of agricultural land is an important component of modern agroecological control. One of the most effective methods of such control is the measurement of the electrical conductivity of the soil environment, which is a comprehensive indicator of its physical and chemical condition. According to data obtained by H.N. Kim & J.H. Park (2024), electrical conductivity is closely related to the content of nutrients in the soil, in particular such as nitrates, potassium and calcium, and also depends on moisture, organic matter content and soil particle size distribution. In their work, researchers R. Mustafa & A. Ansari (2024) confirmed the dependence of soil electrical conductivity on moisture, density, porosity and the degree of saturation with nutrients, which allows it to be used to predict the agrophysical condition and potential of the territory. Modern research pays particular attention to electrical conductivity as an indicator of the physicochemical state of the soil. Electrical conductivity can be used to indirectly assess a number of important properties, such as nutrient content, organic matter content, pH, etc. Studies by P. Mazur *et al.* (2022) have found that soil electrical conductivity has a strong positive correlation with potassium content (0.80) and a moderate correlation with magnesium content (0.48), confirming its high informative value for monitoring. The authors noted that electrical conductivity can be used as an indirect indicator of fertility and a basis for field zoning in precision

farming systems. In addition, this indicator proved to be the most variable among all those studied, which indicates the sensitivity of electrical conductivity to spatial heterogeneity of the soil environment.

In studies by B. Prajuli *et al.* (2025), the physicochemical properties of soils in irrigated agroecosystems were characterised, where electrical conductivity proved to be a sensitive indicator of changes in nutrient content, organic matter and microbiological activity. The authors noted that maintaining electrical conductivity within optimal values is critical for preserving the biochemical balance of the soil and ensuring a stable yield under conditions of intensive irrigation. In the work of W. Mu *et al.* (2024), a method was proposed that allows the salinity of the soil to be assessed based on electrical conductivity and moisture content. The researchers conducted a series of field measurements in arid regions where traditional methods of salt determination are labour-intensive. They proved that electrical conductivity combined with moisture content can be an effective indicator of water-soluble salts. The authors emphasised that the developed method allows for the rapid identification of areas at risk of salinisation. In their work, scientists A. Lazaar *et al.* (2025) developed a model for rapid assessment of saturated extract conductivity using pedotransfer functions, FTIR spectroscopy, and machine learning. The work covered arid regions of North Africa, where traditional conductivity determination is difficult and expensive. The authors showed that the data obtained using these methods, combined with machine learning algorithms, allow for highly accurate prediction of the level of water-soluble salts in the soil. The conclusions of A. Lazaar *et al.* confirmed that electrical conductivity is a reliable indicator of salinisation, and its digital modelling opens up new opportunities for soil monitoring.

Due to military operations in Ukraine, thousands of hectares of fertile chernozems soil have been devastated by combat operations: explosions, fires, bombings, movement of military equipment across fields, etc. According to T. Chaika & I. Korotkova (2023), all this has caused physical, chemical, and biological disturbances to the soil cover. The main issue of concern is how different types of disturbances caused by combat operations affect soil parameters, plant succession, and its potential for recovery. Despite the considerable attention paid by scientists to electrical conductivity as one of the indicators of the physical and chemical state of the soil, the analysed works mainly focused on agronomic aspects, in particular the relationship between electrical conductivity and nutrient content, organic matter content, moisture and granulometric composition of

the soil. At the same time, the impact of military operations and technogenic load on the electrophysical indicators of chernozems has not been sufficiently studied. The nature of the vertical distribution of water-soluble calcium, sodium and potassium cations in soil profiles that have undergone pyrogenic, mechanical and chemical influences, as well as their relationship with electrical conductivity indicators, remains poorly studied.

It is precisely the aspects of the impact of military operations on the electrical conductivity, total mineralisation and salinity of typical chernozems, along with studies of the characteristics of the accumulation of water-soluble salts in various types of disturbed areas, that remain insufficiently covered in the current scientific literature. This necessitated this study, which was aimed at a comprehensive assessment of the electrophysical indicators of typical chernozems under the influence of military degradation and technogenic load compared to natural areas, with the subsequent formation of scientifically based recommendations for their restoration. The aim of the study was to identify changes in the electrophysical indicators of typical chernozems (in particular, electrical conductivity, total mineralisation, salinity) and the content of water-soluble cation salts (calcium, sodium and potassium) under the influence of hostilities, by comparing areas with different types of technogenic, agrogenic and post-agrogenic loads, for further assessment of the degree of soil environment disturbance and determination of its restoration potential.

MATERIALS AND METHODS

The study involved the analysis of electrophysical parameters (electrical conductivity, total mineralisation, and salinity) of typical chernozems across two control variants, representing agrochemical and post-agrochemical influences, located at the Educational-Scientific-Production Centre "Dokuchaev Experimental Field" of the State Biotechnological University, as well as four variants subject to technogenic impact, situated near a research station in Kharkiv region, representing different conditions of military activity. The research was conducted during 2025 as part of the scientific project "Impact of Military Actions on the Soil Cover and Soil Quality in Ukraine" (State Registration No. 0124U005030). Field and laboratory investigations encompassed representative plots with varying degrees of disturbance, enabling comparative analysis of vertical distribution of parameters within the soil profile.

The first variant (burnt fallow) represented a fallow plot partially affected by pyrogenic degradation due to the burning of vegetation during military activities. The second variant (natural fallow) was a fallow plot with a natural grass cover that had developed over more than

70 years (absolute control). The third variant (compact road) included a road constructed across arable land, repeatedly subjected to mechanical stress from the movement of military vehicles. The fourth variant (ploughed road) represented a ploughed section of a road, simulating the aftereffects of technogenic impact caused by vehicle movement. The fifth variant (arable land) consisted of a plot under continuous agrochemical use for over 100 years, without any military impact (control). The sixth variant (equipment parking area) included an area used for temporary stationing of military equipment, with potential contamination of the surface soil layer by fuel and lubricants. Soil samples for analysis were collected using an auger in layers of 0-10 cm, 10-20 cm, 20-30 cm, and 30-40 cm. These layers were chosen due to their agronomic significance, as the upper humus-accumulative horizon of typical chernozems experiences the greatest load. Samples were collected in triplicate to ensure statistical reliability of the data.

To standardise measurement conditions for electrophysical parameters, a 1:1 water-to-soil paste was prepared. This ratio minimises the variability of soil moisture under field conditions, ensures comparability between variants, and provides representative data on the ionic composition of the soil solution. Measurements of electrical conductivity, total mineralisation, and salinity were performed using an EZODO-8200 M conductometer-salimeter (manufacturer: Taiwan). The conductometric method allows rapid and accurate determination of the total ion content in the soil solution and was selected for its high sensitivity to changes in salt composition during operational monitoring of soil degradation processes. The content of water-soluble cationic salts of calcium, sodium, and potassium was determined using portable HORIBA LAQUAtwin ion meters (manufacturer: Japan). The ionometric method complements the conductometric approach and enables qualitative assessment of salt composition. Pairwise correlation analysis was applied to establish relationships between electrical conductivity and the content of water-soluble salts. Statistical processing, graph construction, and result summarisation were conducted using Microsoft Excel (Microsoft 365 Education), ensuring calculation accuracy and clear visualisation. The results were analysed by comparing variants under different types of stress. This comparative-analytical approach allowed the identification of characteristic changes in parameters depending on the type of impact, as well as assessment of the recovery potential of typical chernozems.

To standardise the conditions for measuring electrical conductivity, total mineralisation, soil solution salinity and the content of water-soluble calcium, sodium

and potassium cations, a method was used to prepare a water-soil paste in a 1:1 ratio. Soil samples were pre-dried to an air-dry state at room temperature and ground in a mortar to a homogeneous powdery state. From each prepared sample, a 10 g sample of air-dry soil was taken and placed in a chemically inert polypropylene container. Distilled water was pre-checked for electrical conductivity and salt content. In the absence of impurities, 10 ml of water was added to the soil sample, after which the mixture was intensively stirred for two minutes with a glass rod to ensure uniform moistening and activation of ion exchange (saturation). The prepared paste was kept for 24 hours in closed containers at a temperature of 20-22°C. After aging, direct measurement of the electrophysical parameters in the paste was carried out without additional filtration. Electrophysical indicators (electrical conductivity, total mineralization, salinity) were determined using the EZODO-8200 M conductometer-salinity meter (EZODO Instruments, Taiwan). The content of water-soluble calcium, sodium and potassium salts was determined using portable ion meters HORIBA LAQUAtwin (HORIBA Ltd., Japan): Na-11 (Na⁺); K-11 (K⁺); Ca-11 (Ca²⁺). This approach made it possible to level out the variability of natural soil moisture, ensure the comparability of results between variants, and obtain representative data on the ionic composition of the soil solution. Soil sampling and analysis were carried out in accordance with local environmental standards and without disturbing

the ecological balance, in particular in accordance with the Law of Ukraine No. 1264-XII (2025).

RESULTS

Changes in electrophysical indicators under the influence of combat operations

The results obtained allowed to assess the level of soil electrical conductivity based on the content of water-soluble salts in the soil solution, the degree of salinisation due to changes in the water regime and biological activity. In the fallow variant after thermal exposure, the electrical conductivity in the upper layer of 0-10 cm was 258 $\mu\text{S}/\text{cm}$, and the values of total mineralisation and salinity were 170 and 129 ppm, respectively. With depth, the indicators gradually decreased and in the 30-40 cm layer had values of 185 $\mu\text{S}/\text{cm}$ for electrical conductivity, 122 ppm for total mineralisation and 93 ppm for salinity. This distribution indicated a decrease in the content of easily soluble salts with depth. The electrical conductivity of the typical chernozem fallow variant was 226 $\mu\text{S}/\text{cm}$ in the 0-10 cm layer, total mineralisation was 149, and salinity was 113 ppm. With depth, there was an increase in the electrical conductivity of soil-water suspensions, which was 376 $\mu\text{S}/\text{cm}$, as well as mineralisation to 248 ppm and salinity to 188 ppm. Thus, the distribution of salts indicated a natural accumulation of easily soluble salts in the lower layers studied, which could be the result of biological processes, capillary moisture rise, and the absence of mechanical impact on the soil (Fig. 1).

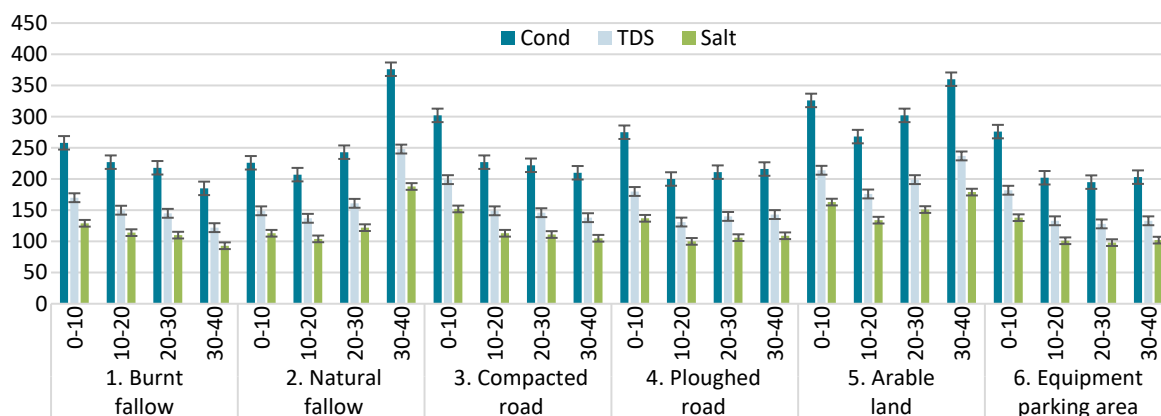


Figure 1. Vertical distribution of electrical conductivity, total mineralisation

and salinity of typical chernozems under different types of agrogenic, technogenic and combat loads

Notes: electrical conductivity (Cond), $\mu\text{S}/\text{cm}$; total dissolved solids (TDS), ppm; salinity (Salt), ppm (LSD05 Cond – 30, Salt – 25, TDS – 20)

Source: created by the authors

The surface layer of 0-10 cm on the road variant had a slightly increased level of electrical conductivity up to 302 $\mu\text{S}/\text{cm}$, as well as total mineralisation – 199 ppm and salinity – 152 ppm. However, in other studied layers from 10

to 40 cm, electrical conductivity decreased to 210-227 $\mu\text{S}/\text{cm}$, indicating an uneven distribution of easily soluble salts at different depths. The absence of a clear and gradual change in electrophysical indicators could have been

caused by technogenic soil compaction, which disrupts the natural differentiation of the soil. In the ploughed road variant, the electrical conductivity in the 0-10 cm layer was 275 $\mu\text{S}/\text{cm}$, mineralisation was 180 ppm, and salinity was 137 ppm. At other studied depths from 10 to 40 cm, the electrical conductivity decreased to 200-216 $\mu\text{S}/\text{cm}$, which indicates a partial accumulation of easily soluble salts in the lower studied layers of typical chernozem.

The highest electrical conductivity values among the other studied variants were characteristic of the arable land variant and reached 326 $\mu\text{S}/\text{cm}$. The values of total mineralisation and salinity were also elevated – 214 $\mu\text{S}/\text{cm}$ and 163 ppm. With depth, the electrophysical indicators decreased slightly but remained at a high level. Thus, at a depth of 30-40 cm, the electrical conductivity was 360 $\mu\text{S}/\text{cm}$. This distribution indicates the accumulation of easily soluble salts in the arable layer, which could be the result of agricultural use, fertiliser application, or insufficient drainage due to compaction of the lower soil layers and the formation of a plough pan. In the case of temporary military equipment storage, the electrical conductivity in the upper layer studied was 276 $\mu\text{S}/\text{cm}$, and the total mineralisation and salinity values were 182 and 138 ppm. At a depth of 10 to 40 cm,

the electrical conductivity decreased to 195-203 $\mu\text{S}/\text{cm}$, indicating local accumulation of easily soluble salts in the surface layer of typical chernozem. This could be the result of both contamination with lubricants and disruption of the soil water regime due to its compaction.

Changes in the content of water-soluble calcium, sodium and potassium cation salts under the influence of combat operations

An analysis was conducted of the content of water-soluble calcium, potassium and sodium cation salts in typical chernozems at depths of 0 to 40 cm. The results obtained made it possible to identify the nature of the distribution of water-soluble salts depending on the type of land use, the existing anthropogenic impact, or the natural state of the study site. In the case of burnt fallow land, the content of water-soluble calcium salts was stable at all depths studied and was at the level of 93 ppm. The sodium content was quite insignificant, with a maximum value of 4 ppm in the lower soil layers. The potassium content showed a clear downward trend from 55 ppm in the surface layer of 0-10 cm to 7 ppm at depths of 20 to 40 cm, indicating its active accumulation in the surface layers of typical chernozem after a fire (Table 1).

Table 1. Content of water-soluble salts of calcium, sodium and potassium cations in typical chernozems affected by military operations, ppm

Variant	Depth, cm	Content of water-soluble cation salts, ppm		
		Ca	Na	K
1. Burnt fallow	0-10	93	0	55
	10-20	93	2	20
	20-30	93	4	7
	30-40	93	4	7
2. Natural fallow	0-10	98	0	18
	10-20	110	2	6
	20-30	150	2	4
	30-40	150	2	0
3. Compacted road	0-10	130	2	25
	10-20	100	4	0
	20-30	100	5	0
4. Ploughed road	30-40	110	5	5
	0-10	130	4	11
	10-20	110	4	4
5. Arable land	20-30	100	4	0
	0-10	130	2	14
	10-20	120	2	6
	20-30	140	3	0
6. Equipment parking area	30-40	140	3	0
	0-10	150	2	24
	10-20	120	2	11
	20-30	120	2	5
	30-40	110	3	0
	LSD ₀₅	15	2	8

Source: compiled by the authors

Under the influence of natural fallow use, the calcium salt content increased from 98 ppm in the surface layer of typical chernozem to a maximum of 150 ppm at depths of 20 to 40 cm, indicating its accumulation in the lower layers. Water-soluble sodium salts were almost absent in the profile, amounting to only 0-2 ppm. The content of water-soluble potassium salts decreased from 18 ppm in the upper layer to complete absence at a depth of 30-40 cm, which could be more typical for soils in the recovery phase with increased biological activity. On the road variant, the content of water-soluble calcium salts ranged from 100 to 130 ppm without a clear distribution and decrease in content with depth. Water-soluble sodium salts increased slightly in content with depth from 2 to 5 ppm at a depth of 10-30 cm, while potassium salts had an unclear distribution pattern with a higher content in the 0-10 cm layer up to 25 ppm, a complete absence at depths of 10 to 30 cm, and a slight content at a depth of 30-40 cm – 5 ppm. The uneven distribution of water-soluble salts could have been caused by physical disturbance of the profile as a result of soil compaction by repeated passage of military equipment.

The reduction in the content of water-soluble calcium salts occurred after ploughing the road from 130 ppm to 100 ppm at depths of 20 to 40 cm. Sodium salts were consistently present throughout the entire depth studied in an amount of about 4-5 ppm. The amount of water-soluble potassium salts in the surface layers was 11 ppm, and below that, they were not detected at all. The arable land variant was characterised

by an increase in the content of water-soluble calcium salts in the surface layer 0-10 cm from 130 ppm to 140 ppm at a depth of 20-40 cm, which could have been the result of mixing the upper part of the soil as a result of cultivation. Sodium salts were present in very small amounts, namely 2-3 ppm. Water-soluble potassium salts decreased from 14 ppm in the surface layer to practically no presence at depths of more than 20 cm. The highest values of water-soluble calcium salts were recorded in the variant of temporary military equipment storage, where the content was 150 ppm in the upper layer of 0-10 cm, which could be the result of local accumulation or contamination of the soil surface. With depth, the amount of calcium decreased to 110 ppm. The amount of sodium was low, at around 2-3 ppm, and water-soluble potassium salts showed a decrease from 24 ppm in the 0-10 cm layer to complete absence at a depth of 30-40 cm.

Correlation between soil electrophysical parameters

The correlation analysis of electrophysical indicators was based on averaged data within the depth range of 0-40 cm, which allowed assessing the nature of the relationships between electrical conductivity, total mineralisation, salinity, and the content of water-soluble calcium, potassium, and sodium salts in the studied variants. In general, the correlation indicated a strong positive relationship between electrical conductivity, total mineralisation and salinity, which is to be expected, since these indicators were interrelated and reflected the overall level of easily soluble salts in the soil (Table 2).

Table 2. Correlation matrix of the dependence of electrophysical indicators of typical chernozems under the influence of combat operations

Indicator	Cond	TDS	Salt	Ca ²⁺	Na ⁺	K ⁺
Cond	1.00	+0.98	+0.96	+0.72	+0.89	-0.35
TDS	+0.98	1.00	+0.97	+0.70	+0.87	-0.38
Salt	+0.96	+0.97	1.00	+0.68	+0.91	-0.42
Ca ²⁺	+0.72	+0.70	+0.68	1.00	+0.55	-0.48
Na ⁺	+0.89	+0.87	+0.91	+0.55	1.00	-0.36
K ⁺	-0.35	-0.38	-0.42	-0.48	-0.36	1.00

Note: electrical conductivity (Cond); total dissolved solids (TDS); salinity (Salt); content of water-soluble salts of calcium (Ca²⁺), sodium (Na⁺), and potassium (K⁺)

Source: created by the authors

The content of water-soluble calcium salts had a moderate positive correlation with electrical conductivity, indicating the contribution of these salts to the overall mineralisation of the soil, especially in the upper layers with a high calcium salt content. Sodium, despite its insignificant content, also had a positive correlation with electrical conductivity. In addition, on the road and ploughed road variants, a slightly higher

sodium salt content correlated with increased electrical conductivity. The content of water-soluble potassium salts had a weak or even negative correlation with electrophysical indicators. In the fallow and arable land variants, a decrease in potassium salt content with depth was observed, which was not accompanied by a decrease in soil electrical conductivity. The fallow land variant showed the highest electrical conductivity,

which was confirmed by the accumulation of calcium, but at the same time, sodium salts were at a low level, and potassium was not detected at all. Thus, low-mobility water-soluble salts prevailed in the profile. The arable land variant was characterised by consistently high electrical conductivity values throughout the entire soil thickness studied, which directly correlated with a high level of accumulation of easily soluble calcium salts. On the road and ploughed road variants, the electrophysical indicators had average values, but sodium accumulated the most. Electrical conductivity gradually decreased on the burnt fallow variant, which correlated with a decrease in the content of water-soluble potassium salts, but stable values of calcium salts. A correlation between the electrophysical indicators and the content of water-soluble calcium salts was found on the variant of the military equipment parking area in the surface layer of 0-10 cm.

A summary of the research results indicates a clear differentiation in the electrophysical indicators of typical chernozems depending on the nature of natural, agrogenic, technogenic and military influences. It was established that military impact caused a decrease in electrical conductivity at the studied depth (0-40 cm), uneven distribution of water-soluble salts and local accumulation of calcium and potassium in the surface layers. Variants with compaction and contamination were characterised by an increase in electrical conductivity and total mineralisation, which indicated a disturbance in the salt composition. Agrogenic use led to an increase in electrical conductivity and the amount of water-soluble salts. In the fallow use variant, natural vertical differentiation of salts was observed. The established correlations between electrical conductivity and water-soluble salt content allowed to consider electrophysical indicators as indicators of the degree of soil environment disturbance and its restoration potential.

DISCUSSION

The established patterns of profile distribution of electrical conductivity, total mineralisation and salinity, as well as their correlation with the content of water-soluble salts, are consistent with a number of recent international studies, confirming the relevance of the chosen topic. In the work of G. Kargas *et al.* (2020), a comparison was made between methods for determining soil electrical conductivity based on a soil-to-water ratio of 1:1, 1:5, and the use of a saturated paste-like extract. The researchers' goal was to evaluate the accuracy and practicality of the methods presented. The authors found that the method of determining electrical conductivity using a soil-to-water ratio of 1:1 provides stable results for field conditions, although the values

may be lower than when using a saturated paste-like extract. In the studies conducted, the 1:1 water-soil paste method also demonstrated high reproducibility and allowed for standardisation of measurements between variants. This, in turn, confirmed the feasibility of choosing the method for assessing water-soluble salts in the presented research variants. It should also be noted that a 1:5 ratio was used in the previous stages of the studies, but the transition to a 1:1 ratio was due to the need to increase sensitivity to changes in the salt composition in the analysed soil samples. This approach was consistent with the conclusions of G. Kargas *et al.* who emphasised the practicality of using this ratio, particularly in conditions of limited access to laboratory equipment for preparing saturated paste.

In the publication by M. Sahana *et al.* (2020), satellite indices were used to assess soil salinity in the Sundarban region (India). The authors found that electrical conductivity was a reliable indicator for identifying areas with increased salt load, especially under conditions of anthropogenic impact. Eight salinity indices obtained from satellite images were statistically correlated with measured electrical conductivity values using Pearson's correlation coefficient, confirming its diagnostic value. A similar relationship was established in this study, where the correlation coefficients between electrical conductivity and salt content ranged from +0.68 to +0.91, indicating a strong direct relationship. Researchers I. Stavi *et al.* (2021) examined the mechanisms of soil degradation in arid regions, particularly under the influence of sodium. The authors emphasised that excess sodium in the soil solution caused the dispersion of clay particles, deterioration of structure and reduced aeration, which decreased biological activity and plant productivity. It was also noted that sodium competed with other cations (especially potassium and ammonium) for absorption. Within the scope of the studies, despite the low values of sodium salts, a strong positive correlation was found between electrical conductivity and its concentration (+0.89). At the same time, the negative correlation with potassium (-0.35) was consistent with the mechanism of ion competition and potential salt leaching.

In the article by I.W. Primadipta *et al.* (2025), Landsat 8 data was used to monitor soil salinisation dynamics. It was found that soil electrical conductivity varied depending on the type of land use and the presence of anthropogenic load, particularly in areas of intensive construction and transport infrastructure. These results were comparable for road sections and equipment parking areas, where uneven distribution of salts with depth was recorded. Studies conducted by D. Ma *et al.* (2023) established the spatial and temporal dynamics of land use changes in the chernozem region of China. It was

found that intensive land use over the past decades has been accompanied by land degradation, in particular a deterioration in physical and chemical properties and a loss of ecological functions. As a result of the research conducted under conditions of disturbed water regime, uneven distribution of salts and reduced electrical conductivity were recorded, indicating degradation processes associated with land use characteristics. X. Wan *et al.* (2025) found that soil electrical conductivity had a strong positive correlation with the concentration of ions, in particular sodium, as well as chlorides and sulphates, which allowed the indicator to be used as a salinity indicator. The studies also obtained electrical conductivity values accompanied by an uneven distribution of water-soluble salts, especially in the upper layer.

M.C. Paz *et al.* (2020) used electromagnetic tomography to monitor salinisation dynamics, showing that electrical conductivity varied in time and space depending on hydrological conditions, including drainage, evaporation and salt depth. The patterns identified confirmed the spatial heterogeneity of water-soluble salt content observed in the upper layers of the studied areas with disturbed water balance. M.A. Elshewy *et al.* (2024) developed a model for assessing soil salinity based on satellite data. The authors established a significant correlation between spectral indices and laboratory-measured electrical conductivity, which allowed for rapid assessment of the salt regime over large areas without the need for mass field sampling of soil. This approach was particularly relevant for regions with high spatial variation in salinity. Y. Zhang *et al.* (2025) formulated the statement that poor water infiltration can lead to poor drainage, waterlogging and increased electrical conductivity. For example, on a section of road where the soil had been compacted by repeated movement of military equipment, the electrical conductivity in the upper 10 cm layer was 302 $\mu\text{S}/\text{cm}$, the total mineralisation was 199 ppm, and the salinity was 152 ppm. This indicated a disturbance in the water regime, which caused local accumulation of salts.

I.V. Chushkina *et al.* (2021) noted that soil electrical conductivity is an integral indicator that reflects a combination of physicochemical properties, such as moisture, soil solution mineralisation, cation solution capacity, granulometric composition, and organic matter. A change in any of these parameters in space or time is accompanied by variability in soil electrical conductivity, which allows it to be used as an indicator of the stability or dynamics of the soil environment. The results of the studies confirmed the sensitivity of electrophysical indicators to changes in the composition of the soil solution and showed a strong positive correlation of electrical conductivity, for example, with total

mineralisation (+0.98), salinity (+0.96), and the content of water-soluble calcium (+0.72) and sodium (+0.89) salts. To ensure the comparability of soil electrical conductivity results in field conditions, two approaches are used: measurement in soil with field moisture and under conditions of artificial moistening to full moisture capacity. As noted in the studies by M.M. Omar *et al.* (2024), methods with a fixed soil: water ratio allowed to level out the variability of moisture as one of the most influential factors on electrical conductivity. Thus, a similar approach was used in the studies, where the soil paste was prepared by mixing 10 g of air-dry soil with 10 ml of distilled water, kept for 24 hours, and then measured. This allowed to standardise the conditions for determining electrical conductivity, total mineralisation, salinity, and the content of water-soluble calcium, sodium, and potassium cations.

The application of mineral fertilisers increases soil electrical conductivity due to the influx of cations (Ca^{2+} , K^+ , Mg^{2+} , NH_4^+) and anions (NO_3^- , SO_4^{2-} , Cl^-) into the soil solution. As shown in a study by M.S. Kaufmann *et al.* (2025), electromagnetic induction allows for spatial tracking of fertilisation effects, in particular the accumulation of nitrates and macronutrients, which directly correlates with an increase in electrical conductivity. Thus, on arable land, electrical conductivity exceeded 300 $\mu\text{S}/\text{cm}$, accompanied by a high content of water-soluble calcium salts up to 150 ppm and potassium up to 24 ppm. This indicated the accumulation of nutrients and their contribution to soil electrical conductivity. Within the studied areas of typical chernozems, it was found that electrical conductivity, total mineralisation and salinity decreased with depth. The highest values were observed in the upper studied layers, which is associated with the accumulation of salts. Similar vertical differentiation is confirmed by Yu. Shafrost *et al.* (2024), who pointed to an increase in electrical conductivity in the upper layers due to a higher concentration of ions. Also, in the fallow variant after burning, electrical conductivity decreased from 258 $\mu\text{S}/\text{cm}$ to 185 $\mu\text{S}/\text{cm}$, and calcium content decreased from 55 to 7 ppm. A similar trend was observed in the road and equipment parking variants, indicating surface enrichment with salts. This was consistent with the data of Q. Baloch *et al.* (2025), who recorded similar patterns in semi-arid conditions. Soil electrical conductivity may be one of the key parameters characterising its quality, health and productivity. As noted by L. Gong (2022), it is electrical conductivity that affects yield, nutrient availability and microbiological activity, and Atlas Scientific (2023) emphasised its role in the transport of ions in soil solution. Thus, studies of electrical conductivity proved to be a sensitive indicator of soil condition,

which was related to the content of water-soluble calcium, sodium, and potassium salts, confirming its diagnostic value for assessing the salt regime and land use efficiency. The results of the study of the electrophysical indicators of typical chernozems, which were in natural cover conditions and were also subjected to agrogenic, technogenic and combat influences, confirmed the high sensitivity of electrical conductivity to changes in the ionic composition and salt content in the soil solution.

