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Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
Тел.: +38(0512) 70-93-54
E-mail: ubsras@bsagriculture.com.ua
https://bsagriculture.com.ua/uk

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https://bsagriculture.com.ua/en

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The impact of Mzuri Pro-TIL technology on winter wheat productivity under natural and artificial moisture conditions in southern Ukraine

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

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

Marek Ruzhniak
Doctor of Agricultural Sciences
Mzuri World
89-110, 1 Stawowa Str., Smielin, Poland
https://orcid.org/0009-0007-7762-4232

Iryna Smirnova*
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-8976-3818

Tetiana Kachanova
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0003-0032-3996

Abstract. The article presents the results of studies on the effect of the resource-saving strip tillage technology Mzuri Pro-TIL on the formation of productivity of winter wheat of the Duma Odeska variety under conditions of natural and artificial moisture in the south of Ukraine. The aim of the research was to assess the impact of the Mzuri Pro-TIL technology on the growth, development and productivity of winter wheat under natural and irrigated conditions in southern Ukraine compared with the conventional cultivation technology. A set of generally accepted scientific methods was employed, including analysis and synthesis for theoretical generalisation of the material, as well as laboratory and field methods to obtain reliable empirical data under controlled and natural conditions. The influence of the studied technologies on plant growth and development, stand formation, yield structure components and grain yield of winter wheat was analysed. It was established that the application of the

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*Corresponding author (smirnova@mnau.edu.ua)

Mzuri Pro-TIL technology creates favourable conditions for the autumn development of winter wheat, promotes increased tillering, higher stand density and greater intensity of linear plant growth during the growing season. Under irrigation, the positive effect of the technology was enhanced, as evidenced by increased plant height, a greater number of productive stems and improved formation of generative organs. The Mzuri Pro-TIL technology ensured higher values of spike length and weight, number of spikelets and grains per spike, grain weight per spike and thousand-grain weight compared with the conventional tillage system. The average grain yield under the Mzuri Pro-TIL technology amounted to 5.70 t/ha under natural moisture conditions and 6.56 t/ha under irrigation, exceeding the conventional technology by 0.83 and 0.68 t/ha, respectively. The obtained results confirm the feasibility of the integrated application of modern strip tillage technology and optimisation of the water regime as an effective approach to increasing the productivity of winter wheat in the south of Ukraine

Keywords: strip tillage; plant height; thousand-grain weight; tillering coefficient; Duma Odeska; irrigation; yield

INTRODUCTION

Winter wheat is still strategically important in the crop rotation in southern Ukraine; however, in recent years there has been a decline in its yield and a deterioration in grain quality, which often fails to meet food standards. The main causes are increased abiotic stresses (moisture deficit, high temperatures, uneven rainfall) combined with biotic factors that negatively affect yield formation. The aridisation of the region's climate makes the development and implementation of adaptive, resource-efficient cultivation technologies particularly relevant, aimed at the efficient use of soil moisture, the preservation of soil fertility and the stabilisation of high-quality grain production.

One way to adapt agriculture to climate change, protect soil from erosion and achieve high yields of winter crops is to adopt new technologies, primarily those aimed at minimising tillage (the use of surface loosening technology (Mini-TIL) and zero tillage (No-TIL), strip tillage systems using Mzuri Pro-TIL technology, and a transition to rain-fed farming. Another approach involves the rational use of water for irrigation and the adoption of innovative irrigation methods (drip and subsurface). Strip tillage using the Strip-TIL system from Mzuri Pro-TIL involves working a narrow 12 cm-wide strip of soil, leaving crop residues on the surface between rows (24 cm, 36.4 cm or 58 cm depending on the setting), which allows moisture and organic matter to remain in the soil, as well as helping to increase the earthworm population, significantly improve soil biota composition, enhance soil structure, and more. The use of Mzuri Pro-TIL sowing units creates an ideal seedbed for achieving synchronised plant emergence, enabling crops to withstand climatic stresses and maximise their genetic potential.

The Mzuri Pro-TIL seed drill operates on the principle of precision strip tillage, combining the cutting of crop residues, loosening of the seedbed and the simultaneous application of fertiliser to a specified depth. Roll-down ensures optimal seed-to-soil contact, which improves germination rates and sowing uniformity. Research by I. Koženiauskas (2021) has shown that such strip tillage has a positive effect on the soil's agrophysical properties, reduces energy consumption during tillage, helps preserve soil structure and minimises the negative impact on the environment. In turn, this improves resource efficiency and crop yield stability, which is particularly important under conditions of limited moisture and intensive farming. Such precise localised application helps preserve soil structure, reduce energy costs for tillage and increase crop productivity.

In recent scientific research, considerable attention has been paid to assessing the effectiveness of resource-saving soil cultivation technologies in the context of increasing climate instability. In particular, the study by V. Shebanin *et al.* (2025) conducted a comprehensive assessment of the economic efficiency of winter wheat cultivation using the Mzuri Pro-TIL technology. The authors found that the implementation of this technology reduces production costs by cutting the number of operational steps, reducing fuel consumption and optimising the use of mineral fertilisers through their localised application to the root zone of the plants. Research has also demonstrated that the Mzuri Pro-TIL technology contributes to increased yield stability of winter wheat, particularly under conditions of insufficient and erratic moisture supply, which is characteristic of southern Ukraine. The authors emphasise that leaving plant residues on the soil surface and minimising disturbance to its structure have a positive effect on the soil's hydration regime, reduce moisture loss through evaporation and improve the efficiency of rainfall utilisation.

According to research by O. Mayorov & M. Tsekhmeystruk (2021), it has been established that the conventional method of wheat cultivation involves soil preparation, sowing, crop management and harvesting.

Soil preparation involves ploughing, cultivation and harrowing to create a uniform seedbed, which provides optimal conditions for seed germination and root system development. Sowing is carried out in accordance with sowing dates and rates, whilst crop management includes fertiliser application, protection against weeds, pests and diseases, and soil moisture control. Harvesting is aimed at minimising grain losses and preserving grain quality. Research by V. Hakhula & Y. Kiruta (2023) have shown that conventional farming also improves aeration, mixes organic matter and distributes moisture evenly, but intensive tillage can compact the lower soil layers, contribute to erosion and reduce fertility, as well as requiring high energy and material costs. Thus, conventional farming ensures stable yields, but is limited in terms of preserving long-term soil fertility and the efficient use of resources.

The importance of state support for the introduction of innovative technologies in agriculture is particularly significant under martial law, when ensuring food security and economic stability is paramount. The Mzuri Pro-TIL technology aligns with these priorities, as it helps to increase yields, promote the efficient use of resources and reduce production costs, even under adverse conditions. Scientific research, notably the work of Z. Ding *et al*. (2020) and M. Habib-Ur-Rahman *et al*. (2022), confirm that resource-saving technologies enable increased wheat productivity, reduced tillage and preservation of soil structure, which positively impacts the fertility and environmental sustainability of agricultural production. At the same time, the issue of the economic efficiency of applying the Mzuri Pro-TIL technology in the Ukrainian agricultural sector requires further study, in particular an assessment of implementation costs and potential yield increases. Taking these aspects into account will enable a well-founded recommendation for the large-scale application of the technology in southern Ukraine to enhance the productivity and economic stability of agricultural production. The aim of the research was to determine the impact of the Mzuri Pro-TIL technology on the growth and development of winter wheat under natural and artificial irrigation conditions in southern Ukraine, compared with conventional technology.

MATERIALS AND METHODS

The study was conducted between 2022 and 2024 at the experimental field of the Educational, Scientific and Research Centre of Mykolaiv National Agrarian University, located in the southern soil and climate zone of Ukraine. The soil of the experimental plot is a southern chernozem of medium humus content, with a humus content in the arable layer of 2.8-3.2%; the soil solution pH is close to neutral. The climate of the zone is characterised by insufficient moisture, high air temperatures in summer and an uneven distribution of precipitation throughout the year. The study utilised the soft winter wheat variety "Duma Odeska", which was entered into the State Register of Plant Varieties Suitable for Distribution in Ukraine in 2017. The variety is characterised by high yield potential, adaptability to the soil and climatic conditions of the Steppe and Forest-Steppe zones of Ukraine, and resistance to major diseases and abiotic stress factors, in particular drought and low temperatures (State Register of Plant Varieties…, 2024). The winter wheat was sown on 10 October at a seeding rate of 2.5 million seeds per hectare.

The experimental design included cultivation variants using the Mzuri PRO-TIL technology: Factor A: technology: 1 – Mzuri PRO-TIL, 2 – conventional; Factor B: irrigation method: 1 – natural, 2 – irrigation. The area of the sown plot was 1.2 ha, and the plot area was 0.5 ha. The experiment was repeated three times, with plots arranged in a sequential design. The agronomic practices for growing the crops under study were standard for the Southern Steppe region of Ukraine, with the exception of the factors under investigation. The Mzuri-ProTil technology involved the use of a specialised seed drill, which in a single pass provided localised soil loosening, application of mineral fertilisers and precise seed sowing. The row spacing under strip tillage technology was 12 cm between rows within a strip and 36.4 cm between adjacent strips. Conventional technology involved a full cycle of primary and pre-sowing soil cultivation using traditional agricultural practices and a standard crop management system.

In the irrigated treatments, a sprinkler irrigation system using front-type sprinkler equipment was employed. Irrigation was carried out in accordance with the biological requirements of the crop during the critical growth and development stages of winter wheat (tillering, stem elongation, heading, and grain filling). Soil moisture was monitored using the thermostatic-gravimetric method by taking soil samples from the arable layer (0-30 cm) prior to irrigation. Moisture content was determined as a percentage of the mass of absolutely dry soil. The criterion for irrigation was a reduction in soil moisture to 70-75% of the minimum moisture capacity (MMC) Irrigation rates were set on a case-by-case basis depending on actual soil moisture, meteorological conditions and the crop's growth stage. Water application was recorded based on the sprinkler's technical specifications and irrigation duration, followed by a calculation of the total irrigation rate for the growing season.

Growth parameters for the autumn growing season of winter wheat were determined during the 2022-2023 period, and for the spring growing season during the 2023-2024 period. Plant height was determined by measuring the distance from the soil surface to the tip of the ear (excluding awns) in 20 representative plants at each plot using a measuring ruler; the average value of the indicator was calculated based on the results. The number of stems was determined by counting the total number of productive stems in a sample of 20 plants in each experimental treatment, followed by conversion to an average per plant. Ear width was measured with a vernier caliper at the central part of the ear. To improve accuracy, three consecutive measurements were taken of each ear with slight rotation around the axis, and the maximum value was recorded; the arithmetic mean for the sample was entered into the tables. The length of the ear was determined from the base to the tip (excluding awns), with the results subsequently averaged.

The bushiness coefficient was defined as the ratio of the total number of developed stems to the number of plants in the sample. To this end, 20 representative plants were selected from each plot, the total number of stems (productive and non-productive) was counted, and the average per plant was calculated by dividing the total number of stems in the sample by the number of plants counted. The number of spikelets per ear was determined by counting their total number on 20 representative ears selected from each experimental treatment; the data obtained were averaged. The number of grains per ear was determined by threshing each of the 20 selected ears individually, followed by manual counting of the grains and calculation of the average value. The grain weight per ear was determined by individually threshing 20 ears selected from each experimental treatment on a representative basis. The grains obtained from each ear were weighed individually on electronic scales to an accuracy of 0.01 g. The average value of the indicator was calculated based on the measurement results. The weight of 1,000 grains was determined in accordance with current methodological guidelines: two samples of 500 grains each were taken from the average grain sample, weighed on electronic scales, after which the obtained value was doubled and the average calculated; the results were reported to an accuracy of 0.1 g (DSTU ISO 520:2015, 2015). Grain yield was determined using the total accounting method by harvesting from the accounting area of each plot, followed by conversion to 1 ha and adjustment to standard grain moisture content (14%). The experimental data obtained during the studies were subjected to mathematical and statistical analysis using the specialised software "Agrostat". To determine the influence of the studied factors and their interaction on the productivity indicators of winter wheat, methods of analysis of variance (ANOVA) were applied. The statistical significance of differences between the mean values of the variants was determined using the significance criterion at a significance level of $p \leqslant 0.05$.

RESULTS AND DISCUSSION

The results of the studies reflect the impact of the Mzuri Pro-TIL technology on the yield potential of winter wheat under natural and artificial irrigation conditions in southern Ukraine. The analysis of the data obtained was carried out taking into account the specific soil and climatic conditions of the study area, the hydrothermal regime during the observation years, and the biological characteristics of the Duma Odeska cultivar. The main focus is on assessing the response of winter wheat plants to the application of the resource-saving strip tillage technology, which combines local loosening with the simultaneous application of mineral fertilisers, compared to the traditional tillage system. The research results indicate that the use of the Mzuri Pro-Til technology creates more favourable conditions for plant growth and development during the autumn growing season, which is crucial for the formation of winter wheat yield potential. The retention of plant residues on the soil surface, the improvement of its agrophysical properties and the more efficient use of soil moisture, particularly under conditions of limited moisture, had a positive effect on the initial stages of the crop's organogenesis.

It is the autumn growth of plants and the level of vegetative mass development prior to the cessation of vegetative growth that determine the intensity of tillering, winter hardiness and the subsequent course of growth processes in spring. In this regard, the next stage of research is aimed at assessing the state of growth processes in Duma Odeska winter wheat prior to winter set-in under various tillage technologies and irrigation regimes, which allows us to substantiate the impact of the Mzuri Pro-Til technology on the realisation of the crop's productive potential. At the beginning of the third ten-day period of November, the winter wheat was in the tillering stage, which is critical for the formation of the plant stand and the crop's potential yield (Table 1). Under the Mzuri Pro-TIL technology, the height of winter wheat plants under natural moisture conditions was 21.1 cm, whilst under irrigation conditions it increased to 23.5 cm. A similar trend was observed for the tillering coefficient, which increased from 2.5 to 3.1 units. The number of stems using this technology also increased – from 665.0 to 736.3 stems when switching from natural moisture to irrigation. Under the traditional

technology, an increase in all studied indicators was observed under the influence of irrigation: plant height increased from 20.1 to 21.9 cm, the tillering coefficient from 1.8 to 2.2 units, and the number of stems from 688.1 to 841.0. Moreover, the difference between the technologies was statistically significant ($p < 0.05$), indicating the effectiveness of Mzuri Pro-TIL in the formation of productive stems and the preparation of winter wheat for overwintering in the conditions of the Southern Steppe of Ukraine.

Table 1. *Growth status of Duma Odeska winter wheat crops before winter set-in (average for 2022-2023)*

Technology (factor A)	Indicator	Irrigation method (factor B)	
		natural	irrigation
Mzuri Pro-TIL	plant height, cm	21.1 ± 0.61	23.5 ± 0.68
	tillering coefficient, units	2.5 ± 0.07	3.1 ± 0.09
	number of stems, pcs.	665.0 ± 19.2	736.3 ± 21.3
Conventional	plant height, cm	20.1 ± 0.58	21.9 ± 0.63
	tillering coefficient, units	1.8 ± 0.05	2.2 ± 0.06
	number of stems, pcs.	688.1 ± 19.9	841.0 ± 24.3

Source: *compiled by the authors*

Meanwhile, the data in the table shows that, with the Mzuri Pro-TIL technology, the initial plant density was slightly lower than with the traditional method. However, due to the higher tillering coefficient and better plant survival during the autumn growing season, this technology ensured the formation of a more uniform and potentially productive stand. This indicates increased crop adaptability and more efficient utilisation of the plants' biological potential. Analysis of the obtained indicators suggests that the plants were in good physiological condition: the leaf area was sufficient for effective photosynthesis, and the root system was adequate to ensure water and nutrient uptake. The high level of plant development in irrigated plots confirms the effectiveness of supplementary irrigation in increasing potential yield.

During the first ten days of May, agrometeorological conditions for winter wheat growth were satisfactory. At the same time, due to a lack of rainfall, there was a rapid depletion of available moisture from both the topsoil and subsoil layers. On irrigated plots, a single sprinkler irrigation was carried out at a rate of 300 m^3/ha. More developed plants consumed moisture and nutrients more intensively, outpacing the growth of weakened plants and increasing their suppression by shading them from the sun (Table 2).

Table 2. *Growth dynamics of winter wheat crops depending on irrigation method and cultivation system (average for 2023-2024), cm*

Technology (factor A)	Growth and development stages	Irrigation method (factor B)	
		natural	irrigation
Mzuri Pro-TIL	stem elongation	40.9 ± 1.18	46.9 ± 1.35
	ear emergence	76.2 ± 2.20	80.5 ± 2.33
	milk ripeness	90.4 ± 2.61	96.8 ± 2.80
Conventional	stem elongation	31.3 ± 0.90	37.8 ± 1.09
	ear emergence	67.3 ± 1.94	75.9 ± 2.19
	milk ripeness	86.9 ± 2.51	92.6 ± 2.67

Source: *compiled by the authors*

Studies have shown that the Mzuri Pro-TIL cultivation technology delivers consistently higher shoot growth in winter wheat compared to the traditional system at all key stages of development – from stem elongation to milk ripeness. Supplementary irrigation significantly increases plant height, particularly in the early (stem elongation) and late (milk ripeness) stages, highlighting the importance of optimal water supply for the formation of a productive canopy and the realisation of yield potential. The difference between the technologies was statistically significant ($p < 0.05$), and irrigation increased all growth parameters compared to natural moisture, demonstrating the effectiveness of Mzuri Pro-TIL in enhancing growth intensity and the formation of productive winter wheat stems. The greatest increase in plant height was observed during the milk ripeness stage, highlighting the critical importance of water management and modern technologies for maximising the crop's genetic potential. The data demonstrate the effectiveness of an integrated approach, where the application of advanced technology is combined with optimised irrigation, ensuring better development of morphological traits and the plants'

potential yield. Many factors influence the yield of winter wheat, including irrigation methods and cultivation techniques. Depending on these, different plant densities are formed (Table 3).

Table 3. *Plant density of winter wheat at the stage of full grain maturity, depending on irrigation method and farming practices (average for 2023-2024), plants/m²*

Technology (factor A)	Indicator	Irrigation method (factor B)	
		natural	irrigation
Conventional	total number of stems	565 ± 16.3	625 ± 18.1
	including productive stems	501 ± 14.5	562 ± 16.2
Mzuri Pro-TIL	total number of stems	648 ± 18.7	714 ± 20.6
	including productive stems	583 ± 16.8	643 ± 18.6

Source: *compiled by the authors*

In plots with natural moisture levels, the highest plant density was observed during the stem elongation and heading stages, when temperatures rose. Research findings indicate that the plant density of winter wheat was influenced by both cultivation practices and weather conditions. Thus, the highest plant density of 714 plants per 1 m² was achieved by the Duma Odeska crop under irrigation and Mzuri Pro-TIL. Studies determined that a greater number of productive stems were formed in irrigated plots using the technologies under investigation. Overall, winter wheat crops produced a higher number of productive stems using the Mzuri Pro-TIL technology, both under natural moisture conditions and on irrigated plots, which was 82 plants/m² and 81 plants/m² respectively more than with the traditional technology. The plant density of winter wheat at full maturity was higher with the Mzuri Pro-TIL technology compared to the traditional system, with irrigation increasing plant density, and the difference between the technologies was statistically significant ($p < 0.05$), confirming the effectiveness of Mzuri Pro-TIL in the formation of productive winter wheat stems.

The higher number of productive stems at the stage of full grain maturity achieved using the Mzuri Pro-TIL technology is due to a combination of agrobiological and technological factors. First and foremost, this system involves minimal disturbance of the soil profile and the retention of plant residues on the surface, which promotes better moisture accumulation and retention, stabilisation of soil temperature, and activation of microbiological processes. Under such conditions, a more developed root system forms, the efficiency of nutrient utilisation increases, and moisture losses are reduced, which has a positive effect on autumn tillering and the preservation of shoots during the winter period. As a result, a larger proportion of the stems formed in autumn do not die off but survive until the ripening phase and realise their productive potential. Thus, the Mzuri Pro-TIL technology ensures a denser stand and a greater number of productive stems compared to the traditional system, regardless of the irrigation method. Irrigation further increases plant density, boosting both the total number of stems and the number of productive ones, which confirms the importance of water management in achieving high crop yields. Overall, combining modern cultivation technology with optimal moisture management promotes more efficient utilisation of plant potential and the formation of a more productive stand, which is a key factor in increasing winter wheat yield. The second key indicator of winter wheat productivity is the grain weight per ear. In the studies conducted, this ranged from 1.03 g using conventional technology under natural moisture conditions to 1.56 g using the Mzuri Pro-TIL technology on irrigated plots, demonstrating a significant increase in productivity when modern technology and optimal water supply are applied (Table 4).

Table 4. *Performance indicators for winter wheat at the stage of full grain maturity, depending on irrigation method and cultivation technology (average for 2023-2024)*

Indicator	Mzuri Pro-TIL technology Irrigation method		Conventional technology Irrigation method	
	natural	irrigation	natural	irrigation
Ear length, cm	10.3 ± 0.30	11.5 ± 0.33	9.5 ± 0.27	10.1 ± 0.29
Ear width, cm	1.4 ± 0.04	1.5 ± 0.04	1.1 ± 0.03	1.1 ± 0.03
Ear weight, g	3.43 ± 0.10	3.53 ± 0.10	2.25 ± 0.07	3.15 ± 0.09
Number of spikelets per ear, pcs.	20 ± 0.58	22 ± 0.64	17 ± 0.49	19 ± 0.55
Number of grains per ear, pcs.	54 ± 1.56	60 ± 1.73	48 ± 1.39	56 ± 1.62
Grain weight per ear, g	1.49 ± 0.04	1.56 ± 0.05	1.03 ± 0.03	1.08 ± 0.03
Weight of 1,000 grains, g	42.5 ± 1.23	45.8 ± 1.32	34.0 ± 0.98	35.4 ± 1.02

Source: *compiled by the authors*

The highest values for ear length (11.5 cm) and width (1.5 cm) were recorded in winter wheat grown using the Mzuri Pro-TIL method with irrigation. Under natural moisture conditions, these figures are slightly lower (10.3 cm and 1.4 cm respectively). The conventional technology yields smaller ear parameters: a length of 9.5-10.1 cm and a width of 1.1 cm, regardless of moisture conditions. This indicates the positive impact of modern technology and supplementary water supply on ear formation. The Mzuri Pro-TIL technology produces a higher ear weight: 3.43 g under natural moisture conditions and 3.53 g with irrigation, whereas with the conventional technology, ear weight ranges from 2.25 to 3.15 g. The number of spikelets per ear and grains per ear was also higher with Mzuri Pro-TIL, particularly on irrigated plots: 22 spikelets and 60 grains per ear compared to 19 spikelets and 56 grains per ear with conventional technology under irrigation. Irrigation improved all indicators of winter wheat productivity compared to natural moisture supply, and the difference between the technologies was statistically significant ($p < 0.05$), which substantiates the effectiveness of Mzuri Pro-TIL in the formation of productive ears and the increase in winter wheat grain yield under the conditions of the Southern Steppe of Ukraine. All these factors also influenced the grain yield of winter wheat. The research results indicate that the use of Pro-TIL technology ensures higher yields in all years of the study and under both moisture regimes, particularly when combined with irrigation (Fig. 1). This points to more efficient use of soil moisture and more favourable conditions for yield formation compared to conventional tillage technology.