CONCLUSIONS

Based on a comprehensive analysis of electrophysical indicators and the content of water-soluble cation salts in typical chernozems that have been subjected to various types of impact, including natural, agrogenic, technogenic, and combat, it was established that the distribution of water-soluble salts and the electrical conductivity of the soil solution varied significantly depending on the type of load. Natural variants had a clearly expressed vertical differentiation of easily soluble salts, with a gradual decrease in electrical conductivity at the studied depths. The lowest values of up to 185 $\mu\text{S}/\text{cm}$ were recorded in the lower horizons of typical fallow chernozem. In contrast, areas that had been subjected to military impact (compaction, burning, contamination) were characterised by uneven distribution of salts with depth and their local accumulation in the upper layers. The highest electrical conductivity values of up to 360 $\mu\text{S}/\text{cm}$ were observed on arable land, which could be the result of anthropogenic impact (fertiliser application) and the parking of machinery – up to 302 $\mu\text{S}/\text{cm}$, which also indicated technogenic enrichment of the soil solution. According to the results of the analysis of the content of water-soluble cation salts, it was established that the amount of calcium was the highest in the studied variants, where its content reached 150 ppm, sodium was the lowest, and the amount of potassium depended on the nature of the impact and use of typical chernozems. In natural variants, a gradual accumulation of calcium and a decrease in potassium to 7 ppm was

observed, while technologically disturbed variants as a result of hostilities had a disturbed profile and a differentiated distribution of salts at the studied depths.

A stable positive correlation was established between electrical conductivity and the content of calcium (+0.72) and sodium (+0.98) salts, which confirmed the diagnostic informativeness of electrophysical indicators for assessing the degree of soil environment disturbance. A negative correlation with potassium (-0.35) could indicate its loss or accumulation under certain types of impact in the surface layers studied, in particular burning (thermal degradation). The method of preparing a water-soil paste in a 1:1 ratio with an exposure time of 24 hours ensured the stability of the measurement conditions, levelled out the influence of humidity and allowed for comparable results between the variants. This confirmed the feasibility of using standardised approaches to assess the salt regime in degraded chernozem soils. It was found that electrical conductivity can be used not only as an indicator of salinisation, but also as an operational indicator of the degree of anthropogenic disturbance, in particular in cases of local pollution, compaction and thermal damage. The results obtained are part of a broader study of the physical properties of soils disturbed by military operations. In further stages, it is planned to supplement the study with the determination of density, porosity, dispersibility, hardness, moisture capacity, etc., and to establish their connection with microbiological characteristics, which will allow the formation of a comprehensive model of agrophysical degradation of militarily damaged chernozems.

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Електрофізичні показники чорноземів типових під впливом бойових дій та техногенного навантаження

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Анотація. У статті представлено результати дослідження електрофізичних показників типових чорноземів, що зазнали впливу бойових дій та техногенного навантаження, а також агрогенного використання. Метою роботи було виявлення змін електропровідності, загальної мінералізації, солоності та вмісту водорозчинних солей катіонів кальцію натрію і калію шляхом порівняння ділянок із різним типом техногенного, агрогенного та постагрогенного навантаження. Згідно із методологією відбір зразків було проведено від 0 до 40 см через кожні 10 см. Вимірювання електрофізичних параметрів проводилося у водно-ґрунтово пасті (1:1) за допомогою кондуктометра EZODO-8200 М та іономірів HORIBA LAQUAtwin. Додатково було встановлено кореляційні зв'язки між електропровідністю, загальною мінералізацією, солоністю та вмістом водорозчинних солей. Бойовий вплив спричиняв зниження електропровідності з глибиною, нерівномірний розподіл та накопичення солей натрію та калію у верхніх шарах. На випаленому перелозі електропровідність знижувалась із 258 до 185 мкСм/см а вміст солей калію від 55 до 7 мг/л. У варіантах дороги та стояння техніки спостерігалось підвищення електропровідності (до 302 мкСм/см) та накопичення солей кальцію до 150 мг/л і калію – до 24 мг/л. У варіанті ріллі електропровідність залишалася стабільно високою (до 360 мкСм/см), що викликано агрогенним накопиченням солей. На розораній ділянці дороги показники були помірними, що свідчило про часткове відновлення. Встановлено сильну кореляцію електропровідності з кальцієм (+0,72) та натрієм (+0,89), а також негативну з калієм (-0,35). Практичне значення отриманих результатів дослідження полягає в можливості використання електропровідності та вмісту водорозчинних солей як індикатора ступеня порушення ґрунтового середовища, що дозволило оперативно оцінювати деградацію агрогенних та техногенно порушених ділянок чорноземів унаслідок бойових дій, а також можливості формування рекомендацій щодо відновлення ґрунтового покриття в умовах постконфліктного землекористування

Ключові слова: мілітарна деградація; електропровідність; водорозчинні солі; постконфліктне землекористування; агрогенне використання; перелогове використання

Evaluation of onion protection against diseases

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Abstract. The destruction of pathogenic microflora on vegetable plantations improves the phytosanitary condition of cenoses, and quality control of disease pathogens allows onion plants to realise their varietal yield potential. The aim of the experiment was to compare the effectiveness of synthetic preparations for phytosanitary control of peronosporosis, alternariosis and fusariosis pathogens: Ridomil Gold MZ 68 WG and Quadris 250 SC, as well as to consider the biological preparation Phytocide as an alternative to chemical protection. During the experiment, the dynamics of the leaf surface area was determined by the method of cutting and subsequent weighing, the height of onion plants was determined by measuring with a ruler, and the incidence of plant diseases was determined according to the methodology for recording diseases of vegetable and melon crops. The results of studies on the protective effect of fungicides were analysed. Spraying the plots with a mixture of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals) allowed onion plants to grow taller than the control plants – by 4.5 cm – and to exceed the control plants in terms of leaf area dynamics by 37.4-59.6%. Treatment with this mixture contributed to the best control of onion disease pathogens and ensured the formation of bulb yield on average over two years of research at the level of 55.7 t/ha with a marketability index of 85.3%. Treatment of the plots with a biofungicide also provided high-quality protection against diseases, high biometric indicators in plants and a significant increase in onion yield. The highest marketability of bulbs – 85.5% – was observed in the variant with the application of the biological preparation Phytocide, which exceeded the control by 8.7%. The biological fungicide was slightly inferior to synthetic preparations in terms of protecting onions from pathogens, but the slight lag in yield was offset by higher marketability of the product. The analysis of the obtained results provides practical guidance for vegetable growers on how to effectively protect onion plants from diseases using various preparations or their combinations

Keywords: *Allium cepa*; fungicides; pathogens; marketability; onion yield

INTRODUCTION

Diseased onion plants differ from healthy ones in that their physiological processes are slowed down due to the body's resistance to pathogens. The presence of toxins produced by fungi inside the affected plants leads to tissue destruction. As a result, crop yields decrease and product quality deteriorates. Protection against infection and treatment of plants against diseases preserves a significant part of the formed organic matter.

According to research by S.Ye. Okrushko & L.A. Yakovets (2025), phytoncidal protection against diseases was not sufficient to achieve a significantly higher onion yield. The research was conducted on binary crops of vegetables: onions, carrots and peas. Among other things, it was noted that onion phytoncides had a positive effect on the protection of carrots. Constant phytosanitary monitoring, together with forecasting

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the incidence and development of diseases in onion fields, provides the opportunity for rapid intervention to protect cultivated plants. According to research by H. Van der Heyden *et al.* (2020), forecasting systems are important for making informed decisions about treating diseases on a short-term basis. This type of decision-making is often referred to as tactical because it occurs during the harvest season with the intention of protecting the current crop.

The presence of morning dew is a favourable factor for the germination of spores of the fungus *Peronospora destructor*, which belongs to the oomycetes. The incubation period of the disease after infection of the plant lasts from 3-5 to 15 days. A significant problem in onion cultivation is that the fungus can form up to six generations per season. The only advantage is that in dry, hot weather, the development of the disease is suspended, but with an increase in humidity, it continues. Usually, during June of both experimental years, peronosporosis spread and developed moderately in the experimental plots, becoming more active after precipitation (Goryainova *et al.*, 2023). The causative agent of alternaria is *Alternaria porri*. The first symptoms of this disease appear on old onion leaves in the form of water-saturated spots with a white centre. The spots develop at the tips of the onion feathers or in the middle part. Then the leaf breaks at the spot where the spot formed, and the edges of the affected parts turn brown, and the yellowing spreads above and below the feather. Eventually, the scales of the bulb are affected. Onion bulbs become infected with alternaria through the neck. The disease begins to develop on leaves that have already been affected by downy mildew or grey rot, as well as on those damaged by thrips. The fungus can develop within a fairly wide temperature range: from +6 to +32°C. The presence of moisture droplets or air humidity above 90% for 12 hours also contributes to plant infection. Alternaria infection leads to the death of the photosynthetic apparatus, which in turn reduces the size of the bulbs and causes them to rot during storage (Goryainova *et al.*, 2023). Fusarium wilt of onion leaves appears at all stages of plant growth. The causative agent of the disease is *Fusarium oxysporum* or *Fusarium culmorum*, and the development of fusarium wilt is facilitated by high air and soil humidity and high air temperature.

Onions are vulnerable to certain groups of microorganisms that cause plant diseases. Scientists E.R. Araújo *et al.* (2020) studied the protection of onion plants against downy mildew using various preparations. They controlled the disease by applying fungicides weekly and concluded that fungicides consisting only of systemic molecules are not recommended for controlling downy mildew in onions under Brazilian conditions.

According to T.A. Bhatti *et al.* (2021), the use of the fungicide Cabrio Top reduced the number of affected plants more than other fungicides compared to the control, regardless of their concentration; however, the number of affected plants decreased with increasing fungicide concentration. They obtained these data as a result of field studies. This is particularly valuable because the results of laboratory or vegetation studies may differ significantly from those obtained in field conditions. A. Yağmur *et al.* (2024), after studying the biological control of onion fusarium wilt, concluded that *F. mosseae* and a combination of AMF with *T. harzianum* have significant potential for use in controlling FOC in onions. According to their data, arbuscular mycorrhizal fungi and *Trichoderma harzianum* had a positive effect on the root system, onion height and weight. According to researchers O. Borzykh *et al.* (2023), fungicide treatments, by reducing plant damage from diseases, contributed to an increase in onion yield by 1.3-6.9 t/ha, depending on the variety and preparation. Fungicides were 45.8-89.1% effective against leaf spots (alternaria and stemphylosis) and 57.9-70.5% effective against fusarium wilt. Among the varieties studied, the highest yield was obtained with the Medusa variety (40.7 t/ha), and among the fungicides, the highest yield increase was provided by the fungicide Fandango 200 EC, KE (1.25 l/ha).

Different fungicides with different application rates depending on weather conditions and onion variety characteristics have different effects on pathogen control. Therefore, scientists and farmers continue to search for high-quality protection for onion plants against diseases. The two-year cycle of growing this crop requires significant material costs, which do not always lead to the formation of high-quality products. According to researcher V. Shvets (2025), the strategic directions for the development of vegetable growing in Ukraine include expanding the area under vegetable crops and increasing yields. Given the high ploughing intensity of land in Ukraine, in order to increase the area under vegetable cultivation, it is necessary to reduce the area under other crops. Changing crop rotation patterns requires a transition period and the selection of high-quality predecessors for vegetable crops, and the formation of the onion crop, like any other crop, depends on the combined action of a set of factors (Lohosha *et al.*, 2025). Each factor can either strengthen or weaken the overall effect of the combination. However, the harmful activity of pathogens can significantly interfere with physiological processes in plants and nullify several months of human labour. The aim of this article was to investigate the impact of fungicidal plant protection against diseases in onion cultivation technology on the formation of yield and

marketable product output and to assess the economic efficiency of these measures.

MATERIALS AND METHODS

Field studies were conducted during 2023-2024 at Vinnytsia National Agrarian University in four replicates. The object of the study was onion plants, their development processes, and the effect of disease protection options. In accordance with the Convention on Biological Diversity (1992), ethical standards for the treatment of plants were observed in the study. The 'Forum' variety was grown, which belongs to the mid-season group and has a growing season of 110-120 days. The total area of the experimental plot was 12 m², and the recorded area was 10 m². Potatoes were the predecessor crop to onions. The recording of onion plant diseases was carried out in accordance with Methods for recording diseases of vegetable and melon crops (n.d.). The onion plots were examined for peronosporosis, alternariosis and fusariosis at each repetition of the experimental variants in two places equally distant from each other. At each point, 10 plants were examined in a row (20 in total). The counts were carried out when the first signs of disease appeared, as well as during the period of mass infection of onion plants, using a universal scale: 0 – onion feathers are healthy; 1 point – up to 10% of the leaf surface is affected; 2 points – 10 to 35% of the leaf surface is affected; 3 points – 36 to 60% of the leaf surface affected; 4 points – 61 to 95% of the leaf surface affected; 5 points – plant dies, more than 95% of the leaf surface affected. The leaf surface area was determined by weight (first, cuttings were made, weighed and calculated proportionally).

To accelerate the process of nutrient outflow, 10 kg/ha of monopotassium phosphate was applied to the bulbs by fertigation. The bulb yield was recorded, divided into marketable and non-marketable fractions, in accordance with the requirements of DSTU 3234-95 (1996). Synthetic fungicides were selected for the experiment: Ridomil Gold MZ 68 WG and Quadris 250 SC, as well as the biological fungicide Phytocide. During the development of the experimental design, scientific and practical recommendations developed by a group of authors from Ukraine (Mohylna *et al.*, 2021) were taken into account. The fungicide Ridomil Gold MZ 68 WG was recommended for protecting onions from disease pathogens. It is a combined preparation with systemic and contact action due to the active ingredients mancozeb and metalaxyl-M. Ridomil Gold MZ 68 WG is available in the form of water-soluble granules. The fungicide provides not only curative but also eradicated, antispore and protective action. It is recommended to apply it at the onset of disease development, when only 3% of plants are affected. Ridomil Gold MZ 68 WG belongs to the class of low-toxicity preparations ($LD_{50} > 2000$ mg/kg). The fungicide Quadris 250 SC is advertised by Syngenta as an effective product for controlling four classes of fungi that are the most common causative agents of plant diseases: *Deuteromycetes*, *Basidiomycetes*, *Ascomycetes*, and *Oomycetes*. Its mechanism of action on pathogens ensures that there is no cross-resistance, and it destroys not only hyphae but also fungal spores. Quadris 250 SC is safe not only for plants but also for the environment. The waiting period for the product to take effect on vegetables is 5 days. The following scheme was developed for the research (Table 1).

Table 1. Scheme of the experiment on protection against onion diseases

Option	Protection against diseases
1 control	Without fungicide
2	Ridomil Gold MZ 68 WG 2.5 kg/ha three times at 10-day intervals
3	Quadris 250 SC 0.6 l/ha twice at 10-day intervals
4	Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals)
5	Phytocide 2.5 l/ha (three times at 10-day intervals)

Source: compiled by the author

The control variant consisted of plots where no fungicides were applied after the planting of onion sets. In the fourth variant, a reduced amount of a mixture of Ridomil Gold MZ 68 WG and Quadris 250 SC was applied twice per season, and the third treatment was with Ridomil Gold MZ 68 WG alone. In the fifth variant, onion plants were sprayed with the biological product Phytocide to protect them from pathogens. This biofungicide is recommended for protection not only against fungal but also bacterial diseases. It contains live *Bacillus subtilis*

bacteria (at least 1.0×10^9 CFU/cm³), which inhibit the development of a wide range of pathogens and simultaneously stimulate plant growth. It was planned to grow onions under drip irrigation conditions for better and timely provision of moisture and nutrients, with drip irrigation tubes placed every 2 rows. Since semi-rotted manure was applied to the plots at a rate of 20 t/ha for the previous crop, a universal complex fertiliser $N_{20}P_{20}K_{20}$ was used for pre-sowing cultivation. During the period of active bulb growth, $N_{25}P_{25}K_{25}$ was applied with

irrigation water. Every 10 days, three times per season, Ridomil Gold MZ 68 WG (Metalaxyl-M, 40 g/kg + mancozeb 640 g/kg) was applied at a rate of 2.5 kg/ha to protect onion plants from downy mildew. Quadris 250 SC (azoxystrobin, 250 g/l) was also applied at a rate of 0.6 l/ha to protect against downy mildew and fusarium wilt. Thirty days before harvesting, it was recommended to stop treating with these fungicides, which was followed in the experiment. To maintain soil moisture at 75-80%, drip irrigation was used during the growing season of onions.

According to V.M. Svyrydovskiy (2019), in order to achieve high bulb yields, the leaf area of onions must reach 35-40 thousand m²/ha and remain active for as long as possible. During the growing season, according to the research plan, measurements of onion height were taken and the leaf area was periodically determined in order to understand how comfortably the plants were growing and forming a yield, and

how disease control measures affected the intensity of growth processes. Despite the fact that drip irrigation was used instead of sprinkler irrigation, signs of peronosporosis, alternariosis and fusariosis appeared on onion plants in the experimental plots. Weather conditions during the growing season contributed to the development of these diseases: initially, moderate daytime temperatures and cold nights against a backdrop of high humidity, and later, high soil temperatures and dry air. Therefore, based on monitoring and forecasting of the phytosanitary condition of the experimental plots, measures to protect against these diseases were periodically carried out, and one treatment against onion flies and thrips was performed with the insecticide Engeo 247 CS 0.18 l/ha using a backpack sprayer. The water consumption rate was 250 l/ha. Table 2 presents information on the average daily temperature and precipitation for each month over the years of research.

Table 2. Weather conditions characteristics

Months	2023		2024	
	Precipitation, mm	Average temperature, °C	Precipitation, mm	Average temperature, °C
January	20.1	0.9	71.6	-1.6
February	35.5	0.2	38.2	4.8
March	35.0	5.4	35.5	5.2
April	92.7	8.5	84.5	12.2
May	2.7	15.5	22.9	15.8
June	71.6	19.2	80.0	21.1
July	64.5	21.3	57.2	23.5
August	36.0	22.8	32.6	22.2
September	34.6	17.8	30.7	18.8
October	34.0	11.5	43.7	9.7
November	57.0	4.4	46.3	2.5
December	51.4	1.1	49.0	0.6
Total for the year	501.1		592.2	

Source: compiled by the author based on Vinnytsia Regional Hydrometeorological Centre (n.d.)

In total, from April to June inclusive, 167 mm of precipitation fell in 2023, and 187.4 mm in 2024. However, their distribution over the growing season was quite uneven. In particular, it should be noted that in April 2023, the average monthly temperature was 3.7°C lower than in April 2024 (Meteopost, n.d.). Although onions are a cold-resistant crop, low temperatures are conducive to the growth of pathogens. The average monthly temperature in June 2024 was 1.9°C higher than in 2023. The hot weather during the bulb growth period was compensated for by irrigation to create favourable conditions for cultivated plants.

RESULTS AND DISCUSSION

Weather conditions had a significant impact on the development and spread of onion pathogens. Onions are a

crop that requires early planting, so both the amount of precipitation and the average monthly temperature in March had a significant impact on the initial conditions for plant growth and development. The temperature regime and precipitation during the growing season influenced the emergence and development of diseases in the test crop and also significantly affected the microclimate conditions in the phytocenosis. Since moisture is necessary for the germination of fungal spores, their epiphytic development was observed during increased atmospheric precipitation in the first half of the growing season. Critical for the infection of onion plants was the condition of high relative air humidity (90-100%) lasting at least 10 hours and a temperature regime within 13-18°C. The average results of biometric indicators of onions for two years of research are presented in Table 3.

Table 3. Biometric indicators of 'Forum' onions depending on the disease protection system (2023-2024)

Option	Plant height, cm	Dynamics of leaf surface area, m ² /ha					
		I decade of May	II decade of May	III decade of May	I decade of June	II decade of June	III decade of June
1	37.1	354	1,494	6,484	12,042	20,484	27,161
2	40.2	492	2,987	8,158	17,118	27,418	35,499
3	40.5	508	2,999	8,226	17,848	28,110	36,187
4	41.6	565	3,155	8,715	18,034	29,016	37,311
5	40.7	510	2,998	8,311	17,954	28,107	35,945

Source: compiled by the author

The lowest plant height was observed in the control variant – an average of 37.1 cm over two years of research. Variants protected against onion diseases with only one synthetic fungicide showed almost no difference in plant height. Treatment of the plots with a mixture of fungicides resulted in the highest onion height, exceeding the control by 4.5 cm. The difference from the control variant in the plots with biological protection of onions with the Phytocide preparation was +3.6 cm, and with the variant of combined use of fungicides, the difference was +0.9 cm. Thus, the greater plant height and leaf area in variant 4 is evidence of successful phytosanitary control, which allowed the plants to fully realise their varietal potential. In other words, plant health was a key factor in its productivity.

Protecting onions from diseases in the experimental plots allowed for the formation of a larger leaf surface area than in the control. In terms of dynamics during the growing season, onion plants in the treatment variant with Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals) had the highest leaf surface area. Plant protection in the fifth variant with the biofungicide Phytocide 2.5 l/ha (three times at 10-day

intervals) showed a leaf area in the second decade of May of 2,998 m²/ha, which was almost the same as in variants 2 and 3, where chemical protection of onions was used. At that time, the application of a tank mixture of pesticides provided higher leaf area indices – 3,155 m²/ha, which exceeded the control by 2.1 times. At the end of June, in variant 3, where Quadris 250 SC 0.6 l/ha was applied twice at 10-day intervals, the leaf area was 36,187 m²/ha, which is 10,120 m²/ha less than in the fourth variant, but 9,026 m²/ha more than in the control. The last count before harvesting showed that the control indicators for leaf area were exceeded by 8,338 m²/ha in the second variant. The degree of onion plant damage by peronosporosis in the control variant was 15% in 2023 and 12% in 2024; and by alternariosis and fusariosis – 11% and 10% respectively for each year. At the research planning stage, the idea of T. Belo *et al.* (2023) was taken into account, namely that in drier climates, drip and furrow irrigation reduce the risk of onion disease compared to overhead irrigation. Despite spraying the experimental plots with fungicides, diseased plants were found during the surveys. Their presence did not exceed 3% by year and experimental variant (Table 4), but they served as a source of infection.

Table 4. Damage to 'Forum' onions depending on the plant disease protection system (2023-2024), points

Option	Peronosporosis		Alternariosis		Fusariosis	
	2023	2024	2023	2024	2023	2024
1	2	2	2	2	2	2
2	1	0	0	0	1	1
3	0	0	1	1	1	1
4	0	0	0	0	0	0
5	1	1	0	0	0	0

Source: compiled by the author

As shown in the data in Table 4, spraying onions with Phytocid proved to be less effective against downy mildew compared to other disease protection methods. Also, in 2023, Ridomil Gold MZ 68 WG 2.5 kg/ha applied three times at 10-day intervals was less effective against downy mildew than Quadris 250 SC 0.6 l/ha applied twice at 10-day intervals. However, in 2024, its effect was excellent. As for the control of Alternaria, two

years of research revealed signs of the disease in the variant with Quadris 250 SC 0.6 l/ha applied twice at 10-day intervals. Fusarium affected plants in variants with single applications of synthetic pesticides. Treatment with a tank mixture of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals) effectively controlled the pathogens of all onion diseases studied.

When the plants began the active process of transferring plastic substances from the leaves to the bulb, the onion feathers began to lodge. The application of monopotassium phosphate by fertigation accelerated this process. Ten days after such treatment, the experimental crop was ready for harvesting.

High-quality protection against peronosporosis, alternariosis and fusarium wilt of onion leaves ensured an increase in the marketability of bulbs and an increase in yield. This is consistent with the data of M.I. Fedorchuk & V.M. Svyrydovskyi (2018). The dispersion analysis they conducted allowed them to establish that plant protection has a decisive impact on plant productivity, accounting for 63.5% of the effect, while irrigation regimes also had a significant impact on the indicator under study (12.9%), as did the interaction of the factors under study. The content of sugar, vitamin C and dry matter varied to different degrees depending on the irrigation regime and plant protection. Statistical analysis of the data obtained showed a significant increase in onion yield in all experimental variants. On plots with three applications of Ridomil Gold MZ 68 WG at a rate of 2.5 kg/ha three times at 10-day intervals, marketability was 3.3% higher than in the control variant. Over two years of research, protecting onions with the Quadris 250 SC fungicide at a rate of 0.6 l/ha twice at 10-day intervals increased the marketability of bulbs by 3.6%. Treatment of plots with a mixture of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals) sharply reduced the yield of non-marketable products to 14.7%.

The differences in the yield of 'Forum' onions significantly exceeded the smallest significant difference over the years of research. The highest yield was obtained in 2024, when weather conditions were more favourable for the growth and development of this crop. Protecting onions with the biofungicide Phytocid also showed not only high biometric indicators, but also high yields. The 2.7 t/ha yield lag in this variant from the combined application of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) and Quadris 250 SC 0.4 l/ha is compensated by higher product quality (not only in terms of marketability, but also in terms of the absence of residual pesticides) and a reduction in the pesticide load on the environment. It should not be forgotten that biological products also have a certain impact on the environment. As confirmed by a study conducted by S.B. Tagele & E.W. Gachomo (2025), the chemical and biological fungicides SoilGard and Ridomil significantly affected the diversity of soil bacteria, but their effects varied and depended on time. It is also important to consider the condition of the onions

during storage. If the infection persists on the surface or inside the harvested product, these harmful microorganisms will cause the emergence and development of diseases in the autumn-winter period under favourable conditions in the storage facility. In particular, according to G.I. Yarovyj *et al.* (2023), during storage, onions were most affected by neck rot (*Botrytis allii*) and less by root rot (*Fusarium oxysporum*), with onion losses from disease ranging from 3.1 to 5.2%.

The impact of irrigation and plant protection regimes on onion productivity and quality was studied by M.I. Fedorchuk & V.M. Svyrydovskyi (2018), according to which the maximum crop yield in the experiment at the level of 83.5-84.2 t/ha was formed in variants with irrigation of 80-90% of the field capacity and the use of chemical plant protection. The best marketability within the range of 85.3-90.7% was achieved with irrigation at 90% of field capacity, and the highest average bulb diameter – 64.8 mm – was also achieved with this irrigation regime and the use of chemical plant protection. According to A.O. Lymar (2012), onion plants are characterised by a photoperiodic response, which determines the basis of their biological characteristics and economically valuable traits: the duration of the growing season, the rate of growth of the assimilation apparatus and bulb formation, resistance to pathogens, bolting, and plant productivity. Also, H. Myronova *et al.* (2023) proved that improving the agricultural background of cultivation resulted in a slight reduction in potato tuber damage. Since onions also form their yield underground, it is worth considering that fertilising the crop has a positive effect on its resistance to diseases. That is why this study determined the biometric indicators of plants in the experimental plots. Although the absolute yield indicators differ, the study data correlate with the results of the article and agree on a key point: the use of chemical protection is one of the important factors for increasing both the yield and marketability of onions.

In order to transition to biological methods of protecting vegetable crops in modern agriculture, the use of biological preparations, in particular biofungicides, is becoming increasingly widespread, but their effectiveness is usually lower than that of chemical preparations due to their narrow spectrum and slow action. Due to the absence of phytotoxicity and harm to the environment, a certain part of farmers refuse to use pesticides in favour of biological protection. Unlike synthetic pesticides, the use of biological products is accompanied by the stabilisation of biocenotic relationships in the ecosystem, the preservation and restoration of soil fertility, and the improvement of the ecological state of the environment. Chemical fungicides, in turn, provide

powerful, comprehensive and long-lasting protection for cultivated plants, but they have a phytotoxic effect and harm the environment. As stated by O.M. Mohyl'na *et al.* (2021), modern crop cultivation technologies require the mandatory use of pesticides. It is also important to consider the negative impact of pesticides and mineral fertilisers on soil fertility. According to research by O.P. Tkachuk & V.I. Verhelis (2023), the use of green manure has a positive effect on the agroecological condition of the soil. Fertilisation and irrigation are also important in the process of plants realising their genetic potential. The introduction of mineral fertilisers into the soil environment changes the conditions for the life of microflora, including pathogenic microflora, and artificial improvement of the soil water

regime through irrigation can significantly activate the microbiota. The results obtained by I.V. Honcharuk & Ya.V. Hontaruk (2024) on the effectiveness of fertilisation using soil and foliar application schemes indicated the need for an individual approach to each crop and specific growing conditions, which directly correlates with the data of this study, since high-quality fungicide protection that maximises yield can only be effective against the background of optimal nutrition and water regime. As indicated by S. Kalogiannidis *et al.* (2022), in order to ensure modern food security, it is necessary to improve existing technologies so that moisture is not a limiting factor in yield formation. Calculations of the economic efficiency of protecting onions from diseases confirmed the feasibility of using fungicides (Table 5).

Table 5. Yield of 'Forum' onions depending on the plant disease protection system (2023-2024), t/ha

Option	2023	2024	Average	Deviation, +	Marketability, %
1	45.1	47.5	46.3	-	76.8
2	50.8	54.9	52.9	6.6	80.1
3	51.0	55.1	53.1	6.8	80.4
4	54.3	57.0	55.7	9.4	85.3
5	50.9	55.0	53.0	6.7	85.5
HIP ₀₅	2.1	2.3			

Source: compiled by the author

In the fourth variant, where the plots were treated with a mixture of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals), the net profit was 48.8 thousand UAH with a profitability level of 128%. Other experimental options showed slightly lower economic indicators. As noted by L. Fenta & H. Mekonnen (2024), improving methodologies and interdisciplinary research will be the focus of future research to create high-quality, safe and cost-effective plant protection solutions. The calculation of economic indicators reflected the success of the agrotechnical measures carried out in the experiment. The highest net profit and profitability were achieved through a combination of high yield and crop protection efficiency in option 4. At the same time, it is worth highlighting the advantages of the biological product Phytocide, because despite worse economic indicators and lower yields compared to the combined application of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals), its choice may be justified in the context of reducing pesticide load and obtaining environmentally friendly products.

CONCLUSIONS

Onion plants grown in the control variant without fungicide treatment were affected by peronosporosis,

alternariosis and fusariosis (over the years of research, 10 to 35% of the leaf surface was affected). Accordingly, diseased plants produced the lowest yield in the experiment – 46.3 t/ha with the lowest marketability – 76.8%. High-quality protection of 'Forum' onion plants from the most common diseases contributed to higher plant height, better leaf surface growth dynamics, and, accordingly, higher marketability and yield of onions. Spraying the plots with a mixture of Ridomil Gold MZ 68 WG 2.0 kg/ha (three times at 10-day intervals) + Quadris 250 SC 0.4 l/ha (twice at 10-day intervals) contributed to better functioning of the photosynthetic apparatus of cultivated plants, which ensured the formation of onion yield on average for 2023-2024 studies at the level of 55.7 t/ha. The marketability index for the fourth variant was 85.3%, which exceeded the control variant by 8.5%. The highest net profit – 48.8 thousand UAH – and the highest level of profitability – 128% – were obtained for this variant.