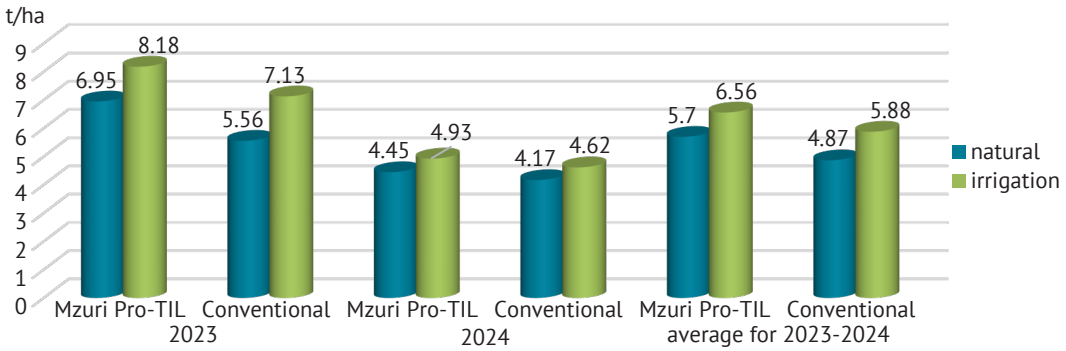

Figure 1. *Winter wheat grain yield by cultivation method and irrigation method (average for 2023-2024), tonnes per hectare*

Source: *compiled by the authors*

In 2023, under natural irrigation conditions, the yield using the Mzuri Pro-TIL technology was 6.95 t/ha, which exceeded the corresponding figure for the conventional technology (5.56 t/ha) by 1.39 t/ha. Under irrigation conditions, an increase in yield was observed in both variants; however, the highest value was recorded specifically for the Mzuri Pro-TIL technology – 8.18 t/ha, whereas for the conventional technology it was 7.13 t/ha. This indicates the higher efficiency of the energy-saving technology when combined with irrigation. In 2024, the overall yield level was lower compared to 2023. Under natural moisture conditions, the yield using the Mzuri Pro-TIL technology was 4.45 t/ha, whereas with the conventional method it was 4.17 t/ha. Under irrigation conditions, yields increased to 4.93 t/ha (Mzuri Pro-TIL) and 4.62 t/ha (conventional technology). The advantage of the Mzuri Pro-TIL technology remained, although the difference between the variants was less pronounced than in 2023.

The average data over two years confirm the consistent advantages of the Mzuri Pro-TIL technology. Under natural irrigation conditions, the average yield was 5.70 t/ha, which is 0.83 t/ha higher than that achieved with conventional technology (4.87 t/ha). Under irrigation conditions, the average yield using the Mzuri Pro-TIL technology reached 6.56 t/ha, whereas with the conventional method it was 5.88 t/ha. According to the results of the analysis of variance, it was determined that the NIR05 for factor A was 0.25 t/ha, and for factor B – 0.37 t/ha. Joint studies demonstrate that strip tillage technologies contribute to a comprehensive increase in winter wheat productivity. Thus, D. Xu. (2022) found that Strip-TIL improves plant growth, nitrogen use efficiency and yield in a rice-wheat rotation, which is consistent with improved stem development in trials using the Mzuri Pro-TIL technology. Similarly, Q. Wang *et al.* (2024) demonstrated that the combination of Strip-TIL and periodic deep loosening promotes better nitrogen uptake and higher winter wheat productivity. Furthermore, D. Hobson *et al.* (2022) noted the positive impact of strip tillage on root system development, photosynthetic parameters and grain

filling, which influences 1,000-grain weight and overall yield. Finally, a meta-analysis indicates a general trend towards higher crop yields with Strip-TIL compared to conventional technology.

At the same time, as noted by V. Havrysh *et al.* (2020), the introduction of energy-saving technologies in agriculture is a priority area for improving production efficiency. The Mzuri Pro-TIL technology fully meets these requirements, as it reduces the number of passes made by machinery across the field, ensuring the rational use of energy resources and cutting production costs. Unlike traditional precision farming systems, which focus on high-precision seed and fertiliser application, Mzuri Pro-TIL offers a comprehensive approach: simultaneous strip tillage, fertiliser application and seedbed preparation. Such integration of operations not only reduces energy and material costs but also increases crop yields, making the technology economically viable and promising for large-scale implementation in resource-efficient farming.

Recent scientific research indicates that the adoption of resource-saving soil cultivation techniques, particularly strip tillage, plays a key role in enhancing the adaptability of agricultural production to arid conditions. According to G. Taye *et al.* (2024), minimising mechanical disturbance to the soil helps reduce moisture loss through evaporation and curb erosion processes, which is particularly important for regions with unstable moisture conditions. Improving soil structure enhances its water permeability and water-holding capacity, creating more favourable conditions for plant growth and yield formation.

Research findings confirm the conclusions of M. Lozinskiy *et al.* (2021) that grain weight per ear is a key factor in winter wheat productivity, and show that the Mzuri Pro-TIL technology increases grain weight and 1,000-grain weight through strip tillage, localised fertiliser application and the retention of plant residues. These findings are consistent with those of M. Rozewicz *et al.* (2024), who noted improvements in soil porosity and aeration, reduced compaction and stimulation of the root system, which increases the efficiency of water and nutrient use.

The use of resource-saving techniques in winter wheat cultivation, in particular strip tillage systems, helps to increase productivity and make more efficient use of soil moisture, as well as ensuring that the genetic potential of the varieties is realised, which is particularly important when growing wheat following sunflowers in the Southern Steppe region of Ukraine (Gamayunova *et al.*, 2022). Similar results were obtained in studies by M. Korkhova *et al.* (2023), where it was established that optimising stubble tillage improves the agrophysical properties of the soil and contributes to increased winter wheat productivity. The results obtained are consistent with the data presented and confirm the effectiveness of the Mzuri Pro-TIL strip tillage technology, which ensures better moisture retention and higher crop yields in the conditions of the Southern Steppe of Ukraine. Water availability and nutrient supply are key factors in determining winter wheat yield, as they influence the intensity of growth processes and the realisation of the varieties' productive potential. Research shows that increasing moisture levels and optimising mineral nutrition contribute to a significant increase in the yield of winter wheat varieties (Gamayunova *et al.*, 2022; Korkhova & Panfilova, 2024). In the conditions of the Southern Steppe of Ukraine, where crop productivity may decline due to climatic constraints or external factors such as armed conflict, the application of adaptive technologies becomes extremely relevant (Nasibov *et al.*, 2024). Combining the Mzuri Pro-TIL strip-till technology with natural or artificial irrigation ensures more efficient use of soil moisture and nutrients, creating favourable conditions for increasing winter wheat productivity in the region.

The results of the studies are consistent with the findings of Q. Chen *et al.* (2021), who demonstrated that minimised and strip tillage improve soil physico-chemical properties, conserve moisture and promote root system development, thereby increasing the yield of field crops. Furthermore, K. Song *et al.* (2019) demonstrated that combining minimum tillage with the return of crop residues improves soil structure, stabilises organic carbon and increases crop yields. In current studies, the Mzuri Pro-TIL technology, which combines strip tillage, localised fertiliser application and the retention of plant residues, ensured optimal soil water and nutrient conditions, increased the density of productive stems and grain weight, leading to higher winter wheat yields. This confirms that the integration of modern tillage technologies, taking into account varietal characteristics and water regime, effectively realises the crop's productive potential.

CONCLUSIONS

Studies conducted in Ukraine between 2022 and 2024 have shown that the Mzuri Pro-TIL technology creates favourable conditions for the growth of the Duma Odeska winter wheat, ensuring consistently higher linear plant growth, greater tillering and stem density compared to the conventional tillage system. This demonstrates the effectiveness of the resource-saving strip tillage technology, which combines localised soil loosening with the application of mineral fertilisers, in shaping the morphological characteristics of the crop. Irrigation significantly increases plant productivity,

particularly during critical development stages – stem elongation and milk ripeness. Additional water supply promotes the formation of a more productive canopy, active shoot growth and the effective utilisation of the variety's genetic potential. The use of Mzuri Pro-TIL technology in combination with optimal water supply stimulates the formation of larger and more productive ears, increasing their length, width, weight, number of spikelets and grains per ear, as well as the weight of a single grain and the weight of 1,000 grains. These factors directly contribute to an increase in the potential yield of winter wheat.

According to the results of two years of observations, the average winter wheat yield using the Mzuri Pro-TIL technology was 5.70 t/ha under natural irrigation and 6.56 t/ha under artificial irrigation, exceeding the figures for conventional technology by 0.83 and 0.68 t/ha respectively. This confirms the effectiveness of an integrated approach, where modern tillage technology is combined with optimised water management. The use of Mzuri Pro-TIL technology ensures a higher number of productive stems, a denser stem stand and better grain-filling of the ears, which are key factors in increasing the yield and stability of winter wheat production in the southern region of Ukraine. The research results demonstrate the importance of the combined effect of agronomic practices: combining a modern tillage system with optimal water supply allows the variety's potential to be realised to the fullest and enables the effective use of available natural resources. In the future, a detailed study is planned to investigate the impact of the Mzuri Pro-TIL technology and various irrigation regimes on grain quality indicators, including morphological, physiological and technological characteristics. This will enable a more comprehensive assessment of the effectiveness of an integrated approach to winter wheat cultivation and optimise the farming system to improve grain yield and quality in the southern region of Ukraine.

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CONFLICT OF INTEREST

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Вплив технології Mzuri Pro-TIL на продуктивність пшениці озимої за умов природного та штучного зволоження півдня України

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

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

Марек Ружняк
Доктор сільськогосподарських наук
Mzuri World
89-110, вул. Ставова, 1, м. Смєлін, Польща
https://orcid.org/0009-0007-7762-4232

Ірина Смірнова
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-8976-3818

Тетяна Качанова
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0003-0032-3996

Анотація. У статті наведено результати досліджень впливу ресурсоощадної технології смугового обробітку ґрунту Mzuri Pro-TIL на формування продуктивності пшениці озимої сорту Дума одеська за умов природного та штучного зволоження в умовах півдня України. Метою досліджень було оцінити вплив технології Mzuri Pro-TIL на ріст, розвиток і продуктивність пшениці озимої за умов природного та штучного зволоження півдня України порівняно з класичною технологією вирощування. Для проведення дослідження було використано комплекс загальноприйнятих наукових методів, зокрема аналіз і синтез для теоретичного узагальнення матеріалу, а також лабораторні й польові методи для отримання достовірних емпіричних даних у контрольованих і природних умовах. У процесі проведення досліджень застосовували загальноприйняті наукові методи, зокрема аналіз і синтез, а також комплекс лабораторних і польових методів. Проаналізовано вплив досліджуваних технологій на ріст і розвиток рослин, формування стеблостою, елементи структури врожаю та урожайність зерна пшениці озимої. Встановлено, що застосування технології Mzuri Pro-TIL створює сприятливі умови для осіннього розвитку пшениці озимої, сприяє підвищенню кущистості, щільності стеблостою та інтенсивності лінійного росту рослин упродовж вегетації. За умов зрошення позитивний ефект технології посилювався, що проявлялося у збільшенні висоти рослин, кількості продуктивних стебел та кращому формуванні генеративних органів. Технологія Mzuri Pro-TIL забезпечила вищі показники довжини й маси колоса, кількості колосків і зерен у колосі, маси зерна з колоса та маси 1 000 зерен порівняно з традиційною системою обробітку ґрунту. Середня урожайність зерна за технології Mzuri Pro-TIL становила 5,70 т/га за природного зволоження та 6,56 т/га за зрошення, що відповідно на 0,83 і 0,68 т/га перевищувало показники класичної технології. Отримані результати підтверджують доцільність інтегрованого застосування сучасної смугової технології обробітку ґрунту та оптимізації водного режиму як ефективного напряму підвищення продуктивності пшениці озимої в умовах півдня України

Ключові слова: смуговий обробіток ґрунту; висота рослин; маса тисячі зерен; коефіцієнт кущистості; Дума одеська; зрошення; урожайність

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Influence of herbicides on the growth and development of the invasive species *Heracleum Sosnowskyi* Manden.

Hanna Korpita*
PhD in Agricultural Sciences, Associate Professor
Stepan Gzhytskyi National University of Veterinary Medicine and Biotechnologies of Lviv
80831, 1 Volodymyr Velykyi Str., Dublyany, Ukraine
https://orcid.org/0000-0002-0908-0129

Abstract. The aim of the study was to evaluate the effectiveness of different herbicide treatments in suppressing the growth, development, and regenerative capacity of the invasive species *Heracleum sosnowskyi* Manden. The study was carried out using four variants: control without herbicides, Slash KE (1.5 L/ha), Roundup Max RK (4.0 L/ha), and combined application of Elumis OD (2.0 L/ha) and Roundup Max RK (2.5 L/ha). To assess herbicide effects, plant morphometric parameters (height, stem diameter, leaf area), phenological stages (stem elongation, budding, flowering), and the number of regenerative shoots were recorded over a 30-day observation period. Results showed that control plants exhibited high growth rates, significant increases in morphometric parameters, and active generative activity, including the formation of regenerative shoots. Application of single herbicides led to partial suppression of growth and generative development, while regenerative shoots still formed, although in smaller quantities compared to the control. The most pronounced effect was observed under the combined application of Elumis OD (2.0 L/ha) and Roundup Max RK (2.5 L/ha). In this variant, plant height, stem diameter, and leaf area were reduced to minimal values, the generative cycle was almost completely blocked, and the number of regenerative shoots remained stable or decreased, indicating complete suppression of the regenerative mechanisms of *Heracleum sosnowskyi*. The practical significance of the results lies in the fact that combined herbicide treatment can be an effective method for controlling this invasive species in agroecosystems and semi-natural habitats, preventing its spread and reducing the negative impact on agricultural productivity

Keywords: chemical control; physiological response; morphometric analysis; phenological changes; weed management

INTRODUCTION

The invasion of alien plant species represents a major global ecological challenge, with far-reaching consequences for both the structure and functional integrity of natural and semi-natural ecosystems. These species can drastically alter plant community composition, leading to homogenisation of habitats and loss of native biodiversity. According to C. Fritsch *et al*. (2025), the expansion of invasive plants not only changes the species composition of phytocenoses but also disrupts trophic interactions, including herbivore-plant and predator-prey relationships, ultimately reducing the capacity of ecosystems to provide essential services such as nutrient cycling, pollination, and soil stabilisation. A. Rysiak *et al*. (2021) further emphasised that the combination of increasing anthropogenic pressure, such as land-use change, agricultural intensification, and urban

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Corresponding author (korpita@ukr.net)

expansion, together with ongoing climate change, creates favourable conditions for invasive species. These species often exhibit high phenotypic plasticity, rapid growth rates, and superior reproductive strategies, which confer significant competitive advantages over native plants and facilitate their rapid spread and stable establishment in previously uncolonised areas. Moreover, the ecological impact of invasions is not limited to plant communities; it cascades across multiple trophic levels, affecting microbial communities, invertebrates, and even higher vertebrates, thereby reshaping ecosystem functionality and resilience over both short and long temporal scales.

In Ukraine, the spread of invasive species has become particularly concerning, as highlighted by H. Korpita (2025), due to intensive landscape transformation driven by urbanisation, infrastructure development, and changes in agricultural practices. These anthropogenic changes lead to the reduction of traditionally cultivated areas and the fragmentation of habitats, while the destruction of natural barriers – such as hedgerows, forests, and riverine corridors – removes critical constraints that previously limited the expansion of alien plants. As a result, invasive species such as *Heracleum sosnowskyi* are able to rapidly colonise new territories, establish dense populations, and outcompete native flora, creating significant ecological and socio-economic challenges.

Among alien flora, *Heracleum sosnowskyi* Manden. is considered one of the most aggressive and ecologically destructive species. E. Grzędzicka (2022) highlighted its high ecological plasticity, rapid growth, and significant seed productivity, which enable the formation of dense monodominant stands that displace native species, reduce herbaceous biodiversity, and disrupt natural vegetation regeneration, while also posing socio-economic risks due to the phototoxic furanocoumarins in its aerial parts. Current control methods for *Heracleum sosnowskyi* include mechanical, agronomic, biological, and chemical approaches. A. Judžentienė *et al*. (2026) emphasised that simple mechanical mowing or digging often fails to achieve long-term suppression because the plant can actively regenerate from underground organs. Biological control, although promising, remains limited in practical application. Therefore, systemic herbicides are regarded as one of the most effective strategies for controlling this invasive species, especially in large or difficult-to-access areas.

As noted by E. Borska *et al*. (2025), the effectiveness of herbicides should not be evaluated solely by population reduction. Systemic chemical action triggers physiological disruptions, including inhibited growth, altered morphogenesis, and phenological shifts, ultimately reducing the plant's recovery capacity. A. Čerevková *et al*. (2024) stressed that a comprehensive, multi-level evaluation of plant responses is necessary for an objective assessment of chemical control efficacy. International studies also provide valuable insights. D.P. Barrett *et al*. (2021) demonstrated that herbicide treatments applied at early growth stages achieve the greatest effectiveness, while later stages are much less responsive to chemical control. L.S. Pile Knapp *et al*. (2023) further showed that research on *Heracleum sosnowskyi* extends beyond control efforts to exploring biomass utilisation and potential beneficial applications. Additionally, C.S. Rodriguez *et al*. (2024) and S. Kalisz *et al*. (2021) analysed invasion dynamics and practical management measures, including mechanical and chemical methods, emphasising the importance of integrated approaches that combine quantitative and qualitative evaluations of plant responses.

The scientific literature clearly demonstrates the active and multifaceted development of research devoted both to the spread dynamics of *Heracleum sosnowskyi* and to a deep evaluation of its significant ecological impact, as well as the search for the most effective control methods. Among these, chemical approaches, particularly herbicide treatments, consistently occupy a central role. At the same time, ongoing efforts to develop radically new approaches and expand existing invasion management models further emphasise the continuous and critical relevance of this topic for modern science. The aim of this study was to determine the effectiveness of systemic herbicides and their combinations in suppressing growth, generative development, and regenerative potential of *Heracleum sosnowskyi*.

MATERIALS AND METHODS

The study was conducted during 2020-2025 in natural phytocenoses of the Western Forest-Steppe of Ukraine. The objects of investigation were biennial and perennial plants of *Heracleum sosnowskyi*. Field observations were carried out on plots with relatively uniform vegetation density, ensuring the comparability of obtained results. Herbicide treatments were applied at the rosette stage and during the initial phases of intensive vegetative growth, which are considered the most sensitive to systemic herbicides. This timing of application allowed the evaluation of the maximum biological effect of the herbicides at the early stages of *H. sosnowskyi* development. The control treatment involved no herbicide application. The working solution was applied using a tractor-mounted sprayer with controlled pressure to ensure uniform coverage of the plants (Table 1).

Table 1. *Herbicides, application rates and active ingredients used in the experiment*

Variant	Herbicide	Application rate	Active ingredient
I	Control (without herbicide application)		
II	Slash	1.5 L/ha	5 g/L Halauxifen-methyl; 120 g/L clopyralid
III	Elumis + Roundup Max	2.0 L/ha + 2.5 L/ha	30 g/L nicosulfuron; 75 g/L mesotrione + 450 g/L glyphosate (acid equivalent)
IV	Roundup Max	4.0 L/ha	450 g/L glyphosate (acid equivalent); 551 g/L as potassium salt of glyphosate

Source: *developed by the author*

The physiological state of plants was evaluated based on visual and morphological traits. The analysis included assessment of growth inhibition, disruption of morphogenesis in vegetative organs, the rate of dieback in apical and lateral growth points, and the plants' ability to regenerate after chemical treatment. Physiological changes were recorded 7, 14, and 30 days after herbicide application. During this period, observations included the appearance of leaf blade deformities, changes in growth intensity, partial or complete loss of turgor, development of chlorosis and tissue necrosis, as well as cessation of central shoot growth. The physiological effect of herbicides was determined by the nature and rate of symptom manifestation, allowing evaluation of the systemic activity of the compounds even in the absence of quantitative biochemical indicators.

Morphometric analysis was conducted to quantitatively assess the biological effectiveness of chemical control on *Heracleum sosnowskyi*. During the study, plant height, stem diameter at the base, leaf surface area (calculated from linear measurements of leaves), and the number of regenerated shoots after treatment were determined. Measurements were carried out on fixed monitoring plots before herbicide application and 30 days after treatment. The obtained data were used for comparative analysis between control and treated variants. Morphometric parameters allowed an objective assessment of the degree of growth inhibition, disruption of structural organisation, and the plants' regenerative capacity following chemical exposure.

Phenological observations were performed to determine the effects of herbicides on the developmental rhythm and generative cycle of *Heracleum sosnowskyi*. Throughout the growing season, the timing of key developmental phases was recorded, including regrowth, stem elongation, bud formation, and flowering, as well as shifts in phenological phases following herbicide treatment. Particular attention was given to delays or complete suppression of flowering processes and disruption in the formation of generative organs. Plants that failed to transition to the generative phase after treatment were considered a key indicator of high chemical control efficacy. Morphometric data were analysed using variance statistics to determine mean values and relative changes compared to the control. The technical effectiveness of herbicides was assessed based on the degree of plant growth suppression and the reduction in their regenerative capacity.

The methodology was developed based on a combination of peer-reviewed scientific literature, technical reports, and legal frameworks. Sources such as A. Čerevková *et al.* (2024), E. Borska *et al.* (2025), and A. Judžentienė *et al.* (2026) provided guidance on evaluating herbicide effects and systemic activity in invasive plants. The study was conducted in compliance with current ethical guidelines for plant research. Observations and herbicide applications were carried out in natural habitats without causing irreversible damage to surrounding ecosystems or endangered species. Additionally, all plant collections and interventions adhered to the CITES (Convention on international trade in endangered species of wild fauna and flora) (n.d.), confirming that no protected or regulated species were impacted during the study. The choice of these sources was justified by their international recognition, relevance to the research objectives, and applicability to invasive plant management under field conditions.

RESULTS AND DISCUSSION

The study of systemic herbicides on *Heracleum sosnowskyi* demonstrated pronounced growth inhibition and disruption of morphogenesis. Visual assessment of physiological traits showed that by the 7th day after treatment, plants began to exhibit leaf deformation, reduced turgor, and slowed apical growth. Symptoms intensified by the 14th day, with partial dieback of lateral shoots and the appearance of chlorosis and tissue necrosis. By 21-30 days, in treatment III (Elumis OD, 2.0 L/ha + Roundup Max RK, 2.5 L/ha), most plants experienced complete dieback of growth points, and regenerated shoots were weak and did not form generative organs. Treatments II (Slash KE, 1.5 L/ha) and IV (Roundup Max RK, 4.0 L/ha) exhibited less intensive growth suppression with a greater delay, confirming their limited systemic activity.

Data from Table 1 indicate significant differences in the growth and development of *Heracleum sosnowskyi* depending on the treatment applied. In the control, throughout the observation period, plants showed intensive growth with steady increases in all morphometric

parameters. By the 14th day, plant height nearly doubled compared to the 7th day, reaching 90 cm by the 30th day. Similar dynamics were observed for stem diameter and leaf area, indicating high adaptive capacity and active vegetative growth in the absence of herbicide influence. The number of regenerated shoots in the control also steadily increased, confirming the significant regenerative potential of *Heracleum sosnowskyi*.

Application of Slash caused moderate inhibition of growth processes. Although increases in height, stem diameter, and leaf area continued throughout the observation period, growth rates were significantly lower than in the control. By the 30th day, plant height in this treatment was more than twice as low as in the control, and leaf area decreased nearly threefold. The number of regenerated shoots also increased more slowly, indicating partial limitation of regenerative capacity, though without complete cessation of growth.

The most pronounced inhibitory effect was observed in the combined treatment of Elumis OD, 2.0 L/ha + Roundup Max RK, 2.5 L/ha. This treatment showed a clear trend of gradual reduction in all morphometric parameters over time. Plant height decreased from 22 cm on day 7 to 14 cm on day 30, indicating not only growth suppression but also degradation of aboveground biomass. Similar dynamics were observed for stem diameter and leaf area, reflecting disruption of photosynthesis and formation of vegetative organs. The number of regenerated shoots in this treatment remained minimal throughout the period, confirming effective blocking of *Heracleum sosnowskyi*'s regenerative mechanisms (Table 2).

Table 2. *Morphometric parameters of Heracleum sosnowskyi*

Treatment	Day	Height (cm)	Stem diameter (cm)	Leaf area (cm²)	Regenerated shoots
Control	7	25 ± 2	1.5 ± 0.2	180 ± 20	0.5 ± 0.1
	14	45 ± 4	2.5 ± 0.3	350 ± 35	1.0 ± 0.2
	21	65 ± 5	3.8 ± 0.4	600 ± 55	1.8 ± 0.3
	30	90 ± 7	5.0 ± 0.5	900 ± 80	2.8 ± 0.4
Slash KE. 1.5 L/ha	7	23 ± 2	1.4 ± 0.2	160 ± 18	0.4 ± 0.1
	14	30 ± 3	1.8 ± 0.2	220 ± 25	0.6 ± 0.2
	21	35 ± 4	2.1 ± 0.3	260 ± 30	0.7 ± 0.2
	30	40 ± 4	2.4 ± 0.3	300 ± 35	0.8 ± 0.2
Elumis OD. 2.0 L/ha + Roundup Max RK. 2.5 L/ha	7	22 ± 2	1.3 ± 0.2	150 ± 18	0.3 ± 0.1
	14	20 ± 2	1.2 ± 0.2	135 ± 16	0.26 ± 0.1
	21	17 ± 2	1.0 ± 0.1	115 ± 14	0.22 ± 0.1
	30	14 ± 2	0.8 ± 0.1	90 ± 12	0.2 ± 0.1
Roundup Max RK. 4.0 L/ha	7	24 ± 2	1.4 ± 0.2	170 ± 20	0.4 ± 0.1
	14	35 ± 3	2.0 ± 0.2	260 ± 30	0.7 ± 0.2
	21	45 ± 4	2.6 ± 0.3	340 ± 35	1.0 ± 0.3
	30	55 ± 5	3.2 ± 0.3	420 ± 40	1.3 ± 0.3

Source: *developed by the author*

In the treatment with Roundup Max RK alone (4.0 L/ha), pronounced but less intensive growth suppression was observed compared to the combined herbicide application. Although all parameters increased over time, their absolute values remained substantially lower than in the control. By the 30th day, plant height, stem diameter, and leaf area were maintained at levels indicating partial inhibition of growth processes, while the ability for vegetative regeneration was retained, as evidenced by the increase in the number of regenerated shoots.

Overall, the results indicate that *Heracleum sosnowskyi* exhibits high growth activity and significant regenerative potential in the absence of herbicide application. Herbicide treatments suppressed plant morphogenesis to varying degrees, with the most effective being the tank mixture of Elumis OD (2.0 L/ha) + Roundup Max RK (2.5 L/ha), which provided a consistent reduction in morphometric parameters and minimised regenerative processes. This treatment can be considered the most promising for controlling the spread of the invasive species *Heracleum sosnowskyi* in agro- and semi-natural ecosystems.

The data also clearly demonstrate the significant impact of herbicides on the phenological development of *Heracleum sosnowskyi*. In the control, most plants completed all stages of organogenesis: 100% reached the stem elongation phase, 90% reached bud formation, and 85% reached flowering. Application of Slash KE (1.5 L/ha) substantially restricted the transition of plants to subsequent phenological phases. The proportion of plants in the stem elongation phase decreased to 45%, more than halving compared to the control. Only 25% of plants reached

bud formation, and flowering was observed in just 5%, indicating strong suppression of generative development and a significant reduction in seed production potential (Fig. 1).

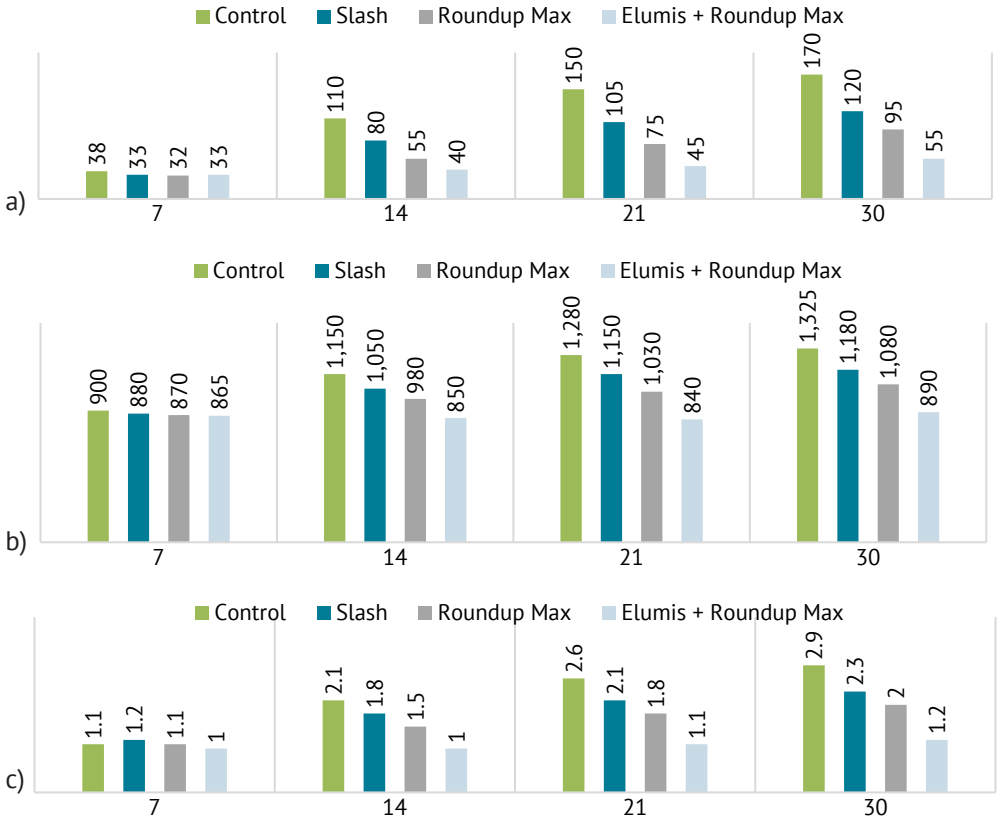

Figure 1. *Dynamics of growth (a), leaf area development (b), and regenerated shoots (c) of Heracleum sosnowskyi after treatment with different herbicides*

Source: *developed by the author*

The most pronounced effect was observed in the treatment with the tank mixture of Elumis OD (2.0 L/ha) + Roundup Max RK (2.5 L/ha). In this case, only 35% of plants reached stem elongation, which is 65% lower than in the control. Only 15% of plants reached bud formation, and the transition to flowering was completely blocked (0%). These results indicate full cessation of generative development under combined herbicide treatment. In the treatment with Roundup Max RK alone (4.0 L/ha), suppression of phenological development was less pronounced but remained significant. Stem elongation occurred in 50% of plants, bud formation in 30%, and flowering in 10%. Compared to the control, this represents an 8.5-fold reduction in the proportion of flowering plants, indicating a strong, though not complete, limitation of the species' reproductive capacity (Fig. 2).

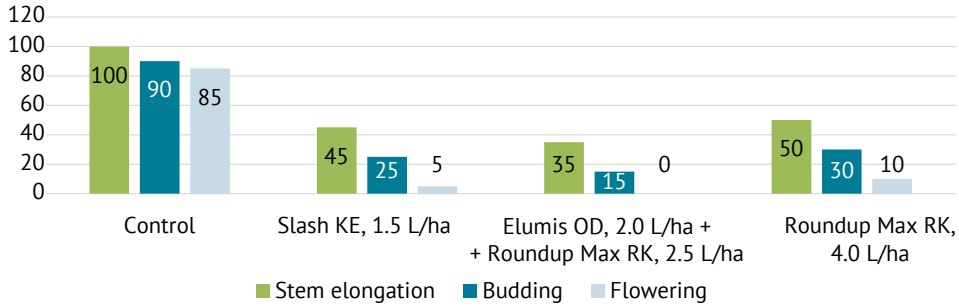

Figure 2. *Effect of herbicides on the phenological phases of Heracleum sosnowskyi (%)*

Source: *developed by the author*

A comprehensive analysis of physiological, morphometric, and phenological parameters showed that the highest efficacy in controlling *Heracleum sosnowskyi* is achieved through the combined application of Elumis OD (2.0 L/ha) and Roundup Max RK (2.5 L/ha). This tank mixture causes maximal growth suppression, delays generative development, and almost completely blocks regenerative capacity. Application of a single herbicide was less effective, due to the limited spectrum of action and slower systemic activity of individual compounds.

The results demonstrated the high effectiveness of systemic herbicides in controlling *Heracleum sosnowskyi*. Physiological observations revealed that this treatment rapidly suppresses apical and lateral growth, causes leaf deformation, turgor loss, and tissue necrosis within 7-14 days after application. Morphometric parameters confirmed these findings: plant height, stem diameter, and leaf area were reduced by 45-53%, and regenerated shoots were almost absent after 30 days. Phenological observations indicate complete blockage of transition to the generative phase, preventing seed formation and the establishment of a seed bank.

The results of the study showed that the most appropriate phase for the use of systemic herbicides is the rosette stage and the initial stages of intensive vegetative growth. During this period, plants showed increased sensitivity to the action of herbicides, which ensures maximum growth inhibition, disruption of morphogenesis and prevention of the formation of generative organs. Treatment at later stages, when the formed stems and leaves have already reached a significant mass, turned out to be less effective, since the plants partially retain the ability to regenerate and continue to enter the generative phase. It is considered that combining the chemical method with the mechanical one can significantly increase control effectiveness.Preliminary mowing or cutting of the above-ground mass allows to reduce the density of the thickets and at the same time improves the penetration of the working solution of the herbicide into the plant tissues. This approach not only increases the speed and depth of systemic action, but also prevents seed dispersal, which is especially important in urban and communal areas.

Based on the data obtained, a practical step-by-step control scheme for municipal services can be developed. It involves early detection of *Heracleum sosnowskyi* rosettes in the spring, the use of mechanical thinning where possible, and subsequent treatment with systemic herbicides in the early growth phase. Monitoring plant regeneration after 2-3 weeks allows for an assessment of the effectiveness of the initial treatment, and re-treatment of those shoots that have survived ensures complete blocking of regenerative mechanisms and prevents population recovery. The results also showed that a single treatment is often insufficient for complete control, especially in dense or perennial populations. Re-treatment 2-4 weeks after the initial herbicide application is necessary to eliminate residual shoots and prevent the formation of a soil seed bank. The combined application of Elumis OD (2.0 L/ha) and Roundup Max RK (2.5 L/ha) provides maximum growth suppression, blocking of generative development and almost complete elimination of regenerative capacity, making this approach the most promising for the control of *H. sosnowskyi* in agro- and semi-natural ecosystems. The integration of mechanical methods with a stepwise treatment strategy increases the long-term effectiveness and stability of control, reducing the risk of re-spreading of the invasive species.

These results were consistent with numerous Ukrainian and international studies, but a more detailed comparison provides additional insights. I. Shuvar *et al*. (2025) investigated the efficacy of systemic herbicides based on glyphosate, both alone and in combination with acetochlor or mesotrione, on perennial invasive species of *Apiaceae* and *Asteraceae*, including *Heracleum sosnowskyi* and *Solidago canadensis*. They measured growth suppression, morphometric changes, and generative development. Their results showed that combined herbicide treatments not only reduced leaf area and inhibited growth points but also effectively blocked the transition to generative phases, which aligns closely with received findings regarding the superior efficacy of the Elumis OD + Roundup Max mixture. It is widely accepted that early application during the rosette or early vegetative stage is critical for maximum effect.

In this direction, I. Gazoulis *et al.* (2022) also worked, who studied the effect of systemic herbicides on Heracleum mantegazzianum populations. The authors found that the use of glyphosate-containing preparations in the early phases of plant development provides a significant reduction in biomass, and also significantly inhibits the formation of generative organs. The researchers emphasised that the effectiveness of control increases significantly in the case of combining herbicides with different mechanisms of action, which confirms the feasibility of using tank mixtures for the control of *H. sosnowskyi*.

J. Soler & J. Izquierdo (2024) focused on the comparison of single versus combined systemic herbicide applications on invasive perennial plants. J. Soler & J. Izquierdo (2024) quantified morphometric parameters and regenerative potential over a 30-day period, demonstrating that tank mixtures produce faster and

more pronounced reductions in leaf area, stronger inhibition of apical and lateral growth, and near-complete suppression of regenerative shoots. These results corroborated present observations that combined treatments achieve greater systemic activity than single herbicides, confirming the advantage of multi-compound approaches in controlling *H. sosnowskyi*.

Similar results were obtained by W.-T. Gao & W.-H. Su (2024), who studied the regeneration ability of invasive perennial species after treatment with systemic herbicides. The authors found that the use of combined herbicide preparations contributes to the faster destruction of the photosynthetic apparatus of plants and significantly more effectively inhibits the formation of new shoots compared to single-component preparations. Therefore, this indicates the advantage of using tank mixtures for the control of aggressive invasive species.

X. Ye. *et al.* (2023) and I. Gruss *et al.* (2025) analysed herbicide sensitivity across different developmental stages of invasive plants. Both studies found that rosette-stage plants exhibit the highest susceptibility, while later stages such as stem elongation or bud formation show partial resistance due to more developed tissue and reduced systemic uptake. The current results are fully consistent with this pattern, as treatments applied in the early vegetative phases in the study performed achieved the greatest growth inhibition and almost complete blocking of generative development, while treatments in later stages were less effective.

Similar conclusions were obtained by L. Bobuľská *et al*. (2025), who studied the ecological features of invasive plants and their response to control measures. The authors emphasise that young plants of invasive species are characterised by significantly higher sensitivity to herbicides due to a less developed root system and more active processes of transport of active substances in tissues. This explains the higher efficiency of treatments carried out in the early phases of vegetation.

A. Valiño *et al*. (2023) investigated single-compound herbicide applications on perennial invasive species, reporting only partial growth inhibition and slower systemic action. While author confirmed the potential of glyphosate-based treatments, their findings highlighted the limitations of single-herbicide approaches. These observations are consistent with previous findings, where single-herbicide treatments (Slash KE or Roundup Max alone) suppressed growth and delayed development but did not completely prevent regeneration or flowering. Therefore, tank mixtures are considered preferable for achieving comprehensive control of *H. sosnowskyi*. In addition, recent studies have provided new perspectives on integrated and stepwise control strategies. For example, T. Žalnierius *et al*. (2025) examined the combination of chemical and mechanical methods in field populations of invasive plants, including *H. sosnowskyi*, and demonstrated that sequential mowing followed by systemic herbicide application significantly enhances suppression, reduces seed production, and minimises reinfestation risk. This complements the present findings and supports the practical recommendation to integrate mechanical removal with early chemical treatment, particularly in urban or semi-natural areas. K. Słowiński *et al*. (2024) evaluated phenological shifts in invasive species under herbicide treatment. The study demonstrated that early application of systemic herbicides not only delays or suppresses flowering but also reduces seed viability and limits long-term population establishment. These findings are directly consistent with the observations: the tank mixture of Elumis OD + Roundup Max completely blocked flowering and generative organ formation in *H. sosnowskyi*, confirming both immediate growth suppression and prolonged inhibition of reproductive capacity.

Similarly, T.I. Kose *et al*. (2025) investigated the effectiveness of combined herbicide applications on perennial invasive plants, including *Heracleum* species. They found that tank mixtures significantly reduce leaf area, suppress apical and lateral growth points, and limit regenerative potential, particularly when applied during early vegetative stages. These results align closely with this study, reinforcing the conclusion that early, combined chemical treatments provide the most reliable control of *H. sosnowskyi*, effectively minimising both vegetative and generative regeneration. Finally, I. Gruss *et al.* (2025) investigated the economic efficiency of chemical control of invasive perennial plants. Authors found that early application of systemic herbicides reduces the frequency of repeated treatments, lowers management costs, and prevents establishment of persistent seed banks. Thus, the results confirmed that timely early herbicide applications significantly reduce the need for re-applications, demonstrating the advantage of combination treatments in terms of cost and effectiveness.

Overall, the reviewed literature generally supported the present findings that systemic herbicides, particularly in tank mixtures, are most effective when applied at early vegetative stages. While single-herbicide applications provide partial control, combined treatments maximise growth inhibition, block generative development, and minimise regenerative potential. The consensus among these studies reinforces the importance of early detection, timing, and integrated chemical-mechanical strategies, which is consistent with the observed physiological, morphometric, and phenological responses

of *H. sosnowskyi* in the present study. The study confirmed that combined herbicide application is the most effective method for chemical control of *Heracleum sosnowskyi* under field conditions, providing maximal growth suppression, blocking generative development, and significantly reducing regenerative capacity. The results are consistent with international research and can be used to develop practical recommendations for managing invasive populations of *Heracleum sosnowskyi*.

CONCLUSIONS

The study demonstrated that *Heracleum sosnowskyi* exhibits high growth activity and a pronounced regenerative potential under control conditions (without herbicide application). After 30 days, plant height reached 90 ± 7 cm, stem diameter was 5.0 ± 0.5 cm, leaf surface area amounted to 900 ± 80 cm^2, and the number of regenerative shoots increased to 2.8 ± 0.4, indicating intensive vegetative growth and recovery capacity. Application of the herbicide Slash EC at a rate of 1.5 L/ha significantly suppressed plant growth. On the 30th day, plant height decreased to 40 ± 4 cm, stem diameter to 2.4 ± 0.3 cm, leaf area to 300 ± 35 cm^2, and the number of regenerative shoots was reduced to 0.8 ± 0.2.

Treatment with Roundup Max SL at rates of 2.5-4.0 L/ha resulted in moderate growth inhibition. On day 30, plant height reached 55 ± 5 cm, stem diameter was 3.2 ± 0.3 cm, leaf surface area amounted to 420 ± 40 cm^2, and the number of regenerative shoots was 1.3 ± 0.3, indicating partial suppression of vegetative growth and generative development. The highest efficacy was observed with the tank mixture of Elumis OD (2.0 L/ha) and Roundup Max SL (2.5 L/ha). Under this treatment, plant height on the 30th day was reduced to 14 ± 2 cm, stem diameter to 0.8 ± 0.1 cm, leaf surface area to 90 ± 12 cm^2, and the number of regenerative shoots remained minimal at 0.2 ± 0.1.

Analysis of phenological development revealed that in the control treatment, 100% of plants reached the stem elongation stage, 90% entered the budding stage, and 85% reached flowering. Application of Slash EC (1.5 L/ha) reduced these values to 45%, 25%, and 5%, respectively, while treatment with Roundup Max SL (4.0 L/ha) resulted in 50% stem elongation, 30% budding, and 10% flowering. In contrast, the tank mixture of Elumis OD (2.0 L/ha) and Roundup Max SL (2.5 L/ha) completely blocked the flowering stage (0%) and significantly limited stem elongation and budding (35% and 15% of plants, respectively).

The obtained results indicate that the combined application of Elumis OD (2.0 L/ha) and Roundup Max SL (2.5 L/ha) provides the most effective suppression of growth, generative development, and regenerative processes of *Heracleum sosnowskyi*, whereas the use of single herbicide treatments is less effective due to a narrower spectrum of action and slower systemic activity.Future research should focus on evaluating the long-term effects of repeated herbicide applications on soil seed banks and the potential development of herbicide resistance in *Heracleum sosnowskyi*. Additionally, studies could explore integrated management strategies that combine chemical, mechanical, and biological control methods to optimise both ecological and economic efficiency in different habitat types.

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CONFLICT OF INTEREST

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Вплив гербіцидів на ріст та розвиток інвазивного виду *Heracleum sosnowskyi* Manden.