The results of using the biological fungicide Phytocide were slightly lower compared to the chemical control with a mixture of onion disease preparations. The decrease in yield compared to the fourth option was 2.7 t/ha over two years of research. However, when comparing onion yields with single applications of synthetic preparations, i.e. with options 2 and 3, the deviation from the control option is close to their level. In other words, the quality of protection provided by

the biological fungicide Phytocide can compete with the chemical method. It should also be noted that the option of biological protection of onion plants against diseases ensured a reduction in the pesticide load on the territory. The direction of further research is to study the effectiveness of biological preparations for the protection of other vegetable crops against diseases in the Vinnytsia region.

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Оцінка захисту цибулі ріпчастої від хвороб

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Анотація. Знищення патогенної мікрофори на овочевих плантаціях поліпшує фітосанітарний стан ценозів, а якісний контроль збудників хвороб дозволяє рослинам цибулі реалізувати сортовий потенціал врожайності. Метою експерименту було порівняти ефективність синтетичних препаратів для фітосанітарного контролю збудників пероноспорозу, альтернаріозу та фузаріозу: Ридоміл Голд МЦ 68 WG та Квадріс 250 SC, а також розглянути як альтернативу хімічному захисту – біологічний препарат Фітоцид. Під час експерименту методом висічок із подальшим зважуванням визначили динаміку площі листової поверхні, методом вимірювання лінійкою визначали висоту рослин цибулі та згідно з методикою обліку хвороб овочевих і баштанних культур визначали ураженість рослин хворобами. Проаналізовано результати досліджень щодо захисної дії фунгіцидів. Обприскування ділянок сумішшю препаратів Ридоміл Голд МЦ 68 WG 2,0 кг/га (тричі з інтервалом в 10 днів) + Квадріс 250 SC 0,4 л/га (двічі з інтервалом в 10 днів) дозволило рослинам цибулі сформувати вищу висоту ніж на контролі – на 4,5 см та перевершувати в динаміці площі листової поверхні на 37,4-59,6 % контроль. Обробка цією сумішшю сприяла найкращому контролю збудників хвороб цибулі, та забезпечила формування урожайності цибулин в середньому за два роки досліджень на рівні 55,7 т/га із показником товарності 85,3 %. Обробка ділянок біофунгіцидом теж забезпечила якісний захист від хвороб, високі біометричні показники у рослин та істотне зростання урожайності цибулі. Найвища товарність цибулин – 85,5 % була на варіанті внесення біологічного препарату Фітоцид, що перевищила контроль на 8,7 %. Біологічний фунгіцид за ефективністю захисту цибулі від патогенів дещо поступався синтетичним препаратам, але незначне відставання урожайності компенсувалося вищою товарністю продукції. Аналіз отриманих результатів показує овочівникам як на практиці якісно захистити рослини цибулі від хвороб різними препаратами або їх комбінацією

Ключові слова: *Allium cepa*; фунгіциди; патогени; товарність; урожайність цибулі

Technological environment and feeding of dairy cows under conditions of keeping in a cros-barn

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Abstract. Dairy farming is one of the most important branches of animal husbandry, as it provides essential food products to the population and raw materials to milk processing enterprises. The study was aimed at investigating how the conditions of keeping and feeding with complete monomixes affect the level of milk productivity of Holstein first-calf heifers during first lactation period. The animals in the experimental group were kept in a microclimate controlled cros-barn, while those in the control group were kept in a pavilion-type barn with natural ventilation. The intensity of lactation in the first half was analysed and it was found that in cows of the experimental group, the yield per 100 days and on the peak day of lactation was, respectively, 103.3 kg ($p < 0.001$) and 1.1 kg ($p < 0.05$) higher than in animals of the control group. The analysis showed that cows in the experimental group with high productivity (>9643 kg) had a longer period of reaching peak lactation. This indicator exceeded the duration of the same period in cows from the groups with productivity “ <8423 ” and “ $8424-9642$ ” by 20.3 ($p < 0.001$) and 5.9 ($p < 0.001$) days, respectively. In addition, within the experimental group, cows with shortened, average, and prolonged reproductive cycles had higher milk yields during the first 100 days of lactation – by 94.0 kg ($p < 0.001$), 115.6 kg ($p < 0.001$), and 93.4 kg ($p < 0.001$), respectively, compared to their peers in the control group with a similar distribution of cycle duration. A summary of the results for the combined indicators showed that the animals in the experimental group demonstrated better production and physiological characteristics compared to the control group. Thus, keeping Holstein cows in a cros-barn provides a comfortable technological environment that meets biological needs in the first half of lactation, minimises heat stress, and promotes the realisation of genetic potential for high productivity. The material is relevant for livestock breeders and technologists in milk production in industrial complexes

Keywords: holstein breed; cows maintenance; lactation; milk productivity; reproductive capacity

INTRODUCTION

Increasing gross milk production remains a challenging and strategically important issue in modern dairy farming. This task is being addressed not only through genetic improvement of cattle and selection

of high-yielding specimen, but also through comprehensive improvement of husbandry, feeding, and care technologies. Spatial planning solutions in livestock buildings are also important, as they ensure an optimal

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microclimate, adequate hygiene, comfort, and reduced stress factors for animals. Creating a favorable technological environment makes it possible to more fully realise the genetic potential of specialised dairy breeds, since it is under conditions that are as close as possible to their biological needs that the productive capabilities of the organism are effectively realised. A rational combination of genetic, technological, and organisational factors is a key prerequisite for increasing herd productivity, improving reproductive performance, and ensuring the stable development of dairy farming as a whole.

Particular productivity growth has been achieved in agricultural enterprises that have significantly greater technological capabilities to ensure conditions for effective dairy farming and high-quality milk production. The main directions for the development of highly intensive dairy farming are a solid feed base, stable state support, a well-established veterinary service system, and the need to improve the management mechanism of a progressive system of milk production intensification based on the use of a highly productive loose housing system for cows (Antoshchenkova, 2020). Research conducted by M.M. Lutsenko & I.O. Lastov's'ka (2022) showed the significant advantages and prospects of loose housing of high-yielding cows in easily assembled barns with a width of 32.5 and 36 m. It has been established that new spatial planning and technological solutions for housing highly productive cows provide comfortable conditions. The presence of side curtains and light ventilation ridges in the design of the premises increases the air velocity more than threefold (0.5 m/s vs. 0.16 m/s), the ammonia content in the air of the premises is reduced by 8-9 times compared to traditional cowsheds, and bacterial contamination is reduced to a minimum (2.8 thousand/m³ at $P > 0.999$) due to an increase in the volume of the premises to 129.6 m³ per head.

M.R.H. Rakib *et al.* (2020) proved that the financial efficiency of dairy farming is determined by many factors that combine the effective use of production, material, and labor resources. At the same time, it was emphasised that in order to obtain a large amount of high-quality products, first of all, it is necessary to create optimal conditions for keeping cows, ensuring comfortable climatic and microclimatic conditions depending on the physiological state of the animals. L.M. Sorathiya (2024) noted that the introduction of integrated dairy farming practices that prioritise livestock welfare not only improves health and reduces stress, but also leads to increased productivity and sustainable development of dairy farming. Emphasising the interdependence of dairy cattle welfare and productivity, attention was drawn to feeding animals with high-quality feed, which is important for maintaining animal health and milk production.

One of important conditions for high productivity, reproductive qualities, and health preservation in animals is their proper nutrition. In particular, the content and ratio of minerals in their diet is crucial. Optimising the mineral and vitamin nutrition of cows through the use of mineral and vitamin supplements helps to normalise metabolism and increases productivity. The absence, deficiency, or excess of certain mineral elements, as well as an imbalance of their ratio in diets, leads to a decrease in the efficiency of feed nutrient utilisation, a decrease in animal productivity, and disease development (Valldecabres & Silva-del-Rno, 2022). A study by V.A. Hlavatchuk (2024) showed that adding a mineral and vitamin premix to the diet of dairy cows balanced its composition in terms of phosphorus, manganese, copper, zinc, iodine, cobalt, vitamin D, and selenium. This had a positive effect on milk productivity, the chemical composition of milk, and the reproductive functions of the animals. The average daily yield of natural fat milk increased by 1.5 kg or 5.9%, the mass fraction of fat and protein in milk by 0.05 and 0.07%; the duration of the service and inter-calving periods was reduced by 8 days, and the insemination index decreased by 10.3%. The increase in cow productivity was accompanied by a decrease in feed consumption per 1 kg of milk by 0.09 energy feed units.

According to A.T. Tsvigun *et al.* (2021), with a milk yield of 25-30 kg per day, dry matter intake should be 16-20 kg with a metabolisable energy of over 14 MJ. The simplest solution to this problem is to divide the herd into groups with more uniform productivity. Dividing the herd into production groups is, to a certain extent, a compromise and cannot completely solve the problem of standardised feeding. V.S. Kozyr (2022) emphasised the importance of balanced nutrition for dairy cattle, as it satisfies their daily need for interrelated nutrients (protein, fat, carbohydrates), minerals, trace elements, and vitamins in optimal proportions. With such a diet, which is based on the energy and protein value of feed, the animals' bodies develop, grow, and function normally.

Therefore, in order to avoid negative environmental influences, in particular high temperatures and humidity, it is necessary to control the number of animals in the sections; ensure intensive ventilation of the cowshed using fans to create air circulation and an optimal microclimate. Along with the maintenance conditions, maximum comfort of the technological environment for dairy cattle is ensured by feeding animals with fresh feed and providing free access to water, especially during the hot season. The aim of the study was to evaluate the intensity of lactation during the calving period of first-calf Holstein cows under comfortable conditions in a cross-barn and feeding with complete monomixes from feeder trays.

MATERIALS AND METHODS

The scientific and experimental research was conducted at a breeding farm for Holstein cattle, "Promin" Agricultural Limited Liability Company (ALLC) in Mykolaiv Oblast. This farm is one of the leaders in the dairy business, where intensive milk production technology is based on loose housing of cows, feeding them complete mono-mixtures from feeding tables, and milking them on an automated Carousel-type conveyor-ring milking machine with 80 cow slots. These technical and technological solutions contributed to high levels of productivity in animals. Milk yield per cow averaged 12703 kg in 2023 and 13200 kg in 2024 (Pidpala & Holosnyi, 2024).

Using Dairy Comp and Microsoft Excel, two groups were formed: experimental ($n = 300$) – animals were kept in a cross-barn with artificial ventilation, and control ($n = 300$) – animals were kept in a pavilion-type barn with natural ventilation. The comfort of the technological environment for Holstein cows, especially during the hot summer period, was ensured by keeping them loose in a cross-barn with an artificially controlled microclimate. Depending on the specific zone, the air in the room moved at a speed of 0.5-3.0 m/s in one direction – across the building. The barn, 356 m long and 4-6 m high, is equipped with 114 exhaust fans on one side along the entire perimeter, each with a diameter of over 1 m and a power of 2.5 kW. Due to the power of the exhaust ventilation system, the air in the building was expelled outside and intensive air exchange took place, ensuring the best gas composition of the air, i.e., the lowest gas content in the room. In addition, in the rest area, the air movement accelerated to 2.5 m/s and a

noticeable breeze was created, which cooled the animals during their rest, i.e., cooling off the cows by the airflow. This ventilation minimised heat stress in cows during the summer and also ensured cleaner air due to its circulation. An optimal microclimate with the required temperature and air velocity was maintained using a special computer program. The rest area was equipped with beds with clean bedding, which consisted of solid manure.

Cows were fed a mixed diet (complete monomix) from the feeding trays with 80 cm long feeding front. To prepare and distribute feed mixtures, the author's feed and mobile feed dispensers/crushers (mixers) were used. The optimal grinding and homogeneity of the general mixed ration was achieved thanks to the developed technology of sequential loading of feed into the mixer hopper. First, straw and hay were loaded, then silage and haylage, and finally, compound feed and diluted molasses, which not only added flavor to the total mixed ration but also acted as a binder for the crushed feed and regulated the moisture content of the complete mono-mixture. To prevent acidosis and improve feed quality during the preparation of the total mixed ration, baking soda was used in an amount of 1% in the compound feed. For feeding cows in the first half of lactation, a ration was developed (Table 1), which contained, based on consumption per head: dry matter – 28.2 kg (experimental group) and 27.3 kg (control group), compound feed – 12.69 kg (experimental group) and 11.17 kg (control group). In terms of the composition of different types of feed, the general mixed diet was similar and met the biological needs of highly productive animals in the first half of lactation.

Table 1. Nutrition ration for experimental cows in the first half of lactation (14-160 days)

Feed	Physical mass, kg	Dry matter, kg	Feed	Physical mass, kg	Dry matter, kg
silage	27.5	9.71	soybean oilcake	1.900	1.672
corn silage	1	0.65	wheat	1.000	0.880
rye silage	8.7	2.86	limestone flour	0.160	0.141
straw	0.35	0.30	corn gluten	0.350	0.308
molasses	1.5	1.13	polfamix premix	0.150	0.132
sunflower	0.5	0.45	salt	0.130	0.114
alfalfa silage	3.50	1.13	sodium bicarbonate	0.160	0.141
water	1.5	0.00	rumen-protected fat	0.200	0.176
compound feed	12.69	11.17	buffer for cows	0.070	0.062
including:	-	-	feed-grade urea	0.050	0.044
corn	5.500	4,840	magnesium oxide	0.040	0.035
rapeseed oilcake	1.100	0.968	monocalcium phosphate	0.030	0.026
soybean oilcake	0.700	0.616	bentonite	0.050	0.044
sunflower oilcake	1.100	0.968	-	-	-
total mixed ration		cross-barn		57.5	28.2
per cow, per day		pavilion-type barn		56.1	27.3

Note: the average moisture content of the total mixed ration during this period was 48.6%

Source: authors' data obtained in the laboratory of "Promin." ALLC

Control over the adequate feeding of high-yielding cows was carried out by predicting dry matter intake based on actual initial data (Tsvigun *et al.*, 2021), and rations were balanced taking into account daily productivity, dry matter intake, energy balance, and changes in body condition during lactation. Optimal moisture content was monitored using an express method by drying samples of the total mixed ration in a microwave oven. Lactation intensity was assessed based on indicators in the first 100 days after calving in experimental groups of first-calf heifers, distributed according to milk yield, reproduction cycle duration (intercalving period – ICP), and the development of combined traits – milk production and reproductive capacity. The experimental group of cows was differentiated according to the average milk yield for the first lactation (9033 kg of milk) by a deviation of 0.67σ into three groups: animals with a milk yield <8423 ($n = 68$), with a milk yield of 8424-9642 ($n = 158$), and with a milk yield >9643 ($n = 74$). According to the duration of the reproductive cycle, they were differentiated by a deviation of 0.67σ from the average value of ICP = 384.4 days after the first calving into three groups: with a shortened duration (intercalving period “ <373.4 ”; $n = 72$); average duration (intercalving period “ $373.5-395.3$ ”; $n = 151$) and with prolonged reproduction cycle duration (intercalving period “ >395.4 ”; $n = 77$). The control group of cows, based on the average milk yield during the first lactation (8.521 kg of milk), was differentiated by a deviation of 0.67σ into three groups: animals with a milk yield of <7943 ($n = 71$), with a milk yield of 7944-9097 ($n = 157$), and with a milk yield of >9098 ($n = 72$). According to the average value of the reproduction cycle of 386.5 days: animals with a shortened duration, taking into account 0.67σ , had an intercalving period of 375.6 days or less ($n = 74$); average duration – 375.7-397.3 ($n = 156$) and with an extended reproduction cycle duration – >397.4 ($n = 70$). The χ^2 (chi-square) criterion was used to determine the conformity of the

distribution of animals into three groups to the patterns of normal distribution (Pidpala *et al.*, 2012).

The test animals were divided into four groups based on the combination of deviations in the plus (1) and minus (2) directions from the average value of milk yield and reproductive capacity: 1-1, 1-2, 2-1, 2-2 (Pidpala *et al.*, 2012). The research materials were processed using statistical methods (Kramarenko *et al.*, 2019), in particular, the determination of the arithmetic mean (\bar{X}), the error of the arithmetic mean (S_x), the standard deviation (σ), coefficient of variation (C_v) to conduct a comparative analysis of the studied traits between the experimental and control groups and to establish the influence of different conditions of keeping and feeding on the productivity of Holstein heifers during their calving period. During the keeping of the experimental animals at the industrial complex and throughout all manipulations with them, the provisions of Law of Ukraine No. 249 (2012) and the European convention for protection of vertebrate animals used for experimental and other scientific purposes (1986) were observed.

RESULTS AND DISCUSSION

Observations have shown that the cows ate the complete monomix (total mixed ration) most intensively immediately after milking. Therefore, the fresh total mixed ration was distributed after removing feed residues from the feed table while the animals were in the milking parlor. Thus, the maximum level of consumption of a complete monomix was achieved, calculated as 28.2 kg of dry matter per head (experimental group) and 27.3 kg (control group), which contributed to high productivity in first-calf heifers during their calving period. It was found that under different conditions of comfort, in particular in a mega-barn with a controlled microclimate and in a pavilion-type barn with natural ventilation, the cattle in the experimental and control groups differed in terms of milk yield and lactation intensity in the first half of lactation (Table 2).

Table 2. Characteristics of lactation intensity in first-calf Holstein cows divided into groups according to their milk yield in the first lactation

Indicator	Research group		
	$\bar{X} \pm S_x$	σ	$C_v, \%$
Cows with milk yield <8423 ($n = 68$)			
Milk yield per 100 days of lactation, kg	3221.6 \pm 11.27	11.3	3.0
Period until peak lactation, days	101.6 \pm 1,15	1.2	9.6
Milk yield on the peak lactation day, kg	35.9 \pm 0,60	0.6	14.2
Cows with milk yield 8424-9642 ($n = 158$)			
Milk yield per 100 days of lactation, kg	3008.5 \pm 9,63	9.6	3.9
Period until peak lactation, days	116.0 \pm 0.46	0.5	4.8
Milk yield on the peak lactation day, kg	37.0 \pm 0.34	0.3	11.4

Table 2, Continued

Research group			
Indicator	$\bar{X} \pm Sx$	Parameters σ	Cv,%
Cows with milk yield >9643 (n = 74)			
Milk yield per 100 days of lactation, kg	3003.4 ± 11.40	11.4	3.3
Period until peak lactation, days	121.9 ± 0.93 ^{2,1}	0.9	6.7
Milk yield on the peak lactation day, kg	36.4 ± 0.34	0.3	8.1
Average across the entire selection (n = 300)			
Milk yield per 100 days of lactation, kg	3058.3 ± 8,20 ^{***}	8.2	4.6
Period until peak lactation, days	114.1 ± 0,61	0.6	9.2
Milk yield on the peak lactation day, kg	36.6 ± 0.24*	0.2	11.4
Control group			
Indicator	$\bar{X} \pm Sx$	Parameters σ	Cv,%
Cows with milk yield <7943 (n = 71)			
Milk yield per 100 days of lactation, kg	2956.0 ± 6.19	52,2	1.8
Period until peak lactation, days	113.7 ± 0.72	6.0	5.3
Milk yield on the peak lactation day, kg	35.7 ± 0.64	5.4	15.0
Cows with milk yield 7944-9097 (n = 157)			
Milk yield per 100 days of lactation, kg	2953.2 ± 4.98	61.4	2.1
Period until peak lactation, days	114.2 ± 0.55	6.8	5.9
Milk yield on the peak lactation day, kg	35.4 ± 0.39	4.8	13.5
Cows with milk yield >9098 (n = 72)			
Milk yield per 100 days of lactation, kg	2961.8 ± 7.01	59.5	2.0
Period until peak lactation, days	113.4 ± 0.62	5.2	4.6
Milk yield on the peak lactation day, kg	35.5 ± 0.60	5.1	14.4
Average across the entire selection (n = 300)			
Milk yield per 100 days of lactation, kg	2955.0 ± 11.65	131.8	4.5
Period until peak lactation, days	113.8 ± 0.93	10.5	9.2
Milk yield on the peak lactation day, kg	35.5 ± 0.37	4.2	11.9

Note: \bar{X} – arithmetic mean; Sx – arithmetic mean error; σ – standard error; Cv – coefficient of variation; * – $p < 0.05$; *** – $p < 0.001$ compared to the control group; 1 – $p < 0.05$; 2 – $p < 0.001$ compared to groups “<8423” and “8424-9642”

Source: compiled by the authors

In terms of milk yield in the first 100 days of lactation, cows in the experimental group prevailed, which indicates the suitability of the technological environment, comfort of keeping, and adequacy of feeding to their biological needs during the intense period of milk production in the body of lactating animals. It was found that the average milk yield for 100 days of lactation in cows in the experimental group was 103.3 kg ($p < 0.001$) or 3.5% higher than in animals in the control group, which is explained by the comfort of their housing and the sufficiency of feeding with a general mixed diet from the feeder trays. As for the period before the peak of lactation, no significant difference was found between the experimental and control groups, as the difference was 0.7 days or 0.6%. Milk yield on the peak day of lactation was 1.1 kg ($p < 0.05$) or 3.1% higher in cows in the experimental group than in their peers in the control group. By determining the intensity of lactation in the first half of lactation in cows with different

milk yields per lactation, it was found that high-yielding cows with a milk yield >9643 in the experimental group were characterised by a longer period before the peak of lactation, which was 121.9 days. The difference compared to groups “<8423” and “8424-9642” was 20.3 ($p < 0.001$) and 5.9 ($p < 0.001$) days, respectively, i.e., they reached the highest milk yield earlier, followed by a gradual decline. A similar tendency was not observed in the control group during the period before the peak of lactation. Regardless of the level of milk yield during the first lactation, the animals reached the peak of lactation on average at 113.4-114.2 days.

A comparative analysis showed that cows with a milk yield of <8423 in the experimental group had a 7.3% higher milk yield per 100 days of lactation than their highly productive counterparts. However, their milk yield per lactation was 7776 kg of milk, since after reaching the highest daily milk yield on the peak day of lactation, there was a rapid decline. The studied

traits, such as milk yield per 100 days of lactation and the period before the peak of lactation, were characterised by low coefficients of variation in both the experimental ($Cv = 3.0-9.6\%$) and control ($Cv = 1.8-9.2\%$) groups, while milk yield on the peak day of lactation was characterised by medium coefficients of variation ($Cv = 11.4-14.2\%$ and $Cv = 11.9-15.0\%$, respectively), which indicates the combined influence of environmental and genetic factors on the development of this trait. The exception is high-yielding cows with milk yield >9643 in the experimental group, which are characterised by a low coefficient of variation. Thus, with a similar feed background but different comfort levels, in particular in a mega-barn with an artificially controlled

microclimate, the individual characteristics of high-yielding Holstein cows are manifested. That is, in a mega-barn, the comfort of the technological environment meets the biological needs of lactating cows to the fullest extent possible and contributes to the manifestation of individual genetic predispositions for high productivity in the Holstein breed. Conversely, in a pavilion-type barn with natural ventilation, no such ability to develop productive traits in animals has been established. Studies of lactation intensity in the first half of lactation in cows from the experimental and control groups, distributed according to the duration of the reproductive cycle, revealed a difference in milk yield per 100 days and on the peak day of lactation (Table 3).

Table 3. Characteristics of lactation intensity in first-calf Holstein cows with different reproductive cycle periods

Research group			
Indicator	$\bar{X} \pm Sx$	Parameters σ	$Cv, \%$
Group of cows with ICP duration <373.4 (n=72)			
Milk yield per 100 days of lactation, kg	3068.9 \pm 18.56***	157.4	5.1
Period until peak lactation, days	114.3 \pm 1.11	9.4	8.2
Milk yield on the peak lactation day, kg	36.5 \pm 0.46	3.9	10.6
Group of cows with ICP duration 373.5-395.3 (n=151)			
Milk yield per 100 days of lactation, kg	3057.8 \pm 10.55***	129.7	4.2
Period until peak lactation, days	113.9 \pm 0.9	11.1	9.7
Milk yield on the peak lactation day, kg	36.6 \pm 0.35**	4.2	11.6
Group of cows with ICP duration >395.4 (n=77)			
Milk yield per 100 days of lactation, kg	3049.5 \pm 17.24***	151.3	5.0
Period until peak lactation, days	114.2 \pm 1.20	10.5	9.2
Milk yield on the peak lactation day, kg	36.5 \pm 0.50	4.4	12.0
Control group			
Indicator	$\bar{X} \pm Sx$	Parameters σ	$Cv, \%$
Group of cows with ICP duration $<375,6$ (n=74)			
Milk yield per 100 days of lactation, kg	2974.9 \pm 14,54	125.1	4.2
Period until peak lactation, days	115.9 \pm 1.12	9.6	8.3
Milk yield on the peak lactation day, kg	36.0 \pm 0.43	3.7	10.4
Group of cows with ICP duration 375.7-397.3 (n=156)			
Milk yield per 100 days of lactation, kg	2942.2 \pm 11,25	138.7	4.7
Period until peak lactation, days	114.0 \pm 0.87	10.7	9.4
Milk yield on the peak lactation day, kg	35.3 \pm 0.32	4.0	11.3
Group of cows with ICP duration >397.4 (n=70)			
Milk yield per 100 days of lactation, kg	2955.9 \pm 15.18	127.0	4.3
Period until peak lactation, days	112.4 \pm 1.26	10.5	9.4
Milk yield on the peak lactation day, kg	35.8 \pm 0.43	3.6	10.2

Note: **- $p < 0.01$; ***- $p < 0.001$ compared to the control group; \bar{X} – arithmetic mean; Sx – arithmetic mean error; σ – standard error; Cv – coefficient of variation

Source: compiled by the authors

In the experimental group, animals with shortened, average, and prolonged inter-lactation periods had a 94.0 kg ($p < 0.001$) or 3.2% higher weight gain over 100 days; 115.6 kg ($p < 0.001$) or 3.9% and 93.4 kg ($p < 0.001$) or 3.2% higher than in their peers of similar

distribution in the control group. The increase in milk yield on the peak day of lactation in cows of the experimental group of the above distribution by the duration of the reproductive cycle compared to the animals of the control group was 0.5 kg; 1.3 kg ($p < 0.01$) and

0.7 kg, respectively, which was 1.4%, 3.7% and 2.0% higher. According to such an indicator as the duration of the period before the peak of lactation, no significant differences were found between the distribution groups in the experimental and control groups. Therefore, it can be noted that Holstein cows are prone to a prolonged reproductive cycle, and the peak day of lactation occurs on the 112th-116th day of lactation. For the characteristics describing lactation intensity in the first 100 days, low and medium variability indices were established in the groups distributed according to the duration of the reproductive cycle. In first-calf cows with shortened, average, and prolonged inter-calving periods in both the experimental and control groups, low coefficients ($C_v = 4.2-9.7\%$ and $C_v = 4.2-9.4\%$, respectively) indicated a negligible influence of the environment on their manifestation. Such a trait as milk yield on the peak day of lactation in the specified distribution groups was characterised by a medium

degree of variability ($C_v = 4.2-9.7\%$ and $C_v = 10.2-11.3\%$, respectively), which indicated the influence of environmental factors on its manifestation.

As a result of investigating lactation stress in cows classified according to a combination of characteristics (milk yield and reproductive capacity), it was established that in the experimental group, cows in groups 1-1 and 1-2 differed in higher milk yield over 100 days of lactation, a longer period before reaching peak lactation, and milk yield on the peak day of lactation compared to their peers of similar distribution in the control group (Table 4). The differences were 33.6 kg; 1.9 days; 1.1 kg and 102.9 kg. ($p < 0.001$); 6.9 days ($p < 0.001$); 1.7 kg ($p < 0.05$), respectively. This manifestation of the studied characteristics in the animals of the experimental group is explained by the comfort of their maintenance in a mega-barn and proper feeding with a mixed diet from feeder trays, which ensured continuous free access to the consumption of monomix.

Table 4. Characteristics of lactation intensity in first-calf Holstein cows in groups according to a combination of characteristics

Group by combined characteristics	Research group					
	Milk yield per 100 days of lactation, kg		Period before peak lactation, days		Milk yield on the peak lactation day, kg	
	$\bar{X} \pm S_x$	$C_v, \%$	$\bar{X} \pm S_x$	$C_v, \%$	$\bar{X} \pm S_x$	$C_v, \%$
1-1 (n=78)	3016.6 ± 14.06	4.10	117.6 ± 1.02	7.60	37.1 ± 0.44	10.50
1-2 (n=63)	3022.2 ± 14.50***	3.8	118.6 ± 1.10***	7.5	36.1 ± 0.50*	9.9
2-1 (n=55)	3138.3 ± 20.30	4.8	107.9 ± 1.60	10.9	35.8 ± 0.60	13.1
2-2 (n=104)	3069.3 ± 14.40	4.8	112.0 ± 0.90	8.6	36.9 ± 0.40	12.0
Group by combined characteristics	Control group					
	Milk yield per 100 days of lactation, kg		Period before peak lactation, days		Milk yield on the peak lactation day, kg	
	$\bar{X} \pm S_x$	$C_v, \%$	$\bar{X} \pm S_x$	$C_v, \%$	$\bar{X} \pm S_x$	$C_v, \%$
1-1 (n=69)	2983.0 ± 14.73	4,1	115.7 ± 1.17	8.4	36.0 ± 0.43	10.0
1-2 (n=62)	2919.3 ± 16.98	4,6	111.7 ± 1.52	10.7	34.4 ± 0.51	11.8
2-1 (n=58)	2955.9 ± 17.33	4,5	116.3 ± 1.16	7.6	35.9 ± 0.56	12.0
2-2 (n=111)	2951.3 ± 12.95	4,6	113.3 ± 1.01	9.4	35.8 ± 0.34	10.0

Note: * - $p < 0.05$; *** - $p < 0.001$ compared to the control group; \bar{X} - arithmetic mean; S_x - arithmetic mean error; σ - standard error; C_v - coefficient of variation

Source: compiled by the authors

A similar trend in milk yield variability over 100 days of lactation was established for groups distributed according to combined traits, indicating the influence of genetic factors. The reduced influence of heredity on the trait of milk yield on the peak day of lactation is indicated by the coefficients of variability of the experimental and control groups. Thus, according to the distribution by combined traits (milk yield and reproductive capacity), the animals in the experimental group, which were kept in a mega-barn with the most comfortable technological environment for maintaining their welfare and high productivity, had an advantage in the studied indicators. The

results show an increase in milk productivity in Holstein cows kept in a mega-barn with a complete mixed diet. These conclusions prompt a discussion on the impact of various factors on the realisation of the genetic potential of specialised dairy cattle breeds to increase the competitiveness and profitability of the dairy industry. The study proves the prospects and feasibility of introducing cross-ventilated and microclimate-controlled premises for dairy cattle in industrial milk production complexes, which will contribute to the creation of a comfortable environment, the maintenance of animal welfare, high productivity, and an increase in gross milk production.