Ганна Корпіта
Кандидат сільськогосподарських наук, доцент
Львівський національний університет ветеринарної медицини та біотехнологій імені С. З. Ґжицького
80831, вул. Володимира Великого, 1, м. Дубляни, Україна
https://orcid.org/0000-0002-0908-0129

Анотація. Метою дослідження було оцінити ефективність різних гербіцидних обробок щодо пригнічення росту, розвитку та регенераційних здібностей інвазійного виду *Heracleum sosnowskyi* Manden. Дослідження виконано з використанням чотирьох варіантів: контроль без гербіцидів, Слаш КЕ (1,5 л/га), Раундап Макс РК (4,0 л/га), а також комбіноване внесення Елюміс ОД (2,0 л/га) та Раундап Макс РК (2,5 л/га). Для оцінки ефекту гербіцидів визначали морфометричні показники рослин (висота, діаметр стебла, площа листків), фенологічні фази (стеблування, бутонізація, цвітіння) та кількість відновних пагонів у динаміці спостережень протягом 30 діб. Результати показали, що у варіанті контролю рослини характеризувалися високими темпами росту, значним збільшенням морфометричних показників та активною генеративною діяльністю, включно з формуванням відновних пагонів. Застосування одиночних гербіцидів призвело до часткового пригнічення росту та генеративного розвитку, при цьому відновні пагони утворювалися, хоча й у меншій кількості порівняно з контролем. Найбільш виражений ефект спостерігався за комбінованого внесення гербіцидів Елюміс ОД (2,0 л/га) та Раундап Макс РК (2,5 л/га). У цьому варіанті висота рослин, діаметр стебла та площа листків знижувалися до мінімальних значень, генеративний цикл практично блокувався, а кількість відновних пагонів залишалася стабільною або зменшувалася, що свідчить про повне пригнічення регенераційних механізмів *Heracleum sosnowskyi*. Практичне значення отриманих результатів полягає в тому, що комбінована гербіцидна обробка може бути ефективним методом контролю інвазійного виду в агроекосистемах і напівприродних угіддях, запобігаючи його поширенню та зменшуючи негативний вплив на продуктивність сільськогосподарських культур

Ключові слова: хімічний контроль; фізіологічна реакція; морфометричний аналіз; фенологічні зміни; контроль бур'янів

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The effect of industrial crossbreeding with terminal line boars on the growth and development of young pigs

Andrii Karatieiev
Postgraduate Student
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0009-0008-3345-0450

Olena Karatieieva*
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-0652-1240

Michael Gill
Doctor of Agricultural Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-7353-9865

Abstract. One of the most effective methods of genetic improvement in pigs is crossbreeding, which, when based on carefully selected breed combinations, contributes to increased productivity and reduced costs in pig production. The aim of the study was to assess the influence of different maternal genotypes, when crossed with terminal boars of the MaxGrow line, on growth parameters, weight gain, final live weight of piglets and the level of heterosis under commercial pig farming conditions. Experimental studies were conducted on three groups of pigs comprising purebred, crossbred (½ Large White × ½ Landrace of English selection) and specialised sows from Genesus, using terminal boars of the MaxGrow line. This approach ensured an objective assessment of the influence of the maternal genotype on the growth parameters of the offspring under conditions of a standardised paternal component. It was established that the sows' genotype is a determining factor in growth rate, daily weight gain and final live weight of the piglets. The highest values for absolute (107.37 kg), average daily (596.5 g) and relative (32.3%) weight gains throughout the entire rearing period were observed in pigs of the Genesus × MaxGrow genotype, indicating the effective realisation of the heterosis effect. Crossbred animals occupied an intermediate position (104.6 kg; 578.7 g and 32.0% respectively), demonstrating a consistent advantage over the purebred control (100.82 kg; 560.1 g and 30.5% respectively). The results of the growth index assessment and two-way analysis of variance confirmed the dominant role of genotype (38.0-56.0%) in the formation of productive traits and the high reliability of the data obtained. It was concluded that the use of MaxGrow terminal boars in combination with specialised and crossbred maternal lines is a scientifically sound and technologically feasible approach to improving breeding programmes in commercial pig farming. It can be utilised by breeding specialists and pig farm technologists to optimise industrial crossbreeding schemes with the aim of increasing the growth rate of young stock and the efficiency of pork production

Keywords: breeding programmes; terminal boars; heterosis effect; hybrid vigour; specialised lines; growth rate

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*Corresponding author (karateeva1207@gmail.com)

INTRODUCTION

Rational improvement of breeding programs in pig farming is a necessary condition for ensuring the stable development of the industry and increasing its economic efficiency. In the system of artificial insemination of pigs at production complexes, the leading role belongs to breeding boars, since they largely determine the level of realisation of the hereditary potential of the offspring. In this regard, the scientifically substantiated selection of boars for use in crossbreeding schemes is of decisive importance for obtaining competitive products and meeting modern market requirements.

According to S. Vaishnav *et al*. (2025), selection and mating systems are integral components of improvement programs for any pig breed. Various parameters, such as the choice of traits, their number, and genetic properties, especially the level of heritability, must be taken into account when making decisions regarding selection in the breeding herd. The choice of breeds for the breeding method, namely purebred breeding or crossbreeding, is also a very important technique. Different crossbreeding systems are practiced in order to utilise the effects of heterosis and complementarity in pig farming. As indicated by S.P. Turner *et al*. (2024), optimisation of pig breeding programs is an important prerequisite for achieving sustainable and economically efficient pork production. In artificial insemination technologies for pigs, the role of breeding boars is undoubtedly key, since they are an integral factor of genetic potential. Therefore, the correct selection of boars for crossbreeding is important for maintaining high-quality pork production and adapting to constantly changing market requirements. Y. Steyn *et al*. (2021) concluded that crossbreeding is one of the key tools in pig breeding. When properly applied, it allows pork producers to genetically increase production efficiency and, accordingly, reduce production costs. The widespread use of crossbreeding is due to the fact that offspring obtained from mating animals of different breeds are usually characterised by higher viability, faster growth rates, and better productivity indicators compared with purebred animals. The advantage of crossbred offspring over the average indicators of its purebred parents is defined as heterosis, or hybrid vigour.

According to P. Nevrkla *et al*. (2021), pig breeding is influenced by a number of factors, among which one of the most important is the genotype of sows, which is half determined by terminal boars. The selection of appropriate genotypes for mating is one of the decisive factors. The criteria for choosing an appropriate breeding combination are the results of testing hybrid populations. Their main principle is the selection of genetically optimal populations for specific conditions. In addition, the phenotypic level of expression of parameters of live weight and growth intensity of young pigs is also significantly influenced by sows – the maternal genetic effect. According to M.C. Fabbri *et al*. (2024), crossbreeding can be an effective strategy for increasing the value of local pig breeds as well. Since it can reduce homozygosity and, as a consequence, provide hybrid vigour to improve physical condition and productive traits. In addition, P. Duenk *et al*. (2021) proved that the crossbreeding system can be used to reduce the level of inbreeding in offspring. Another advantage of crossbreeding is the manifestation of heterosis, also known as hybrid vigour. Hybrid vigour is a phenomenon in which the performance of crossbred individuals exceeds the average performance of the parental lines. Hybrid vigour is the opposite of inbreeding depression, and inbreeding generally leads to a greater number of gene pairs in an individual being homozygous. Crossbreeding, on the contrary, generally leads to a greater number of gene pairs being heterozygous. Crossbreeding is regularly used in many commercial pig farming systems because, in general, the offspring are more robust, with better indicators of growth and development.

As indicated by R. Pereira-Pinto *et al*. (2025), pig growth indicators, expressed by daily gain, feed conversion efficiency, and lean meat content, have significantly improved due to selection and continue to improve thanks to available genetic and breeding approaches. In addition, pig crossbreeding has a progressive effect on such characteristics as growth rate, feed efficiency, and reproductive indicators due to hybrid vigour (heterosis). A.S. Kramarenko *et al*. (2024) report that the origin of boars and sows affects not only the productive traits of pigs but also reproductive qualities, stillbirth rate, and piglet mortality after farrowing. The authors note that boars of the Pietrain breed, which are used as terminal sires, have better fertilising ability and a higher number of piglets at birth. The studies of P. Nevrkla *et al*. (2021) describe the effect of crossbreeding on the growth intensity of piglets, mainly on live weight at birth and subsequent growth energy. Nevertheless, studies analysing the influence of terminal boars on the growth intensity of piglets before and after weaning are rare, although their influence may be significant, since they account for 50% of the genetic potential of piglets. This is what aroused interest in determining the influence of the use of terminal boars on the growth intensity of piglets during the suckling period and after weaning, in particular on indicators of live weight at birth and subsequent growth dynamics, taking into account their contribution to the realisation of the genetic potential of the offspring. Therefore, the aim of the study was to determine

the effect of using terminal boars of the MaxGrow line in combination with different maternal genotypes on the live weight of piglets at birth, growth intensity during the suckling period and after weaning, as well as on the level of realisation of genetic potential and the heterosis effect under conditions of industrial pig farming.

MATERIALS AND METHODS

The studies were conducted on the facilities of Agricultural LLC "Promin" in Pervomaisk Raion during the period of 2025. For this purpose, three groups of pigs were formed using purebred sows, crossbred sows of the Large White breed (LW) and Landrace (L) obtained from English selection (1/2LW × 1/2L), and sows of the Genesus company; the breeding scheme is presented in Table 1. The selection of the studied breeds was determined by their availability at the specific farm on the basis of which the research was conducted. The formation of experimental groups was carried out according to the principle of analogous groups with random distribution of animals, while feeding and housing conditions for all groups were identical. The used genotypes MaxGrow and Genesus belong to commercial terminal lines; their exact breed composition and genetic structure are a commercial secret. In the practice of breeding research, such genotypes are identified by trade names, and comparative analysis is carried out in order to determine their productive efficiency.

Table 1. *Scheme of formation of experimental groups of pigs*

Indicator	Group		
	I (control)	II (experimental)	III (experimental)
n	50	50	50
Sow breed	LW	1/2LW×1/2L	Genesus
Boar breed	MaxGrow	MaxGrow	MaxGrow

Source: *developed by the authors*

The control group (I) consisted of the offspring of Large White (LW) sows, while the II experimental group included crossbred animals (½ Large White × ½ Landrace of English selection), and the III group consisted of pigs of the Genesus genotype. In all groups, boars of the MaxGrow line were used for insemination, which made it possible to objectively assess the influence of the paternal factor and the role of crossbreeding in the formation of productive traits of the offspring. The experimental groups were formed according to the principle of analogous groups by random assignment, and their feeding and housing conditions were completely identical. The growth intensity of the experimental piglets was monitored by individual weighing at birth, at one month of age, and at 60-, 90-, 150-, and 180-day ages using platform industrial scales TV1 "Tekhnovahy". According to the generally accepted methodology, absolute, average daily, and relative gains in the live weight of piglets were calculated. The main indices of the intensity of organism formation were evaluated according to the methods described in K.V. Harmatiuk (2022). The index of organism formation intensity (Δt) according to the formula:

$$\Delta t = \frac{W_2 - W_1}{0.5(W_2 + W_1)} - \frac{W_3 - W_2}{0.5(W_3 + W_2)}, \quad (1)$$

where W_1, W_2 і W_3 are live weight at a certain age; 0.5 is a coefficient. The index of uniformity of pig growth (I_u) according to the formula:

$$I_u = \frac{1}{1+\Delta t} \times DG, \quad (2)$$

where Δt is the intensity of organism formation; *DG* is the average daily gain for different age intervals; 1 – coefficient, in calculations shows how much the index deviates from 100%. The index of growth tension (I_t) of the pigs according to the formula:

$$I_t = \frac{\Delta t}{RG} \times DG, \quad (3)$$

where Δt is the intensity of organism formation; *AD* – average daily gain for different age intervals; *RG* – relative gain for different age intervals. The role of the presented indices of organism formation intensity, growth uniformity, and growth tension lies in the objective assessment of the characteristics of growth processes of animals at different stages of their development. These indicators make it possible to determine the rate of organism formation, establish the uniformity of live weight increase, and assess the degree of growth tension during individual age periods. The use of these indices allows a more complete characterisation of the biological features of animal growth, identification of the influence of genotypic factors on the intensity of their development, and substantiation of the effectiveness of the applied technological solutions in the system of rearing and fattening. Such indicators are important criteria in evaluating productivity and predicting the further growth and development of animals. All statistical processing was carried out based on the

methodologies presented in the manual by R.R. Sokal & F.J. Rohlf (1995), using the free-ware software JAMOVI v. 2.6.19 (Navarro & Foxcroft, 2025).

To evaluate the strength of the influence of different factors – genotype (factor A) and age period (factor B) – on the growth and development of young pigs, a two-factor analysis of variance (ANOVA) was used with subsequent post-hoc analysis based on Fisher's criterion for multiple comparisons. The Shapiro-Wilk test was applied to verify normality: for group 1 – $p = 0.011$, for group – 2 $p = 0.017$, for group 3 – $p = 0.0067$. In all three groups p is greater than 0.05. Therefore, it was concluded that all samples have a normal distribution. Taking into account that the paternal factor (MaxGrow boar) was constant, the variation was formed due to the maternal genotype and age period. The evaluation was performed using the values of the sum of squares of deviations (*SS*), mean squares (*MS*), the actual value of Fisher's criterion (F_{crit}), the level of significance (p), and the proportion of factor influence (η^2) (Kramarenko *et al.*, 2019). Animal handling procedures fully complied with European legislation (Council Directive No. 98/58/EC, 1998; Nalon & Stevenson, 2019). The research protocol was approved by the bioethics committee in accordance with the standards of good clinical practice regarding the protection and humane treatment of experimental animals.

RESULTS AND DISCUSSION

The dynamics of the live weight of pigs of different genotypes during the rearing period from birth to 6 months of age were studied. It was established that at birth piglets of all groups were characterised by almost identical live weight, which ranged within 1.56-1.59 kg, and the difference between the indicators was statistically insignificant. This indicates the homogeneity of the experimental population at the start of the experiment and the validity of further comparisons (Table 2).

Table 2. *Dynamics of live weight of piglets of different genetic origin, kg*

Age, months	Group					
	I (control)		II (experimental)		III (experimental)	
Sow breed	LW		1/2LW × 1/2L		Genesus	
Boar breed	MaxGrow		MaxGrow		MaxGrow	
At birth	155	1.56 ± 0.033	160	1.58 ± 0.041	158	1.59 ± 0.013
1 month	153	9.04 ± 0.335	157	9.15 ± 0.329	147	9.37 ± 0.364
2 months	147	21.92 ± 0.434	155	22.65 ± 0.335	143	23.37 ± 0.401*
3 months	145	37.93 ± 0.539	150	38.69 ± 0.581*	138	39.38 ± 0.563*
5 months	144	78.46 ± 0.84	146	80.12 ± 0.79*	137	82.35 ± 0.88*
6 months	142	102.38 ± 1.12	146	105.74 ± 1.08*	135	108.96 ± 1.15*

Note: ** = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$*

Source: *developed by the authors*

At one month of age, the live weight of piglets in all experimental groups increased 5.7-5.9 times compared to birth weight, which indicates a high intensity of growth during the suckling period. During this period, animals obtained as a result of crossbreeding, as well as piglets from specialised meat maternal forms, tended to have higher live weight indicators; however, the difference compared with the control animals remained statistically insignificant. This indicates a limited manifestation of genetic differences in the early postnatal period under the conditions of using MaxGrow terminal boars. Beginning from two months of age, when the role of the animal's own genotype in the formation of growth processes increases, intergroup differences intensified significantly. Piglets of the III experimental group (Genesus × MaxGrow) significantly ($p < 0.05$) exceeded the control group in live weight, which indicates the effective realisation of the genetic potential of the specialised meat genotype under the conditions of the rearing period and confirms the expediency of using terminal crossbreeding. At three months of age, both piglets of group II ((½LW × ½L) × MaxGrow) and those of the III experimental group already demonstrated a statistically significant advantage over the control animals. This indicates a positive effect of combining maternal forms with terminal boars, which is manifested in higher rates of live weight gain during the phase of intensive growth. The most pronounced intergroup differences were recorded in the final period of rearing – at 5-6 months of age. At 6 months, the live weight of pigs of the II experimental group exceeded the control by 3.36 kg (3.3%), while animals of the III group exceeded it by 6.58 kg (6.4%) with a statistically significant difference ($p < 0.05$). The obtained results convincingly confirm the higher genetically determined growth potential of pigs of the Genesus genotype and the effectiveness of using terminal crossbreeding with MaxGrow boars, as well as the expediency of involving crossbred maternal forms (½LW × ½L) under industrial pork production conditions (Fig. 1).

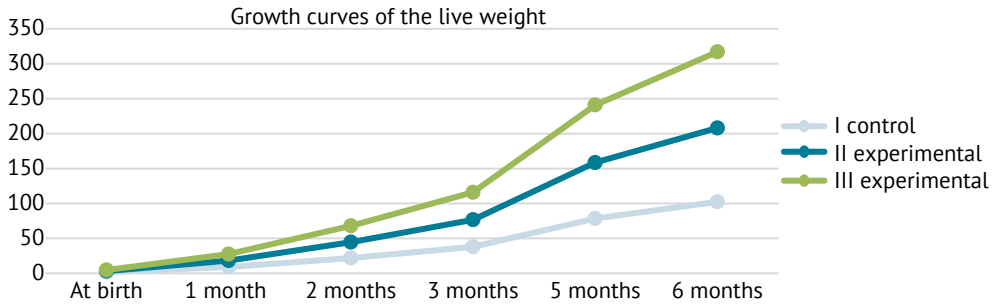

Figure 1. *Growth curves of live weight of piglets of different genetic origin*
Source: *developed by the authors*

The constructed graph clearly demonstrates the parallel nature of growth in animals of all groups at an early age and the gradual divergence of the curves starting from 2-3 months of age. The curve of the III experimental group is positioned above the others throughout the entire rearing period, visually confirming the advantage of the Genesus crossbred genotypes in terms of live weight. The II experimental group occupies an intermediate position between the control and the III group, demonstrating consistently higher growth rates compared to purebred Large White pigs. Live weight gain is one of the key indicators characterising growth intensity and the efficiency of realising the genetic potential of pigs during the rearing process. The analysis of absolute, average daily, and relative gains allows for an objective assessment of the influence of genotype on the formation of productive traits. The data presented in Table 3 reflect the dynamics of absolute, average daily, and relative live weight gains of pigs of different genotypes during the rearing period from birth to 6 months of age.

Table 3. *Dynamics of live weight gains of piglets of different genetic origin*

Age, months Sow breed Boar breed	Group I (control) LW MaxGrow		II (experimental) 1/2LW × 1/2L MaxGrow		III (experimental) Genesus MaxGrow	
Absolute gain, kg						
birth-1 month	155	7.48 ± 0.34	160	7.57 ± 0.32	158	7.78 ± 0.31
1-2 months	153	12.88 ± 0.41	157	13.50 ± 0.38	147	14.00 ± 0.36*
2-3 months	147	16.01 ± 0.52	155	16.04 ± 0.49	143	16.01 ± 0.47
3-5 months	145	40.53 ± 0.87	150	41.43 ± 0.81*	138	42.97 ± 0.79*
5-6 months	144	23.92 ± 0.69	146	25.62 ± 0.65*	137	26.61 ± 0.63*
The whole period	149	100.82 ± 1.12	154	104.16 ± 1.09*	145	107.37 ± 1.15*
Average daily gain, g						
birth-1 month	155	249.3 ± 11.3	160	252.3 ± 10.7	158	259.3 ± 10.3
1-2 months	153	429.3 ± 13.7	157	450.0 ± 12.6	147	466.7 ± 12.0*
2-3 months	147	533.7 ± 17.3	155	534.7 ± 16.4	143	533.7 ± 15.7
3-5 months	145	675.5 ± 14.5	150	690.5 ± 13.5*	138	716.2 ± 13.2*
5-6 months	144	797.3 ± 23.0	146	854.0 ± 21.7*	137	887.0 ± 21.0*
The whole period	149	560.1 ± 6.2	154	578.7 ± 6.1*	145	596.5 ± 6.4*
Relative gain, %						
birth-1 month	155	479.5 ± 18.2	160	479.1 ± 17.6	158	489.3 ± 16.9
1-2 months	153	142.5 ± 5.1	157	147.5 ± 4.8	147	149.4 ± 4.6*
2-3 months	147	73.0 ± 2.6	155	70.8 ± 2.4	143	68.5 ± 2.3
3-5 months	145	106.9 ± 3.8	150	107.1 ± 3.6	138	109.1 ± 3.4*
5-6 months	144	30.5 ± 1.1	146	32.0 ± 1.0*	137	32.3 ± 0.9*

Note: ** = p < 0.05; ** = p < 0.01; *** = p < 0.001*
Source: *developed by the authors*

During the suckling period (birth-1 month), the absolute live weight gain of piglets in all groups was practically the same and ranged from 7.48 to 7.78 kg, while intergroup differences did not reach the level of statistical significance. This indicates similar initial growth conditions and the absence of a significant

genotype effect at an early age. Beginning from the period of 1-2 months, animals of the III experimental group (Genesus × MaxGrow) showed a significantly higher absolute gain (+1.12 kg; $p < 0.05$) compared with the control, indicating a faster realisation of the genetically determined growth potential after weaning. At the age of 3-5 and 5-6 months, pigs of groups II and III also significantly exceeded the control values, with the greatest intergroup differences observed in animals of the Genesus genotype. Over the entire rearing period from birth to 6 months of age, the absolute gain in the control group was 100.82 kg, while in animals of the II and III experimental groups it amounted to 104.16 and 107.37 kg, respectively, which is 3.3% and 6.5% higher compared with the control group ($p < 0.05$).The analysis of average daily gains revealed a similar pattern in the growth dynamics of pigs when crossbreeding schemes using MaxGrow terminal boars were applied. During the suckling period, no significant intergroup differences were found, indicating a relatively similar realisation of growth potential at the early stages of postnatal development regardless of genotype.

However, already at the age of 1-2 months, pigs of the III experimental group (Genesus × MaxGrow) were characterised by significantly higher average daily gains compared with the control animals (466.7 vs. 429.3 g; $p < 0.05$), which indicates a more effective interaction between the maternal meat genotype and the terminal paternal component during the post-weaning period. During the phase of intensive growth (3-5 months), the average daily gains of pigs in the II ((½LW × ½L) × MaxGrow) and III experimental groups significantly exceeded those of the control group by 15.0-40.7 g ($p < 0.05$). The obtained data indicate a positive effect of industrial crossbreeding and a better ability of crossbred and specialised meat genotypes to efficiently utilise feed nutrients during the period of maximum growth intensity. In the final fattening period (5-6 months), the advantage of animals obtained through terminal crossbreeding schemes became even more pronounced, confirming the stability of the heterosis effect at later stages of ontogenesis. On average, for the entire rearing period, the average daily gain of pigs in the control group was 560.1 g, whereas in animals of the II and III experimental groups it amounted to 578.7 and 596.5 g, respectively, which significantly exceeded the control value ($p < 0.05$).

The analysis of relative live weight gains also confirmed the established patterns. At an early age, intergroup differences were insignificant, indicating a limited manifestation of genetic advantages during the suckling period. However, during the periods of 1-2 and 3-5 months, pigs of the III experimental group, obtained from specialised maternal forms in combination with terminal MaxGrow boars, significantly exceeded the control group in relative gains ($p < 0.05$). At the age of 5-6 months, both the II and III groups maintained significantly higher indicators of relative gain, which indicates a prolonged and stable advantage of crossbreeding schemes using terminal boars throughout the entire rearing period. The index-based evaluation of growth indicators represents a generalised approach to analysing the intensity, tension, and uniformity of body formation in animals during ontogenesis. The application of indices makes it possible to comprehensively characterise the course of growth processes at different age periods. Therefore, the indices of body formation intensity, growth tension, and growth uniformity were studied in crossbred pigs of different maternal origins. It is important to note that all experimental animals, except those of the control group, were obtained from crossbred sows and inseminated with boars of the MaxGrow line, which ensured the uniformity of the paternal genotype and made it possible to objectively assess the effect of crossbreeding and hybridisation on the characteristics of growth processes (Table 4).

Table 4. *Intensity of body formation in young pigs*

Age, months	Group					
	I (control)		II (experimental)		III (experimental)	
Sow breed	LW		1/2LW × 1/2L		Genesus	
Boar breed	MaxGrow		MaxGrow		MaxGrow	
index of organism formation intensity						
0-3 months	152	0.55 ± 0.02	157	0.53 ± 0.02	149	0.52 ± 0.02*
0-6 months	149	0.55 ± 0.02	154	0.53 ± 0.02	145	0.52 ± 0.02*
index of growth tension						
0-3 months	152	2.14 ± 0.09	157	2.12 ± 0.09	149	2.06 ± 0.08*
0-6 months	149	1.82 ± 0.06	154	1.87 ± 0.06	145	1.91 ± 0.06*
index of growth uniformity						
0-3 months	152	0.47 ± 0.02	157	0.47 ± 0.02	149	0.49 ± 0.02*
0-6 months	149	0.55 ± 0.02	154	0.53 ± 0.02	145	0.52 ± 0.02*

Note: ** = p < 0.05; ** = p < 0.01; *** = p < 0.001*

Source: *developed by the authors*

The analysis of the body formation intensity index indicates that during the period of 0-3 months its value in pigs of the control group was 0.55, whereas in animals of the II and III experimental groups it was 0.53 and 0.52, respectively. The decrease in the body formation intensity index in pigs of the Genesus genotype was statistically significant ($p < 0.05$), which indicates relatively more intensive growth rates during the post-weaning period compared with the early stage of ontogenesis. A similar pattern was observed over the entire rearing period (0-6 months), where the lowest value of the body formation intensity index was also characteristic of the III experimental group (Genesus × MaxGrow). This indicates an earlier and more pronounced shift in growth phases in pigs of this genotype. The growth tension index during the period of 0-3 months was the highest in animals of the control group (2.14), while in crossbred pigs of the II (½LB × ½L × MaxGrow) and III (Genesus × MaxGrow) groups it decreased to 2.12 and 2.06, respectively. The significantly lower value observed in pigs of the Genesus genotype ($p < 0.05$) indicates less abrupt fluctuations in growth intensity within the early postnatal period. At the same time, during the 0-6 month period an opposite trend was observed: the growth tension index in animals of the III group was significantly higher than in the control (1.91 vs. 1.82; $p < 0.05$). This indicates a more intensive course of growth processes on average throughout the entire rearing period and confirms the higher genetically determined growth potential of pigs of this genetic combination. The growth uniformity index during the period of 0-3 months was practically identical in pigs of the I and II groups (0.47), whereas in animals of the III experimental group it was significantly higher and amounted to 0.49 ($p < 0.05$). This indicates a more uniform course of growth processes at an early age in pigs of the Genesus genotype. However, over the entire rearing period (0-6 months), the growth uniformity index in pigs of the III group was the lowest (0.52), which, in combination with the increased growth tension index, indicates a more intensive but less uniform pattern of growth on average throughout the entire ontogenetic period.

To evaluate the influence of genotype (factor A) and age period (factor B) on the main growth indicators of pigs, a two-factor analysis of variance was performed. The results indicate that the genotype of the animals had a statistically significant effect on the live weight of pigs. The F_{crit} value for factor A was 21.69 at $p = 0.044$, confirming the significance of differences between the groups. The share of genotype influence in the total variability of the trait was high and amounted to 56.0%, indicating the leading role of hereditary factors in the formation of live weight under conditions of identical paternal origin (Table 5).

Table 5. *Two-factor analysis of variance of the influence of genotype and age period on pig growth indicators*

Factor	SS	df	MS	F_{crit}	p	η_x^2
Live weight						
A – genotype	1,844,431.343	2	883,749.134	21.68857442	0.044035832	56.0
B – age	31,230.13548	1	28,361.1527	0.663452385	0.563954488	35.0
Random factors	64,518.44444	2	35,161.1462			9.0
Total variability	1,738,817.721	5				
Absolute gain (0-6 months)						
A – genotype	0.066633333	2	0.03431557	288.5613127	0.003778430	55.0
B – age	0.001066667	1	0.00114448	7.135886421	0.088169365	37.0
Random factors	0.000233333	2	0.00011337			8.0
Total variability	0.066633333	2	0.03431557	221.5613127	0.003778430	
Average daily gain (0-6 months)						
A – genotype	3,728.553333	2	2,927.26668	35.64455364	0.038136508	38.0
B – age	2,411. 662211	1	5,946.13287	0.533442532	0.632297979	21.3
Random factors	0.11100317	2	5,551.24856			40.7
Total variability	3,969.333333	5				

Source: *developed by the authors*

The influence of the age period (factor B) on the live weight indicator under conditions of using MaxGrow terminal boars proved to be statistically insignificant ($F_{crit} = 0.66$; $p = 0.564$), and its share in the structure of total variability amounted to 35.0%. This indicates that within the analysed age intervals, changes in live weight were less pronounced compared with intergenotypic variability caused by the characteristics of maternal origin. The small share of random factors in the total variability (9.0%) indicates high uniformity of the experimental livestock and the correctness of the experimental design under conditions of a standardised paternal factor. The analysis of absolute gain over the entire rearing period showed a very high and statistically

significant influence of genotype when using terminal crossbreeding schemes. The value of F_{crit} for factor A (genotype) was 288.56 at $p = 0.0038$, and the share of its influence reached 55.0% of the total variability of the trait. The obtained results convincingly confirm the decisive role of the maternal genotype in the formation of growth intensity in offspring under conditions of using MaxGrow terminal boars, which ensures the maximum realisation of the genetic growth potential. The influence of the age period was less pronounced and statistically insignificant ($F_{crit} = 7.14$; $p = 0.088$), although its share in the total variability amounted to 37.0%, which indicates the presence of a tendency toward age differentiation of gains within the studied period. The minimal share of random factors (8.0%) indicates the stability of trait manifestation and the high repeatability of results within the terminal crossbreeding system.

According to the average daily gain indicator, a statistically significant influence of genotype was also established under the condition of using MaxGrow terminal boars. The value of F_{crit} for factor A was 35.64 at $p = 0.038$, which confirms the presence of significant intergenotypic differences in the realisation of growth potential. The share of genotype influence in this case was 38.0%, which indicates its substantial, although somewhat smaller role compared with absolute gain. The influence of the age period proved to be statistically insignificant ($F_{crit} = 0.53$; $p = 0.632$), and its share in the total variability amounted to 21.3%, which indicates the secondary nature of this factor in the formation of average daily gains within the analysed period. At the same time, the relatively significant share of random factors (40.7%) may be associated with individual characteristics of animal growth, physiological differences in the utilisation of feed nutrients, and adaptive responses of the organism during different phases of ontogenesis, even under conditions of a uniform paternal genotype. Improving productivity is a common goal of both practitioners and scientists in the field of animal husbandry and pig production in particular. This improvement is achieved through crossbreeding and the selection of the best predecessors (Dotché *et al.*, 2019). Piglets obtained as a result of crossbreeding become heterozygous at all loci, while their original parental breeds are homozygous for another allele. When crossbreeding is used to create a new synthetic line, two or more parental breeds can be mated in rotation. The resulting offspring can then be interbred in each generation. After several generations, the animals will become genetically uniform, and this population can be considered a new terminal line. The development of such terminal lines is an important aspect in the management of genetic diversity during the selection process (Ganteil *et al.*, 2021).

Positive effects of crossbreeding and the use of terminal boar lines are also indicated by M. Cao *et al.* (2026), who note that if there is a certain relationship between animal productivity and their genotype, then prolonged breeding of pigs in a closed population over several generations under strong selection pressure for a limited number of traits leads to lower genetic diversity and a higher deficit of heterozygotes, which may result in inbreeding depression. This can be avoided through the use of terminal lines in crossbreeding to increase herd heterozygosity. The use of hybrid pigs in the breeding process was investigated by J. Zhou *et al.* (2024), who found that the productive qualities of pigs significantly improved through the combination of Pietrain and Yorkshire populations and their reciprocal hybrid crossbreeding. The researchers note that the inclusion of the hybrid population in genomic prediction may improve the accuracy and reliability of prediction compared with the baseline model that uses only purebred animal data. The results of studies by L. De Prekel *et al.* (2025) emphasise the importance of selecting terminal sire lines when considering heat stress management, since the use of terminal lines in pig production can play a decisive role in improving strategies for mitigating the negative effects of heat stress on productivity.

In the studies of M. Kremez *et al.* (2024), it was established that hybrid piglets outperformed their crossbred counterparts from direct crossbreeding in average daily and absolute gains, live weight at the end of the rearing period, and survival rate. At the same time, they consumed more feed during the rearing period compared with their crossbred and purebred peers and had better feed conversion. This is also confirmed by the data of the present study. According to G. Kadirvel *et al.* (2023), in the pork production system of the Eastern Himalayan mountain region, crossbred pigs demonstrated better growth rates and larger litter size at birth and weaning than purebred local pigs. Therefore, the researchers believe that the application of crossbreeding and hybridisation will increase productivity and reproductive capacity of pigs.

D. Baranovskyi & O. Tkachuk (2024) established that pig production can be effective when pigs are used in different combinations. Thus, crossbred piglets had high growth energy indicators and were characterised by good slaughter and meat-fat qualities. The researchers recommend combining Large White sows with boars of the Landrace, Duroc, and Pietrain breeds. The improvement of growth indicators of local pigs in Benin through crossbreeding is also reported by C. Bankolé *et al.* (2025). The authors emphasise that the most productive exotic breeds adapted for use in

tropical environments are Large White, Landrace, Duroc, and Pietrain. Among the mentioned breeds, Pietrain demonstrates a high potential for crossbreeding and exhibits the highest heterosis effect on live weight indicators. The obtained results demonstrate that Pietrain pigs can be used in crossbreeding schemes to improve the growth indicators of local pigs in Benin. H. Wen *et al.* (2026) also indicate the necessity of applying different crossbreeding models when developing breeding programs, since there are significant differences in genetic diversity, population structure, and origin within Duroc subpopulations and between Duroc and other pig breeds. The observed levels of inbreeding in Duroc subpopulations indicate the need for better management of genetic diversity within the breed and the application of different variants of crossbreeding and hybridisation when working with this population, which fully corresponds with the statements of previous researchers.

Thus, crossbreeding programs are widely used to improve the overall production performance of pigs while maintaining higher productivity only in F1 crossbred offspring. However, due to the breakdown of epistatic complexes in the F2 generation, improvement and stabilisation of the obtained heterosis based on additive and dominant breed effects is a significant challenge. Therefore, in order to ensure the most stable manifestation of heterosis over several generations or to create specialised hybrid lines, it is advisable to evaluate different breed combinations and implement the lower level of the hybridisation pyramid, which involves the use of three-breed commercial pigs obtained by inseminating two-breed sows with terminal boars.

CONCLUSIONS

The results of the conducted studies convincingly indicate that under the conditions of applying industrial crossbreeding schemes using terminal MaxGrow boars, the leading factor determining growth intensity, the pattern of gain formation, and the final live weight of young pigs is the maternal genotype. Standardisation of the paternal component made it possible to objectively assess genetically determined differences between the groups and to minimise the influence of random factors. The highest values of absolute (100.82 kg, which is 6.5% higher compared to the control), average daily (596.5 g, which is 6.5% higher than in the control group), and relative gains throughout the entire rearing period were characteristic of pigs of the Genesus × MaxGrow genotype, which confirms their high genetic growth potential and the effective realisation of the heterosis effect under terminal crossbreeding conditions. Crossbred animals (½LW × ½L)×MaxGrow occupied an intermediate position, demonstrating a stable advantage over the control pigs (3.3% and 1.5%, respectively), which indicates the expediency of using combined maternal forms in industrial pork production schemes. The results of the growth index evaluation according to the methodology of V.P. Kovalenko complement the obtained data and indicate a significant influence of maternal origin on the intensity (0.52-0.55), tension (1.82-1.91), and uniformity of offspring body formation (0.52-0.55). Pigs of the Genesus × MaxGrow genotype were characterised by more balanced growth at an early age (0.49) and higher intensity of growth processes on average (0.52) over the entire rearing period, which is biologically and technologically expedient for intensive fattening systems and confirms the effectiveness of its use for assessing growth intensity.

Two-factor analysis of variance confirmed that genotype is the leading factor in the variability of growth indicators (ηx^2 = 38.0-56.0%), whereas the age period within the experiment did not exert a statistically significant influence (ηx^2 = 21.3-37.0%), although in some cases a tendency toward an increase in its share in the structure of total variability was observed. The low or moderate share of random factors (ηx^2 = 8.0-40.7%) indicates the high reliability of the experiment and the correctness of the applied biometric methods. Summarising the obtained results, it can be concluded that the use of terminal MaxGrow boars in combination with specialised and crossbred maternal forms is an effective breeding-technological approach that ensures increased growth intensity of young pigs and promotes the maximum realisation of the genetic potential of pigs under conditions of intensive industrial pig production. A promising direction for further research is the combination of traditional zootechnical evaluation methods witeth molecular-genetic and bioinformatic approaches for identifying markers associated with growth intensity and the manifestation of the heterosis effect in the offspring of Genesus × MaxGrow and (½LW × ½L) × MaxGrow genotypes.

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CONFLICT OF INTEREST

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Вплив промислового схрещування з кнурами термінальної лінії на показники росту та розвитку молодняку свиней

Андрій Каратєєв
Аспірант
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0009-0008-3345-0450

Олена Каратєєва
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-0652-1240

Михайло Гиль
Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-7353-9865

Анотація. Одним із найбільш ефективних методів генетичного поліпшення свиней є схрещування, яке за обгрунтовано підібраних поєднань порід сприяє зростанню продуктивності та зниженню витрат на виробництво свинини. Метою досліджень було оцінити вплив різних материнських генотипів у поєднанні з термінальними кнурами лінії MaxGrow на показники росту, прирости, кінцеву живу масу молодняку та рівень прояву гетерозису за умов промислового ведення свинарства. Експериментальні дослідження проведено на трьох групах свиней, сформованих із чистопородних, помісних (½ велика біла × ½ ландрас англійської селекції) та спеціалізованих свиноматок компанії Genesus за використання термінальних кнурів лінії MaxGrow. Такий підхід забезпечив об'єктивну оцінку впливу материнського генотипу на показники росту потомства за умов стандартизованого батьківського компонента. Встановлено, що генотип свиноматок є визначальним чинником інтенсивності росту, формування приростів і кінцевої живої маси молодняку. Найвищі значення абсолютних (107,37 кг), середньодобових (596,5 г) і відносних (32,3 %) приростів упродовж усього періоду вирощування відзначено у свиней генотипу Genesus×MaxGrow, що свідчить про ефективну реалізацію гетерозисного ефекту. Помісні тварини займали проміжне положення (104,6 кг; 578,7 г та 32,0 % відповідно), демонструючи стабільну перевагу над чистопородним контролем (100,82 кг; 560,1 г та 30,5 % відповідно). Результати індексної оцінки росту та двофакторного дисперсійного аналізу підтвердили провідну роль генотипу (38,0-56,0 %) у формуванні продуктивних ознак і високу надійність отриманих даних. Зроблено висновок, що використання термінальних кнурів MaxGrow у поєднанні зі спеціалізованими та помісними материнськими формами є науково обґрунтованим і технологічно доцільним напрямом удосконалення селекційних програм у промисловому свинарстві. Досліження може бути використано фахівцями з селекції та технологами свинарських господарств для оптимізації схем промислового схрещування з метою підвищення інтенсивності росту молодняку та ефективності виробництва свинини

Ключові слова: селекційні програми; термінальні кнурі; ефект гетерозису; гібридна сила; спеціалізовані лінії; інтенсивність росту

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Pre-sowing preparation and agrotechnics of sowing as factors of soil germination seeds of *Thuja plicata* Don. ex D. Donn

Iryna Ivashchenko*
PhD in Agricultural Sciences, Associate Professor
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0001-5831-8490

Volodymyr Vitenko
Doctor of Agricultural Sciences, Professor
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0001-5762-9238

Valentina Mamchur
PhD in Agricultural Sciences, Associate Professor
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0000-0003-1579-4467

Anastasia Kozhebash
PhD in Horticulture
Uman National University
20301, 1 Instytutska Str., Uman, Ukraine
https://orcid.org/0009-0009-7322-0200

Abstract. This study aimed to determine the optimal conditions for pre-sowing seed preparation and sowing depth to improve soil germination of *Thuja plicata*. The study was conducted using *Thuja plicata* seed material collected in the National Dendrological Park "Sofiyivka" of the NAS of Ukraine to evaluate seed quality, germination, and the effects of different pre-sowing treatments using standard methods. The results demonstrated significant effects of collection time, germination temperature, pre-sowing treatments, and sowing depth on seed performance. Seeds collected in autumn from standing trees showed higher germination energy (35.4-39.2%) and laboratory germination (44.4-48.7%) compared with seeds collected in winter from the snow surface, which demonstrated lower values of germination energy (27.1-31.6%) and laboratory germination (34.3-39.1%). Germination at +25°C increased germination energy and final laboratory germination compared with room temperature (18-20°C). Soil germination was strongly influenced by sowing depth and pre-sowing treatments. The highest soil germination (43.2 ± 2.1%) was recorded at a sowing depth of 0.5 cm after 30-day snow stratification, which exceeded the control treatment (32.7 ± 1.8%). Water soaking for 12 hours also improved germination, reaching 39.3 ± 1.9% at the same sowing depth. Increasing sowing depth to 2.0 cm resulted in a sharp decline in soil germination, reaching 10.1 ± 1.2% after snow stratification and complete absence of seedlings in the control treatment. Snow stratification

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*Corresponding author (ivashchenko_iy@ukr.net)

also accelerated seedling emergence, reducing the time to first emergence from 14 days in the control to 12 days. These findings indicate that autumn seed harvesting, 30-day snow stratification, and shallow sowing (0.5-1.0 cm) provide the most favourable conditions for successful germination and seedling establishment of *Thuja plicata*

Keywords: introduced taxon; conifer reproduction; stratification methods; adaptive capacity; planting material production

INTRODUCTION

Seed propagation remains an important method for the large-scale reproduction of woody plant species and the production of planting material for forestry and ornamental horticulture. The use of seeds allows the production of genetically diverse and well-adapted planting material, which often develop stronger root systems and demonstrate greater ecological stability during early growth stages. For introduced coniferous species, the optimisation of seed propagation techniques is particularly important, since successful seedling establishment determines the efficiency of introduction and the long-term stability of cultivated populations. Therefore, understanding the factors that regulate germination and early seedling development is a key prerequisite for improving nursery technologies and ensuring the successful cultivation of introduced species.

Recent studies demonstrate that seed dormancy is a complex physiological mechanism that regulates the timing of germination and allows plants to synchronise seedling emergence with favourable environmental conditions. P. Awasthi (2023) investigated the ecological role of dormancy in forest plant species and demonstrated that dormancy regulates germination timing through physiological mechanisms that respond to environmental signals. The author showed that dormancy release is strongly associated with temperature and moisture conditions and concluded that appropriate dormancy-breaking treatments significantly improve germination synchrony and seedling establishment. Y. Song *et al*. (2023) analysed the influence of cold stratification on germination behaviour in several coniferous species. Their experimental results showed that stratification not only increases the percentage of germination but also expands the optimal temperature range in which germination occurs. The authors concluded that cold stratification modifies physiological processes in the embryo, thereby improving germination energy and accelerating early seedling development.

B. Kohinoor *et al*. (2024) examined the role of pre-sowing treatments in improving seed performance under stress conditions. Their experiments demonstrated that seed priming and other preparatory treatments enhance germination uniformity and increase tolerance to both biotic and abiotic stress factors during the initial stages of seedling growth. According to the authors, pre-sowing treatments stimulate metabolic activity in seeds and promote faster transition from dormancy to active germination. Environmental factors also play an important role in regulating germination processes. J. Wang *et al*. (2024) investigated the relationship between dormancy type and environmental signals controlling germination in forest plants. Their study showed that temperature fluctuations and moisture availability act as key environmental cues that determine the timing and success of germination. The high effectiveness of snow stratification confirms the findings of Y. Song *et al*. (2023), who identified cold stratification as a key practice for improving conifer seed germination. Recent genomic studies further confirm the reproductive stability of *Thuja plicata* populations. Research conducted in European forest stands demonstrated that western redcedar maintains high genetic diversity from adult trees to offspring, indicating stable reproductive processes even under introduction conditions, as reported by L. Guillardín *et al*. (2025). The combined analysis of all experimental factors demonstrates that successful cultivation of *Thuja plicata* from seeds under introduction conditions requires an integrated technological approach. The use of high-quality seeds harvested in autumn, appropriate storage conditions, effective pre-sowing treatments-particularly snow stratification-and shallow sowing ensures higher soil germination, more uniform seedling emergence, and improved seedling quality.

A. Ferras *et al*. (2025) applied a time-to-event analytical approach to study temperature-dependent germination patterns in forest species. The researchers demonstrated that germination dynamics differ significantly among species and reflect ecological adaptation to specific environmental niches. Their findings indicated that analysing germination timing provides valuable information about physiological dormancy status and species-specific ecological strategies. Seed germination and early seedling establishment are particularly sensitive to environmental conditions in introduced species. Despite the progress achieved in recent studies, there is still limited empirical evidence regarding the combined influence of seed harvesting time,

temperature regime, storage conditions, and specific pre-sowing treatments on soil germination and seedling establishment of *Thuja plicata* under open-field conditions. Most available studies focus on general physiological aspects of dormancy or laboratory germination responses, while practical aspects of nursery cultivation remain insufficiently investigated. Therefore, the present study aimed to determine effective pre-sowing treatments and optimal sowing depth that improved soil germination and early seedling development of *Thuja plicata* under open-field conditions.

MATERIALS AND METHODS

The study was conducted using seeds of *Thuja plicata* reproduced at the National Dendrological Park "Sofiyivka" of the National Academy of Sciences of Ukraine. Seeds were collected from mature generative trees growing under introduction conditions in the park. After collection, the seed material was cleaned and air-dried at room temperature (18-20°C) until constant weight was achieved. Seed sowing quality parameters, including thousand-seed weight, germination energy, and germination capacity, were determined according to current interstate standards and generally accepted methodologies used for forest reproductive material. Laboratory germination tests were carried out in Petri dishes on moistened filter paper. Each experimental treatment included 100 seeds with four replicates. The filter paper was moistened with distilled water and maintained at constant humidity throughout the experiment. Germination was evaluated under two temperature regimes: room temperature (18-20°C) and constant temperature conditions in a thermostat (+25°C). To assess the effect of seed collection time, seeds were collected in two periods: in autumn from standing trees immediately after cone maturation and in winter from the surface of the snow cover beneath the trees.

Seed germination was monitored daily to determine the timing of seedling emergence. The first seedlings appeared within 12-24 days depending on the treatment. The final count of soil germination was carried out 30 days after sowing, when no further emergence of seedlings was observed. The date of the first emergence was recorded as the day when the first visible radicle protrusion was observed in at least one seed within a replicate. Germination energy was determined on the day corresponding to the peak of intensive germination, while final laboratory germination was recorded at the end of the observation period. Soil germination was evaluated under open-field conditions in the experimental nursery plot of the dendrological park. Sowing was performed in the second ten-day period of April. To determine the effect of sowing depth, seeds were sown at depths of 0.5, 1.0, 1.5, and 2.0 cm. Seeds were covered with a substrate consisting of turf soil and sand mixed in a 3:1 ratio, which ensured sufficient aeration and moisture retention. During the experiment, the substrate maintained stable structure and moisture conditions; no significant surface crusting or excessive compaction was observed, which allowed normal seedling emergence under shallow sowing conditions. Each experimental variant included four replicates of 100 seeds each, allowing quantitative assessment of soil germination and seedling emergence.

Additionally, experiments were conducted to determine the effectiveness of different pre-sowing seed treatments. Although *Thuja plicata* seeds do not exhibit strict physiological dormancy, pre-sowing treatments may improve germination uniformity and accelerate seedling emergence. The following pre-sowing treatments were tested: snow stratification for 30 days, soaking in water for 12 hours, storage in moist sand, storage in moist peat, and untreated seeds used as the control treatment. For storage in sand and peat, seeds were mixed with moist substrate at a ratio of 1:3 (seed: substrate). The moisture content of the substrates was maintained at approximately 60-70% of full water-holding capacity. The containers with the seed-substrate mixture were stored at a temperature of 3-5°C for 30 days, which corresponds to conditions of cold moist stratification.