An increase in milk yield was determined in the first half of lactation by 3.5% and on the peak day of lactation by 3.1% in cows kept in a mega-barn with a controlled microclimate and fed a complete monomix containing 28.2 kg of dry matter per head. These findings are consistent with the research of S.H. Pishchan & K.A. Sylychenko (2021), which showed that feeding cattle a pre-calculated diet that included food supplements containing vitamins, minerals, and compound feed generally satisfied their energy needs. The high energy content of the feed mixture in the diet of milking and newly calved Swiss cows during the autumn-winter calving period contributed to milk yields of 3539.6-3570.0 kg of milk during the first 100 days of lactations I-III. Many factors influence the vitality and productivity of dairy cattle, but among them the most significant are the environment, genetics, and biological needs of animals. The results of studies by H. Atashi *et al.* (2021) showed that the age of insemination of heifers affects the stability of lactation in first-calf heifers. They found a higher rise in the lactation curve and its subsequent rapid decline after reaching peak productivity in animals that calved for the first time at an older age. The study showed that heifers inseminated at an early age after calving were characterised by a lower but more stable lactation curve. A.S. Kramarenko *et al.* (2022) argued that the productivity of dairy cattle depends on a number of different factors, including genotypic and paratypic ones, but at the same time, feeding remains the most important among them, as it determines the success of any livestock industry, as evidenced by a comprehensive assessment of the characteristics of intensive milk production technology.

In a study by A. Kitaieva *et al.* (2024), cows were fed a single feed according to a developed diet, which included corn silage, alfalfa haylage, alfalfa hay, molasses, compound feed (corn, wheat, brewers' spent grains, sunflower oilcake, soybean oilcake), salt, chalk, premix for dairy cows, sodium bicarbonate, and monocalcium phosphate. For better consumption of the monofeed, 7.0 l of water per head was added to the feed mill. In both studies, Holstein cows showed high productivity when fed a complete diet. The average daily milk yield for the group of cows in the first 100 days of lactation was 32.1 kg, which is 7.0% higher than the planned yield, and in this study, it was over 35 kg. According to D. Mundan *et al.* (2020), the daily milk yield in Holstein cows ranged from 26.2 to 27.4 kg, and these figures were lower than the results of the current study of the daily milk yield of cows in the experimental group by 23.7-27.0% and in the control group by 26.2-23.2%. M. Gaworski & P. Kic (2024) evaluated production technologies on dairy farms in terms of animal comfort and

welfare, which is ensured by free access to feed and reduced competition between animals in the resting area. In uninsulated high-capacity barns with natural ventilation, the comfort of dairy cattle is achieved through air movement using fans, spraying the cows' bodies, and high-pressure mist (evaporation) to cool the surrounding air, which also minimises the effect of solar radiation. D. Sreekumar & V. Sejian (2024) emphasised the importance of cow comfort, which includes the environment, in particular ventilation temperature, continuous access to feed and drinking water, and well-organised rest with sufficient lying space. Both studies emphasised the creation of comfortable conditions and the maintenance of animal welfare through the maintenance of an optimal microclimate, the avoidance of heat stress, and, most importantly, not only free and constant access to feed, but also its freshness and availability. The authors also note that high-volume premises should be used for dairy cattle housing.

C. Kipp *et al.* (2021) and R. Bleizgys *et al.* (2023) noted that one of the most important conditions for keeping cows is ensuring the necessary microclimate parameters in the barn. At the same time, an increase in temperature and humidity in the room can cause heat stress, which negatively affects the physiological state and productivity and even worsens the quality of milk produced. Similar conclusions were made in studies by A. Shevchenko & O. Petrenko (2020) and C.B. Tucker *et al.* (2021), who pointed out that it is impossible to achieve maximum productivity without creating conditions that comply with hygiene and veterinary and sanitary standards. Unfavorable conditions, such as poor ventilation, insufficient air exchange, heat, and rain, deteriorate the air and cause microbial contamination, while increased temperature and humidity worsen the microclimate. According to K.D.M. Frigeri *et al.* (2023), dairy cattle barns should be monitored for thermal conditions to reduce the harmful effects of heat stress, which will help increase milk production, improve milk quality, ensure herd health, and improve cow comfort. As noted, heat stress leads to sudden changes in the health and productivity of dairy cows. Studies have shown that in a barn with an artificially controlled microclimate, air circulation creates an optimal microclimate with the desired temperature, reduces gas accumulation in the room, and cools the animals in the rest area during the summer. The comfort of the technological environment contributes to the well-being of dairy cattle and high milk productivity. Thus, the technology of keeping dairy cattle in a mega-barn maximally meets the biological needs of milking cows, minimises heat stress, and contributes to the realisation of the genetic potential of high productivity of the Holstein breed.

CONCLUSIONS

Studies have shown that loose housing of Holstein cows in a mega-barn with an artificially controlled microclimate provides the most comfortable technological environment and contributes to maintaining their welfare. It was determined that in terms of the composition of different types of feed, the general mixed diet was similar and satisfied the biological needs of highly productive cows in the first half of lactation, based on dry matter consumption per head of 28.2 kg (experimental group) and 27.3 kg (control group), taking into account their productivity, lactation period, and body condition. It has been proven that with a similar feed background but different comfort levels, in particular in a mega-barn with an artificially controlled microclimate, the individual genetic predisposition of Holstein cows to high productivity manifests itself. In a pavilion-type barn with natural ventilation, such an ability to develop productive traits in animals has not been established. The average milk yield per 100 days of lactation in cows of the experimental group was 103.3 kg ($p < 0.001$) or 3.5% higher than in animals of the control group.

A comparative assessment of lactation stress in the first half of lactation in groups classified by milk yield, reproduction cycle duration, and combined traits determined the comfort of keeping cows in a mega-barn and the feasibility of feeding Holstein cows a mixed diet from feeder trays. In the experimental group, animals

with shortened, average, and prolonged intercalving periods had milk yields per 100 days that were 94.0 kg ($p < 0.001$) 115.6 kg ($p < 0.001$) and 93.4 kg ($p < 0.001$) higher than in their peers of similar distribution in the control group. A study of lactation intensity in cows distributed according to combined characteristics found that the experimental first-calf heifers in groups 1-1 and 1-2 differed in higher milk yield per 100 days of lactation, a longer period before reaching peak lactation, and milk yield on the peak day of lactation compared to their peers of similar distribution in the control group. The difference was 33.6 kg; 1.9 days; 1.1 kg and 102.9 kg ($p < 0.001$); 6.9 days ($p < 0.001$); 1.7 kg ($p < 0.05$), respectively. Prospects for further research include expanding the list of economically useful traits and studying their manifestation in Holstein cows during three lactations under mega-barn conditions.

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Технологічне середовище і годівля дійних корів за умов утримання в крос-корівнику

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Анотація. Молочне тваринництво є однією з найважливіших галузей тваринництва, оскільки забезпечує населення необхідними продуктами харчування та сировиною для підприємств з переробки молока. Дослідження мало на меті вивчити, як умови утримання та годівлі повними мономіксами впливають на рівень молочної продуктивності первісток голштинської породи в перший період лактації. Тварини експериментальної групи утримувалися в крос-корівнику з контрольованим мікрокліматом, а тварини контрольної групи – в корівнику павільйонного типу з природною вентиляцією. Було проаналізовано інтенсивність лактації в першій половині, і встановлено, що у корів експериментальної групи надої за 100 днів і в піковий день лактації були відповідно на 103,3 кг ($p < 0,001$) і 1,1 кг ($p < 0,05$) вищими, ніж у тварин контрольної групи. Аналіз показав, що корови в експериментальній групі з високою продуктивністю (>9643 кг) мали довший період досягнення піку лактації. Цей показник перевищував тривалість аналогічного періоду у корів з груп з продуктивністю « <8423 » та « $8424-9642$ » відповідно на 20,3 ($p < 0,001$) та 5,9 ($p < 0,001$) днів. Крім того, в експериментальній групі корови зі скороченим, середнім і подовженим репродуктивним циклом мали вищу молочну продуктивність протягом перших 100 днів лактації – на 94,0 кг ($p < 0,001$), 115,6 кг ($p < 0,001$) та 93,4 кг ($p < 0,001$) відповідно, порівняно з їхніми однолітками в контрольній групі з подібним розподілом тривалості циклу. Підсумок результатів за комбінованими показниками показав, що тварини в експериментальній групі продемонстрували кращі виробничі та фізіологічні характеристики порівняно з контрольною групою. Таким чином, утримання корів голштинської породи в крос-корівнику забезпечує комфортні технологічні умови, що відповідають біологічним потребам у першій половині лактації, мінімізують тепловий стрес і сприяють реалізації генетичного потенціалу високої продуктивності. Матеріал актуальний для тваринників і технологів у галузі виробництва молока на промислових комплексах

Ключові слова: голштинська порода; утримання корів; лактація; молочна продуктивність; репродуктивна здатність

Assessing the efficiency of water reuse at Khorostkiv sugar factory

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Abstract. The Ukrainian sugar industry applies large amounts of water for production needs but is not sufficiently focused on the optimal use of water resources. The aim of this study was to evaluate the effectiveness of reusing condensate and cooling water to optimise water resource use and reduce the volume of water intake from surface water bodies. Based on the data from official reports of the Khorostkiv Sugar Factory in 2017-2024 years an analysis of the water use changes after improvement of the circulating-water system was conducted. In particular, a statistical method was used to calculate changes in water intake and the water recycling coefficient, as well as to conduct an environmental and economic assessment. It has been found that the total water intake since 2019 has decreased by approximately 8.1-21.3 times (2019-2024) compared to the value calculated for 2017. It has been shown that the water use process has been optimised through the functioning of a modern recycling system with the effective use of condensate and cooling water. It was emphasised that such optimisation led to the termination of discharge of heat-exchange wastewater into surface water bodies. It was estimated that the economic effect of reusing cooling and condensate water only for a rental fee led to a reduction in the company's annual financial costs of approximately 350-400 thousand hryvnias. The practice of reusing cooling water and condensate water can be recommended for use at other Ukrainian sugar enterprises

Keywords: hydric resources; sugar industry; effluents; water optimisation; condensate; cooling water

INTRODUCTION

The sugar industry is a water-intensive sectors of the economy, using large amounts of water resources for various stages of production and producing significant volumes of wastewater of various categories. The latter can be successfully reused, but it is necessary to treat such water and control its quality. Category I water – condensate and heat exchange water – does not undergo significant changes in chemical parameters but

is characterised by higher temperatures and requires cooling for further return to the water cycle.

Previous studies have shown that the discharge of untreated or inadequately treated wastewater causes changes aquatic ecosystems. For example, researchers M.A. Rahim & M.G. Mostafa (2021) published the results of a two-year monitoring of samples of wastewater, surface and underground water. A significant decrease

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in dissolved oxygen content and a steady increase in BOD₅ levels in water were detected, which led to a deterioration in the existence of aquatic organisms in the studied water bodies. In particular, according to the survey data, there was a decrease in the numbers of fish in surface water bodies in the range of 50-95%. Elevated concentrations of metals (Fe³⁺, Mn²⁺ and Pb²⁺) were found in soil samples, which may lead to bioaccumulation of these elements in plants. Even the discharge of treated wastewater requires monitoring of the content of various components in it. Given the need to treat wastewater from sugar factories, a large number of review and experimental studies have been devoted to this issue. The latest achievements in the use of physical, chemical, and biological methods to eliminate or minimise pollutants generated at various stages of sugar production were presented, in particular, in K.B. Shivaram *et al.* (2024). It was noted that, along with traditional physical, chemical, and biological methods (adsorption, chemical and electrocoagulation, anaerobic and/or aerobic biological treatment, membrane treatment, etc.), the implementation of new promising methods was being investigated.

J. Malinauskaite *et al.* (2024) described the practices for treated wastewaters of different origin and the possibilities for its further application. The researcher indicated that primary treatment is provided for wastewater after washing sugar beets. Effective sedimentation of such loaded wastewater is achieved by their mechanical treatment in settling tanks. The possibility of using wastewater from the sugar industry, obtained after primary treatment, for irrigation of agricultural land and partial overcoming of water shortages in European countries was investigated. J. Hristov *et al.* (2021) noted that sugar beets are agricultural crops that are mainly grown using irrigated farming methods. Accordingly, the use of re-treated water is considered an economically appropriate approach. The most difficult to treat is wastewater from the direct processing of raw materials, as it is saturated with large amounts of organic and inorganic substances. The use of membrane technologies allows for more thorough treatment of wastewater, which can then be reused. The possibility of using such water for irrigation, as well as for reuse in a closed-loop water supply system, was being considered by A.W. Nouhou Moussa *et al.* (2023). The reuse of treated water to overcome water shortages in various sectors of the economy is regulated by various legislative initiatives, including the European Union (2019). These documents are primarily aimed at addressing issues related to the optimisation of water resources, which are rapidly declining due to global climatic changes. The study presented by European Environmental Agency (2018)

demonstrated increasing water shortage in European countries. K. Hryhorieva (2024) analysed the wastewater treatment process in terms of its benefits to society and noted the steps taken in some countries to regulate the reuse of treated wastewater. It should be mentioned that this publication focuses on the use of such water for irrigation as one of the alternatives to overcoming water shortages due to climate change.

It should be noted that Ukrainian researchers mainly assessed the pollution of wastewater from sugar factories and studied methods for its treatment. Thus, N.O. Bubliko (2021) presented a classification of wastewater from the sugar industry into three categories and analysed the use of wastewater of category III for biomethane production. It was noted that wastewater of this category is the most difficult to treat. Methane fermentation was proposed as a highly effective method of treating highly concentrated wastewater, during which large volumes of biogas are produced that can be used as a renewable energy source. The author analysed in detail the use of inactivated anaerobic activated sludge to start fermentation processes and noted that this reduces the start-up time of the methane tank. In this publication, the researcher did not detail the possibilities of using category I and II wastewater, although the researchers emphasised the need to optimise the use of water resources, which are used in huge volumes in the operation of a sugar factory. A. Rohovyk *et al.* (2021) provided a detailed diagram of the formation of different wastewater categories at sugar enterprises and noted that, in terms of percentage distribution, the largest amount of wastewater fell into the categories II and I. The main focus of this study was on improving wastewater treatment systems at sugar production facilities using developed control systems, where the key component was the use of a chemical oxygen consumption monitor.

O. Salavor *et al.* (2024) emphasised that the volumes of water required for the operation of a sugar factory are enormous, and the wastewater produced varies in terms of treatment and reuse. In their work, the authors focused on the treatment of category II wastewaters, which are identified as transporter and washing waters. The scientists developed a method for purifying these waters using basic aluminium salts. It was noted that this physicochemical purification method improved the quality of category II wastewater, which can be reused in recirculation systems. It was noted that this improvement led to a reduction in water consumption and a positive impact on the hydrosphere as a whole, but the optimisation of water resource use through category I wastewater was not considered. The aim of the study was to determine the economic and environmental

benefits of improving water use processes at sugar industry enterprises in Ukraine, in particular using the example of a specific sugar factory, given the lack of data on the reuse of Category I wastewater and analysis of the effectiveness of such measures.

MATERIALS AND METHODS

The object of the study was the water use at the Khorostkiv sugar factory. This enterprise is a structural subdivision of the Radehiv Sugar LLC which is part of the

German group of companies Pfeifer & Langen. It was the first factory among the group's six to introduce a modernised water use system. For production needs, water intake is mainly carried out from surface water bodies (the Taina River in the Dniester basin, located in Ternopil Region). Small amounts of water for utility purposes and certain technological processes are taken from the artesian well located in the territory of the sugar factory. The approximate distribution of water supply during the operation of the sugar factory is shown in Table 1.

Table 1. Approximate water use structure at the Khorostkiv sugar factory

Category	Type of source	Share of the total, %*
Production needs (transportation and washing of sugar beet, diffusion, filtration, evaporation, etc.)	Water intake from Taina River + underground water	~93.7
Service-utility needs (drinking water, showers, dining room, laboratories)	Underground water	~6.3

Note: * as a percentage of the total volume of water intake from natural sources

Source: compiled by the authors based on data from official reports provided by the Khorostkiv Sugar Factory

Information on the total volume of water used during the year, obtained from various water intake sources (groundwater and surface water), was taken from the official reports prepared by of the Khorostkiv Sugar Factory. The sources were compiled in accordance with the Procedure for State Accounting of Water Use (Order of the Ministry of Ecology and Natural Resources of Ukraine No. 78, 2015), and the data was entered into official forms entitled Form No. ZTP-vodgosp (annual) (State accounting of water use, 2015). These reports are submitted annually to the territorial divisions of the State Water Agency and are stored as internal documents (not available for public access) at the enterprise responsible for completing the forms. In addition, data on annual water limits from both water sources were also provided. Data from the explanatory note on maximum permissible discharges for the Khorostkiv sugar factory was used, as well as materials from the technical and economic substantiation of the reconstruction of the vacuum condenser unit at this enterprise. All the information provided corresponds to the actual state of water management activities at the Khorostkiv sugar factory during 2017-2024 and was confirmed by documentary evidence.

The main equipment involved in returning used water to the water management system includes two cooling ponds located on the sugar factory territory, a cooling tower, and a vacuum condenser unit. The latter was reconstructed, in particular, new efficient water distributors were installed on condensers, automatic water supply and non-condensed gas bypass lines were introduced in condensers. These measures made it possible to increase the efficiency of heat exchange in condensers,

reduce the amount of circulating water for condensers, and adjust the temperature of circulating water to the temperature of vapor. All calculations were performed using appropriate formulas and statistical method of comparative analysis – the method of relative values (coefficients), which is implemented in the Microsoft Office package using the Microsoft Excel spreadsheet program. The statistical method used is a classic example of relative dynamics, in which the ratio of two water intake values is calculated: the base value (maximum, 2017) and the current value (after modernisation of the recycling system with efficient use of condensate and cooling water). Thus, the comparative coefficient of water use by year (k_{comp}) was calculated using the formula:

$$k_{comp} = V_{max} / V_{year}, \quad (1)$$

where k_{comp} – comparative coefficient of water use by year; V_{max} – volume of maximal water intake; V_{year} – volume of water intake in appropriate year.

The economic effect was assessed by calculating the rental pay for each production season. The formula for calculating the rental pay (RP) for special water use is as follows:

$$RP = V_o \cdot V_f \cdot R \cdot k_c, \quad (2)$$

where V_f – actual volume of water used, m^3 ; V_o – volume of water for which the rate is set ($100 m^3$); R – rent rate for V_o ; k_c – correlation coefficient (Law of Ukraine No. 3817-IX, 2024).

The water use balance of a sugar industry enterprise can be represented in the following general form:

$$V_{pr} + V_s = V_{swb} + V_{aw} + V_{sb} + V_r - V_l, \quad (3)$$

where V_{pr} – the volume of water for production use; V_s – the volume of water for service-utility use; V_{swb} – the volume of water intake from a surface water body; V_{aw} – the volume of water intake from an underground source (artesian well); V_{sb} – the volume of water released from sugar beet; V_r – the volume of water that was reused; V_l – the volume of water losses (evaporation, leakage, etc.).

RESULTS

Water use at the Khorostkiv sugar factory can be divided into several main categories: production (technological needs for water directly involved in the sugar production process), utility purposes (drinking water, sanitary and hygiene needs of the personnel), cooling needs (feeding there cycling cooling water system), losses (water that leaves the cycle due to evaporation or leaks), and reuse (water that circulates and is reused). Until 2018, water supply to the Khorostkiv sugar factory had been carried out using a classic open system with partial reuse. The pumping station was intaking huge volumes of water from the Taina River. Various stages of the technological process led to the formation of wastewater of varying composition, for which the enterprise has implemented a separate discharge system. The treatment and further management of wastewater is determined by the technological process that produced such water. Water circulating through the heat exchange equipment of sugar factories (evaporator condensers, diffusion juice coolers, heat exchangers of thermal power plants, etc) was characterised by an actual change in temperature range, since the water does not come into direct contact with products or reagents but rather removes excess heat from heated equipment. In terms of chemical composition, it is close to the original

river water, and some of its parameters only slightly exceed natural background and sanitary standards.

However, discharging water heated by heat exchangers into water bodies leads to a decrease in the concentration of dissolved oxygen, which affects the state of aquatic ecosystems. In previous years (until 2018), heated water from the Khorostkiv sugar factory was discharged into the Taina River, and industrial wastewater of categories II and III was diverted to filtration fields. Thus, most of the water, after passing through the technological process, did not return to the enterprise. Small volumes of water after cooling down the equipment could be directed to washing sugar beets. To meet the constant demand for water, the pumps operated almost 24 hours a day throughout the season (120 days a year). The pumping equipment was designed for huge volumes: the installed units delivered hundreds of cubic meters per hour. Approximately, prior to modernisation, the total water intake was ~0.5-1.5million m³ per season. In 2018, the modernisation of the water supply system began: two artificial reservoirs connected by a pipeline were built in the territory of the factory. The construction of the ponds took five months, and the reservoirs were put into operation at the end of 2018. Heated water from heat exchangers flows into the artificial reservoirs, where it cools down, and then is pumped back to the heat exchange equipment. This cycle repeats without any external discharges. Due to evaporation, some of the water is lost, so fresh water from the river was constantly added to the ponds to maintain the level. Replenishment was carried out within the established limit, which is approximately 314.4 thousand m³/year from the Taina River and 16.9 thousand m³/year from the well (special water use permit No. Ek-000000037). The actual replenishment was significantly lower than these limits (Table 2).

Table 2. The volumes of water intake at the Khorostkiv sugar factory in 2017-2024

Year	Water intake from Taina River, thousand m ³ /year	Water intake from underground source, thousand m ³ /year	Total for the year, thousand m ³ /year	k_{comp}
2017	~1,200	~17	~1,217	-
2018	~850	~16	~866	1.4
2019	64.7	13.3	78.0	15.2
2020	41.5	14.0	55.5	21.3
2021	63.1	14.7	77.8	15.2
2022	129.5	17.1	146.6	8.1
2023	99.2	15.3	114.5	10.3
2024	55.5	7.6	63.1	18.8

Note: k_{comp} – comparative coefficient of water use by year

Source: compiled by the authors based on data from official reports provided by the Khorostkiv Sugar Factory

Due to the lower need for fresh water supply, it was possible to modernise the pumping equipment, which

was converted to a flexible operating mode: modern pumps of lower capacity are automatically switched on

as needed, maintaining the water level in the ponds. Previously, the pumps operated for about 2,880 hours per season (120 days of 24 hours), but after modernisation they operated for only a part of this time (for example, in 2020, the total operating time of the pumps was approximately 600 hours, which is ~79% less than previously), the rest of the time the system operated on recirculation. Water intake volume has also decreased: from several hundreds of m³/hour to several dozens of m³/hour, since fresh water intake is only necessary to compensate for losses due to evaporation and certain technological deviations. In addition to the closed cooling system, the factory has implemented the use of water for other needs as well. For example, purified condensate water from the evaporation station is used to prepare diffusion juice; warm water can be partially used for washing beets, etc. All these activities minimise the need for fresh water. The main water losses from the system are evaporation (from the surface of

cooling ponds and cooling towers of thermal power plants) and moisture removed with products and waste (pressed pulp, molasses, water, etc.). These losses are compensated by the fresh water from both water sources. As a result, the balance is closed: the intake water either circulates repeatedly or eventually returns to the environment in the form of vapor or recycled waste, but is not discharged as wastewater into the river. Due to the implementation of a closed cycle of the use of water heated by heat exchangers, there is no discharge into the river, and it only occurs in exceptional situations when there is a need for discharge of excessive water from the ponds due to heavy rains or when cleaning the reservoirs, but this was not observed in 2022-2024. Figure 1 shows the dynamics of surface and groundwater intake in 2017-2024, which indicates a sharp decline in water intake since 2018, following the introduction of reuse of a significant portion of water resources that were previously used for the needs of the enterprise.

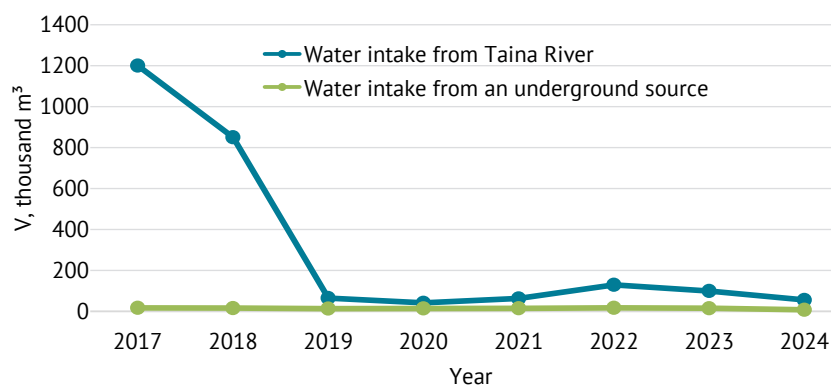


Figure 1. Dynamics of surface and underground water intake by the Khorostkiv Sugar Factory in the period 2015-2024
Source: compiled by the authors based on data from official reports provided by the Khorostkiv Sugar Factory

Fluctuations in water consumption during the period 2019-2024 were attributed to changes in the volume of sugar beet processing. Thus, in the period from 2020 to 2021, minimal water intake was observed due to a decrease in the raw material base and the Covid-19 pandemic. Starting in 2022, increased production volumes led to higher water consumption, but the level of water intake remained significantly lower than in 2018. These results were achieved at the Khorostkiv sugar factory due to the installation of the circulating water supply systems. It should be noted that certain volumes of water involved in technological processing are covered by the large moisture content in the raw material itself. Sugar beets are an extremely moist material: approximately 75-80% of their mass consists of water (Muir, 2022). That is, each ton of root crops contains an average of 0.7-0.8 m³ of water, which is released during processing. At the factory, this internal moisture plays a

significant role in the water balance, actually becoming the source of technological water.

The remaining water is distributed between products and waste: it remains in molasses, pulp and condensates. According to regulatory data of the Khorostkiv sugar factory, processing 1,000 tonnes of beet per day yields approximately 700 m³ of internal water. This is approximately 84,000 m³ of moisture entering the system together with raw materials during the 120 days of the production season. In fact, the internal water of beets replaces the fresh water that would otherwise have to be taken from the river. The high moisture content of the raw material has a positive effect on the water balance. The factory can maintain an almost continuous water cycle with minimal external replenishment. The water that evaporates from the diffusion juice is condensed and reused – it is used to extract sugar again or to heat the diffusion device. The moisture from the beets also

reduces the need for fresh water for washing: the roots arrive at the wash already wet, and part of the water after washing is returned to the fields along with the soil residues. As a result, almost all of the internal water of the sugar beets that evaporates is further condensed and returned to the closed cycle, or is pressed out of the solid waste. The remaining water needs were covered by

the internal moisture of the raw materials and recycled water. Due to the modernisation, the annual volume of saved water was very significant, which indicates a positive environmental and economic effect. In monetary terms, the saving was also noticeable. As an example, the rental pay of water was calculated and the financial savings were evaluated considering this value (Table 3).

Table 3. Calculation of rent payments at the Khorostkiv sugar factory

Year	Rent rate, in hryvnias	Number of volume units (100 m ³)	Rental pay in hryvnias	Cost savings compared to 2017 in hryvnias
2017	35.66	12,000	427,920.0	0
2018	38.47	8,500	326,995.0	100,925.0
2019	39.47	647	25,537.09	402,382.9
2020	39.9	415	16,558.5	411,361.5
2021	39.9	631	25,176.9	402,743.1
2022	39.9	1,295	51,670.5	376,249.5
2023	39.9	992	39,580.8	388,339.2
2024	39.9	555	22,144.5	405,775.5
Cost savings from 2018 to 2024				2,487,777.7

Source: compiled by the authors based on data from official reports provided by the Khorostkiv Sugar Factory and values of rent rate from 2017 to 2024 based on Law of Ukraine No. 3817-IX (2024)

In addition, less water intake means less pumping and potential treatment costs, which gives an additional financial benefit. After transition to a recirculating system, the operating time of the pumps was reduced several times, and their capacity was reduced. At the same time, reducing the load on the equipment extends its service life and reduces repair costs. Saving electricity on pumps has an impact on reducing CO₂ emissions at the power plant. The saved ~300 thousand kWh is equivalent to ~150 tons of CO₂ (at a rate of ~0.5 kg CO₂ per 1 kWh), which were not emitted as a greenhouse gas into the atmosphere, and that has a positive impact on the company's contribution to the implementation of decarbonisation measures and is consistent with the practice of achieving a reduction in greenhouse gas emissions produced during wastewater treatment (European Commission, 2022). This contribution can be enhanced by equipping a biogas plant for waste, which would allow the waste recycling (pulp, molasses) to produce biogas for the enterprise's own boiler house, as well as to return part of the water. The operation of an anaerobic reactor leads to the production of biogas and the accumulation of fermentation products. The latter can be separated into a solid fraction, which is subsequently used as organic fertiliser, and a liquid fraction, which after minimal purification can be returned for the enterprise's needs. Thus, the factory will receive an additional source of energy and further close its water cycle reducing the moisture content of the waste.