To evaluate seedling performance, morphological observations of emerging seedlings were conducted throughout the germination period. Seedlings were examined for uniformity of emergence, vigour, and general morphological condition. Qualitative characteristics used in Table 2 were defined as follows: "uniform" refers to dense and evenly distributed seedlings with well-developed hypocotyls and cotyledons; "well-developed" indicates vigorous seedlings with normal morphology and strong tissues; "satisfactory" describes seedlings with normal development but slightly reduced density; "sparse" denotes a low density of seedlings with uneven distribution; "weakened" refers to seedlings with elongated hypocotyls, thin tissues, or delayed development; "single" indicates the presence of isolated individual seedlings; and "absent" means that no seedlings were observed. In addition to visual assessment, a basic morphological analysis of seedlings was performed, including measurements of hypocotyl length and overall seedling vigour, which allowed comparative evaluation of seedling development under different treatments.

Statistical analysis of the experimental data was performed using generally accepted methods. Mean values (M) and standard errors (±m) were calculated for each experimental treatment. The least significant

difference ($LSD_{0.05}$) was determined to evaluate statistically significant differences between treatments.

RESULTS AND DISCUSSION

In accordance with the research program, the effect of the time of collection of forest reproductive material and the temperature regime of germination on the germination of *Thuja plicata* seeds was studied. Prior to the germination experiments, the basic sowing quality indicators of the seed material were evaluated. In particular, the thousand-seed weight was determined as an important indicator of seed fullness and potential viability. The average thousand-seed weight of *Thuja plicata* seeds collected from generative trees in the National Dendrological Park "Sofiyivka" was 1.26 g. This value indicates satisfactory seed development and filling of the reproductive material. Adequate seed mass is generally associated with higher germination energy and improved seedling vigour, since larger seeds usually contain greater reserves of nutrients required for the initial stages of germination and early seedling development. The results of laboratory germination depending on seed collection time and temperature regime are presented in Table 1.

Table 1. *Laboratory germination of Thuja plicata seeds depending on seed collection time and germination temperature*

Seed origin	Germination temperature, °C	Germination energy, %	Laboratory germination, %
Seeds collected in autumn from standing trees	+18-20	35.4	44.4
	+25	39.2	48.7
Seeds collected from the surface of the snow cover	+18-20	27.1	34.3
	+25	31.6	39.1

Source: *developed by the authors*

The data presented in Table 1 indicated that the technical germination and germination energy of *Thuja plicata* seeds depend significantly on both the timing of seed collection and the temperature regime during germination. The laboratory germination of *Thuja plicata* seeds ranged from 34.3 to 48.7%, while germination energy varied between 27.1 and 39.2%. The analysis of laboratory germination parameters revealed substantial differences between seeds harvested at different times. Seeds collected in autumn directly from standing trees showed consistently higher germination energy and final laboratory germination compared with seeds collected in winter from the surface of the snow cover. This can be explained by the more favourable physiological condition of autumn-harvested seeds, which complete maturation under relatively stable environmental conditions and are less exposed to damaging abiotic factors. Seeds that overwinter on the soil surface are exposed to repeated freeze-thaw cycles, excessive moisture, and prolonged low temperatures, which may lead to partial degradation of reserve substances and physiological ageing of the seed. Similar physiological changes associated with the deterioration of *Thuja plicata* seeds during storage, as well as the influence of seed maturity and storage conditions on the viability of forest reproductive material, have been noted in the studies of V. Terskikh *et al.* (2008) and in classical works on forest seed production (Debryniuk *et al.*, 1998). Similar effects of temperature on the viability and germination of conifer seeds were also reported in experimental studies by B. Hawkins *et al.* (2003). The obtained germination values are also consistent with earlier experimental data for introduced coniferous species, where considerable variability of germination parameters depending on seed maturity and environmental conditions was reported (Smahliuk, 1976; Marynych, 1998).

The temperature regime during germination exerted a pronounced influence on both the rate and extent of seed germination. Germination at +25°C resulted in higher germination energy and slightly higher final laboratory germination compared with room temperature conditions (18-20°C). Elevated temperatures intensify metabolic activity, promote faster imbibition, and accelerate enzymatic processes associated with the mobilisation of reserve compounds. However, observations of seedling morphology indicated that excessively high temperatures may negatively affect early growth stages, as seedlings developed elongated hypocotyls and weaker tissues. Similar sensitivity of *Thuja plicata* seedlings to environmental conditions during early development has been reported in experimental studies analysing seedling growth under different light regimes (Wang *et al.*, 1994). Such morphological responses are typical for seedlings developing under accelerated metabolic conditions. Therefore, the temperature of +25°C can be considered optimal primarily for laboratory assessment of germination potential, where the objective is to determine the maximum viability of seeds. However, for practical nursery cultivation and the production of high-quality planting material, more moderate temperature conditions (18-20°C) appear preferable

because they provide a better balance between germination intensity and the formation of morphologically stronger seedlings. These observations correspond with the reproductive biology of *Thuja plicata* described by J. Owens & M. Molder (2011), who emphasised the sensitivity of early seedling development to environmental conditions. Recent reviews of the biology and ecological characteristics of western redcedar also indicate that environmental factors during germination significantly influence seedling establishment and subsequent growth (Antos *et al.*, 2016; Aldana *et al.*, 2023). The depth of seed placement significantly affects the processes of germination and subsequent seedling development. Under deeper sowing conditions, seeds are supplied with a more stable moisture regime; however, seedlings experience greater mechanical resistance when penetrating the soil layer, which may delay or prevent emergence. The influence of pre-sowing treatments and sowing depth on soil germination of *Thuja plicata* seeds is presented in Table 2.

Table 2. *Soil germination of Thuja plicata seeds depending on pre-sowing treatment method and sowing depth*

Pre-sowing seed treatment	Sowing depth, cm	Soil germination, % (M ± m)	Time to first emergence, days	Seedling characteristics
Control (untreated)	0.5	32.7 ± 1.8	14	sparse
	1.0	25.4 ± 1.6	16	weakened
	1.5	18.5 ± 1.4	18	single
	2.0	0.0	-	absent
Snow stratification (30 days)	0.5	**43.2 ± 2.1**	12	uniform
	1.0	40.1 ± 2.0	13	well-developed
	1.5	37.1 ± 1.9	15	satisfactory
	2.0	10.1 ± 1.2	21	weakened
Water soaking (12 h)	0.5	39.3 ± 1.9	13	uniform
	1.0	35.6 ± 1.8	14	satisfactory
	1.5	28.9 ± 1.6	16	weakened
	2.0	8.7 ± 1.1	22	single
Storage in sand	0.5	35.4 ± 1.7	14	satisfactory
	1.0	31.2 ± 1.6	15	sparse
	1.5	24.6 ± 1.5	17	weakened
	2.0	6.3 ± 0.9	23	single
Storage in peat	0.5	33.9 ± 1.6	14	satisfactory
	1.0	29.8 ± 1.5	15	sparse
	1.5	22.7 ± 1.4	18	weakened
	2.0	5.1 ± 0.8	24	single

Source: *developed by the authors*

The obtained experimental data indicated a significant influence of both pre-sowing seed treatment methods and sowing depth on the formation of *Thuja plicata* seedlings under soil conditions. Regardless of the treatment variant, an increase in sowing depth from 0.5 to 2.0 cm resulted in a clear decrease in soil germination rates. The first seedlings appeared between 12 and 24 days after sowing, depending on the treatment. Snow stratification accelerated seedling emergence compared with the control treatment. The final assessment of soil germination was carried out 30 days after sowing, when no further seedling emergence was observed. The highest soil germination values were recorded at a sowing depth of 0.5 cm. Under these conditions, snow stratification for 30 days proved to be the most effective treatment, resulting in 43.2 ± 2.1%, which significantly exceeded the control variant (32.7 ± 1.8%). A further increase in sowing depth to 2.0 cm resulted in a sharp decline in soil germination in all experimental variants. In the control treatment, seedling emergence was absent. Even with the application of pre-sowing treatments, germination values remained low and did not exceed 10.1 ± 1.2% in the snow-stratified variant. The lowest soil germination was recorded for seeds stored in peat – only 5.1 ± 0.8%, indicating the unfavourable nature of combining this preparation method with deep (2.0 cm) seed placement. The decline in soil germination with increasing sowing depth agrees with observations by J. Young & C. Young (1993) and N. Khadduri (2007).

Pre-sowing treatments significantly enhanced soil germination and seedling emergence. Among the tested methods, 30-day snow stratification proved to be the most effective, resulting in the highest and most uniform germination. This treatment likely mimics natural winter conditions, facilitating the physiological after-ripening of seeds, activation of hydrolytic enzymes, and increased permeability of the seed coat. Consequently, stratified seeds exhibited faster emergence and greater

resistance to unfavourable early-spring environmental conditions. Water soaking for 12 hours and storage in sand or peat also positively affected germination; however, their effectiveness was lower compared with snow stratification, indicating only partial alleviation of dormancy mechanisms. Similar physiological mechanisms of dormancy release in conifer seeds have been widely discussed in modern studies of seed dormancy and germination ecology (Baskin & Baskin, 2014).

Sowing depth was identified as one of the most critical agrotechnical factors influencing seedling establishment. Shallow sowing at a depth of 0.5 cm provided optimal conditions for oxygen diffusion, moisture availability, and rapid emergence, resulting in the highest soil germination rates across all treatments. As sowing depth increased to 1.0 and 1.5 cm, soil germination gradually declined, likely due to increased mechanical resistance of the substrate and depletion of seed reserves before emergence. At a depth of 2.0 cm, seedling emergence was extremely limited or completely absent, even when pre-sowing treatments were applied. This clearly indicates that deep sowing creates unfavourable conditions for *Thuja plicata* seeds and should be avoided in nursery practice. The influence of sowing depth observed in the present study corresponds with recommendations provided in propagation protocols for *Thuja plicata*, where shallow sowing depths are considered optimal for ensuring successful seedling emergence (Plant Propagation Protocol for *Thuja plicata*, 2021). Experimental studies investigating the combined effects of light and stratification on conifer seed germination have also demonstrated that environmental conditions and substrate characteristics strongly influence germination dynamics in this species (Young & Young, 1993; Shlapak & Vitenko, 2010). N. Khadduri (2007) analysed the influence of sowing conditions on the emergence and early growth of conifer seedlings in nursery environments. The study demonstrated that sowing depth and substrate characteristics significantly affect seedling emergence rates and survival during the initial stages of development. The author concluded that optimisation of sowing conditions is essential for improving the efficiency of seed propagation in conifer nurseries. Further insights into germination ecology were provided by C. Schopmeyer (1974), who analysed germination responses of forest tree species under different environmental conditions. Their study showed that variations in temperature and moisture availability significantly influence germination success and seedling vigour. The authors emphasised that understanding species-specific germination requirements is essential for developing effective nursery cultivation techniques. The conducted studies demonstrated that the sowing quality and soil germination of *Thuja plicata* seeds are determined by a complex interaction of biological and technological factors, including the time of seed harvesting, germination temperature, pre-sowing treatments, storage conditions, and sowing depth. Each of these factors plays a specific role in regulating seed viability, dormancy release, and seedling establishment, which is especially important for introduced woody species cultivated outside their natural range. These results are consistent with general patterns reported for introduced coniferous species and emphasise the necessity of adapting sowing techniques to the biological characteristics of the species.

CONCLUSIONS

The sowing quality and germination performance of *Thuja plicata* seeds were significantly influenced by the timing of seed harvesting, germination temperature, pre-sowing treatments, and sowing depth, which confirms the multifactorial nature of seed viability and early seedling establishment under introduction conditions. The interaction of these biological and technological factors determines not only the final germination percentage but also the rate of emergence and the initial quality of seedlings, which are critical parameters for successful nursery production. Seeds collected in autumn directly from standing trees consistently exhibited higher germination energy and laboratory germination than seeds harvested in winter from the surface of the snow cover. This highlights the importance of timely seed collection immediately after physiological maturation, when seeds are less affected by adverse abiotic factors such as prolonged low temperatures, excess moisture, and freeze-thaw cycles. The use of high-quality autumn-harvested seed material therefore represents a key prerequisite for achieving stable and predictable germination results. Germination under a constant temperature of +25°C enhanced both germination energy and final laboratory germination; however, the negative effects observed on early seedling morphology suggest that excessively high temperatures may compromise seedling quality. As a result, moderate temperature regimes appear more suitable for producing physiologically balanced and morphologically robust planting material intended for practical use. Under open-field conditions, soil germination is generally lower than laboratory germination, reflecting the influence of fluctuating environmental factors. Nevertheless, soil germination can be substantially improved through the optimisation of storage conditions and the application of appropriate pre-sowing treatments, demonstrating the necessity of adapting laboratory-based findings to real nursery environments. Among the tested treatments, 30-day snow stratification proved to be the most effective, significantly

increasing soil germination and ensuring more uniform and synchronous seedling emergence compared with water soaking or storage in sand and peat. Sowing depth was identified as a critical agrotechnical factor influencing seedling establishment. Shallow sowing at depths of 0.5-1.0 cm provided optimal conditions for oxygen availability, moisture supply, and rapid emergence, whereas deeper sowing at 2.0 cm resulted in a sharp decline in germination and should therefore be considered unsuitable for nursery practice. Overall, the combined application of autumn seed harvesting, snow stratification, and shallow sowing can be recommended as an effective and scientifically justified technological approach for the propagation of *Thuja plicata* from seed in nursery and open-field conditions. Future research should focus on assessing the subsequent growth dynamics, physiological stability, and field survival of seedlings produced under these optimised conditions in order to further refine cultivation recommendations.

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Передпосівна підготовка та агротехніка сівби як чинники ґрунтової схожості насіння *Thuja plicata* Don. ex D.Donn

Ірина Іващенко
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0001-5831-8490
Володимир Вітенко
Доктор сільськогосподарських наук, професор
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0001-5762-9238
Валентина Мамчур
Кандидат сільськогосподарських наук, доцент
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0000-0003-1579-4467
Анастасія Коджебаш
Доктор філософії зі спеціальності «Садово-паркове господарство»
Уманський національний університет
20301, вул. Інститутська, 1, м. Умань, Україна
https://orcid.org/0009-0009-7322-0200

Анотація. Метою дослідження було визначення оптимальних умов передпосівної обробки насіння та глибини посіву для підвищення схожості насіння туї звичайної (*Thuja plicata*) у ґрунті. Дослідження проводилося з використанням насіннєвого матеріалу туї звичайної, зібраного в Національному дендрологічному парку «Софіївка» НАН України, з метою оцінки якості насіння, схожості та впливу різних методів передпосівної обробки за допомогою стандартних методів. Результати показали значний вплив часу збору, температури пророщування, передпосівних оброблень та глибини посіву на показники насіння. Насіння, зібране восени з живих дерев, показало вищу енергію проростання (35,4-39,2 %) та лабораторну схожість (44,4-48,7 %) порівняно з насінням, зібраним взимку з поверхні снігу, яке продемонструвало нижчі показники енергії проростання (27,1-31,6 %) та лабораторної схожості (34,3-39,1 %). Пророщування при температурі +25°C підвищило енергію проростання та кінцеву лабораторну схожість порівняно з кімнатною температурою (18-20°C). На схожість у ґрунті значний вплив мали глибина посіву та передпосівні обробки. Найвища схожість у ґрунті (43,2 ± 2,1 %) була зафіксована при глибині посіву 0,5 см після 30-денної снігової стратифікації, що перевищило показники контрольного варіанту (32,7 ± 1,8 %). 12-годинне замочування у воді також покращило схожість, яка досягла 39,3 ± 1,9 % при тій самій глибині посіву. Збільшення глибини посіву до 2,0 см призвело до різкого зниження схожості в ґрунті, яка після снігової стратифікації становила 10,1 ± 1,2 %, а в контрольному варіанті – до повної відсутності сходів. Снігова стратифікація також прискорила сходження сходів, скоротивши час до першого сходження з 14 днів у контролі до 12 днів. Ці результати свідчать про те, що осінній збір насіння, 30-денна снігова стратифікація та неглибокий посів (0,5-1,0 см) забезпечують найсприятливіші умови для успішного проростання та вкорінення сходів *Thuja plicata*

Ключові слова: інтродукований таксон; розмноження хвойних; методи стратифікації; адаптивна здатність; виробництво посадкового матеріалу

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The effect of adding a dietary fibre feed supplement on sow welfare, reproductive performance, and farrowing economic indicators

Serhii Luhovyi*
Doctor of Agricultural Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/ 0000-0001-6505-8105

Mykola Povoznikov
Doctor of Agricultural Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
https://orcid.org/0000-0002-8187-4812

Halyna Kalynycnenko
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-0909-0044

Liudmyla Onyshchenko
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0003-2666-9813

Ihor Moisei
Postgraduate Student
Sumy National Agrarian University
40000, 160 Herasyma Kondratieva Str., Sumy, Ukraine
https://orcid.org/0009-0006-0486-959X

Abstract. The purpose of the research was to study the effect of including 1.0% of the feed fibre supplement in the diets of pregnant and lactating sows on the course of farrowing, reproductive performance, growth intensity and survival of piglets, as well as the economic efficiency of production. The study was conducted under the conditions of an industrial pig complex on two groups of sows formed according to the principle of analogues. The control group received standard compound feed according to physiological condition, while the sows of the experimental group additionally received the fibre supplement JELUVET® at a dose of 10 kg/t of compound feed. Feed conversion was recalculated per one weaned piglet and per 1 kg of piglet weight gain. It was established that the use of fibre reduced the proportion of farrowings with complications by 2.83% and decreased expenditures on preventive and therapeutic measures by 72.16 UAH per sow (34.4%). Number born alive piglets

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*Corresponding author (lugsergey23@gmail.com)

in the experimental group increased by 0.58 (4.1%), and the total number of piglets born per farrowing exceeded the control by 0.51 (3.4%). The average weight of stillborn piglets decreased by 1.07 percentage points, while the litter weight of piglets at birth increased by 1.06 kg (5.7%) and at weaning by 2.92 kg (3.5%), without a negative effect on individual piglet weight gains. The use of the supplement did not increase total feed consumption; however, it reduced feed expenditure per 1 kg of piglet weight gain by 0.21 kg (3.3%) and per one weaned piglet by 1.71 kg (4.2%). Economic evaluation showed that the additional profit per sow amounted to 622.07 UAH, which confirmed the economic feasibility of using the fibre supplement. The obtained results indicated that the inclusion of 1.0% fibre supplement in the diet of pregnant and lactating sows improved the course of farrowing, increased prolificacy and the total productivity of piglet litters, promoted efficient feed utilisation, and ensured a significant economic effect

Keywords: piglets; pregnancy; lactation; dietary fibre; economic efficiency

INTRODUCTION

Intensive pig breeding aimed at increasing reproductive productivity and prolificacy of sows has led to significant changes in their physiology, especially during the critical periods of pregnancy and lactation. Under conditions of modern intensive production, animals are subjected to excessive metabolic stress, which manifests in disorders of the digestive and endocrine systems, an increased incidence of constipation, complications during farrowing, and significant body weight losses during lactation. This, in turn, negatively affects the survival and viability of offspring, reduces the growth intensity of piglets, increases perinatal mortality rates, and creates serious economic and ethical challenges for modern pig production.

Analysis of publications showed that increasing the content of dietary fibre in the diet of pregnant and lactating sows is one of the promising approaches for correcting digestive function, intestinal microbiota, and reproductive performance of animals during periods of increased stress. In their studies, J. Hu *et al*. (2021), D.S. Rosero (2024), and Y. Ji (2025) demonstrated that the inclusion of high-fibre components in the diet contributed to improved intestinal motility and reduced the incidence of constipation in sows during the final phase of pregnancy and in the first days of lactation. This improvement was accompanied by increased voluntary feed intake during lactation, which is a key factor for maintaining energy balance and optimal animal productivity. C.A. Montoya *et al*. (2023) and S. Oh *et al*. (2024) confirmed a positive correlation between a high dietary fibre content in the diet and stabilisation of the intestinal microbiota, which had an indirect effect on reducing oxidative stress indicators and improving reproductive results. The study by C.A. Montoya *et al*. (2023) examined the mechanisms of fibre influence on intestinal microbiota and SCFA (short-chain fatty acid) production. The authors showed that different types of fibre differently modulate microbial composition, which directly affects the immune status and energy metabolism of sows during periods of pregnancy. This emphasises the importance not only of the total fibre level, but also of its qualitative composition and fermentation properties.

Research data from Y.K. Adi *et al*. (2022) and Y. Liu *et al*. (2022) showed that the addition of dietary fibre to the diet during the final phase of pregnancy reduces the incidence of constipation and contributes to shortening the duration of farrowing, which positively affects animal welfare and reduces the likelihood of complications. Simultaneously with the above-described positive effects of fibre supplementation, T. Feyera *et al*. (2021) and R. Boonprakob *et al*. (2024) reported in their works a positive effect of high-fibre diets on reducing the proportion of stillborn piglets and increasing postnatal survival rates, but they emphasised the high variability of results depending on the type of fibre, its level, and duration of application. These studies highlight the potential of differentiated use of fibres, but at the same time indicate the complexity of optimising such practices in farm management. Correction of the fibre composition of the diet, as noted by T. Pedersen *et al*. (2020) and D. Lu *et al*. (2022), contributes to increased satiety, improved intestinal microbiota, and increased production of short-chain fatty acids (SCFA), which ensures a reduction in farrowing duration by 5-12% and a decrease in the incidence of complications by 2-4%, increasing piglet viability and voluntary feed intake by sows during lactation.

Thus, the analysis of modern publications from 2020-2025 shows that although most studies are devoted to the influence of dietary fibre on digestive function and certain reproductive indicators of sows, the issues of the optimal combination of soluble and insoluble fibres, taking into account their fermentation properties, dietary energy density, and long-term effects on sow productive cycles and the economic

efficiency of pork production remain insufficiently studied. In addition, there are insufficient studies evaluating the economic aspects of introducing specific fibre sources into industrial practice while maintaining or increasing reproductive productivity, which determined the relevance of conducting this research. Therefore, its aim was to study the effect of adding the feed supplement as a source of dietary fibre to the basal diet of pregnant and lactating sows on the course of farrowing, reproductive performance, growth and survival of piglets during the suckling period, as well as on the economic efficiency of pork production.

MATERIALS AND METHODS

The study was conducted under the conditions of Reproducer No. 2 of the Limited Liability Company (LLC) "Scientific and Production Enterprise 'Hlobyne Pig Complex'" of Kremenchuk District, Poltava Region, Ukraine, during the period from February 6 to July 4, 2025. All animal handling procedures fully complied with the requirements of Council Directive 98/58/EC (1998). The research protocol was approved by the Bioethics Commission of Sumy National Agrarian University (certificate No. BT2025/07/19-02), in accordance with the standards of good clinical practice regarding the protection and humane treatment of experimental animals. To accomplish the assigned tasks, two groups of sows were formed according to the principle of paired analogues, taking into account age, live weight, and farrowing number. The number of animals in the experiment in each group was 320 heads, which corresponded to one weekly technological group. During pregnancy and the suckling period, the sows of the experimental group received standard compound feed for pregnant and lactating sows with the addition of the feed product JELUVET® in the amount of 10 kg per 1 ton of compound feed, in accordance with the recommendations of the supplier company.

Animals of the control group received compound feed with similar nutritional value, but without the addition of JELUVET®. Throughout the entire experimental period, all technological, veterinary-preventive, and zoohygienic measures were carried out according to the same scheme for both groups of animals in accordance with the housing technology adopted at the enterprise. During the pregnancy and suckling periods, daily clinical monitoring of the health status of the sows was conducted, with recording of cases of physiological disorders. During the farrowing period, the operator of the farrowing unit registered in the stall card near each stall, with subsequent transfer to the research journal, the number of farrowings with complications, as well as their main causes. Simultaneously, upon completion of farrowing in each stall, which was determined by placenta expulsion, the total number of piglets born was recorded, including live-born, weak (non-registered), stillborn, and mummified piglets.

After the birth of piglets, sow prolificacy was determined as the number of live-born piglets, and their live weight was also determined by weighing the litter using automatic scales of the Dutch company MS Pigscale (MS Schippers) with a division value of 0.005 kg. Supplementary feeding of piglets from the 2nd day of life until weaning at 21 days was carried out using the liquid milk replacer Optikee Milk with the help of the Cullina Mix Pro feeding kitchen. Throughout the entire suckling period, the number and body weight of piglets that were removed were recorded, with indication of the reasons for removal. At weaning, the number of piglets in each litter was recorded, and the litter weight was determined using MS Pigscale, on the basis of which the average body weight of piglets was calculated separately for the control and experimental groups. Based on the number of born alive piglets and the number of piglets at weaning, the survival rate until weaning was calculated by dividing the number of piglets at weaning by the number of born alive piglets at birth, which was expressed as a percentage. Recording of compound feed consumption by sows during the pregnancy and suckling periods was carried out daily using torsion scales installed under the feed temporary storage bunker.

The amount of fed pig milk replacer was recorded automatically according to the data of the feeding kitchen processor. Based on the obtained indicators of sow productivity and piglet survival in the control and experimental groups, the economic efficiency of using the feed product JELUVET® was calculated, taking into account the cost of the preparation, feed expenditures, piglet output, and survival in accordance with the methodology for determining the economic efficiency of scientific research in pig production (Khmelnychyi *et al.*, 2023). For this purpose, based on the research data on the quantity of feeds of different formulations and the price excluding value-added tax per unit of feed of the corresponding formulations provided by the farm accounting department for the research period, the cost indicators of feeds, milk replacers, and feed additives were determined. Based on these data, the feed cost of maintaining one sow was calculated (by dividing the gross cost of all feeds consumed by the sow by their quantity at the end of the study); similarly, the feed cost of a piglet litter, one weaned piglet, and a unit of weight gain were calculated.

Expenditures on preventive and therapeutic measures were determined by dividing the gross expenditures

on these measures in a specific technological (experimental) group obtained from primary zootechnical and accounting records by the number of sows, piglets, and their gross weight gain. To test the null hypothesis regarding the absence of differences between the control and experimental groups of pigs, Student's t-test for independent samples was used. At the same time, estimates of arithmetic means and their statistical errors were determined. Differences between group means were considered significant at the following significance levels: $p < 0.05$ for the first level, $p < 0.01$ for the second level, and $p < 0.001$ for the third level. Statistical processing of the obtained data was performed using methods of variation statistics (Kramarenko *et al.*, 2019) with the help of the MS Excel spreadsheet editor.

RESULTS AND DISCUSSION

The addition of 1.0% of a fibre feed supplement to the diet of pregnant and lactating sows significantly affected the course of farrowing, the health status of sows, and the level of production costs compared to the control group, which received a standard diet according to physiological condition (Table 1).

Table 1. *Proportion of farrowings with complications and expenditures on preventive and therapeutic measures for sows under different feeding strategies*

Indicator	Group	
	I control	II experimental
Number of sows at the beginning of the experiment, heads	315	314
Proportion of farrowings with complications, %	11.7	8.9
Expenditures on preventive and therapeutic measures per sow, UAH	209.97	137.81
Expenditures on preventive and therapeutic measures per piglet, UAH	17.87	15.45
Piglet survival during the suckling period, %	93.37 ± 1.131	93.64 ± 1.071

Source: *developed by the authors*

The proportion of farrowings with complications in the sows of the experimental group decreased by 2.8 percentage points. The obtained data indicate a positive effect of the fibre supplement on the course of the parturition process, which is consistent with the results presented in Table 2 regarding the reduction in the proportion of stillborn piglets. The decrease in the frequency of complicated farrowings was directly reflected in the level of expenditures on preventive and therapeutic measures. Thus, expenditures per sow in the experimental group decreased by 72.16 UAH or 34.4%. A similar trend was observed when calculating expenditures per piglet: in the experimental group they were 2.42 UAH or 13.5% lower. The piglet survival rate during the suckling period in both groups was high and did not differ statistically; however, it showed a tendency to increase in the experimental group-being higher by 0.27 percentage points. Despite the absence of a significant difference, the combination of slightly higher survival and higher prolificacy in the experimental group ensured an overall increase in piglet output per sow. Taken together, the obtained results indicate that the inclusion of a fibre additive in the diet of sows during pregnancy and lactation improves sow welfare by reducing the proportion of complicated farrowings, improving the overall physiological state of the animals, and significantly reducing expenditures on veterinary preventive and therapeutic measures without negatively affecting piglet survival. This emphasises both the biological and economic feasibility of using dietary fibre in sow feeding. The addition of dietary fibre also indirectly affected the reproductive performance of sows (Table 2).

Table 2. *Reproductive performance indicators of sows under different feeding strategies*

Indicator	Group	
	I control	II experimental
Total number of piglets born per farrowing, heads	15.16 ± 0.133	15.67 ± 0.171*
Prolificacy, heads	14.08 ± 0.127	14.66 ± 0.162**
Number of stillborn piglets per farrowing, heads	1.08	1.01
Proportion of stillborn piglets per farrowing, %	5.40	4.33
Number of weak non-registered piglets per farrowing, heads	1.14	1.18
Proportion of weak non-registered piglets per farrowing, %	7.52	7.56
Number of mummified piglets per farrowing, heads	0.26	0.33
Proportion of mummified piglets per farrowing, %	1.72	2.11
Birth weight of registered piglets, kg	1.31 ± 0.011	1.33 ± 0.009

Table 2, Continued

Indicator	Group	
	I control	II experimental
Litter weight of born alive piglets at birth, kg	18.44 ± 0.213	19.50 ± 0.196***
Number of piglets in litter at weaning, heads	13.14 ± 0.143	13.73 ± 0.114**
Body weight of one piglet at weaning, kg	6.35 ± 0.071	6.29 ± 0.059
Litter weight of piglets at weaning, kg	83.44 ± 1.191	86.36 ± 1.125

Note: ** = p < 0.05; ** = p < 0.01; *** = p < 0.001*
Source: *developed by the authors*

The total number of piglets born per farrowing in the experimental group was higher by 0.51 or 3.4% compared to the control group (p < 0.05). A similar trend was observed for prolificacy, which in sows of the experimental group exceeded the control by 0.58 or 4.1% (p < 0.01). The key factor contributing to the increase in prolificacy in the experimental group was a reduction in the number and proportion of stillborn piglets. The average number of stillborn piglets per farrowing in sows receiving the tested fibre additive decreased by 6.5%, and their proportion decreased by 1.07 percentage points. Against the background of the reduced number of stillborn piglets, a higher output of live-born piglets was recorded in the experimental group. The number of weak (non-registered) piglets per farrowing did not differ significantly between groups, indicating the absence of a negative effect of the increased fibre level on the viability of newborn animals. A similar pattern was observed for mummified fetuses. The use of the fibre additive led to a tendency toward an increase in piglet birth weight. The average birth weight of registered piglets in the experimental group was 0.02 kg or 1.5% higher than in the control. Against the background of higher prolificacy, this resulted in a significant increase in litter weight of live-born piglets at birth-by 1.06 kg or 5.7% (p < 0.001).

In the subsequent suckling period, the positive effect of fibre consumption was also observed. The number of piglets per litter at weaning in the experimental group was higher by 0.59 or 4.5% compared to the control (p < 0.01). At the same time, the average body weight of one piglet at weaning did not differ significantly between groups, indicating the absence of a negative effect of larger litter size on individual piglet growth. However, due to the higher number of piglets per litter, an increase in litter weight at weaning was observed in the experimental group – by 2.92 kg or 3.5% compared to the control group. Thus, the inclusion of 1.0% dietary fibre supplement in the diet of sows during pregnancy and lactation contributes to a reduction in the proportion of stillborn piglets, an increase in prolificacy, and an increase in litter weight at birth and weaning, without adversely affecting individual piglet growth performance. At the same time, it was noted that the addition of the specified supplement did not negatively affect the growth rate of piglets during the suckling period, while leading to certain differences in the distribution of productivity between individual and litter-level indicators (Table 3). The absolute weight gain per piglet in the experimental group was lower by 0.08 kg or 1.6% than in the control. A similar trend was observed for average daily gain and relative growth rate. However, analysis of litter growth indicators as a whole showed the opposite pattern. The absolute weight gain of the piglet litter in the experimental group was higher by 1.87 kg or 2.9% than in the control group.

Table 3. *Growth intensity of piglets in litters of sows under different feeding strategies*

Indicator	Group	
	I control	II experimental
Absolute weight gain per piglet, kg	5.04 ± 0.073	4.96 ± 0.056
Average daily gain per piglet, g	233 ± 7.2	228 ± 6.1
Relative growth rate per piglet, %	131.59 ± 1.058	130.18 ± 1.003
Absolute weight gain of piglet litter, kg	64.99 ± 1.091	66.86 ± 1.007
Average daily gain of piglet litter, kg	3.01 ± 0.008	3.07 ± 0.011

Source: *developed by the authors*

A similar trend was observed for the average daily weight gain of the litter, which in sows of the experimental group was higher by 0.06 kg or approximately 2.0%. The revealed differences are primarily explained by the larger number of piglets per litter in the experimental group, as shown in Table 2. Under conditions of a larger litter size, the average individual weight and growth rate of a single piglet

are naturally somewhat reduced due to competition for maternal milk; however, the total productivity of the litter increases. Thus, the use of the studied fibre additive indirectly contributed to an increase in the total output of live weight of piglets per sow during the suckling period. The obtained results are consistent with physiological concepts regarding the effect of dietary fibre on the course of farrowing, colostrum secretion, and lactation stability, which collectively ensure better realisation of the reproductive potential of sows even under slightly lower individual piglet growth rates. The addition of dietary fibre to the diet of sows did not lead to an increase in total feed intake over the experimental period, while positively affecting feed conversion indicators in relation to the obtained production (Table 4).

Table 4. *Feed intake of different feed formulations by sows and piglets under different feeding strategies*

Indicator	Group	
	I control	II experimental
Amount of feed consumed during pregnancy, kg	362.89	355.31
Average daily feed intake during pregnancy, kg	2.93	2.87
Amount of feed for lactating sows consumed, kg	168.48	171.35
Average daily feed intake during lactation, kg	7.80	7.86
Total feed intake, kg	531.37	526.65
Amount of JELUVET® supplement consumed per sow, kg	0.00	5.16
Total feed substances consumed per sow, kg	531.37	531.81
Feed consumed per weaned piglet, kg	40.44	38.73
Average daily feed intake over the experimental period, kg	3.65	3.65
Feed consumed per 1 kg piglet weight gain, kg	6.37	6.16
Milk replacer consumed per litter of piglets, kg	2.94	3.46
Milk replacer consumed per 1 kg piglet weight gain, g	35.3	40.1

Source: *developed by the authors*

During the pregnancy period, sows of the experimental group, which were fed a bulkier diet, consumed 7.58 kg or 2.1% less compound feed compared to their analogues in the control group. This occurred due to the greater volume of the compound feed. Accordingly, the average daily feed intake during this period decreased by 0.06 kg or 2.0%. The obtained results indicate more stable functioning of the digestive tract and better satiety of the ration due to structural fibre. During the lactation period, conversely, a tendency toward slightly higher feed intake was observed in sows of the experimental group (by 2.87 kg or 1.7%), which was due to by the larger number of piglets in their litters. The average daily feed intake during this period was also higher in the experimental group (by 0.06 kg or 0.8%), which is physiologically justified given the higher number of piglets per litter and greater nutritional demand for lactation.

Despite these differences, the total amount of feed consumed over the experimental period was practically the same between groups when taking into account the consumption of the feed supplement in the amount of 5.16 kg per sow. An important indicator of feeding efficiency is feed expenditure per unit of production. Feed expenditure per weaned piglet in the experimental group was 1.71 kg or 4.2% lower than in the control group. A similar advantage was observed for feed expenditure per 1 kg of piglet weight gain, which decreased in the experimental group by 0.21 kg or 3.3%. The average daily feed intake over the entire experimental period was identical in both groups and amounted to 3.65 kg, indicating the absence of an effect of the fibre additive on the overall feeding intensity. The different number of piglets per sow during the suckling period also resulted in different consumption of pig milk replacer. Its consumption in the experimental group was slightly higher – by 0.52 kg or 17.7% compared to the control group. Accordingly, milk replacer costs per 1 kg of piglet weight gain increased by 4.8 g or 13.6%. This is explained by the larger number of piglets in the litters of the experimental group and increased competition for maternal milk, which required partial compensation through supplementary feeding.

Overall, the use of the studied dietary fibre supplement in the feeding of pregnant and lactating sows allows for improved feed efficiency in piglet production, reduced feed costs per unit of output, and ensures stable feed intake without energy overconsumption, which is an important factor in the economic feasibility of such a feeding strategy. Differences in feed intake and its price influenced the economic outcomes of applying different feeding strategies for sows during pregnancy and lactation (Table 5). The use of the additive was accompanied by a certain increase in direct feed costs; however, these costs were partially offset by increased reproductive and production efficiency. During pregnancy, the cost of feed consumed by sows in the

experimental group was 66.7 UAH or 2.1% lower. This is consistent with the data in Table 4 regarding slightly lower feed intake by sows in the experimental group during pregnancy.

Table 5. *Cost of feed consumed by sows and piglets under different feeding strategies*

Indicator	Group	
	I control	II experimental
Cost of feed consumed during pregnancy, UAH	3,193.4	3,126.7
Cost of lactation feed consumed, UAH	1,988.1	2,021.9
Cost of JELUVET® additive used, UAH	0.0	290.0
Cost of all feed consumed per sow, UAH	5,181.5	5,438.6
Cost of milk replacer per litter, UAH	331.13	389.25
Cost of milk replacer per weaned piglet, UAH	25.20	28.35
Cost of milk replacer per 1 kg piglet weight gain, UAH	5.09	5.82
Cost of all feed consumed by sow and piglets per litter, UAH	5,512.6	5,827.8
Cost of all feed consumed by sow and piglets per weaned piglet, UAH	419.5	424.5
Cost of feed consumed per 1 kg piglet weight gain, UAH	84.8	87.2
Total feed and veterinary costs, UAH	5,722.60	5,965.65

Source: *developed by the authors*

At the same time, during the lactation period, feed costs in the experimental group increased by 33.8 UAH or 1.7% compared to the control group. Additionally, the cost of the used feed supplement must be taken into account, which amounted to 290.0 UAH per sow, whereas such costs were absent in the control group. As a result, the total cost of all feed consumed per sow in the experimental group was 257.1 UAH or 5.0% higher than in the control group. A similar difference was observed for the indicator of feed cost consumed by the sow and piglets per litter, which in the experimental group was 315.2 UAH or 5.7% higher than in the control group. However, when recalculated per unit of production, the difference between the groups was much less pronounced. The cost of feed consumed per weaned piglet in the experimental group was only 5.0 UAH or 1.2% higher than in the control group. Similarly, the cost of feed per 1 kg of piglet weight gain increased by 2.4 UAH or 2.8%. Costs associated with the use of milk replacer were higher in the experimental group, which corresponds to the data presented in Table 4. The cost of milk replacer per litter increased by 58.12 UAH or 17.6%, and per weaned piglet by 3.15 UAH or 12.5%. Milk replacer costs per 1 kg of piglet weight gain also increased by 0.73 UAH or 14.3%. The summarising indicator of the economic assessment was the total cost of feed and veterinary preparations, which in the experimental group was 243.05 UAH or 4.2% higher.

Thus, the use of the dietary fibre supplement led to a moderate increase in direct costs associated with feeding and management; however, considering the reduction in the proportion of complicated farrowings, lower expenditures on veterinary measures, and a higher output of viable piglets, such costs are economically justified. The obtained results indicate the appropriateness of evaluating the effectiveness of fibre additives not only based on absolute costs but also using integrated indicators of reproductive and production performance, since the outcome of commercial pig production is not only physiological parameters and animal welfare but also the concrete economic feasibility of using a particular feeding strategy. Therefore, the data in Table 6 are relevant, summarising the economic results of using the dietary fibre supplement in the feeding of pregnant sows and reflecting the integrated impact of changes in reproductive, productive, and cost indicators.

Table 6. *Economic efficiency of using the dietary fibre additive*

Indicator	Group	
	I control	II experimental
Market value of weaned piglet litter, UAH	24,697.9	25,563.1
Additional value of weaned piglet litter, UAH	0	865.12
Additional costs for feed and veterinary preparations, UAH	0	243.05
Additional profit per sow, UAH	0	622.07
Additional profit per weaned piglet, UAH	0	45.31
Additional profit per 1 kg of piglet weight gain, UAH	0	9.13

Source: *developed by the authors*

The market value of the weaned piglet litter in the experimental group increased to 25,563.1 UAH, which provided an additional litter value of 865.12 UAH or +3.5%. The obtained increase in value was primarily due to the higher number of weaned piglets and the greater total litter weight, as shown in Tables 2 and 3. At the same time, the application of the supplement was accompanied by additional costs for feed and veterinary preparations in the amount of 243.05 UAH per sow, which corresponds to the results presented in Tables 4 and 5. The main components of these costs were the price of the supplement itself, slightly higher expenditures on lactation feed and milk replacer, as well as total preventive measures costs. However, despite the higher costs associated with the use of the additional fibre additive, the comparison of additional revenues and costs indicates a clearly expressed positive economic effect of its use. Thus, the additional profit per sow in the experimental group amounted to 622.07 UAH, which exceeds the additional costs by more than 2.5 times. Per unit of production, this provided an additional income of 45.31 UAH per weaned piglet and 9.13 UAH per 1 kg of piglet weight gain.

As a result of the study, it was established that the addition of dietary fibre to the diet of pregnant and lactating sows had a positive effect on the course of farrowing. A reduction in the proportion of complicated farrowings was observed, which in turn led to a decrease in the number of stillborn piglets. The addition of dietary fibre indirectly affected the reproductive performance of sows. Animals receiving this feed supplement had higher prolificacy by 0.58 (4.1%; $p < 0.01$), a higher number of piglets at weaning by 0.59 (4.5%; $p < 0.01$), and higher litter weights at birth and at weaning by 1.06 kg (5.7%; $p < 0.001$) and 2.92 kg (3.5%), respectively, compared to their counterparts that did not receive the supplement. These results are consistent with the findings of B. Liu *et al*. (2021) and G. Cong *et al*. (2025), who showed that increased fibre content in the late gestation phase contributes to reduced farrowing duration, decreased incidence of constipation, and increased prolificacy. The obtained results also align with studies by Y. Adi *et al*. (2022), Y. Liu *et al*. (2022), and R. Boonprakob *et al*. (2024), which demonstrated that increasing dietary fibre content during late gestation and early lactation was associated with a 3-8% reduction in constipation incidence, a shortening of farrowing duration by 0.5-1.2 hours, and an increase of 0.3-0.7 live-born piglets. In experiments by T. Feyera *et al*. (2021), fibre supplementation reduced perinatal piglet mortality by 3.9%, while Y. Li *et al*. (2021) reported an increase in litter weight of born alive piglets by 1.1 kg at birth and 2.9 kg at weaning. Researchers T. Pedersen *et al*. (2020) and D. Lu *et al*. (2022) also noted improved nutritional status of the fetus and offspring health with increased fibre intake.

The results of B. Liu *et al*. (2021) and A. Grahofer & K. Plush (2023) also confirmed that an increase in litter size, under adequate nutritional support, does not reduce total litter productivity. The addition of dietary fibre to sow diets positively affected feed conversion efficiency, while the total feed intake over the experimental period did not differ significantly between groups. Improvements in feed conversion and stabilisation of feed intake during lactation due to structural fibre, which influences intestinal motility, microbiota formation, and sow appetite, were confirmed by the findings of H. Jo & B. Kim (2023). At the same time, no negative effects of dietary fibre supplementation were observed, such as those reported by Y. Li *et al*. (2021) and X. Liu *et al*. (2024) – namely reduced dietary energy density and feed palatability, which negatively affect fetal growth and litter parameters. Despite positive physiological effects, the economic aspects of fibre inclusion remain insufficiently studied. P. Zhou *et al*. (2025) noted the need to evaluate costs of ingredients, fibre inclusion, and long-term benefits such as reduced piglet mortality, increased lactation feed intake, and improved productivity in subsequent reproductive cycles.

H. Jo & B. Kim (2023) described interconnected mechanisms of fibre action, including the mechanical effect of insoluble fibre, which increases satiety and reduces behavioural stress. J. Moturi *et al*. (2022) reported that fermentation of soluble and partially fermentable fibres in the large intestine produces SCFAs (acetate, propionate, butyrate), which regulate metabolism, appetite, and inflammatory processes. Similarly, R. Jha *et al*. (2019) and E. Rinninella *et al*. (2019) noted that modulation of the gut microbiota increases the abundance of *Prevotellaceae* and *Ruminococcaceae*, altering SCFA profiles and inflammatory markers, thereby supporting optimal performance during late gestation and milk production. Overall, the results of the study confirm the conclusions of the aforementioned researchers, indicating the economic feasibility of rational dietary fibre inclusion to optimise costs and increase profitability of pork production. Thus, the use of 1.0% dietary fibre supplement in sow feeding is an effective strategy for improving their health and reproductive performance, especially during late gestation and early lactation.

CONCLUSIONS

It was established that the inclusion of 1.0% of the fibre feed supplement in the diet of pregnant and lactating sows significantly affects the course of farrowing, reproductive performance, and economic efficiency of

production. The proportion of farrowings with complications in the experimental group decreased by 2.8% compared to the control group, which was accompanied by a reduction in the number of stillborn piglets by 6.5% and a decrease in their proportion by 1.07 percentage points. As a result, prolificacy in the experimental group increased by 0.58 or 4.1%, and the total number of born alive piglets per farrowing increased by 0.51 or 3.4% ($p < 0.05$). The increase in total litter weight at birth amounted to 1.06 kg or 5.7% more, and at weaning by 2.92 kg or 3.5% more than in the control group. Despite slightly lower absolute individual piglet weight gains during the suckling period (-0.08 kg or -1.6% compared to the control), total litter productivity increased. It was found that the total feed intake during the pregnancy period decreased by 7.58 kg or 2.1% in the experimental group, while average daily feed intake decreased by 0.06 kg or 2.0%.