Optimising the use of water resources at the Khorostkiv sugar factory not only resulted in significant cost

saving for the enterprise, but also had a positive effect on the environment. The absence of discharges into the Taina River since 2022 has eliminated problems that previously arose when warm heat-exchange waters entered the river, which led to a decrease in dissolved oxygen content, siltation of the riverbed, etc. Currently, these impacts are absent – the river actually receives only natural runoff from the territory (rain and drainage water), but not industrial discharges. The absence of large intakes and discharges not only improved the quality of the river water, but also led to the stabilisation of the river's hydrological regime. Previously, the intake of 1-2 million m³ of water per season could significantly reduce the level of the Taina River during low water in the middle of summer. Now, the intake of ≤0.15 million m³ has almost no effect on the river level, that is, the Taina River retains more natural inflow, which is important for fish, especially in the summer low-water period. In addition, eliminating heat stress helps to preserve fish populations, as previously, excessively warm water sharply reduced the concentration of dissolved oxygen and could cause fish mortality.

Having achieved significant success in water saving, the enterprise is developing a number of promising measures that can increase the efficiency of water use and the environmental friendliness of production. These include the expansion of cooling ponds or the construction of an additional pool, provided that production capacity is increased, or to meet the needs in case of abnormally warm seasons with higher evaporation. This will increase cooling capacity and provide a

water reserve. It is also advisable to carry out dredging and sealing of the existing reservoirs (for example, lining the bottom with a geomembrane to reduce filtration into the soil) and equipping them with aeration fountains for better cooling. Modernisation of the pumping equipment (installation of frequency drives) allows for more precise regulation of the fresh water supply and a reduction in energy consumption. Other measures include the use of rainwater, as such water currently flows from roofing and asphalt surfaces into the river or onto filtration fields. A promising solution is to arrange a rainwater collection system by installing gutters on roofs, drainage of yard runoff, and using a storage tank. The collected rainwater after settling can be used for non-potable purposes, for example, for washing beets, moistening pulp, and watering green spaces in the territory. This will reduce water intake from the river and lead to efficient use of natural precipitation.

The study found a significant reduction in water intake from surface and underground sources following the modernisation of the water supply system in 2018 and the introduction of a closed-loop water cycle at the Khorostkiv Sugar Factory. The creation of two artificial reservoirs has enabled a closed loop for cooling water from heat exchangers. The water is cooled in ponds and returned to production, eliminating the need for constant fresh water intake and stopping the discharge of heat exchange wastewater into the Taina River. Purified condensate water from the evaporation station is used for the preparation of diffusion juice and other technological needs. In addition, the internal moisture of sugar beets plays a significant role, condensing and returning to a closed cycle, minimising the need for external replenishment. The reduction in water intake, in particular savings on water rental fees and reduced pump operating time, had resulted in significant financial savings. Modernisation and investment in improving the water recirculation system not only proved to be economically beneficial for the enterprise, but also had a direct social and environmental benefits for the entire local community. On the one hand, a significant reduction in water abstraction ensured a more stable water level in the Tayna River, and the absence of direct discharges contributed to the preservation of the stability of the aquatic ecosystem. On the other hand, it is worth noting the positive social effect, as reduced water consumption means that more water remains for other consumers – the local water supply company, farmers and local residents.

DISCUSSION

The problem of rational use of water resources, considering the water shortage caused by climate change,

according to S. Snizhko *et al.* (2024), remains relevant for various sectors of the Ukrainian economy, in particular the sugar industry. The authors analysed how other factors, such as war, occupation of part of Ukraine's territory, and the destruction of the Kakhovka a reservoir, affected the supply of water for different needs, including water resources used for irrigation of agricultural land. The destruction of a significant number of water infrastructure facilities not only created a threatening environmental situation but also affected food security in Ukraine and worldwide. L. Parkhomenko (2024) pointed out in her work that the Ukrainian sugar industry has undergone significant changes during 2019-2022 years due to a reduction in the area under sugar beet cultivation, a decrease in the number of sugar factories, and a drop in production volumes. The author analysed that in 2023-2024 years, despite the challenges caused by military actions in the territory of Ukraine, it has been possible to significantly increase the rate of raw sugar production and increase the volume of its exports to the world market. In 2023-2024, Radekhiv Sugar LLC was the largest sugar producer in Ukraine, so modernising production, including optimising water use, is an important condition for the company's successful development.

Sh.V. Wadodkar *et al.* (2020) noted that one of the water management problems of the sugar industry is the consumption of large volumes of water and the generation of large amounts of wastewater. Statistical data presented in the United Nations Environment Programme (2023) indicated that a significant proportion of untreated wastewater (more than 50%) in the world in was returned to water bodies, while only approximately 11% was recycled. It should be noted that for European countries this value was even lower (Interreg North-West Europe, 2020). Modern world practices are oriented towards such water resource management at sugar industry enterprises, in which the optimal use of water taken from external sources involves maximum purification of the generated wastewater with its subsequent return to production processes. Researchers S. Fida *et al.* (2025) noted that the implementation of new promising methods is being investigated. This paper analysed the possibilities of optimising the use of water resources at the Khorostiv sugar factory (Ukraine). As a result of the analysis, it was found that the main volume of water consumed at this enterprise is for production needs – more than 80%, therefore, optimisation measures were focused on the development of measures for such water. The efficiency of returning cooling heat-exchange water to production processes, reducing the consumption of fresh water during water intake were assessed, and approaches to the possibility of implementing a closed water use cycle were considered.

Similar practices are already being used at sugar factories around the world. For example, the article by P. Ranjan *et al.* (2023) analysed water reuse at sugar factories in India, where the raw material for processing was sugarcane. The possibilities of using heat exchange and condensate water, which is necessary to ensure the operation of sugar refinery equipment, were analysed. It was noted that water reuse has made it possible to reduce the need for water from underground sources and partially cover the need for irrigation water for watering nearby fields. Similar technologies were described in the article by G.K. Deshmukh & N.P. Sonaje (2017), where the specific case of a sugar factory emphasised the importance of using condensate water, which was generated as a result of cooling the turbine cooling towers. In particular, the volumes required to ensure both direct sugar production and for auxiliary operations, which include water for boiler operation, washing, and cooling of equipment, were analysed. The use of condensate water and its recirculation were described in detail, and the results of a water balance study were presented. The results of the latter indicated the elimination of the need for constant replenishment of fresh water for certain technological operations. The modernisation measures carried out at the Khorostkiv sugar factory, including the commissioning of settling ponds and the operation of a cooling tower and vacuum condenser unit, have resulted in the reduction in water intake since 2018. Since 2019, significant volumes of water have been used in a virtually closed cycle, due to which only a minor replenishment of fresh water from an external source was required to compensate for losses. As a result, in 2019, for the first time, there were no direct discharges of wastewater into the river.

The transition to a virtually continuous water supply closed-loop recirculation system can be achieved using different systems. Thus, W.H. Balla *et al.* (2017) pointed out the advantages of using an open recirculating cooling system compared to one-time cooling. Such cooling can be achieved using cooling towers, spray ponds, and evaporative condensers. Two cooling ponds have been put into operation at the Khorostkiv sugar factory, the main function of which is to provide recirculation cooling of technological equipment. The ponds act as open cooling towers (coolers), into which water heated during the production process is directed, where it is cooled and fed back into the technological cycle. Since the cooling water is not contaminated with production impurities, after cooling it can be re-used for technological needs without additional purification. It should be noted that in cooling ponds, a process of natural self-purification of water occurs: mechanical impurities settle to the bottom, organic pollutants are

partially oxidised biologically. Thus, even with long-term circulation, the water quality remains acceptable for reuse. Cooling ponds have become a key element of the water supply cycle, which has made it possible to abandon the constant discharge of coolant into the river and thereby improve its ecological state. Due to the commissioning of two artificial cooling ponds, it was possible to loop the heat exchange flows, so the pumping station for intaking river water began to be used much less frequently – only to replenish losses.

Saving water resources is achieved by various methods, including the use of water condensed from raw materials in technological processes. Thus, this practice of using moisture from sugarcane was presented in the article by P. Ranjan *et al.* (2023). At the Khorostkiv sugar factory, where sugar beet was processed and which had a higher moisture content than sugar cane, the water released from the raw material was recovered and fully returned to the system through condensates and recycles. Due to this, the need for external water was significantly lower than it would be without taking into account the moisture of the sugar beets. The technological process of processing raw materials can be optimised, in terms of reducing evaporation by modernising the evaporation station. Evaporation of juices is one of the key stages where significant flows of water vapor circulate. A promising direction is the introduction of thermocompression vapor technology (TVR/MVR), when the secondary vapor from the evaporators is compressed by a compressor and reused to heat the next body of the evaporation unit. This reduces the need for fresh vapor and, accordingly, reduces the load on the condensers and the cooling system. Thus, reducing the volume of vapor will lead to reduced heat input into the water and, accordingly, less evaporation from the ponds. This technology requires investment in vapor compressors, but in the long term it will have an impact on saving water and energy resources. Therefore, at the Khorostkiv sugar factory it is necessary to take into account such recommendations as maintaining the proper condition of the existing facilities, in particular, regular cleaning of cooling ponds from excess sediment, monitoring the tightness of dams, and calibrating measuring instruments. It is important to implement new measures that help save the water usage, in particular, to establish a full-fledged online monitoring system for water supply and drainage, which will allow real-time monitoring of all parameters (in particular, water consumption at each site, water levels in tanks, pressure, temperature, quality indicators). Based on this data, automatic control of pumps and valves will be carried out, and the operation modes of the equipment will be optimised. In this way, the supply of make-up water from the river will be

switched on in a timely manner, based on the weather forecast. Automation eliminates the influence of the subjective human factor regarding possible overruns or negligence, and also promptly signals about leaks (sudden drop in water level), the need to clean filters, etc.

Improving water use efficiency will also be facilitated by conducting a water balance analysis using the water pinch-analysis technique to identify even minor points of loss. This technique is widely tested at foreign enterprises of food industry. For example, K. Nemati-Amirkolaii *et al.* (2019) analysed the features of applying water pinch analysis as a technology aimed at reducing water consumption and water discharge in the food industry, particularly in the sugar industry. It has been shown that the key point of the methodology is the identification of water flows that can be reused in other processes with lower quality requirements. The authors noted that this method should be more actively implemented to save water resources in industries that are water-intensive and energy-consuming. J.R. Vidal *et al.* (2024) noted that the use of pinch-analysis at sugar factories not only contributed to water conservation, but also had a positive impact on the energy efficiency of such enterprises. The authors analysed that specialised software made it possible to control energy flows in sugar production, which reduced cold and hot water consumption and optimised the operation of heat exchange systems. The energy efficiency of sugar factories can be ensured through biogas obtained from raw material residues and highly concentrated wastewater. The article presented by M. Dębowski & M. Zieliński (2022) described the successful implementation of such practices around the world. The authors analysed modern technologies for managing wastewater with a high concentration of organic pollutants, including an analysis of their potential use for biogas production as an alternative energy source. The proposed innovative method using fluidised active filling increased the efficiency of the anaerobic bioreactor in treating sugar industry wastewater and improved the quality of the biogas obtained due to its high methane concentration.

It is also worth emphasizing that the introduction of a water recycling system allows the enterprise to avoid penalties from regulatory authorities. Previously, fines and claims for damages could be imposed for exceeding limits or polluting a water body. Now there are no such risks, which saves money and reduces the negative impact on the environment. Rational water use has increased the environmental reputation of the enterprise, which indirectly contributes to investment attractiveness and trust of partners. In addition, improving environmental performance can provide preferences when obtaining environmental certifications, it also increases

the chances of receiving international and Ukrainian grants. The Khorostkiv sugar factory is an example of the successful implementation of certain practices for the maximum use of water resources and the successful reduction of their intake from external sources. An analysis of the volume of intake/used water at this enterprise indicates the effectiveness of the reuse of water involved in production cycles, this also indicates the prospects for the implementation of recycled water use, which can be applied at other Ukrainian sugar factories. Effective water resource management and organisation of a closed water-use cycle is a promising direction that the Ukrainian sugar industry should focus on in order to be resource-saving, energy-efficient, and environmentally friendly, that is, to function and develop in accordance with the principles of sustainable development.

CONCLUSIONS

The analysis of data obtained during the 2017-2024 period included information on the volumes of water intake from surface and underground sources, which was carried out at the Khorostkiv sugar factory; also highlighted was the impact of measures to optimise the use of water resources on the ratio of reused and freshly collected water. It was shown that the Khorostkiv sugar factory is currently one of the leaders in the sugar industry in the field of economical water use. The plant has implemented a circulating-water system that allows for transferring heat-exchange heated wastewater into constructed cooling ponds with subsequent return of this water to production processes. Optimising the use of water resources, in addition to implementing a closed cooling cycle, also included recycling and reusing condensates. In fact, each liter of water was used by the factory dozens of times before it was lost to evaporation. The important role of using the internal moisture of beets is shown – practically all water from the raw material was involved in the process and is recycled many times. Such an optimal result from the point of view of resource conservation made it possible to reduce water intake from approximately 1 million m³ per year to 0.1 million m³, to eliminate direct discharges into the Taina River and significantly reduce anthropogenic pressure on the environment. As a result, savings of hundreds of thousands of hryvnias per year were obtained, the risks of environmental fines were eliminated, the company's image was improved, and the impact on the surface water body was minimised, which had a positive social effect for the objects of the territorial community that also use the river's water resources. The implementation of long-term investment projects, such as the construction of a biogas plant, the improvement of evaporation technologies, and the construction

of local treatment systems will contribute to improving water resources management and ensure long-term environmental safety and economic profitability of production. Focusing on a sustainable development strategy and implementing new technologies will allow the Khorostkiv sugar factory to reach a new level of environmental efficiency, approaching the concept of “zero fresh water use” due to a fully closed water use cycle.

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Оцінювання ефективності повторного використання води на Хоростківському цукровому заводі

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Анотація. Українська цукропереробна промисловість використовує великі обсяги води для виробничих потреб, але не приділяє достатньої уваги оптимальному використанню водних ресурсів. Метою даного дослідження було оцінити ефективність повторного використання конденсату та охолоджувальної води для оптимізації використання водних ресурсів та зменшення обсягів водозабору з поверхневих водойм. На основі даних офіційних звітів Хоростківського цукрового заводу за 2017-2024 роки було проведено аналіз змін у використанні води після вдосконалення системи циркуляції води. Зокрема, було використано статистичний метод для розрахунку змін у водозборі та коефіцієнті рециркуляції води, а також для проведення екологічної та економічної оцінки. Встановлено, що загальний обсяг водозабору з 2019 року зменшився приблизно в 8,1-21,3 раза (2019-2024 роки) порівняно з показником, розрахованим для 2017 року. Доведено, що процес водокористування було оптимізовано завдяки функціонуванню сучасної системи рециркуляції з ефективним використанням конденсату та охолоджувальної води. Було підкреслено, що така оптимізація призвела до припинення скидання теплообмінних стічних вод у поверхневі водойми. За підрахунками, економічний ефект від повторного використання охолоджувальної та конденсатної води лише за орендну плату призвів до скорочення річних фінансових витрат підприємства приблизно на 350-400 тисяч гривень. Практику повторного використання охолоджувальної та конденсатної води можна рекомендувати для застосування на інших цукрових підприємствах України

Ключові слова: водні ресурси; цукровий завод; стічні води; оптимізація використання води; конденсат; охолоджувальна вода

The functioning of the dairy product market in Ukraine

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Abstract. Dairy products remain an important part of the Ukrainian population's diet, but the industry faces a number of problems, including negative trends related to declining milk production, a shortage of high-quality raw materials, growing imports, low consumer purchasing power, logistical difficulties and the impact of the war. This requires new approaches to the development of the industry and an in-depth analysis of the dairy market. The aim of the article was to analyse the functioning of the milk and dairy market, identify its problems and propose measures for the successful development of the dairy industry. The following methods were used in the research: abstract-logical, statistical and tabular with the aim of collecting, processing and analysing information on milk production, milk supply to processing enterprises, the quality of raw milk, and the export and import of dairy products during 2017-2024; graphical analysis was used to analyse the export and import of dairy products, to rank regions by milk production in 2024, and to study the raw milk price index; correlation and regression analysis was used to study the dependence of drinking milk and butter consumption in 2023 on per capita production volumes. The results of the study showed that the supply of raw milk on the market did not correspond to the capacity utilisation of milk processing enterprises, as a result of which the volume of dairy products was below the norm of its consumption. The structure and share of Ukrainian dairy exports to countries around the world were outlined. The dependence of drinking milk and butter consumption on raw milk production was studied. The practical significance lies in the fact that research into the functioning of the dairy market can serve as a guide when making decisions on how to increase milk production and processing, increase the consumption of dairy products, and grow the export volumes of the dairy industry

Keywords: production; quality; price index; export; import

INTRODUCTION

Inadequate and unbalanced nutrition is a pressing issue that has a significant impact on human health and physiological development. A balanced diet is possible

by including animal products in the diet, namely eggs, meat and dairy products. A diet rich in dairy products and other animal products, as a source of essential amino

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acids, vitamins and minerals, helps prevent deficiencies in essential nutrients. Dairy products are recognised as an important source of high-quality protein. Consumers are conscious about their diet and health, which is reflected in their consumption of dairy products. They try to consume organic and natural products, which leads to an increase in the range and improvement in the quality of dairy products. Therefore, the development of the dairy industry and the provision of dairy products to the population are of great importance.

Researcher O. Popko (2020) noted in his works that the use of the Brown method makes it possible to predict the dynamics of milk production and the growth in milk yields. In analysing the milk market, the author used the SWOT analysis method. Similar research was conducted by scientists M. Rakhman & D. Gryzlo (2021), who, after conducting their research on the milk market, concluded that based on the use of SWOT and PEST analysis methods, proposals can be made to improve the state of the milk and dairy products market. In their opinion, a combination of state support measures, entrepreneurial efforts, international experience and the use of resource-saving technologies will contribute to maintaining the country's food security and provide the population with high-quality dairy products, reducing imports.

According to researchers L. Ivashyna *et al.* (2024), the formation of the range of dairy products in Ukraine is influenced by consumer demand, competition, state policy, pricing policy, demographic and social trends. In their work, authors M. Talavyria *et al.* (2024) concluded that the main factors influencing the consumption of milk and dairy products are the price level of finished products, income level, and population size. The authors also found that the main factors affecting the supply of milk on the market are the purchase price of raw milk and cow productivity. Their research showed that with an increase in the number of cows, there is no increase in raw milk production, which is evidenced by the use of advanced technologies, the high productive genetic potential of cows, and investments in the dairy industry.

Researchers Yu. Danko & D. Zhivytsky (2024) noted that one of the promising ways to overcome the problems of dairy farming is the creation and development of dairy clusters. These clusters bring together milk producers, processing enterprises, suppliers, scientific institutions, and other organisations involved in the industry. This cluster approach contributes to achieving synergistic effects, increasing productivity and production efficiency, introducing innovations, diversifying activities, and strengthening the competitive position of market participants. The works of P. Borawski *et al.* (2020) examined the impact of global crises on milk

production and analysed trends in the European dairy market. The authors M. Mysyuk *et al.* (2020) analysed the main trends in the Ukrainian milk market in relation to ensuring food security in Ukraine. Researchers L. Ivashyna *et al.* (2024) believed that the development of the milk and dairy products market can be improved by creating an effective legislative framework for milk processing enterprises; ending the slowdown in dairy production; ensuring conditions for healthy competition and protecting consumers from poor-quality products; finding ways to increase sales volumes in the domestic and foreign markets for dairy products; and forming an effective mechanism for monitoring the implementation and enforcement of a programme to improve labour efficiency in the milk and dairy products market. In their work, researchers L. Donets *et al.* (2024) noted that the situation on the milk market can be balanced by creating favourable conditions for transformation into dairy cooperatives and proposing a set of measures that include economic, legal and state support.

Authors L. Tulush *et al.* (2023) noted the need for a rational combination of market self-regulation mechanisms with instruments of state intervention in the development of the dairy sector as an important component of the agricultural market. The authors V. Ivchenko *et al.* (2024) pointed out in their work that overcoming the challenges and risks of the Ukrainian dairy market requires not only state but also international support. In turn, business development must respond to new realities, plans must be developed to increase milk production and strengthen export positions in the global market, logistics must be improved, and risks must be managed effectively. The aim of the study was to identify ways to halt the decline in milk production, improve milk quality in line with European requirements, and increase export of dairy products, which will improve the financial situation of producers and increase state support for enterprises in the dairy industry.

MATERIALS AND METHODS

The study used statistical information for the period 2015-2024, with the main sources of information being the section Livestock in Ukraine (2024) and the statistical yearbook Balances and consumption of main food products by the population of Ukraine (2024), which contains information on milk production, consumption of basic food products and the balance of dairy products. Information on the raw milk price index (milk sales prices by enterprises) and consumer prices for dairy products (cumulative indices) for the period January 2022 – December 2024 was based on data on the quantity and value of milk sales collected as part of the state

statistical observation Sales of agricultural products by enterprises and households (2024).

The theoretical basis of the study was the scientific works of Ukrainian and foreign scientists. The studies by P. Borawski *et al.* (2020), M. Rakhman & D. Gryzlo (2021), L. Donets *et al.* (2024) were analysed, which described the main research on the milk and dairy products market. The study used the dairy product consumption standards recommended by the WHO through its representative offices in Ukraine (Ministry of Health of Ukraine, n.d.). Material from the national programme for the development of dairy cattle breeding and processing enterprises in Ukraine until 2030 (AgroPolit, 2020) was also used. The object of the study was economic entities specialising in the production of dairy products – agricultural enterprises and private farms.

The general scientific research methods included the following: the analysis method, which was used to construct the research algorithm; the comparison method, which was used to compare the indicators of the dairy industry's development; and the abstract-logical method, which was used to form development prospects and conclusions. Correlation and regression analysis was used to construct and analyse the economic-mathematical model of the dependence of drinking milk and butter consumption on milk production per capita in the form of a regression equation for drinking milk $y = 10.718x + 0.2554$ and butter $y = 0.5145e0.0001x$, which provides an assessment of the strength of the relationship. Thus, for drinking milk, the reliability of the approximation is $R^2 = 0.653$, and for butter, $R^2 = 0.8063$, which indicates a high degree of correspondence between the results obtained.

Per capita consumption of dairy products was calculated using the formula:

$$C = \frac{CF}{P}, \quad (1)$$

where C – per capita consumption of dairy products, kg; CF – consumption fund, kg; P – population, persons.

The methodology for calculating raw milk price indices and consumer prices for dairy products included calculations of average selling price indices for raw milk and dairy products, as well as average price indices for purchased raw milk and dairy products. The determination of these indices was important for assessing the state and trends of the dairy industry, developing macroeconomic policy taking into account the interests of the agricultural sector, and making international comparisons. The indices of raw milk prices and consumer prices for dairy products were determined as the ratio of the average sales prices for the reporting month of the current year to the average annual sales prices for

the corresponding types of products for the base period (year) ($I_{i/i-1}$) according to the formula:

$$I_{i/i-1} = \frac{P_i}{P_{i-1}} \times 100\%, \quad (2)$$

where P_i – the average selling price of raw milk and consumer prices for dairy products in the reporting month (i) of the current year (T); P_{i-1} – the average selling price of raw milk and consumer prices for dairy products in the base period (year) ($i-1$).

The study was conducted using the econometric method of data testing in Excel to identify the closeness of relationships that affect the indicators of the dairy industry's development. Tabular and graphical methods were used to improve the analytical perception of statistical information and to form conclusions regarding milk production, the supply of raw milk for processing, the export and import of dairy products, and the formation of supply and sales prices for milk. The sample for the study was formed using data from 24 regions of Ukraine, excluding statistical information from the temporarily occupied territory of the Autonomous Republic of Crimea, the city of Sevastopol, and part of the temporarily occupied territories in the Donetsk and Luhansk regions.

RESULTS

The main task of dairy farming is to provide the population with high-quality dairy products. The biggest problem in this industry is the production of high-quality raw milk. Therefore, milk producers must focus on establishing high-yield and technologically advanced dairy farms. According to the State Statistics Service, the total volume of milk production in Ukraine in 2024 was 7.2 million tonnes, in 2020 it was 9.3 million, and in 2015 it was 10.6 million (Table 1). According to official Ukrainian statistics (Livestock in Ukraine, n.d.), total milk production during 2015-2024 decreased in all categories of farms by 32.1% – from 10.6 million tonnes to 7.2 million tonnes, or 1.5 times, and by 2.9% compared to 2023. The decrease in milk production is mainly due to a reduction in production by private households. In 2024, private households produced 4.261 million tonnes of milk, which is 46.3% less than in 2015, or 7.8% less than in 2023. Agricultural enterprises saw a slight increase of 10.3% between 2015 and 2024, or 5.1% compared to 2023. Comparing the war year of 2022 with the pre-war year of 2021, milk production decreased by 10.9% in all categories of farms, including agricultural enterprises by 5.4% and private farms by 13.4% (Pashchenko, 2024). Comparing 2024 with 2021, the pre-war period, shows (Table 1) that milk production in enterprises increased by 6.6%, while in private

households it decreased by 28.3%. During 2022-2024, i.e. the period of military operations, milk production in enterprises increased by 12.7%, while in private households it decreased by 17.2%. Despite the military operations on the territory of Ukraine, milk production in Ukraine as a whole shows signs of stabilisation. In 2022, according to official data from the State Statistics

Service (Livestock in Ukraine, n.d.), 66.2% of milk was produced by private households and 33.8% by agricultural enterprises, while in 2024 the figures were 59.1% and 40.9% respectively. In 2024, two-quarters (40.9%) of the volume of milk produced was provided by enterprises, in 2022, one-third (33.8%), while in 2015, they produced one-quarter (25%).

Table 1. Milk production in Ukraine during 2015-2024

Indicator	Year								2024 as a % of	
	2015	2016	2019	2020	2021	2022	2023	2024	2015	2023
Milk production in all categories of farms:										
thousand tonnes	10,615	10,064	9,663	9,264	8,714	7,768	7,430	7,213	67.9	97.1
%	100	100	100	100	100	100	100	100	-	-
including:										
agricultural enterprises:										
thousand tonnes	2,669	2,756	2,729	2,761	2,768	2,621	2,810	2,952	110.6	105.1
%	25.1	27.4	28.2	29.8	31.8	33.8	37.8	40.9	-	-
household farms:										
thousand tonnes	7,946	7,309	6,935	6,502	5,946	5,147	4,621	4,261	53.6	92.2
%	74.9	72.6	71.8	70.2	68.2	66.2	62.2	59.1	-	-
Milk production per capita, kg	247.8	238.1	229.9	221.9	210.6	222	224	216	87.2	96.6

Note: '-' indicates missing values for the indicator

Source: calculated by the authors based on Livestock in Ukraine (n.d.)

Gradually, milk production in Ukraine is shifting towards production by enterprises. This is due to increased requirements for the technical level of production, safety and quality of milk. Agricultural enterprises are able to supply high-quality raw milk by improving the technological conditions of milk production, namely by mechanised milking, proper cleaning and cooling of milk, and they are also able to attract investment in the production, processing and sale of milk. Private farms are unable to ensure the proper level of technological processes for its production. During 2015-2021, Ukraine saw a concentration of dairy farms, as it is economically advantageous for enterprises to keep a larger number of cows. With this in mind, the number of specialised dairy farms and the number of cows kept by them increased in Ukraine (Ivchenko *et al.*, 2024). In other words, the consolidation of private farms into cooperatives provides greater opportunities for the restoration and maintenance of cows, improves the quality of raw milk, and increases the prices of milk and dairy products. In EU countries, farms do not sell milk from a single cow.

For example, family farms in Poland keep 25-50 cows, and in Scandinavian countries, 50-100 cows (Ivashyna *et al.*, 2024). This contributes to the mechanisation of the process of keeping and milking cows and obtaining high-quality raw milk. The slow growth of milk production in enterprises cannot fully compensate for the decline in milk production in private households, and reaching the 3 million tonne mark would be a significant achievement for enterprises (Korman *et al.*, 2022). However, the further development of the dairy industry depends on government decisions, namely the tax burden, government support for livestock farming, milk production and processing. Ukraine has a problem with the competitiveness of raw milk, which needs to be addressed as it affects Ukraine's integration into global markets. It is also necessary to analyse regional milk production. Prior to Russia's full-scale invasion in 2015-2021, Ukraine saw a regional decline in milk production of 1,901 thousand tonnes, with growth observed only in the Khmelnytskyi region (73 thousand tonnes) and the Ternopil region (by 2 thousand tonnes) (Table 2).

Table 2. Dynamics of milk production in 2015-2024 by region of Ukraine, thousand tonnes

Regions	Year											2024 to 2015, %	2024 to 2023, %
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024			
Ukraine	10,615	10,382	10,281	10,064	9,663	9,264	8,714	7,768	7,430	7,213		67.9	97.1
regions													
Vynnytsia	838	854	851	825	763	730	686	631	596	577		68.8	96.7
Volyn	425	412	412	391	369	354	338	324	291	279		65.7	95.9

Table 2, Continued

Regions	Year											2024 to 2015, %	2024 to 2023, %
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024			
Dnipropetrovsk	345	320	301	294	285	276	246	229	216	204	59.2	94.4	
Donetsk	228	193	190	186	174	156	144	62	26	27	11.7	102.3	
Zhytomyr	578	567	548	553	518	506	488	464	424	411	71.1	96.9	
Zakarpattia	358	320	325	346	350	337	313	298	284	266	74.2	93.7	
Zaporizhzhia	261	260	261	244	220	202	181	106	16	17	6.7	108.8	
Ivano-Frankivsk	474	467	464	442	429	411	393	370	341	305	64.3	89.3	
Kyiv	446	438	436	433	396	384	368	321	329	331	74.2	100.5	
Kirovohrad	311	308	306	308	300	272	269	273	270	261	84.0	96.7	
Luhansk	159	124	125	127	114	111	102	73	58	49	30.6	83.2	
Lviv	571	543	528	507	481	460	425	388	323	285	49.9	88.3	
Mykolaiv	344	342	342	325	299	279	246	197	190	201	58.4	105.7	
Odesa	385	363	349	335	321	310	291	287	286	280	72.6	97.9	
Poltava	795	797	792	762	759	734	691	663	660	668	84.0	101.1	
Rivne	437	437	433	397	358	337	283	274	289	283	64.7	97.7	
Sumy	418	415	416	411	396	386	355	293	278	257	61.5	92.3	
Ternopil	461	454	451	450	455	468	463	494	505	513	111.3	101.6	
Kharkiv	525	530	523	527	519	470	428	212	214	208	39.5	96.9	
Kherson	300	296	293	284	283	266	238	65	70	60	19.9	85.6	
Khmelnyskyi	581	590	597	624	636	652	654	673	679	656	112.8	96.5	
Cherkasy	530	519	508	484	467	461	436	442	455	465	87.8	102.3	
Chernivtsi	294	287	282	273	260	248	236	227	218	207	70.5	95.3	
Chernihiv	553	550	549	537	511	457	442	402	410	404	73.1	98.6	

Source: calculated by the authors based on Livestock in Ukraine (n.d.)

Table 2 shows that due to the war, Ukraine's dairy industry reduced its raw milk production by 1.5 million tonnes between 2021 and 2024. A significant decrease in production during 2021-2024 was observed in Donetsk (5.3 times), Zaporizhzhia (10.6 times), Kherson (4 times), and Luhansk (2.1 times), while in other regions the decrease averaged 10-35%. However, growth was also

observed in Khmelnytskyi region by 0.3%, Cherkasy region by 6.7% and Ternopil region by 10.8%. A study of the ranking of regions by milk production in 2021 and 2024 showed that the leading positions in milk production are held by Poltava (691 and 668 thousand tonnes), Khmelnytskyi (654 and 656 thousand tonnes) and Vinnytsia (686 and 577 thousand tonnes) regions (Fig. 1a) and b)).

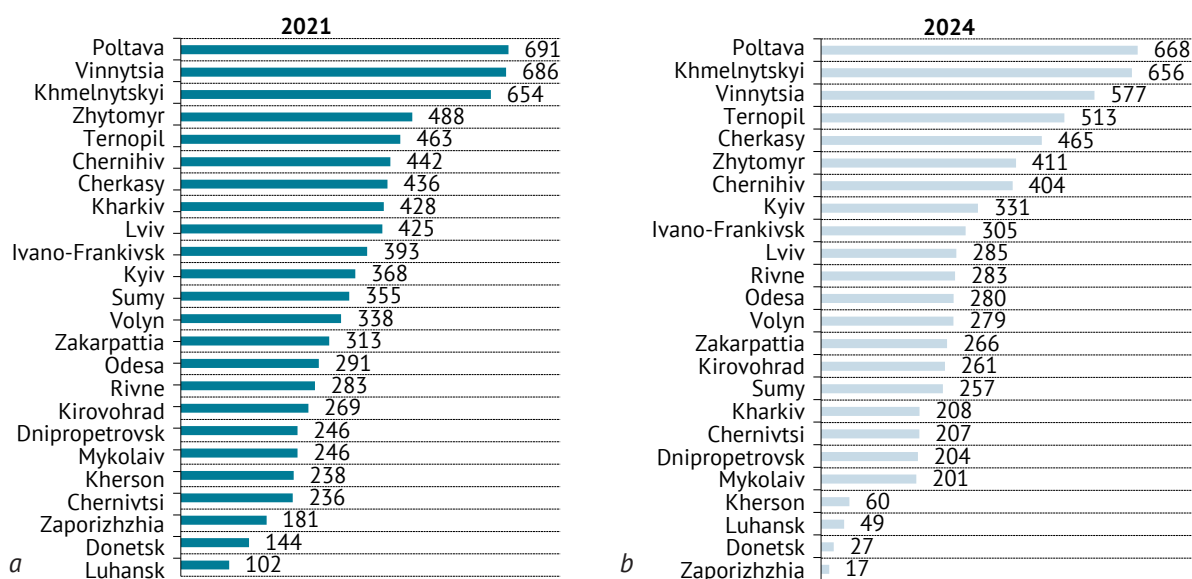


Figure 1. Ranking of regions by milk production, thousand tonnes

Source: calculated by the authors based on Livestock in Ukraine (n.d.)

Among the regions of the country, the largest volumes of milk in 2024 were produced by dairy farms in the Poltava (8.5% of the total volume in Ukraine), Khmelnytskyi (8.7% of the total volume in Ukraine), Poltava (8.5% of the total volume in Ukraine) and Vinnytsia (8.1% of the total volume in Ukraine) regions (Fig. 1b). The lowest positions in milk production in pre-war 2021 were held by Zaporizhzhia (181 thousand tonnes), Donetsk (144 thousand tonnes) and Luhansk (102 thousand tonnes) (Fig. 1a). During the war in 2024, the positions changed: Kherson (60 thousand tonnes), Luhansk (49 thousand tonnes), Donetsk (27 thousand tonnes), Zaporizhzhia (17 thousand tonnes).

It is important to provide milk processing enterprises with milk raw materials. After all, high-quality milk raw materials will contribute to the production of high-quality

dairy products, which will ensure their existence, stable operation and improve the financial situation of enterprises in the dairy industry. According to the State Statistics Service, in 2024 (Livestock in Ukraine, n.d.), processing enterprises in Ukraine received 3,223 thousand tonnes of milk from agricultural enterprises and private households, which is only 43.39% of the total volume of milk produced in Ukraine (Table 3). The largest amount was purchased from agricultural enterprises, 2,887 thousand tonnes (in 2024), i.e. 327 thousand tonnes more in 2024 than in 2023, 582 thousand tonnes more in 2024 than in 2022, 173 thousand tonnes less in 2022 compared to 2021. In private households, 243 thousand tonnes (in 2024), which is 73 thousand tonnes less than in 2023, 110 thousand tonnes less in 2024 than in 2022, and 201 thousand tonnes less in 2022 than in 2021.

Table 3. Milk deliveries to processing enterprises in Ukraine during 2015-2024, thousand tonnes

	Year										
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	
Milk and dairy products – total	4,251	4,183	4,348	4,179	3,800	3,512	3,198	2,740	2,918	3,223	
Purchased	4,090	3,710	3,928	3,809	3,462	3,289	3,032	2,657	2,875	3,130	
including from:											
agricultural enterprises	2,413	2,512	2,689	2,720	2,610	2,556	2,478	2,305	2,560	2,887	
%	59	67.7	68.4	71.4	75.4	77.7	81.7	86.7	89.0	92.2	
private households	1,346	1,198	1,239	1,089	851	733	554	353	316	243	
%	32.9	32.3	31.6	28.6	24.6	22.3	18.3	13.3	11.0	7.8	
Accepted on a tolling basis	138	441	396	346	318	203	148	74.8	37.0	86.3	
Received for processing milk produced by processing enterprises	23.6	32.1	24.6	25	20.4	20.1	17.8	7.8	6.0	6.2	
Average purchase price, UAH per tonne											
Milk and dairy products – total											
Purchased	3,771	4,713	6,388	6,635	7,332	7,899	9,385	10,219	11,693	15,015	
including from:											
agricultural enterprises	4,216	5,277	7,059	7,386	7,958	8,565	9,936	10,678	12,181	15,520	
households	2,841	3,530	4,933	4,758	5,412	5,574	6,921	7,220	7,733	9,029	

Source: calculated by the authors based on Sales of agricultural products by enterprises and households (n.d.)

In 2024, only 34.68% of milk produced in Ukraine was sent to processing enterprises, including 92.2% of raw milk produced by agricultural enterprises and 7.8% of raw milk produced by private households (Table 3). In European countries, almost 96% of milk is processed into dairy products. The share of raw milk supplies from private households decreased from 32.9% to 7.8% during 2015-2024, while from agricultural enterprises, on the contrary, it increased from 59% to 92.2%, and during 2021-2024, respectively, from 18.3% to 7.8% and from 81.7% to 92.2%. According to forecasts, milk production in private households will continue to decline until 2027-2030, and subsequently such milk will be used only for personal consumption (State and prospects of the dairy..., 2025). On a tolling basis and produced by processing enterprises, production decreased by 1.6 and

3.8 times during the corresponding period, but their volumes are insignificant and this did not affect the supply of raw materials to milk processing enterprises.

Problems in the dairy market also include price fluctuations. During 2020-2024, the purchase price of milk from agricultural enterprises and private households increased by 1.5 times, but this did not change the situation with the shortage of raw milk, i.e. the increase in the selling price of milk did not lead to an increase in its production volumes. In 2024, the purchase prices of milk from agricultural enterprises exceeded the purchase prices of private households by 71.89% (Table 3). This is due to the increase in the cost of dairy products and a decrease in their supply on the market, which is why the price of raw milk rose from 9,385 UAH/t in 2021 to 15,520 UAH/t in 2024 (Table 3). In 2015 and 2024, the purchase prices of

raw milk from private households were 1.48 and 1.72 times lower than the purchase prices from agricultural enterprises, which is associated with the low quality of raw milk. As a result, low profits for farmers, which does not encourage them to expand production, so they use most of the milk for their own needs and sell a small portion of it on informal markets. Under conditions of expanded production, commercial milk should be purchased from enterprises that have the capacity to cool and pasteurise it. After all, for the production of high-quality dairy products, it is more economically advantageous for processing enterprises to buy more expensive raw materials from enterprises than cheaper and lower quality raw materials from the population. Therefore, there is a shortage of raw milk suitable for processing enterprises on the domestic market, and demand exceeds supply. In 2021, under the influence of climate change and "green" laws, milk production in Europe began to decline, which alarmed processing enterprises, so they began to stimulate the restoration of its production (The price of milk in the EU..., 2022). The beginning of 2022 brought its own adjustments: Russia's war against Ukraine, sanctions against Russia, rising gas prices, market uncertainty and an increase in consumers forced European producers to raise the price of milk even further, resulting in a record high for the last 10 years in 2022, reaching EUR 58.3/100 kg in December (The price of milk in the EU..., 2022). The price increase does not compensate for the shortage of raw materials. The existing legislative framework is insufficient for the effective operation of the dairy industry. Therefore, there is a need for solidarity among all enterprises in the dairy industry in order to implement the National Programme for the Development of Dairy Farming and the Processing Industry for 2021-2030. The implementation of this programme will require UAH 90 billion over 10 years (UAH 9 billion per year, of which 50% will be state support), and an investment of EUR 750 million will be needed to increase production and processing. At the same time, it is necessary to increase milk production to 8 million tonnes per year, livestock numbers to 3 million head, milk processing volumes to 8 million tonnes, and dairy product consumption per capita to 250 kg, as well as to ensure the competitiveness of the dairy industry in export markets. State support for the dairy industry includes: state subsidies, use of the Agrarian Fund for fi-

nancial and commodity interventions, state subsidies to stimulate exports of dairy products, state tender purchases of dairy products from producers, creation of a livestock support fund (25 head per 100 ha), the creation of an account for the accumulation of customs revenues from imports of dairy products, and exemption from VAT on imported equipment for the dairy industry (AgroPolit, 2020).

During 2015-2024, enterprises increased milk production from 2,669 to 2,952 thousand tonnes, but processing enterprises experienced a shortage as the volume of milk production by private farms decreased from 7,946 thousand tonnes in 2015 to 4,261 thousand tonnes in 2024. The reason for this is Order of the Ministry of Agrarian Policy and Food of Ukraine No. 118 (2019), the provisions of which are mandatory for all categories of farms. On 14 August 2024, the Ministry of Justice of Ukraine registered Order No. 2033 of the Ministry of Agrarian Policy and Food of Ukraine dated 11 July 2024 regarding amendments to the Requirements for the Safety and Quality of Milk and Dairy Products, which were approved by Order of the Ministry of Agrarian Policy and Food of Ukraine No. 118 dated 12 March 2019 (State Service of Ukraine on Food Safety and Consumer Protection, 2024a). Thus, the increase in requirements for raw milk has led to higher requirements for dairy products, so processors are interested in receiving high-quality raw materials for processing.

During 2015-2024, there has been an improvement in the quality of milk supplied for processing by agricultural enterprises, as they have the appropriate conditions for obtaining it and are able to purchase or breed cows with high genetic productivity. During the period 2015-2024, the share of "Extra" grade milk in the structure of output increased (from 10.3% to 54.5%, i.e. by 44.2%), but the share of higher grade milk decreased (from 35.2% to 32.6%, i.e. by 2.6%), first grade (from 49.6% to 17.1%, i.e. by 32.5%), and second grade (from 4.7% to 0.9%, i.e. by 3.8%) (Table 4). This is a positive development, as Ukrainian producers are seeking to enter European milk markets and their milk products must meet European quality standards. At the same time, during the period under review, private farms increased the volume of production of the highest grade (from 0.1% to 1%, i.e. by 0.9%), first grade (from 8.9% to 81.7%, i.e. by 72.8%), but second grade production decreased (from 86.2% to 17.2%, i.e. by 69%) (Livestock in Ukraine, n.d.).

Table 4. Quality of milk supplied for industrial processing during 2015-2024, by grade

Indicators	Year									
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
	according to DSTU 3662:2018					according to DSTU 3662:2018				
	Agricultural enterprises									
Volume of delivered milk, thous t	2,287	2,375	2,533	2,560	2,428	2,348	2,253	2,107	2,356	2,628
converted to basic fat content milk	2,413	2,512	2,688	2,720	2,610	2,556	2,478	2,305	2,560	2,886

Table 4, Continued

Indicators	Year									
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
including by grades:										
- extra	248	366	441	586	710	885	973	1,089	1,395	1,727
specific weight (share), %	10.3	14.6	16.4	21.6	27.2	34.6	39.3	47.2	59.9	54.5
- higher grade	850	923	987	1,036	938	874	875	750	703	730
specific weight (share), %	35.2	36.7	36.7	38.1	35.9	34.2	35.3	32.6	25.3	27.5
- Grade I	1,197	1,056	1,018	895	844	776	614	444	438	414
specific weight (share), %	49.6	42	37.9	32.9	32.3	30.4	24.8	19.3	14.3	17.1
- Grade II	113	160	235	194	97	16	16	21	24	12
specific weight (share), %	4.7	6.4	8.7	7.1	3.7	0.6	0.6	0.9	0.4	0.9
Non-grade	5	6	7	9	21	5	0.5	0.2	0	2
specific weight (share), %	0.2	0.3	0.3	0.3	0.8	0.2	0	0	0.1	0.0
Share in purchased milk, %										
- fat	3.59	3.6	3.6	3.6	3.66	3.7	3.74	3.72	3.69	3.73
- protein	3.05	3.06	3.06	3.1	3.13	3.16	3.19	3.2	3.24	3.24
Household farms										
Volume of delivered milk, thous t	1,312	1,161	1,200	1,054	822	708	531	337	304	233
converted to basic fat content milk	1,346	1,198	1,239	1,089	851	733	554	353	316	243
including by grades:										
Higher grade	1	0.6	1.6	2.3	0.8	1.6	0.7	13.7	3.2	0.1
specific weight (share), %	0.1	0.1	0.1	0.2	0.1	0.2	0.1	3.9	0.1	1.0
Grade I	119	108	110	136	102	586	436	272	258	195
specific weight (share), %	8.9	9	8.9	12.4	12	79.9	78.7	77.1	80.0	81.7
Grade II	1,163	1,028	1,081	904	708	135	108	67	54	48
specific weight (share), %	86.4	85.8	87.2	83	83.2	18.4	19.6	19	19.9	17.2
Non-grade	63	61	46	47	40	10.8	9.1	0.1	0	0
specific weight (share), %	4.7	5.1	3.7	4.3	4.8	1.5	1.6	0	0.0	0.1
Share in purchased milk, %										
- fat	3.49	3.51	3.51	3.51	3.52	3.52	3.54	3.56	3.53	3.55
- protein	2.92	2.93	2.95	2.96	2.94	2.96	2.94	2.96	2.99	2.97

Source: calculated by the authors based on *Livestock in Ukraine (n.d.)*

In 2024, agricultural enterprises mainly supplied extra-grade milk (54.5%) and higher-grade milk (27.5%), while private households supplied grade I milk (87.1%) and did not produce any extra-grade milk at all. This was facilitated by the adoption of Law of Ukraine No. 2132-VI (2015), which provides for the promotion of high-quality milk production in Ukraine through additional payments of 25% for extra-grade milk and 20% for higher-grade milk. First grade milk is not subsidised at all (Order of the Ministry of Agrarian Policy and Food of Ukraine No. z1245-24, 2024). Thus, improving milk quality remains an important condition for the effective functioning and development of the dairy industry and increasing the competitiveness of its products, both on the domestic and foreign markets. Another feature of milk that affects the production of dairy products is its unsuitability for long-term storage and transportability over short distances. Therefore, the guarantee of milk supply to processing enterprises, which will help to provide the population with dairy products in the required quantities, is linked to the stability of sales channels and the

coordinated activities of all components of the technological chain: “production-procurement-processing-sales”.

The Ukrainian dairy market is competitive, which forces producers to constantly develop and expand their range of dairy products. In turn, competition among milk processors forces them to seek and apply new technologies and innovations in the production of dairy products, i.e., to modernise production, which results in the improvement of existing products and the emergence of new ones. Consumers are conscious about their health and consumption, which has affected the consumption of dairy products. The demand for organic and natural dairy products is increasing, prompting their producers to improve their range and offer new products. According to the State Statistics Committee of Ukraine (Statistical Yearbook of Ukraine, n.d.), during 2015-2022, the range of dairy products in Ukraine is diverse, but the volume of dairy production fluctuates, either increasing or decreasing. Thus, according to the consolidated nomenclature of 11 nomenclature items, 10 items reduced production volumes and only one item showed positive dynamics (Table 5).

Table 5. Dynamics of production of main dairy products in Ukraine in 2015-2022, thousand tonnes

Product names according to the industrial product nomenclature	Year							
	2015	2016	2017	2018	2019	2020	2021	2022
Milk and cream, non-condensed and without added sugar, fat content not exceeding 1%, in packages of more than 2 litres, thous t	461	467	464	443	435	434	335	312
Milk and cream, non-condensed and without added sugar, fat content exceeding 1% to 6%, in packages of no more than 2 litres, thous t	472	463	478	497	474	491	465	370
Milk and cream, non-concentrated and without added sugar, fat content over 21%, in packages of over 2 litres, thous t	51	53	48	49	51	46	45	77
Skimmed milk powder (milk and cream in dry matter, fat content not exceeding 1.5%), in packages of over 2.5 kg, thous t	51	49	48	38	35	36	30	34
Butter with a fat content of no more than 85%, thous t	101	102	108	105	92	86	73	68
Fresh cheese, thous t	68	70	68	73	64	79	84	59
Grated, powdered and other unmelted cheese, thous t	97	87	94	97	86	82	77	60
Processed cheese, thous t	27	26	27	29	30	31	28	22
Sweetened condensed milk and cream, thous t	52	44	43	35	35	37	34	30
Curdled milk and cream, yoghurt, kefir, sour cream, and other fermented products, thous t	297	293	272	275	280	309	300	228
Flavoured liquid yoghurt and fermented milk, thous t	106	112	116	126	136	139	141	103

Note: due to the lack of statistical information for 2023-2024, the analysed period is limited to 2015-2022

Source: calculated by the authors based on Statistical Yearbook of Ukraine (n.d.)

As shown in Table 5, between 2015 and 2022, the production of milk and cream without added sugar increased by 26 thousand tonnes. At the same time, the production of fresh cheese decreased by 9 thousand tonnes, processed cheese by 5 thousand tonnes, milk and cream without added sugar (no more than 1%) by 149 thousand tonnes, milk and cream without added sugar (no more than 1-6%) by 102 thousand tonnes, dry milk by 17 thousand tonnes, butter by 33 thousand tonnes, condensed milk and cream – 22 thousand tonnes, coagulated milk and cream, yoghurt, kefir, sour cream, etc. – 69 thousand tonnes, liquid yoghurt – 31 thousand tonnes, liquid yoghurt – 3 thousand tonnes. The decrease in the production of dairy products is due to a decrease in the consumption of milk and dairy products per capita caused by a decrease in the purchasing power of the population and an increase in the price of products sold.

The range of dairy products in Ukraine is quite large, but there are products that contain varying amounts of milk, namely dairy products such as spreads, ice cream, condensed milk analogues, cheese products, etc. In such dairy products, the milk content is difficult to determine and may change over time for a single product from a single manufacturer. The composition of all products manufactured in the country will also change, as will the milk content in dairy products. In this

regard, it is impossible to specify the norm for the use of raw milk in some dairy products, although there are average base coefficients, such as the production of one kilogram of butter requires an average of about 20 kilograms of milk, hard cheese – 10 kilograms, dry skimmed milk – 11 kilograms, dry whole milk – 8 kilograms, yoghurt – 1.1 kg, sour cream – 5 kg. Several products can be produced simultaneously from the same volume of milk. For example, after milk separation, cream is used to make butter and skimmed milk, and the rest is used to make dry powder (Korman *et al.*, 2022).

Despite the war, Ukraine's milk processing enterprises are trying to maintain their capacity, but the dairy industry needs further development and modernisation. The domestic dairy market in Ukraine is underestimated. With the established physiological norm of dairy product consumption at 380 kg per person per year, the country's population consumed 201.5 kg in 2021, only 195.6 kg in 2022, and 196.8 kg in 2024, which is 12.8 kg less than in 2015 and 4.7 kg less than in 2021. 196.8 kg, which is 12.8 kg less than in 2015 and 4.7 kg less than in 2021, and 53.8% and 51.8% of the scientifically based consumption norm of 380 kg (Table 6). This indicator is lower than in EU countries, where annual consumption of dairy products per capita is 260 kg. This indicates significant potential for the domestic dairy market, in which it is possible to invest.

Table 6. Volume of milk consumption in Ukraine in 2015-2024

Indicators	Year									2024 to 2015	
	2015	2018	2019	2020	2021	2022	2023	2024	+/-	%	
Consumption volume, thousand tonnes	8,995	8,355	8,428	8,430	8,337	6,845	6,686	6,565	-2,430	73.0	
% of consumption volume from total production volume	84.7	83.0	87.2	91.0	95.7	88.1	90.0	91.0	6.3	-	

Table 6, Continued

Indicators	Year									2024 to 2015	
	2015	2018	2019	2020	2021	2022	2023	2024	+/-	%	
per capita, kg	210	198	200.5	201.9	201.5	195.6	201.4	196.8	-13.1	93.7	
% of recommended consumption of milk and dairy products	53.8	50.7	52.8	53.1	53.0	51.5	53.0	51.8	-2.0	96.2	

Source: calculated by the authors based on Balances and consumption of main food products by the population of Ukraine (n.d.)

Per capita consumption of dairy products during 2015-2023 (the study was conducted for the limited period of 2015-2023 due to the lack of statistical information for 2024) was determined using formula 1 (specified in the methodology) and fluctuates from year to year. Thus, milk consumption decreased from 117.65 kg

to 102.06 kg by 15.59 kg, butter from 2.12 kg to 1.40 kg by 0.72 kg, and SMP from 0.44 kg to 0.24 kg by 0.2 kg. but cheese consumption increased from 4.02 kg to 4.24 kg, or 0.22 kg (Table 7). A study of the dependence of drinking milk and butter consumption on per capita production in 2023 calculated a regression equation (Fig. 2 and Fig. 3).

Table 7. Consumption per capita in Ukraine during 2015-2023, kg

Year	Milk	Butter	Cheese	SMP
2015	117.62	2.12	4.02	0.44
2016	114.89	2.04	4.1	0.44
2017	110.0	1.8	4.14	0.37
2018	107.54	1.68	4.38	0.53
2019	110.48	1.78	4.56	0.36
2020	112.47	1.86	4.97	0.47
2021	111.97	1.63	5.19	0.47
2022	106.87	1.27	4.26	0.10
2023	102.06	1.40	4.24	0.24

Note: SMP – skimmed milk powder

Source: calculated by the authors based on Statistical Yearbook of Ukraine (n.d.)

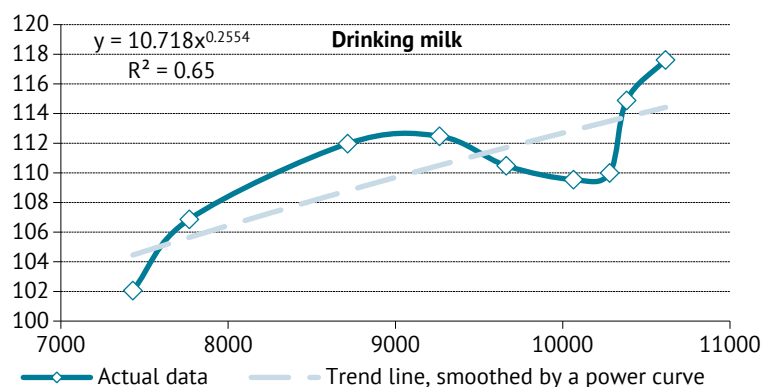


Figure 2. Dependence of per capita consumption of drinking milk on milk production in Ukraine

Source: calculated by the authors based on Statistical Yearbook of Ukraine (n.d.)

Analysing the data presented, it can be concluded that there is a direct correlation between the consumption of drinking milk and its production, as evidenced by the coefficient of determination – more than 0.653. Based on the coefficient of determination, it can be concluded that the consumption of drinking milk depends on milk production by 65.3%. The graph (Figure 2) clearly shows the trend of milk consumption growth from its production and can be described by the equation

$y = 10.718x^{0.2554}$, with the approximation reliability value $R^2 = 0.653$, which indicates a high correspondence of the obtained model. Thus, a 1 kg increase in milk production per capita increases drinking milk consumption by 10.718 kg relative to the average values in the sample.

The coefficient of determination of 0.8063 for butter indicates a direct relationship and a close link between milk production and butter consumption. Based on the coefficient of determination, it can

be concluded that butter consumption depends on milk production by 80.63%. The graph (Fig. 3) clearly shows the trend of increasing butter consumption from its production and can be described by the equation $y = 0.5145e^{0.0001x}$, with the approximation

reliability value $R^2 = 0.8063$, which indicates a high correspondence of the obtained model. Thus, an increase in butter production per capita by 1 kg increases consumption by 0.5145 kg relative to the average values in the sample.

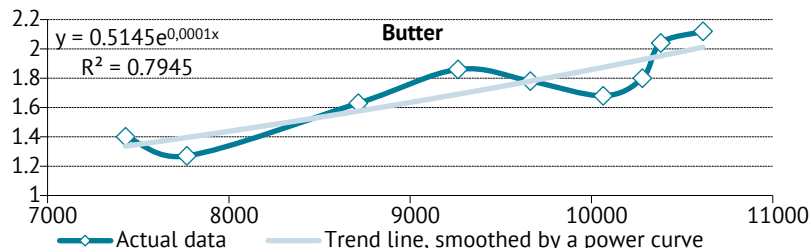


Figure 3. Dependence of per capita butter consumption on milk production in Ukraine

Source: calculated by the authors based on Statistical Yearbook of Ukraine (n.d.)

The increase in purchase prices for raw milk during 2022-2024 contributed to the rise in prices for dairy products to world levels, which led to a decline in sales and ensured adequate prices for raw milk producers (Fig. 4). Thus, during the period under review, the raw milk price

index rose from 1 to almost 1.8. Purchase prices are also subject to seasonality. In the summer, they decrease due to an increase in the supply of raw milk, and in the winter, they increase due to a decrease in the supply of milk. This situation is also characteristic of dairy products.

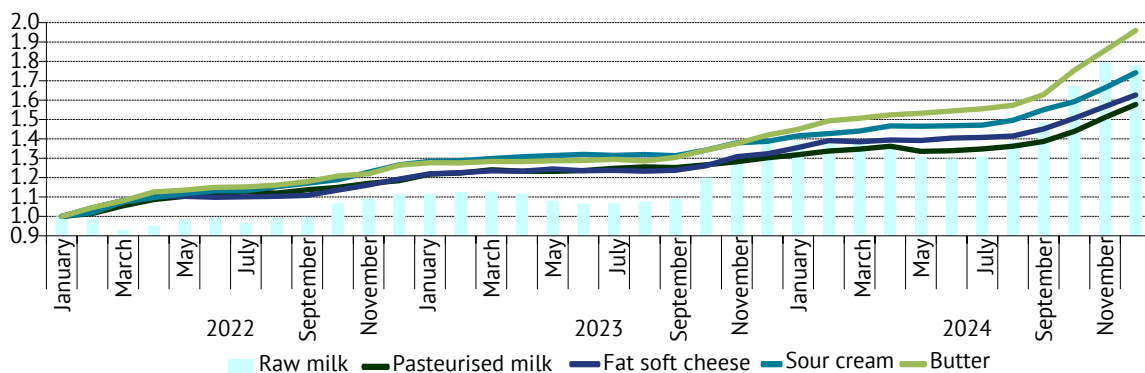


Figure 4. Indices of raw milk prices (milk sales prices by enterprises) and consumer prices for dairy products (cumulative indices for January 2022 – December 2024)

Note: the price study was conducted using a price index calculated according to formula 2

Source: calculated by the authors based on Sales of agricultural products by enterprises and households (n.d.)

The dairy product price index for January 2022 to December 2024 (only three years were taken into account because the study was conducted on a monthly basis) rose from 1 to almost 2. One of the reasons for this is the increase in the price of raw milk. The highest growth index was observed for butter and sour cream. IFCN analysts note that the global supply of milk is limited due to high production costs caused by rising prices for fuel and lubricants, logistics, and new legislative requirements based on greening production and improving animal welfare (Association of Milk Producers, 2024). A study of the dynamics of dairy product exports and imports shows an increase in

export and growth in import (Fig. 5). Between 2015 and 2024, dairy product export increased from USD 178 million to USD 214 million, i.e. by USD 36 million, while import grew from USD 34 million in 2015 to USD 283 million in 2024, i.e. by USD 249 million. Between 2015 and 2019, Ukraine exported more than it imported, as evidenced by a positive balance of USD 144 million in 2015 to USD 75 million in 2019, although this figure decreased by USD 69 million during 2015-2019. During 2020-2024, except for 2022, Ukraine saw imports exceed export, resulting in a negative balance of -126 million US dollars in 2020 to -68 million US dollars in 2024.

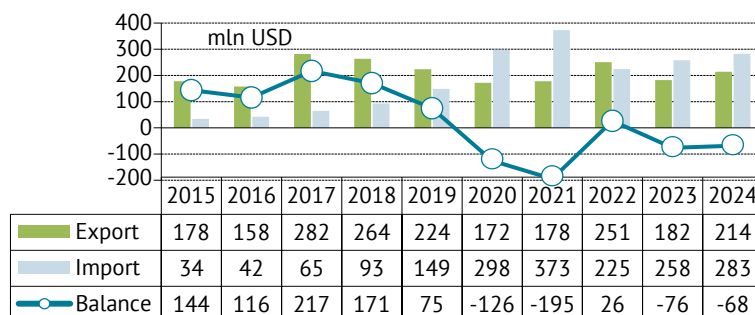


Figure 5. Export and import of dairy products during 2015-2024

Source: calculated by the authors based on Sales of agricultural products by enterprises and households (n.d.)

During the period 2022-2024, exports decreased by 14.74%, while imports increased by 12.78%. In 2022, the foreign trade balance was positive (+26 million US dollars), as Ukraine exported more than it imported. During 2023-2024, Ukraine imported more than it exported, as evidenced by a negative balance of -76 and -68 million US dollars. In 2022, compared to 2021, imports of dairy products to Ukraine decreased by USD 148 million for obvious reasons – the outflow of population abroad and changes in the exchange rate. In 2023 and 2024, the situation changed, with an increase of USD 33 million and USD 58 million compared to 2021. There was a shortage of raw milk in 2021, 2023 and 2024, when dairy products worth USD 195 million, USD 76 million and USD 68 million were imported into Ukraine. In 2024, the main categories of dairy products

exported were (in million tonnes): milk and cream, condensed – 29.5; milk and cream, non-condensed – 26.6; whey – 18.7; cheese – 12.4; butter – 7.2; fermented milk products – 4.4 (Table 8). According to Table 8, the structure of dairy product exports in 2015-2024 showed a 50% decrease in exports of condensed milk and cream, a 29.4% decrease in whey, and a 38.5% decrease in butter. However, in monetary terms, the volume of funds from exports of fermented milk products increased by 78.8%, butter by 63% and cheese by 5.9%. There was a threefold increase in the export of milk and non-condensed cream and a 24% increase in cheese exports, which was due to growing demand for these products. In monetary terms, exports of milk and non-condensed cream increased 3.8 times during the period under review, while cheese exports increased by 54.9%

Table 8. Exports of major dairy products from Ukraine during 2015-2024

Code UKT ZED	Products	Year									
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Volume, thous t											
0401	Milk and cream, non-condensed	8.8	10.5	14.1	20.8	25.2	18.6	14.9	29.4	28.3	26.6
0402	Milk and cream, condensed	59.0	51.9	46.8	35.6	35.8	27.4	22.4	26.7	27.7	29.5
0403	Fermented milk products	3.8	2.9	3.7	5.5	6.1	5.7	5.5	3.1	3.4	4.4
0404	Milk whey	26.5	23.9	31.9	31.9	24.1	26.9	22.2	15.3	16.2	18.7
0405	Butter and other fats	11.7	12.1	30.4	30.4	18.3	11.2	10.9	14.1	7.8	7.2
0406	Cheese	10.8	8.1	9.1	8.3	7.2	6.4	6.9	9.0	8.9	12.4
Value, mln USD											
0401	Milk and cream, non-condensed	4.6	5.4	9.7	14.7	15.3	12.0	10.4	16.4	16.6	17.6
0402	Milk and cream, condensed	89.4	73.7	80.6	59.2	76.2	55.5	57.4	90.0	68.7	74.3
0403	Fermented milk products	3.3	2.6	4.2	8.5	9.9	9.0	8.6	4.7	4.2	5.9
0404	Milk whey	15.5	14.3	24.8	21.9	18.3	22.3	22.8	15.8	10.9	13.4
0405	Butter and other fats	30.0	37.6	129.9	128.6	77.1	48.8	52.3	81.7	41.8	48.9
0406	Cheese	35.0	24.3	32.5	30.8	26.9	24.4	26.7	42.3	40.0	54.2
0401-0406 total		177.9	158.0	281.7	263.7	223.7	172.0	178.2	250.8	182.0	214.3

Note: UKT ZED – names of dairy products

Source: calculated by the authors based on Per capita Consumption (n.d.)

In 2023, 92.3 million tonnes of dairy products were exported, worth USD 182.0 million. In 2024, 98.8 million tonnes of dairy products were exported, worth USD

214.3 million (Table 8). Compared to 2023, in 2024, the volume of exports increased by 7%, and total revenue from dairy exports in 2024 increased by 17.7%

compared to 2023. In 2024, compared to 2023, revenues from exports of milk and non-condensed cream (+6%), condensed milk and cream (+8.2%), fermented milk products (+40.5%), milk whey (+22.9%), butter (+17%), and cheese (+35.5%). The growth in dairy exports was driven by increased demand on the global market. In 2024, the volume of dairy product imports

reached 58.7 million tonnes (Table 9), which is 0.5% more than in 2023. In monetary terms, imports in 2024 amounted to 282.7 million, which is 9.5% more than in 2023. During 2023-2024, imports of butter in monetary terms increased by 12.1%, milk and condensed cream by 12.8%, while other dairy products saw a decline (Per capita Consumption, n.d.).

Table 9. Import of major dairy products to Ukraine in 2015-2024

Code UKT ZED	Products	Year									
		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Volume, thous t											
0401	Milk and cream, non-condensed	0.4	0.6	0.8	1.3	3.6	13.0	14.4	9.4	5.1	2.0
0402	Milk and cream, condensed	0.8	1.1	1.7	2.4	2.6	6.1	7.8	1.2	1.3	1.5
0403	Fermented milk products	2.7	2.6	3.6	4.9	6.2	9.9	14.0	9.5	8.7	8.2
0404	Milk whey	1.1	0.7	1.4	2.1	3.2	5.1	9.6	4.9	6.9	6.1
0405	Butter and other fats	0.7	1.1	0.8	1.1	3.4	10.0	9.1	1.1	2.7	2.6
0406	Cheese	5.4	7.1	10.0	13.7	23.7	46.8	55.2	33.8	33.7	38.3
Value, mln USD											
0401	Milk and cream, non-condensed	0.8	1.1	1.4	2.1	3.6	11.6	13.4	8.6	6.1	4.0
0402	Milk and cream, condensed	1.7	2.1	3.8	5.7	5.8	14.0	21.2	4.0	4.7	5.3
0403	Fermented milk products	3.7	3.9	5.6	7.9	9.1	14.0	20.0	14.9	17.4	16.8
0404	Milk whey	2.1	1.6	2.4	3.1	5.2	6.9	12.3	6.9	12.5	10.8
0405	Butter and other fats	2.6	3.8	4.5	7.5	16.5	40.6	45.5	7.9	16.6	18.6
0406	Cheese	23.5	29.9	47.1	66.8	108.9	210.5	260.3	182.2	200.8	227.1
0401-0406 total		34.3	42.4	64.8	93.1	148.9	297.6	372.8	224.5	258.1	282.7

Note: UKT ZED – classification of goods used by the customs service of Ukraine

Source: calculated by the authors based on Per capita Consumption (n.d.)

According to Table 9, the structure of dairy product imports in 2015-2024 showed a fivefold increase in imports of milk and cream in physical volume and monetary terms, fermented milk products increased 2.3 and 3 times, respectively, milk whey increased 5.5 and 5.1 times, butter increased 3.7 and 7.2 times, and cheese increased 7.1 and 9.7 times. This may be due to a shortage of raw milk on the domestic market and higher prices for goods from Ukrainian producers. In 2024, the natural volume of dairy product imports reached 58.7 million tonnes, which is 0.5% more than in 2023. In monetary terms, imports in 2024 amounted to 282.7 million, which is 9.5% more than in 2023. During 2023-2024, imports of butter increased by

12.1% in monetary terms, milk and condensed cream by 12.8%, while other dairy products saw a decline (Per capita Consumption, n.d.).

In 2024, 58 companies specialising in the production of raw milk, ice cream, dairy products, colostrum and colostrum-based products have permits to export dairy products from Ukraine to the EU (Ukrinform, 2024). In 2024, Ukraine exported 30% of its total dairy exports to EU countries. Between 2015 and 2024, milk processing enterprises exported condensed milk and cream, whey, butter and cheese (Table 10). The information is taken from the gap between 2015-2016 and 2021-2024 in order to more clearly show the change in exports by country.

Table 10. Geography of Ukrainian dairy product exports in 2015-2024 (% of total exports for the product group)

2015		2016		2021		2022		2023		2024	
Country	%	Country	%	Country	%	Country	%	Country	%	Country	%
0402 - Condensed milk and cream											
Bangladesh	11.8	Kazakhstan	20.6	Israel	10.5	Poland	21.1	Poland	21.9	Poland	21.8
Georgia	8.6	Bangladesh	10.6	Malaysia	8.4	Israel	9.3	Bulgaria	10.1	Bulgaria	17.7
Kazakhstan	8.5	Turkmenistan	10.4	Bangladesh	7.8	Netherlands	8.0	Bangladesh	10.1	Israel	8.6
Turkmenistan	8.0	Armenia	8.0	Armenia	7.4	Lithuania	7.4	Israel	8.8	Germany	7.7
Armenia	6.5	Malaysia	5.1	Algeria	6.8	Bangladesh	7.2	Georgia	4.6	Romania	6.5
other countries	56.6	other countries	45.3	other countries	59.2	other countries	47.1	other countries	44.4	other countries	37.7

Table 10, Continued

2015		2016		2021		2022		2023		2024	
Country	%	Country	%	Country	%	Country	%	Country	%	Country	%
0404 – Milk whey											
Kazakhstan	12.0	China	14.8	China	28.1	China	27.0	China	37.2	Poland	26.4
Pakistan	11.5	Vietnam	14.6	Philippines	11.9	Poland	14.8	Poland	16.3	China	21.5
Vietnam	10.3	Pakistan	14.3	Vietnam	11.1	Malaysia	14.7	Jordan	6.9	Philippines	9.2
Egypt	8.1	Kazakhstan	11.1	Pakistan	8.1	Vietnam	7.3	Egypt	5.7	Vietnam	6.8
Myanmar	6.8	Uzbekistan	8.5	Malaysia	7.6	Pakistan	7.3	Turkey	3.7	Egypt	6.4
other countries	51.5	other countries	36.6	other countries	33.1	other countries	28.9	other countries	30.2	other countries	
0405 – Butter and other fats											
Morocco	18.9	Kazakhstan	26.4	Moldova	30.0	Poland	40.8	Moldova	40.5	Moldova	43.9
Azerbaijan	15.6	Georgia	14.7	Azerbaijan	22.3	Moldova	19.0	Azerbaijan	16.0	Azerbaijan	14.5
Egypt	15.2	Egypt	10.8	Kazakhstan	13.4	Azerbaijan	9.7	Israel	11.0	Bulgaria	7.6
Kazakhstan	9.3	Morocco	9.9	Georgia	10.4	Netherlands	5.5	Kazakhstan	10.4	Israel	6.3
Georgia	8.6	Netherlands	6.6	Israel	7.0	Israel	5.3	Poland	4.0	Poland	5.1
other countries	32.4	other countries	31.7	other countries	16.8	other countries	19.7	other countries	18.1	other countries	29.7
0406 – Cheese											
Kazakhstan	38.7	Kazakhstan	53.7	Kazakhstan	47.4	Kazakhstan	38.0	Kazakhstan	45.6	Moldova	33.2
russia	27.2	Moldova	26.8	Moldova	35.2	Poland	25.6	Moldova	31.5	Kazakhstan	30.4
Moldova	18.8	Egypt	7.8	Azerbaijan	4.2	Moldova	21.3	Latvia	6.8	Germany	9.5
Azerbaijan	5.5	Azerbaijan	3.5	Georgia	3.3	Latvia	3.3	Azerbaijan	2.8	Latvia	6.2
Uzbekistan	1.7	UAE	1.6	USA	2.5	Uzbekistan	2.0	USA	2.5	USA	3.3
other countries	8.1	other countries	6.6	other countries	7.4	other countries	9.7	other countries	10.7	other countries	22.6

Source: calculated by the authors based on Per capita Consumption (n.d.)

Table 10 shows that in 2015, the main consumers of condensed milk and cream exports were Bangladesh (11.8%), Georgia (8.6%), Kazakhstan (8.5%), whey – Kazakhstan (12%), Pakistan (11.5%), Vietnam (10.3%), butter – Morocco (18.9%), Azerbaijan (15.6%), Egypt (15.2%), cheese – Kazakhstan (38.7%), Russia (27.2%), Moldova (18.8%). In 2024, the geography of dairy product exports changed. The main consumers of milk and condensed cream exports were Poland (21.8%), Bulgaria (17.7%), Israel (8.6%), whey – Poland (26.4%), China (21.5%), the Philippines (9.2%), butter – Moldova (43.9%), Azerbaijan (14.5%), Bulgaria (7.6%), cheese – Moldova (33.2%), Kazakhstan (30.4%), Germany (9.5%). The State Service of Ukraine on Food Safety and Consumer Protection has opened access for Ukrainian dairy products to the markets of EU countries, as well as countries such as Canada, Japan, Korea, Great Britain, China, the Persian Gulf countries, and African countries, which is 29 countries worldwide (State Service of Ukraine on Food Safety and Consumer Protection, 2024b). The issue of exporting dairy products to Saudi Arabia and Morocco is being raised, as these countries have a high demand for dairy products, which creates opportunities for Ukrainian producers. Exporters and producers of dairy products could include Chile, Indonesia, India, Costa Rica, Colombia, Brazil, Venezuela, etc. (Prospects for the entry of Ukrainian

dairy, 2024). The successful export of dairy products by Ukrainian producers will depend on their adaptation to the requirements of international markets, the transformation of the export capabilities of Ukrainian dairy producers in compliance with international standards, taking into account consumer specifics and competitive conditions, increasing investment in the dairy industry, and improving logistics, despite the fact that raw milk production is carried out in wartime conditions.

Despite the challenges and consequences of the war, Ukraine's dairy industry continues to develop, invest in productivity and technology, increase the volume and quality of raw milk, improve the regulatory framework in line with European requirements, which is positively perceived by market participants, and supply dairy products to Ukrainians and countries around the world. However, its development requires state support, so Ukrainian legislation in the dairy industry must be adapted to EU requirements. Thus, dairy producers are attracting funds from charitable organisations, increasing credit limits under the Affordable Loans 5-7-9 programme (State programme Affordable Loans 5-7-9%, 2024), trying to establish transparent and objective payment terms for dairy products, and expanding state support for investments in the dairy industry. In EU countries, the state compensates 50% of investments in the dairy industry (Gladiy &

Prosovych, 2022), and it would be good if this were also the case in Ukraine. With the help of investments, enterprises will be able to increase milk production, build new factories, modernise existing milk production and processing enterprises, increase exports of dairy products, and introduce innovative technologies that will promote the production of dairy products that meet global quality requirements, reduce production costs, and increase efficiency. Milk producers are also trying to improve the professional and qualification level of personnel involved in the dairy industry, using the experience of practitioners from foreign countries who have the necessary knowledge, innovative technologies and the development of cooperation between milk producers and processors.

The dairy industry provides the population with dairy products, which are part of the country's food security. The efficiency of its activities affects the standard of living of the country's population. Authors V. Sobolev *et al.* (2024) noted that the consumption of dairy products by the population depends on consumption traditions, socio-cultural characteristics, habits, trends in consumption culture, etc. However, the main factor limiting the consumption of dairy products in accordance with rational norms is the low income of the majority of the population. The authors agreed with this study, as dairy products are an important element of a healthy diet and a healthy lifestyle for the population. However, as noted by researchers V. Antoshchenkova & Ya. Kravchenko (2022) in their work, consumers' growing interest in plant-based substitutes for animal milk has led to an increase in the production of animal product analogues. In this regard, in order to maintain the competitiveness of natural milk, it is necessary to convince consumers of its beneficial properties, provide complete and reliable information about the dangers of alternative products, and combat unfair competition and the increase in counterfeit dairy products. Similar research on the development of the dairy industry in Ukraine was conducted by Z. Rozhko *et al.* (2020), who used a systematic approach to the development of the dairy industry in Ukraine and noted that its development depends on investments in this industry, improved customs regulation of product exports, improved logistics, and the benchmarks could be: a balanced chain, supply, technological innovations and automation of production processes, consumer orientation, introduction of new product quality standards, investment in personnel, use of data and analytics, which will allow dairy industry enterprises to have information on the state of the dairy product market and facilitate strategic decision-making.

Researchers O. Kozak & O. Hryshchenko (2022) studied the distribution of dairy farms by herd size. According to their research, in 2021, only 3% of farms

worldwide had more than 10 cows, which accounted for 37% of the dairy herd and produced 63% of milk, and only 213,000 farms, or 0.2%, were commercial farms, but their share in milk production is 42%. In their opinion, the decrease in the number of dairy farms was accompanied by an increase in their size. The similarity of their research with the authors was that in order to increase the production of high-quality milk raw materials, it is necessary to merge the farms of the population, which are the main producers of milk, into peasant farms or cooperatives, where, in addition to procurement, raw milk is processed and dairy products are sold, which are jointly owned by the producers. The same opinion was expressed by researcher O. Shpychak (2021), who noted that efforts to restructure milk production by increasing the number of cows on farms from 1-3 to 15-40 will contribute to the creation of mini-farms, the elimination of its depersonalisation in terms of sales, and the combination of the producer and seller of dairy products in a single process. Their research also indicated that large integrated milk production and processing systems can be formed on the basis of dairy cooperatives. Scientists S. Poperechny & O. Salamin (2022) believed that cooperatives are viable if, in addition to procurement on a cooperative basis, they also process milk and sell dairy products, and the products produced are jointly owned by the producers of raw materials. The authors of this study agreed with this opinion, since the coordination of interests of all participants in the cooperative ensures proper coordination of activities in the field of production and processing of raw milk. It was also emphasised that the key factor regulating market relations and the volume of dairy production is price, which influences the pace and proportions of development of enterprises and industries, as well as ensuring their profitability.

V. Kotelevich *et al.* (2023) noted that in order to ensure the production of safe dairy products, their competitiveness in the foreign market and demand in the domestic market, it is advisable to introduce international standards and an effective HACCP (Hazard Analysis and Critical Control Points) system, which makes it possible to avoid potential risks during the production of raw materials, processing, storage, transportation, sale and use of milk and dairy products and ensures control and responsibility of producers throughout the food chain from farm to table. Joint cooperation between governments, producers and consumers of milk and dairy products will contribute to safety and appropriate quality. Scientists V. Bondarenko & O. Omelyanenko (2024) proposed the use of SWOT analysis to understand the problems and opportunities of the dairy industry, which allows identifying the strengths and weaknesses of the dairy industry. Among the strengths, they noted the

introduction of innovative technologies, an effective organisational structure and management style, compliance with international quality standards, a wide range of products, and the use of “extra” milk. These factors will contribute to increasing the competitiveness of the dairy industry in times of crisis, which will weaken the position of competitors, creating opportunities for expanding export markets and entering new segments.

Similar to the authors’ research, researcher A. Uzhva (2024) noted that the dairy industry should receive state support. After all, milk production and processing must be profitable, and the mechanisms of state support for the industry must be clear and guaranteed, as the country has the potential for this (land, traditions of dairy farming, skilled labour, water). Scientists M. Gladiy & O. Prosovykh (2022) share this opinion and concluded in their research that it is possible to revitalise the dairy business, but this requires increased state support, namely investments, grants, subsidies and funding for the dairy industry. Only close contact, interaction and consideration of the interests of all stakeholders – producers, processors and the state – as well as the development of a strategy and the implementation of an effective mechanism for its implementation can ensure the sustainable growth of the dairy industry in the long term.

In conclusion, it can be stated that the further development of the dairy sector depends on the coordinated cooperation of all participants in the production of raw milk, processing, storage, transportation, sale and use of dairy products. State funds should be directed towards supporting milk and dairy product producers and increasing their competitiveness in both domestic and foreign markets.

CONCLUSIONS

The dairy market is an important segment in providing the population with valuable food products. Research into its functioning in Ukraine during 2015-2024 showed negative trends, namely a 34% decrease in milk production; an eightfold increase in dairy imports; fluctuations in prices on the milk market; the low technological level of milk production in private households resulted in low-quality raw materials, and the lack of coordination between them and milk processing enterprises led to dairy products not meeting international quality standards. Since private farms are the main milk producers, all efforts should be focused on improving milk quality by purchasing modern milking and cooling equipment and facilitating the creation of conditions for their transformation into dairy cooperatives.

Ukraine has the potential to develop its dairy industry, namely favourable natural and climatic conditions, developed livestock farming and qualified personnel. The successful development of the dairy industry depends on cooperation between milk producers, processors and consumers; compliance with international standards of quality and safety of Ukrainian dairy products, which will contribute to the expansion of the range, increase in the volume and scale of dairy exports, expansion or entry into new international markets, increase in the production of organic and lactose-free dairy products, which are oriented towards consumers who prefer healthy food; adequate state support, namely a regulatory and legislative framework, standards, grants, subsidies, support programmes for raw milk producers, export promotion, and partial indexation of the modernisation of the dairy industry. State support for the development of the dairy industry is important because it will help create opportunities for dairy companies to develop and produce dairy products in accordance with international sanitary standards and will facilitate the entry of dairy products into world markets. Through the joint efforts of the state and dairy producers, the domestic dairy market can successfully sell dairy products on world markets and generate profits for the state and producers. Prospects for further research lie in the development of mechanisms to increase the competitiveness of Ukrainian dairy products on international markets by improving production technologies, ensuring quality and effective state support.

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CONFLICT OF INTEREST

The study relied on reliable information and included references to other scientific works. The authors believe that this fact does not affect the objectivity of data collection, analysis, or the writing of the manuscript. The other authors declare that they have no conflict of interest.

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Функціонування ринку молокопродукції в Україні

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Анотація. Молочні продукти залишаються важливою складовою харчування населення України, однак галузь стикається з низкою проблем, спостерігаються негативні процеси, пов'язані із зменшенням обсягів виробництва молока, дефіцит якісної сировини, зростання імпорту, низька платоспроможність споживачів, логістичні труднощі та вплив війни. Це вимагає нових підходів до розвитку галузі та поглибленого аналізу ринку молокопродуктів. Метою статті було проаналізувати функціонування ринку молока і молокопродукції, виокремити його проблеми та запропонувати заходи успішного розвитку молочної галузі. У процесі дослідження використано такі методи: абстрактно-логічний, статистичний й табличний із ціллю зібрання, обробки й аналізу інформації щодо виробництва молока, надходження молока на переробні підприємства, якості молока-сировини, експорту та імпорту молокопродукції протягом 2017-2024 рр.; графічний був використаний для аналізу експорту й імпорту молокопродукції, при формуванні рейтингу регіонів за виробництвом молока у 2024 р., при дослідженні індексу цін молока-сировини; при дослідженні залежності споживання питного молока та масла у 2023 р. від обсягів виробництва на 1 особу використано кореляційно-регресійний аналіз. Результати дослідження показали невідповідність пропозиції молоко-сировини на ринку щодо завантаженості молокопереробних підприємств, як результат, обсяг молокопродукції нижче норми її споживання. Окреслено структуру й частку експорту української молокопродукції у країни світу. Досліджено залежність споживання молока питного та масла від виробництва молока-сировини. Практичне значення полягає в тому, що дослідження функціонування ринку молокопродукції можуть бути орієнтиром при ухваленні рішень стосовно напрямків збільшення обсягів виробництва й переробки молока, збільшення споживання молокопродуктів та зростанні обсягів експорту продукції молочної галузі

Ключові слова: виробництво; якість; індекс цін; експорт; імпорт

The effect of biostimulants and glyphosate on the vertical migration of elements in agricultural soils

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Abstract. The purpose of this study was to evaluate the vertical migration patterns of macro- and microelements in southern chernozem soils under the influence of binary mixtures of glyphosate-based herbicides and various classes of biostimulants. The intensification of contemporary agricultural systems has precipitated a fundamental shift in the biogeochemical cycling of nutrients and contaminants within the pedosphere. This study presented an exhaustive investigation into the vertical migration mechanics of macro- and microelements within a model soil continuum, specifically analysing the perturbations introduced by the co-application of glyphosate-based herbicides and diverse biostimulant classes (fulvic acids, potassium humates, and complex stubble biodestructors). High-resolution Energy Dispersive X-Ray Fluorescence (ED-XRF) spectrometry was utilised to quantify the redistribution of Fe, K, Ca, Mn, Zn, Cu, and Pb across three distinct soil horizons in controlled microcosms. The research delineated the diametrically opposed geochemical functions of humic fractions: fulvic acids ("BioFulvo") acted as aggressive mobilising agents, stripping transition metals from the medial profile and exacerbating leaching risks (Fe depletion of -30.1% in the transit zone), whereas potassium humates functioned as stabilising geochemical barriers, effectively immobilising anthropogenic lead and retaining nutrients in the root zone. A critical discovery of this study was the identification of a "hyper-mobilisation" phenomenon arising from the synergistic interaction between glyphosate and fulvic acids, which induced a 39% surge in soluble iron concentrations, likely through the development of ternary phosphonate-fulvate-metal complexes. Conversely, microbial-humic biodestructors demonstrated a unique "biofortification" potential, maintaining high zinc and manganese bioavailability without compromising profile stability. These findings underscored the necessity of a differentiated approach to agrochemical management, suggesting that while fulvic acids enhance rapid nutrient transport, their combination with

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herbicides on sensitive soils poses significant environmental risks, which can be mitigated by the buffering capacity of high-molecular-weight humates

Keywords: soil biogeochemistry; vadose zone transport; XRF spectrometry; humic substances; fulvic acids; heavy metal remediation; precision agriculture

INTRODUCTION

The contemporary paradigm of intensive agriculture is defined by a paradoxical challenge: the imperative to maximise crop yields to support a burgeoning global population competes directly with the preservation of the soil resource base. The soil profile, once viewed merely as a physical substrate for plant anchorage, is recognised as a complex, heterogeneous biogeochemical reactor where chemical, physical, and biological processes intersect to determine the fate of both essential nutrients and xenobiotic contaminants. The application of concentrated fertilisers, systemic herbicides, and metabolic enhancers has fundamentally altered the natural lithogenic and pedogenic cycles of elements. A critical, yet often overlooked, aspect of soil health is the vertical distribution of chemical elements within the vadose zone.

Global geospatial modelling by F. Tang *et al.* (2021) confirmed that 64% of agricultural land is at risk of pesticide pollution, explicitly identifying vertical leaching as a critical pathway in permeable soil systems. In natural pedogenesis, this distribution is driven by millennial-scale weathering and leaching processes. However, in modern agroecosystems, the application of agrochemicals introduces rapid, anthropogenic forcing that can overwhelm natural buffering capacities. The mobility of essential micronutrients (e.g., Zn, Mn, Cu) determines crop nutritional quality and resistance to abiotic stress, while the unchecked migration of toxic trace elements (e.g., Pb, Cd, As) poses severe risks to groundwater quality and food safety. The “chromatographic” effect of the soil profile, where different layers act as retention plates or elution zones, dictates whether an element becomes a nutrient for the crop or a pollutant in the aquifer.

The complexity of these interactions has spurred a wave of extensive research, driven largely by advancements in spectroscopic instrumentation and molecular modelling. Consequently, the validation of Portable X-ray Fluorescence (pXRF) has become a central theme in modern pedometrics. R. Ravansari *et al.* (2020) demonstrated the efficacy of pXRF for soil analysis, a conclusion robustly supported by the landmark meta-analysis of E. Jenkins *et al.* (2025). By synthesising data from 84 independent validation studies, E. Jenkins *et al.* (2025) established that advanced pXRF instruments achieve laboratory-grade accuracy for heavy

metals (Pb, As, Zn, Cu), particularly under controlled ex situ conditions. This comprehensive review confirms that minimising matrix interferences through sample drying and homogenisation eliminates moisture-induced scattering and particle-size shadowing, thereby validating pXRF as a reliable platform for high-resolution elemental profiling. Complementing these analytical insights, T. Tavares *et al.* (2023) highlighted that XRF total-element profiling effectively captures the elemental stocks serving as reservoirs for bioavailable pools. The non-destructive nature of this technique allows for the preservation of soil structure, which is critical when assessing the spatial distribution of elements in microcosm studies. Against this technological backdrop, glyphosate [N-(phosphonomethyl)glycine] remains the most widely used herbicide globally, and its geochemical purpose is a subject of intense scrutiny.

E. de Gerónimo & V. Aparicio (2022) reported that glyphosate adsorption depends strongly on soil pH and competing phosphate, and that dissolved organic matter often competes for sorption sites on mineral surfaces; thus, agricultural practices that shift soil pH can substantially alter herbicide mobility. G. Qian *et al.* (2022) found that fulvic acids, due to their lower molecular weight and greater acidity, tend to facilitate arsenic mobility in tailings, whereas humic acids more often immobilise metalloids. The mechanistic understanding of glyphosate mobility has been significantly refined by Y. Jiao *et al.* (2024), who utilised multispectral analysis and Density Functional Theory (DFT) to elucidate the adsorption-complexation dynamics in Mollisols. The research demonstrated that the presence of dissolved organic matter (DOM) fundamentally alters the thermodynamic landscape of the soil solution, shifting glyphosate adsorption from a multilayer heterogeneous process to a single-layer regime. Furthermore, the researchers confirmed that glyphosate forms stable soluble complexes with humic fractions through static quenching mechanisms dominated by hydrogen bonding and van der Waals forces, specifically targeting C-O functional groups. This interaction effectively prevents the herbicide’s fixation onto mineral surfaces, thereby facilitating the “hyper-mobilisation” and co-transport of glyphosate-metal complexes through the vadose zone.

The reviews by R. Zhang *et al.* (2022) and Q. Liu *et al.* (2025) have redefined the role of amino acid biostimulants in nutrient acquisition, classifying them as “natural chelating agents” with distinct thermodynamic properties. Their analysis established that amino acids enhance metal uptake by creating “weak” or moderate chelation complexes that protect nutrients from soil fixation while possessing stability constants low enough to permit rapid ligand exchange at the rhizoplane. This “catch-and-release” mechanism differs fundamentally from the strong, persistent sequestration characteristic of synthetic chelators like EDTA (ethylenediaminetetraacetic acid), ensuring that essential elements are bioavailable for plant metabolic use rather than being solubilised for leaching into the subsoil. This issue is of particular relevance in Ukraine, which holds a significant portion of the world’s chernozem (black soil) reserves.

Despite the breadth of individual studies, there is a paucity of comprehensive research integrating the simultaneous effects of herbicides and different classes of biostimulants on the vertical stratification of the soil chemical matrix. Most studies focus on surface interactions or plant uptake, neglecting the intermediate transport processes within the vadose zone. This gap is critical because the vadose zone acts as the transmission filter between the agrosphere and the hydrosphere. The purpose of the study was to quantify the vertical redistribution of macro- (Fe, K, Ca) and microelements (Zn, Mn, Cu) under the influence of fulvic acids, humic acids, and amino acids. The research objectives were to evaluate the specific impact of glyphosate salt formulations (potassium vs. isopropylamine) on metal mobility, uncover synergistic or antagonistic geochemical effects when biostimulants are co-applied with herbicides, and assess the environmental risks associated with the mobilisation of toxic elements (Pb) utilising the precision of XRF spectrometry.

MATERIALS AND METHODS

Experimental microcosm design

The experimental part of the study, including microcosm preparation and instrumental sample analysis, was conducted between November 14 and 15, 2025. The research was performed at the laboratory of the Department of Ecology and Environmental Protection Technologies, Admiral Makarov National University of Shipbuilding. A controlled laboratory microcosm approach was employed to simulate the dynamics of the arable soil layer and the upper vadose zone (OECD Test Guideline 312 adapted). The soil matrix used was southern chernozem (calcic chernozem) collected from the arable horizon (0–30 cm) in the steppe zone of

Ukraine (Mykolaiv Oblast). The soil was characterised by a heavy loam texture, a humus content of 3.4%, and a slightly alkaline reaction with a pH (KCl) of 7.2. This soil type was characterised by micellar carbonates and high biological activity, making it highly representative of the semi-arid agricultural zones of the Black Sea region. The application of agrochemical agents was executed in a three-stage sequence to model a specific agronomic protocol involving pre- and post-herbicide fertilisation. In the first stage, the soil samples were irrigated with biostimulant solutions to prime the soil matrix: 25 mL of “BioFulvo” solution (at a concentration of 1:100) or 25 mL of “Humate Potassium” solution (at a concentration of 1:300) were applied to the respective experimental units. In the second stage, performed one week after the initial biostimulant application, the herbicide treatments (“Uragan Forte” or “Otaman”) were applied using 15 mL of solution per sample, prepared at a concentration of 10 mL of herbicide per litre of water. In the third stage, one week following the herbicide application, the soil samples were treated again with the biostimulants (“BioFulvo” or “Humate Potassium”) using the exact same volumes and concentrations as in the first stage. This design allowed for the assessment of element migration under conditions of repeated biostimulant loading.

The experimental design involved creating a leaching water regime imitating intensive precipitation or irrigation. During a 30-day incubation period (corresponding to the active vegetation phase), distilled water was added to the columns in a volume equivalent to the monthly precipitation norm for the study region (approximately 60 mm), ensuring a downward moisture flow (eluvial regime). This allowed for the modelling of vertical migration processes of dissolved substances. Upon completion of incubation, the soil monoliths were subjected to rapid freezing to fix chemical gradients and prevent moisture redistribution. The frozen columns were divided into three discrete horizons for subsequent analysis, allowing for a detailed assessment of the profile’s chromatographic effect:

- Zone A (Proximal/Upper): 0–2.7 cm. A zone of direct agrochemical application, maximal root mass concentration (in pot experiments), and highest microbiological activity.
- Zone B (Medial/Transit): 2.7–5.3 cm. A buffer zone where adsorption and desorption processes determine the further fate of migrating elements.
- Zone C (Distal/Lower): 5.3–8.0 cm. A zone of accumulation or washout bordering the drainage system. Increased element concentration in this zone is a direct indicator of leaching risk into groundwater.

Experimental treatments and analytical methods

To investigate the differentiated impact on element migration, a spectrum of preparations representing various chemical classes and mechanisms of action was selected. Among the biostimulants, the study examined “BioFulvo,” a preparation based on highly concentrated fulvic acids. Chemically, these are low-molecular-weight organic acids (under 1,000 Da) enriched with oxygen-containing functional groups, specifically carboxyl (-COOH) and phenolic (-OH) groups. Their presumed mechanism involves high solubility across the entire pH range and the ability to form stable, soluble chelate complexes with polyvalent cations like Fe³⁺, Zn²⁺, and Cu²⁺, thereby promoting their mobilisation.

In contrast to the fulvic acids, “Potassium Humate” was utilised as a source of high-molecular-weight humic acids derived from leonardite. These are macromolecular structures (exceeding 10,000 Da) possessing a polyanionic character with high cation exchange capacity. Their primary function in the soil profile was the synthesis of insoluble complexes with heavy metals and the aggregation of soil particles, effectively acting as a geochemical barrier. Additionally, the complex biological preparation “StimOrganic” was included as a stubble biodestructor. Its composition featured a consortium of living cells and spores of bacteria (*Bacillus subtilis*, *Bacillus licheniformis*) and fungi (*Trichoderma viride*, *Trichoderma lignorum*) with a titre of at least 1.0×10^9 CFU/cm³, enriched with 100 g/L of humic substances and microbial metabolic products. Its mechanism relied on the enzymatic destruction of organic residues and the production of siderophores and organic acids (such as gluconic and citric acids), ensuring biologically regulated element mobilisation.

Regarding herbicides, “Uragan Forte” (Syngenta), a potassium salt of glyphosate (500 g/L), was selected for its specific surfactant system designed for rapid cuticular penetration. As noted by O. Litvinova *et al.* (2023), such surfactants can significantly reduce the surface tension of the soil solution, enhancing the physical migration of substances. This was compared against “Otaman” (Alfa Smart Agro), a classic isopropylamine salt of glyphosate (480 g/L). The isopropylamine cation in this formulation was bulkier compared to the potassium ion, which may influence the kinetics of herbicide sorption on clay minerals. The research

investigated both separate applications of these preparations and their binary mixtures (e.g., Uragan + BioFulvo) to imitate the common tank mix practices in Ukraine. Elemental analysis was conducted using a Hitachi X-MET8000 portable XRF spectrometer (Japan). This instrument represents the advancement in field spectrometry, bridging the gap between field convenience and laboratory precision.

Technical specifications:

- Detector: High-performance Silicon Drift Detector (SDD) with a large active area, allowing for high count rates and excellent energy resolution.

- Excitation Source: X-ray tube optimised with BOOST™ technology, which enhances the sensitivity for heavy elements and allows for lower Limits of Detection (LOD) compared to conventional diode-based systems.

- Calibration: The instrument was calibrated using the Soil-FP (Fundamental Parameters) mode. This algorithm is critical for soil analysis as it mathematically models the interaction of X-rays with the sample matrix, automatically correcting for inter-element matrix effects (absorption and secondary fluorescence) caused by variations in soil density.

Measurements were taken in triplicate for each layer of each replicate to ensure statistical robustness. The spectra were analysed for characteristic K-alpha and L-alpha lines. Specifically, Iron (Fe) was analysed at ~6.40 keV, a region free from significant interference in silicate matrices. Raw spectral data (counts per second) were converted to concentrations (ppm) using the Soil-FP calibration curves. To account for local soil heterogeneity, measurements were performed in triplicate for each specific horizon layer. The final value for each data point was calculated as the arithmetic mean of these three technical replicates, ensuring a representative profile analysis. Consequently, vertical migration trends were evaluated by comparing these averaged concentration gradients, and leaching indices were calculated as the ratio of concentration in Zone C to Zone A.

RESULTS AND DISCUSSION

Baseline geochemical stratification (control group)

The analysis of the control group provides the reference state for the soil's natural vertical distribution. As shown in Table 1, the soil exhibits specific pedogenic trends even without external chemical intervention.

Table 1. Vertical distribution of elements in control soil (ppm)

Element	Layer 1 (0-2.7 cm)	Layer 2 (2.7-5.3 cm)	Layer 3 (5.3-8.0 cm)	Trend analysis
Fe (Iron)	15,536	14,818	15,048	Stable / uniform profile
K (Potassium)	9,750	9,280	10,280	Eluviation (leaching)
Ca (Calcium)	7,727	6,255	6,785	Surface accumulation
Ti (Titanium)	2,439	2,068	2,234	Matrix stability marker

Table 1, Continued

Element	Layer 1 (0-2.7 cm)	Layer 2 (2.7-5.3 cm)	Layer 3 (5.3-8.0 cm)	Trend analysis
Mn (Manganese)	385	340	360	Biogenic accumulation
Zn (Zinc)	81	83	86	Slight downward migration
Pb (Lead)	20	15	19	Variable / anthropogenic

Source: developed by the authors

In the control variant, two competing hydrological and biogeochemical processes are observed. Potassium (K) demonstrates a clear tendency to accumulate in the lower horizon (10,280 ppm vs 9,750 ppm at the surface). This indicates a leaching regime where highly soluble monovalent cations move downward under the influence of gravitational water. This is a typical characteristic of soils with a percolation water regime, where potassium, if not intercepted by roots or fixed by illitic clay minerals, migrates to sub-arable horizons. Conversely, Calcium (Ca) and Manganese (Mn) are enriched in the surface layer. For calcium (7,727 ppm in Layer 1 vs 6,255 ppm in Layer 2), this is likely due to the evaporation effect of the soil solution, which draws bicarbonate-rich water to the surface where calcium carbonate precipitates upon drying. For manganese, such enrichment reflects the “biological pump” mechanism: plants (precursors) uptake Mn from depth and return it to the surface through plant residues, creating a nutrient-rich top layer. The relative uniformity of lithogenic markers, such as Titanium (Ti), confirms the mineralogical

homogeneity of the soil column, validating the experimental design. Iron (Fe) acts as a reference element in these soils. Its stability indicates that without chemical intervention (like chelating agents), the soil matrix is stable, and there is no massive redox-induced migration under natural conditions. In the absence of chelating fertilisers, Zinc (Zn) is relatively immobile. The slight increase in depth might be conditioned by association with clay particles (illuviation) which naturally migrate downwards over long periods. Lead (Pb) is tightly bound to organic matter in the topsoil. Its lack of migration in the control group confirms that there are no natural acidic conditions or complexing agents moving toxic metals into the groundwater – until agents like fulvic acid are added.

Impact of biostimulants and herbicides on the vertical distribution of soil elements

The application of the “BioFulvo” preparation caused the most radical restructuring of the geochemical profile, characterised by aggressive mobilisation of transition metals (Table 2).

Table 2. Element dynamics under “BioFulvo” treatment (ppm)

Element	Layer 1	Layer 2	Layer 3	Deviation from control (Layer 2)
Fe	14,082	10,358	12,400	-30.1% (severe depletion)
Zn	92	58	79	-31.7% (severe depletion)
Cu	23	15	20	-26.8% (mobilisation)

Source: developed by the authors

The comparison of soil horizons in Table 2 reveals a classic chromatographic leaching effect, where the medial soil layer functions as a primary donor of elements rather than a buffer. In the upper proximal zone (Layer 1), the iron concentration stands at 14,082 ppm; while this is lower than the control, it represents only the initial phase of mobilisation where high concentrations of fulvic acids begin to solubilise minerals within the organic-rich surface matrix. A substantial geochemical anomaly emerges in the medial zone (Layer 2), where Iron (Fe) levels precipitously drop to 10,358 ppm and zinc decreases to 58 ppm. This pronounced decline, representing a roughly 30% reduction compared to the control, indicates that low-molecular-weight fulvic acids have effectively stripped metal ions from the exchange complex, transforming

this horizon into a “zone of depletion” or a geochemical vacuum. Although concentrations partially recover in the distal zone (Layer 3) to 12,400 ppm for iron and 79 ppm for Zinc (Zn) – confirming a vertical downward flux from the depleted middle layer – these values remain significantly below the control levels for the same depth. This specific distribution profile suggests that the fulvic acid complexes are sufficiently stable to bypass the lower adsorption barriers, meaning a significant portion of the mobilised metal load likely passed through the entire soil column and was lost to drainage, thereby posing a risk of groundwater contamination. In sharp contrast to the mobilising action of fulvic acids, the “Humate Potassium” treatment acted as a stabilising agent, reinforcing the soil’s capacity to retain cations and structure (Table 3).

Table 3. Element dynamics under “Humate potassium” treatment (ppm)

Element	Layer 1	Layer 2	Layer 3	Key observation
Fe	9,107	14,409	12,411	Apparent surface depletion/masking
K	6,739	9,277	8,294	Fixation/interlayer entrapment
Pb	13	18	15	Surface immobilisation

Source: developed by the authors

The geochemical profile resulting from the application of Potassium Humate demonstrates a distinct mechanism of stabilisation, functioning diametrically opposite to the mobilisation observed with fulvic acids. In the proximal horizon (Layer 1: 0-2.7 cm), a significant reduction in detectable iron concentrations to 9,107 ppm was recorded. Unlike the depletion caused by leaching, this surface reduction is interpreted as an immobilisation phenomenon where high-molecular-weight humic acids form insoluble organo-mineral complexes and coat mineral particles, effectively “masking” the metal from rapid solubilisation. Crucially, the medial zone (Layer 2: 2.7-5.3 cm) retained high iron levels (14,409 ppm), closely mirroring the natural baseline found in the control. This preservation of the middle horizon confirms that the humic amendment successfully shielded the mineral matrix from desorption processes, maintaining the structural integrity of the soil profile preventing the creation of a “depletion zone”. A specific geochemical anomaly was observed regarding Potassium (K) distribution. Despite the introduction of an external potassium source via the humate preparation, the concentration of this element in the upper layer (6,739 ppm) was notably lower than in the control. This counter-intuitive result indicates the activation of a fixation mechanism, where humic substances facilitate the entrapment of potassium ions within the interlayer spaces of clay minerals. Rather than remaining in the soil solution where it would be vulnerable to gravitational washout, the potassium was sequestered into the structural phase of the medial zone (9,277 ppm) and distal zone (8,294 ppm). This

process suggests that the humates promoted the transition of exchangeable potassium into a non-exchangeable, fixed form, thereby reducing immediate losses while conserving the nutrient pool within the soil column.

The barrier function of the humate treatment was most critically evidenced by the behaviour of Lead (Pb). The proximal layer exhibited a reduced concentration of 13 ppm compared to the control baseline of 20 ppm. Most importantly, this surface reduction did not correspond to an accumulation in the distal accumulation zone (Layer 3), where levels remained low at 15 ppm. This distribution pattern confirms that the lead was not washed down but was effectively immobilised in situ at the point of contact or within the upper matrix. The macromolecular humic structures functioned as a “geochemical anchor”, binding the toxic cations through strong inner-sphere complexation and physical entrapment. Consequently, the treatment successfully prevented the vertical migration of lead into the lower horizons, thereby mitigating the risk of groundwater contamination. The treatment with the stubble destructor (“StimOrganic”) occupied a functional middle ground, optimising the “Bioavailability vs. Leaching” trade-off essential for precision agriculture. The data presented in Table 4 illustrates the unique “regulatory” capacity of the StimOrganic biodestructor, which fundamentally differs from both the aggressive chemical mobilisation of fulvic acids and the rigid fixation of humates. The vertical distribution profile of microelements under this treatment is characterised by exceptional uniformity, suggesting a mechanism of biological homeostasis rather than passive physical transport.

Table 4. Micronutrient retention with biodestructors (ppm)

Element	Layer 1	Layer 2	Layer 3	Distribution profile
Zn	107	103	100	High & uniform
Mn	396	350	386	Stable

Source: developed by the authors

In the proximal horizon (Layer 1: 0-2.7 cm), the application of the biodestructor resulted in a high level of zinc bioavailability (107 ppm) compared to the control (81 ppm). Unlike the fulvic acid treatment, where mobilisation led to immediate downward migration, the microbial complex successfully retained these mobilised nutrients in the upper root-accessible zone. This retention

is likely facilitated by the synthesis of microbial biomass and the development of temporary, labile complexes with amino acids and enzymes produced by the *Bacillus* and *Trichoderma* consortium present in the preparation.

The medial zone (Layer 2: 2.7-5.3 cm) demonstrated a remarkable stability that contrasts sharply with the “depletion zones” observed in other treatments.

Zinc concentrations remained at 103 ppm, and manganese at 350 ppm, showing virtually no significant gradient relative to the surface layer. This absence of a sharp concentration drop indicates that the biodestructor prevents the rapid gravitational leaching of elements. Instead of being washed through this layer, the elements are maintained in a state of dynamic equilibrium, likely regulated by the diffusion of microbial siderophores which solubilise metals only to the extent required for biological activity, effectively buffering the soil solution against sharp geochemical fluctuations. The distal zone (Layer 3: 5.3-8.0 cm) confirmed the safety of this approach regarding groundwater contamination risks. Zinc levels (100 ppm) and manganese levels (386 ppm) were comparable to the upper horizons, resulting in a Leaching Index (LI) close to 1.0. This uniform column-wide distribution signifies that the biodestructor achieved “smart mobilisation”: it increased the total pool of available nutrients throughout the profile without creating a surplus of free ions that would be lost to drainage. Consequently, the distinct stratification typical of chemical leaching was replaced by a biologically homogenised profile, optimal for root development throughout the entire depth of the arable layer.

The most interesting finding of the study was the detection of a fundamental divergence in geochemical behaviours when glyphosate herbicides were co-applied with different fractions of humic substances. The interaction between the glyphosate formulation “Uragan Forte” and the fulvic acid preparation “BioFulvo” resulted in a distinct synergistic effect characterised as “hyper-mobilisation”. In this variant, the iron concentration within the soil profile surged to 21,592 ppm, exceeding the control level by 39%. This extreme value, which surpasses natural variability, indicates a massive phase transition of iron from the solid mineral state into the soil solution. This non-additive phenomenon suggests the synthesis of soluble ternary complexes, where fulvic acids destabilise Fe-O bonds on mineral surfaces while glyphosate simultaneously chelates the released metal, effectively maintaining it in a soluble state. Such a mechanism poses a dual risk: potential phytotoxicity due to iron overload and the accelerated leaching of the herbicide itself, as the dissolution of iron oxides – the primary sorbent for glyphosate – facilitates its downward migration. Conversely, the addition of “Potassium Humate” to glyphosate mixtures produced an antagonistic, stabilising effect. In these trials, the system exhibited high retention of calcium (8,805 ppm) and the effective confinement of heavy metals. This stabilisation is attributed to the buffering capacity of high-molecular-weight humic acids, which likely neutralised the pH reduction associated with glyphosate

hydrolysis and provided ample surface area for the re-adsorption of mobilised ions, thereby neutralising the geochemical disturbance caused by the herbicide.

Mechanisms, risks, and contextual significance

The vertical migration of chemical elements within the vadose zone is not merely a physical displacement but the result of a dynamic and competitive equilibrium between sorption processes on the solid soil phase and solubilisation kinetics in the liquid phase. The results of this study clearly delineate the divergent roles played by different fractions of humic substances in this equilibrium, challenging the conventional view of organic amendments as a monolithic group. It is a fundamental and well-established fact in soil chemistry that fulvic acids, characterised by their low molecular weight and high density of oxygen-containing functional groups, function as aggressive transport agents in soil environments. Due to their high stability constants with metal ions and solubility across a broad pH range, these fulvic complexes are capable of overcoming the natural electrostatic and steric barriers of the soil matrix that typically retain cations. In the conducted experiment, this mechanism was evidenced by the critical depletion of iron and zinc in the medial horizons treated with “BioFulvo”. This confirms that on light-textured soils or those undergoing dehumification – a condition increasingly characteristic of degraded Ukrainian chernozems – the application of concentrated fulvic acids carries a significant risk of accelerating the leaching of essential microelements, effectively stripping the arable layer of its nutritional potential.

In contrast to this mobilisation, the application of “Potassium Humate” resulted in the effective immobilisation of Lead (Pb). This aligns with the remediation strategies proposed by O. Sytar & N. Taran (2022) and Y. Lu *et al.* (2025), who advocated for the use of humates to create geochemical barriers. Conversely, Y. Lu *et al.* (2025) demonstrated that humic acid composites (e.g., with hydroxyapatite) effectively immobilise Cd and Pb, reducing their translocation to grains, thus positioning humic acids as remediation agents. Unlike the mobile fulvic fraction, humic acids facilitate the synthesis of insoluble organo-mineral aggregates and promote the fixation of metals within the interlayer spaces of clay minerals. This property is critically important for the restoration of the soil’s barrier function, especially given the data from V. Datsenko (2022) indicating a reduction in the sorption capacity of soils in the Kharkiv Oblast due to anthropogenic acidification. However, the most geochemically significant and ecologically concerning discovery of this study is the “hyper-mobilisation” phenomenon observed when glyphosate herbicides are

co-applied with fulvic acids, resulting in a 39% surge in soluble iron concentrations. While standard models, such as those by X. Li *et al.* (2023) and B. Geysels *et al.* (2025), posit that glyphosate is typically inactivated through adsorption onto iron oxides like goethite and ferrihydrite, the current findings suggest that the presence of fulvic acids fundamentally disrupts this interaction. The data indicate a mechanism of competitive solubilisation or ternary complex formation. By competing for sorption sites or chemically attacking the oxide surface, the fulvic acid dissolves the mineral carrier, releasing the herbicide-metal complex into the soil solution. B. Geysels *et al.* (2025) provided a mechanistic surface-complexation model for glyphosate binding to ferrihydrite, showing primarily binuclear bidentate coordination. This interaction is crucial because iron oxides are the primary “sink” for glyphosate in soils; however, the presence of strong chelators can dissolve these oxides, releasing both the iron and the adsorbed herbicide. The dichotomy between humic and fulvic acids has been refined in evolving scientific discourse. This synergistic solubilisation implies that migration models failing to account for dissolved organic matter may severely underestimate the risk of groundwater contamination, a concern that echoes the warnings of O. Litvinova *et al.* (2023) regarding the deep-profile accumulation of pesticide residues.

Furthermore, the study illuminates the advantages of biological regulation over chemical manipulation. The “StimOrganic” biodestructor demonstrated a strategy of “smart mobilisation”, where nutrient availability is regulated by microbial siderophores. As elucidated by B. Khoshru *et al.* (2023) and M. Maciel-Rodríguez *et al.* (2025), the soil microbiome functions as an active regulator of elemental cycling through siderophore-mediated homeostasis. Their research demonstrated that specific rhizobacteria mobilise manganese and zinc via inducible metabolic pathways – including acidification and enzymatic reduction – that are responsive to environmental depletion signals. This biological feedback loop achieves a state of “smart mobilisation”, where nutrient solubility is synchronised with plant demand, thereby maintaining high bioavailability in the root zone while preventing the unregulated mass leaching losses associated with passive chemical chelators.

These findings have direct implications for agricultural practices in Ukraine, validating the conclusions of O. Litvinova *et al.* (2023) regarding the role of surfactants in pesticides as active geochemical migration agents and confirming the urgent need for organic stabilisation strategies to verify the loss of buffering capacity described by V. Didora *et al.* (2024). Ultimately, regarding the remediation of soils subjected to heavy metal contamination, as described by E. Moliszewska *et al.* (2023)

and O. Datsko *et al.* (2025), the application of potassium humates functions as a critical measure to restore the protective sorption capacity of the pedosphere. The study by O. Litvinova *et al.* (2023) emphasised that the accumulation of surfactants (surface-active agents), which are part of pesticide formulations, significantly alters the migration capacity of biogenic elements, effectively “washing” them out of the root zone. This phenomenon is exacerbated by the use of glyphosate – a herbicide that remains dominant in global and Ukrainian agriculture.

CONCLUSIONS

The comprehensive analysis conducted in this study, utilising high-precision ED-XRF spectrometry, provided critical experimental evidence that necessitated a fundamental revision of current agronomic practices regarding the use of soil amendments and herbicides. The results unequivocally demonstrated that humic substances cannot be treated as a monolithic functional entity in agricultural management, exhibiting instead a strict geochemical dichotomy that determined the fate of soil elements. Fulvic acids were identified as aggressive mobilising agents that induced the rapid desorption and downward migration of essential microelements, specifically iron and zinc. This process posed a significant long-term threat to soil fertility by effectively stripping the arable horizon of its nutritional reserves and translocating them into the subsoil, unavailable to crop roots. Conversely, the application of Potassium Humates proved to be a highly effective strategy for chemical stabilisation, acting as a robust geochemical barrier that immobilises toxic metals, such as lead, via inner-sphere complexation, thereby mitigating the risks of aquifer contamination.

From an ecological perspective, the most alarming finding was the discovery of a synergistic “hyper-mobilisation” mechanism when glyphosate herbicides were co-applied with fulvic acids. The observed 39% surge in soluble iron concentrations indicated that fulvic acids destabilised the mineral matrix, preventing the natural adsorption of the herbicide onto iron oxides. This synthesis of soluble ternary complexes implied that the common practice of tank-mixing these agents may inadvertently facilitate the deep percolation of glyphosate into groundwater, bypassing the soil’s natural filtration capacity. In contrast to these chemical risks, the biological approach utilising microbial-enzymatic biodestructors (“StimOrganic”) offered a sustainable alternative. This treatment achieved an optimal balance of “smart mobilisation”, regulated by microbial siderophores, which ensured high nutrient bioavailability in the rhizosphere without the ecological liability of mass leaching associated with synthetic chelators or pure fulvic acids.

Consequently, to ensure environmental safety and soil health, it is imperative to revise agrochemical protocols: the mixing of glyphosate with high-concentration fulvic acids must be strictly prohibited on soils with low sorption capacity or high-water tables. Priority should be given to high-molecular-weight potassium humates for the recultivation of technogenically disturbed or war-impacted lands. Future scientific inquiries should focus on validating these mechanisms through isotopic labelling (^{14}C – glyphosate) to directly trace the molecular transport of herbicide residues within ternary complexes, and on

implementing longitudinal field studies to assess the scalability of these geochemical interactions under variable climatic conditions.

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Вплив біостимуляторів і гліфосату на вертикальну міграцію елементів у сільськогосподарських ґрунтах

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Анотація. Метою цього дослідження було оцінити закономірності вертикальної міграції макро- та мікроелементів у південних чорноземах під впливом бінарних сумішей гербіцидів на основі гліфосату та біостимуляторів різних класів. Інтенсифікація сучасних аграрних систем спричинила суттєві зміни в біогеохімічному кругообігу поживних елементів і контамінантів у педосфері. У роботі представлено комплексне дослідження механізмів вертикальної міграції макро- та мікроелементів у модельному ґрунтовому профілі з акцентом на порушення, спричинені сумісним застосуванням гліфосатвмісних гербіцидів і біостимуляторів різної природи (фульвові кислоти, гумати калію та комплексні стерньові біодеструктори). Для кількісної оцінки перерозподілу Fe, K, Ca, Mn, Zn, Cu та Pb у трьох ґрунтових горизонтах контрольованих мікрокосмів застосовано високороздільну енергодисперсійну рентгенофлуоресцентну спектрометрію (ED-XRF). Дослідження виявило діаметрально протилежні геохімічні функції гумусових фракцій: фульвові кислоти («BioFulvo») діяли як агресивні мобілізувальні агенти, вилучаючи перехідні метали з середнього горизонту та посилюючи ризики вимивання (зменшення вмісту Fe на 30,1 % у транзитній зоні), тоді як гумати калію виконували роль стабілізуючих геохімічних бар'єрів, ефективно іммобілізуючи антропогенний свинець і утримуючи поживні елементи в кореневмісному шарі. Ключовим результатом роботи стало виявлення феномену «гіпермобілізації», що виникає внаслідок синергічної взаємодії гліфосату та фульвових кислот і призводить до зростання концентрації розчинного заліза на 39 %, ймовірно, через утворення тернарних фосфонат–фульват–металевих комплексів. Водночас мікробно-гумінові біодеструктори продемонстрували унікальний потенціал «біофортифікації», підтримуючи високу біодоступність цинку та марганцю без порушення стабільності ґрунтового профілю. Отримані результати підкреслили необхідність диференційованого підходу до управління агрохімічними технологіями. Хоча фульвові кислоти сприяють швидкому транспорту поживних елементів, їх поєднання з гербіцидами на чутливих ґрунтах несе суттєві екологічні ризики, які можуть бути нівельовані буферною здатністю високомолекулярних гуматів

Ключові слова: біогеохімія ґрунтів; транспорт у вадозній зоні; XRF-спектрометрія; гумусові речовини; фульвові кислоти; ремедіація важких металів; точне землеробство

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