During lactation, there was a tendency toward an increase in feed intake by 2.87 kg or 1.7%, with average daily intake increasing by 0.06 kg or 0.8%, which is explained by the larger number of piglets per litter and the increased nutritional requirements for lactation. Feed expenditure per weaned piglet decreased by 1.71 kg or 4.2%, and per 1 kg of piglet weight gain by 0.21 kg or 3.3%. The economic evaluation showed that direct costs for feed and milk replacer increased by 243.05 UAH or 4.2% per sow. At the same time, the market value of the weaned piglet litter in the experimental group increased by 865.12 UAH or 3.5%, which ensured an additional profit of 622.07 UAH per sow and 45.31 UAH per weaned piglet. Thus, the results of the study demonstrated that the inclusion of 1.0% of the fibre supplement in the diet of pregnant and lactating sows increases reproductive performance, improves animal welfare, reduces the proportion of complicated farrowings and stillborn piglets, promotes piglet growth and survival, and enhances feed utilisation efficiency and the economic profitability of production. Promising directions for further research include optimising doses and the ratio of soluble and insoluble fibres in diets, as well as evaluating long-term effects on productivity and production economics.

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CONFLICT OF INTEREST

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Вплив додавання клітковинної кормової добавки на благополуччя свиноматок, їх відтворювальну продуктивність та економічні показники опоросу

Сергій Луговий
Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-6505-8105

Микола Повозніков
Доктор сільськогосподарських наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
https://orcid.org/0000-0002-8187-4812

Галина Калиниченко
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-0909-0044

Людмила Онищенко
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0003-2666-9813

Ігор Мойсей
Аспірант
Сумський національний аграрний університет
40000, вул. Герасима Кондратьєва, 160, м. Суми, Україна
https://orcid.org/0009-0006-0486-959X

Анотація. Метою досліджень було вивчення впливу включення 1,0 % кормової клітковинної добавки до раціонів поросних і підсисних свиноматок на перебіг опоросу, відтворювальні показники, інтенсивність росту та збереженість поросят, а також економічну ефективність виробництва. Дослідження проведено в умовах промислового свинокомплексу на двох групах свиноматок, сформованих за принципом аналогів. Контрольна група отримувала стандартний комбікорм відповідно до фізіологічного стану, а свиноматки дослідної групи додатково одержували клітковинну добавку JELUVET® у дозі 10 кг/т комбікорму кормової конверсії у перерахунку на одне відлучене порося та на 1 кг приросту поросят. Встановлено, що застосування клітковини зменшувало частку опоросів з ускладненнями на 2,83 % та знижувало витрати на профілактичні та лікувальні заходи на 72,16 грн на одну свиноматку (34,4 %). Багатоплідність у дослідній групі зросла на 0,58 гол. (4,1 %), а загальна кількість народжених поросят на один опорос перевищувала контроль на 0,51 гол. (3,4 %). Середня маса мертвонароджених поросят знизилася на 1,07 в.п., а маса гнізда живих поросят при народженні підвищилася на 1,06 кг (5,7 %), а при відлученні – на 2,92 кг (3,5 %), без негативного впливу на індивідуальні прирости поросят. Застосування добавки не збільшувало загальне споживання кормів, проте зменшувало витрати корму на 1 кг приросту поросят на 0,21 кг (3,3 %) та на одне відлучене порося на 1,71 кг (4,2 %). Економічна оцінка показала, що додатковий прибуток на одну свиноматку становив 622,07 грн, що підтвердило економічну доцільність використання клітковинної добавки. Отримані результати свідчили, що включення 1,0 % клітковинної добавки до раціону поросних і підсисних свиноматок покращувало перебіг опоросу, підвищувало багатоплідність та сумарну продуктивність гнізда поросят, сприяло ефективному використанню кормів і забезпечувало значний економічний ефект

Ключові слова: поросята; поросність; лактація; дієтична клітковина; економічна ефективність

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Increasing the energy efficiency of sprinkler irrigation systems by optimising hydraulic modes and pumping equipment parameters

Mykyta Khramov*
Assistant
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-2537-7344

Iryna Sukovitsyna
Assistant
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-5201-7830

Oleksii Sadovoy
PhD in Technical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-7369-0714

Antonina Haleeva
PhD in Pedagogical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-8017-3133

Abstract. The aim of the study was to determine the energy effect of adaptive regulation of water supply modes and control of pumping equipment in the irrigation process. The study used analytical and balance methods, instrumental measurements of pressure, flow, and electricity consumption. Energy costs for irrigation remained (1,288 kWh/ha) with an average pump operating time of 9.6 h/day, which indicated the complete dependence of the systems on pumping supply (100%). The spatial scale of irrigation was significantly reduced – to about 100 thousand ha in 2023 and 40.5 thousand ha in 2025, which corresponded to only 10-20% of the pre-war potential (approximately 600 thousand ha). This condition was accompanied by losses of water (32-35%), energy (at least 30%) and critical wear of networks (over 75%). Optimisation of hydraulic modes provided a significant reduction in the load on the system, which was manifested in a reduction in the operating pressure from 0.60 to 0.42 MPa, a decrease in the power consumption of pumps from 56 to 39 kW and a decrease in the specific energy intensity of pumping from 430 to 305 kWh/1,000 m^3. The introduction of automated control using a sensor network (humidity and pressure sensors) increased the adaptability of irrigation, increasing the frequency of irrigation adjustments from 1 to 6 times/day. This allowed reducing water supply during rainy periods by 35%, reducing seasonal energy consumption from 210 to 150 MWh and identifying 6 hidden leaks, which together confirmed

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*Corresponding author (my.khramov@ukr.net)

the effectiveness of the transition to managed energy-saving modes of operation. The practical value of the study lies in the possibility of its use by water management organisations, agricultural enterprises and designers of land reclamation systems to reduce energy consumption, optimise irrigation modes and increase the efficiency of operation of existing infrastructure

Keywords: soil moisture sensors; water consumption; loss reduction; irrigation adjustments; network wear

INTRODUCTION

The relevance of this study is due to the growing dependence of the efficiency of agricultural production on irrigation in conditions of increased variability of climatic factors and instability of water supply. Irrigation is increasingly considered as a technological tool for stabilising yields and optimising the use of water resources. At the same time, the importance of the energy component of pumping water is increasing, which forms a significant share of operating costs. At the current stage of the operation of irrigation systems, the issue of increasing the energy efficiency is gaining particular relevance due to the need for rational use of existing infrastructure and limited possibilities for its rapid modernisation. The issues of this study are due to the preservation of non-adaptive hydraulic operating modes of pumping stations, significant energy losses during water transportation and insufficient level of automation of irrigation network management. Operation of systems with fixed pressure-flow parameters makes it difficult to coordinate water supply with actual irrigation needs and leads to overconsumption of electricity. Limited implementation of sensor monitoring and adaptive control algorithms reduces the possibilities of operational optimisation of water supply modes. The combination of these factors forms systemic limitations of irrigation energy efficiency, which require targeted scientific analysis and substantiation of engineering solutions.

As part of the research on irrigation energy supply, O. Sadovoy *et al*. (2024) substantiated the possibility of using solar energy installations to power sprinkler systems. The proposed solutions outlined ways to increase the energy autonomy of pumped water supply. In the works on electrical support of irrigation systems, O. Sadovoy *et al*. (2023) calculated the optimal geometric parameters of electrical control devices. The analysis demonstrated the importance of coordinating the design characteristics of the equipment with the operating modes of irrigation networks. In the direction of engineering optimisation of technical systems, V. Hruban *et al*. (2025) used finite element methods to assess the stress-strain state of agricultural machinery. The modelling performed allowed determining approaches to increasing the operational reliability of structural elements. Taking into account the development of measurement technologies, J. Liu *et al*. (2024) systematised modern sensor solutions for controlling the parameters of hydraulic valves and systems. The above generalisations formed the basis for increasing the accuracy of monitoring and controllability of hydraulic processes.

Within the framework of research on intelligent control of hydraulic systems, P.M. Bhagwat *et al*. (2024) considered the use of adaptive control algorithms to reduce energy costs. The proposed approaches indicated the possibility of increasing the efficiency of hydraulic systems by optimising control effects. In the field of electro-hydraulic drives, R. Jin *et al*. (2024) developed artificial intelligence (AI)-oriented variable speed and displacement drive modules. The results presented demonstrated the potential of intelligent control for energy saving in complex hydraulic systems. In the field of multi-criteria optimisation of pumping modes, B. Brentan *et al*. (2024) considered approaches to controlling pumping stations in water distribution networks, taking into account energy, quality and operational constraints. The proposed control model provided a balance between energy efficiency and system stability. Based on artificial intelligence methods, L.R. Salvino *et al*. (2022) developed a water distribution network control system using artificial neural networks. The applied approach allowed adapting pump operating modes to variable loads with an orientation towards reducing energy costs.

Within the framework of a general review, Y. Ji *et al*. (2023) systematised the directions for increasing the efficiency of hydraulic turbines in energy recovery processes. The analysis outlined the potential for energy recovery in hydraulic and water management systems. From the perspective of industrial digitalisation, K. Sumit *et al*. (2022) investigated the implementation of Industrial Internet of Things technologies in hydraulic presses for the purpose of energy saving. The proposed solutions were based on continuous data collection and adaptive adjustment of equipment operating modes. In the field of mobile hydraulic systems, P. Fresia *et al*. (2022) analysed combined drive speed control and centralised power supply as tools for increasing

energy efficiency. The considered concepts identified the possibilities of reducing energy losses through coordinated control of drive systems. At the level of digital hydraulics, I. Azzam *et al*. (2022) studied approaches to reducing energy consumption in hybrid hydraulic transmissions. The use of discrete flow control ensured an increase in the overall efficiency of systems without complicating the design scheme.

The quantitative assessment of the energy effect of the combination of hydraulic mode optimisation, inverter control and intelligent control in real irrigation networks remained insufficiently studied. The aim of the study was to quantitatively assess the impact of hydraulic mode optimisation, inverter control and automated control on the energy efficiency of pumping water in irrigation systems. The objectives of the study were to analyse the energy characteristics of pumped water supply, assess the effect of optimising hydraulic modes using inverter pumps, and determine the impact of automation and sensor monitoring on the energy consumption of irrigation systems.

MATERIALS AND METHODS

Research conditions and objects of observation

The research was carried out in 2023-2025 on the basis of the scientific park of the Mykolaiv National Agrarian University "Agroperspectiva" with the involvement of a sample of typical operating sprinkler systems in southern Ukraine, which were operated exclusively with pumped water supply and functioned on centralised pressure networks. The sample included 8 pumping stations (n = 8) and 12 irrigation systems (n = 12) with centralised pumping stations and pressure-type distribution networks, focused on ensuring the operation of frontal action (linear move), circular action (centre pivot), drum sprinkler systems (hose reel irrigators), as well as on-farm hydrants. The study combined the generalisation of open statistical materials on the functioning of irrigation systems in Ukraine with an experimental and computational assessment of the effects of optimising hydraulic regimes. Initial data on energy consumption, water supply volumes and spatial scales of irrigation were used to form baseline levels of indicators and normalise results without interfering with the operational modes of the facilities. The research was carried out in compliance with the European Code of Conduct for Research Integrity (All European Academies, 2023), which regulated the ethics, transparency, and reproducibility of scientific research.

The analysis was carried out on existing sprinkler systems in southern Ukraine, which were operated with pumped water supply and were based on centrifugal pumping units of horizontal and vertical design with a nominal flow of 80-150 m^3/h and a head of 40-70 m. Such pumping equipment was selected due to its typical application in land reclamation networks, constructive versatility and technical suitability for the implementation of frequency control without replacing pumps. Pump operation modes were controlled using Danfoss VLT® AQUA Drive FC 202 (Danfoss, Denmark) and Schneider Electric Altivar Process ATV630 (Schneider Electric, France) inverter drives, focused on water supply and wastewater systems. The use of these drives was due to the support for pressure stabilisation, built-in energy optimisation functions, and compatibility with sensor networks of irrigation systems.

Power consumption parameters in pump irrigation systems

Total electricity consumption by pumping stations (million kWh) was formed on the basis of aggregated data for each studied pumping station, with subsequent statistical generalisation. The initial values of energy consumption were taken into account separately for each facility (n stations), after which descriptive statistics methods were applied – summation, calculation of average values and interval estimation of variation (standard deviation, coefficient of variation). The specific energy intensity of water pumping (kWh/1,000 m^3) was determined on the basis of generalised official statistical materials of state water resources management bodies of Ukraine based on the results of the Irrigation season 2025 (2025). The data were formed by aggregating reporting information from pumping stations on actual electricity consumption and volumes of supplied water.

The specific energy consumption of water supply (kWh/m^3) was calculated by formula:

$$E_v = \frac{E_{tot}}{V}, \quad (1)$$

where E_v – specific energy consumption of water supply, kWh/m^3; E_{tot} – total electricity consumption by pumping units for the calculation period, kWh; V – actual volume of water supplied for the same period, m^3. Electricity consumption per 1 ha of irrigation (kWh/ha) was determined by formula (1).

The maximum daily energy intensity of the supply was determined as the ratio of the maximum daily electricity consumption by pumps to the corresponding daily volume of supplied water according to the formula:

$$E_{max} = \frac{E_{d,max}}{V_d}, \quad (2)$$

where E_{max} – maximum daily energy intensity of water supply, kWh/m^3/day; $E_{d,max}$ – maximum daily electricity

consumption by pumping units, kWh; V_d – daily volume of water supplied on the corresponding peak load day, m³. The average duration of pump operation per day was determined instrumentally, for this purpose the Fluke 1738 Power Logger electricity analyser (USA) was used.

Scale and structure of irrigation infrastructure operation

The actual area of irrigation in 2023 (thousand hectares) was determined based on analytical materials from agricultural information resources and industry reviews that summarised official data on the actual operation of irrigation systems after 2022 (In Ukraine, the area..., 2024).

The total area of irrigated land in 2025 (thousand hectares) and the number of regions with active irrigation were determined based on official information reports from central executive bodies and state information agencies that summarised the results of the functioning of the land reclamation infrastructure (In Ukraine, the total area..., 2025). The area with concluded water supply contracts (thousand hectares) was determined based on data from industry analytical reviews formed on the basis of information from irrigation system operators and water users (Ukraine is increasing the area..., 2025).

The average irrigation area per region (thousand hectares/region) was determined by the calculation method using the formula:

$$A_{avg} = \frac{A_{tot}}{N}, \quad (3)$$

where A_{avg} – average irrigated area per region, thousand ha/region; A_{tot} – total area of irrigated land, thousand ha; N – number of regions with active irrigation. The share of the pre-war irrigation level (%) was determined according to the source data containing an estimate of the pre-war base level and current areas (The first step..., 2026).

Operational condition and resource losses of water management networks

The pre-war potential of irrigated areas (thousand hectares) was determined based on generalised analytical materials of agricultural and water management surveys that characterised the design capacity of Ukraine's land reclamation infrastructure until 2022 (In Ukraine, the area..., 2024). Water losses during transportation (%) were determined by the balance method using the formula:

$$L_w = \frac{V_{in} - V_{out}}{V_{in}} \times 100, \quad (4)$$

where L_w – water losses during transportation, %; V_{in} – volume of water supplied by the pumping station to the network, m³; V_{out} – volume of water recorded at the final water intake points, m³.

The share of energy losses in pumping systems (%) was determined based on the results of industry scientific research and generalised technical and economic assessments of the efficiency of pumping stations (Stashuk *et al.*, 2024). The degree of wear of irrigation networks since the beginning of 2022 (%) was determined in specialised industry analytical materials (Irrigation in Ukraine 2026..., n.d.). The share of systems without automated control (%) was determined by the inventory method based on the analysis of the presence of frequency converters and regulators in the pumping stations. Automated systems included stations equipped with frequency converters of the Danfoss VLT Aqua Drive FC 202 type (Denmark).

The impact of pressure regulation and frequency control of pumps

The comparison was performed between the operating modes of pumping stations before optimisation, which were characterised by fixed pressure-flow parameters, and after optimisation, in which the regulation of the operating pressure and flow was carried out by inverter drives taking into account the hydraulic conditions of the network. Monitoring in the "before optimisation" mode lasted 30 days, in the "after optimisation" mode – 30 days; the parameters were recorded in 5-minute increments, which formed 288 measurement intervals per day for each station. The analysis was performed for no less than 10 repetitions of stabilised operating cycles in each mode; the criterion for a stable hydraulic state was considered to be a deviation of the operating pressure of no more than ±3% and a flow of no more than ±5% for at least 20 minutes of continuous operation.

The operating pressure in the network (MPa) was determined by direct measurement using digital strain gauge pressure sensors WIKA A-10 (Germany) and Siemens SITRANS P320 (Germany), installed in the control nodes of the pressure pipelines. The obtained values were used as input parameters for calibrating the hydraulic model of the network in the Environmental Protection Agency Network Evaluation Tool (EPANET), which allowed specifying the spatial distribution of pressures and head losses.

The average water flow rate (m³/h) was determined from the readings of electromagnetic flow meters Siemens MAG 5100W (Germany) or ultrasonic flow meters Endress+Hauser Prosonic Flow W (Switzerland), mounted on the pressure pipelines. The values were averaged

over stable hydraulic conditions, which ensured the representativeness of the data for further calculations. The power consumption of the pumps (kW) was determined from the instantaneous values of active power recorded by three-phase electrical energy analysers Fluke 435-II (USA) or stationary meters Schneider Electric PM8000 (France), with subsequent integration over time.

The specific energy intensity of pumping (kWh/1,000 m^3) was determined by the formula:

$$E_s = \frac{E_{tot}}{V} \times 1{,}000, \quad (5)$$

where E_s – specific energy intensity of pumping, kWh/1,000 m^3; E_{tot} – integrated electricity consumption by pumping units, kWh; V – total volume of pumped water, m^3.

Hydraulic head losses (m) were determined as the difference between the total head at the outlet of the pumping station and the head at the control nodes of the network, taking into account the results of modelling in EPANET 2.2 (U.S. EPA), where the calculation in the Extended Period Simulation mode, actual lengths and diameters of pipelines, roughness coefficients for pipe material, nodal flows, specified boundary conditions based on measured pressure and flow values, as well as a simulation time step of 5-10 min were used. This approach allowed combining the results of field measurements with a computational analysis of the distribution of losses along the network.

Intelligent regulation of water supply under changing conditions

Comparisons were made between the operating modes of irrigation systems without automation, based on fixed water supply settings, and modes with automation, in which control was carried out on the basis of sensor monitoring and adaptive control algorithms. The input variables of the algorithm were the deviation of soil moisture from the established target range and the deviation of pressure in the network from the given setpoint, while the control effect was implemented by changing the frequency of rotation of pumps with inverter drives through the correction of the parameters p_{set} or Q_{set}. The fuzzy rule base was formed in the form of conditional dependencies of the type: if soil moisture decreased below the standard interval at an allowable pressure level, a moderate increase in supply was carried out; optimisation of solutions was carried out according to the criterion of minimising specific energy consumption while simultaneously observing the restrictions on the limit pressure and agrotechnically allowable humidity. The number of soil moisture sensors and wireless pressure sensors (units) was determined by the inventory method based on the actual configuration of the sensor network of the irrigation system. The installed capacitive soil moisture sensors Decagon EC-5 (Meter Group, USA) and wireless strain-resistive pressure sensors WIKA A-10 (WIKA Alexander Wiegand SE, Germany), integrated into the network control nodes and pump groups, were taken into account.

The frequency of irrigation mode correction (times/day) was determined by the calculation method as the number of changes in the water supply control parameters during the daily interval. The calculation was performed according to the formula:

$$f_c = \frac{n_c}{t}, \quad (6)$$

where f_c – frequency of correction of irrigation modes, times/day; n_c – number of corrections of control parameters during the observation period; t – duration of the observation period, day. Corrections were initiated by rule-based and adaptive control algorithms that combined rule-based control and fuzzy logic control. Threshold conditions were formed based on the deviation of soil moisture from the target interval and exceeding the permissible pressure limits in the network, while the fuzzy algorithm ensured a smooth change in pump flow and head in transient modes.

The change in water supply on rainy days (%) was determined by analytical method as the relative difference between the average daily water flow in the absence of precipitation and on days with precipitation ⩾5 mm/day, which were classified as rainy according to the established threshold criterion. The water supply volumes were determined by the readings of electromagnetic flowmeters Siemens SITRANS MAG 5100W (Siemens AG, Germany) installed on pressure pipelines. The seasonal energy consumption of the system (MWh) was determined by integrating the instantaneous values of the active electric power of the pumping units for the entire growing season. The generalised calculation was carried out by formula:

$$E_{season} = \int_0^T P(t)\, dt, \quad (7)$$

where E_{season} – seasonal energy consumption of the system, MWh; $P(t)$ – instantaneous active power of pumping equipment, kW; T – duration of the growing season, h. Power measurements were performed using three-phase PowerLogic PM8000 electricity analysers (Schneider Electric, France).

The detected pipeline leaks (units/season) were determined by the hydraulic method, based on the analysis of the discrepancy between the calculated and measured parameters of pressure and water flow. For this purpose, a comparison of the results of network

modelling in the EPANET 2.2 software environment (U.S. EPA) with the actual data of pressure sensors and flow meters was used, with local anomalies being considered as indicators of possible leaks. The given indicators were given as average values for intervals of stable hydraulic regime, and the variability of the results was assessed by the range of fluctuations and, by the standard deviation, which ensured the correct statistical representation of numerical data.

RESULTS

Energy consumption assessment of water pumping transportation

The analysis of energy consumption within the studied systems allowed forming a quantitative characteristic of the functioning. The total energy consumption by pumps was 51.5 million kWh. The obtained value indicated the energy costs for supporting the water supply system throughout the entire growing season. The value of energy consumption showed a low correlation between the actually irrigated area and its physical characteristics. At the same time, the obtained indicator was consistent with the fact that the inertia of the operating modes of pumping stations, in which a decrease in water supply was not accompanied by a proportional change in pump power or operating time, led to an increase in the energy intensity of the irrigation process in the studied irrigation system. Thus, the energy consumed by pumps did not correspond consistently to the actual load of the system. The specific energy intensity of the water pumping process was 393.7 kWh/1,000 m^3, which reflected the energy costs for water transportation under the established hydraulic conditions. The obtained values confirmed the influence of all factors that formed energy costs in the studied area. Energy costs were based on pressure losses in pumping stations, on the lack of correlation of pump operating modes and on the technical condition of the system pipelines. Therefore, in this form, this analysis of the indicator confirmed that the cause of energy costs was mainly associated with the hydraulic mismatch of the irrigation system, and not with an increase in the need for water supply for irrigation. This level of specific energy intensity indicated the possibility of reducing electricity costs without reducing irrigation volumes in this case. The specific energy consumption of water supply was 0.394 kWh/m^3, which determined the energy costs for transporting a unit of water. The obtained value reflected the average value of all elements of the system, from pumps to the final water distribution nodes. Thus, the analysis of this indicator confirmed that the established operating mode of the pumps achieved stability of water supply. In this case, the pumps exceeded the optimal pressure parameters, which indicated a non-adaptive approach to resource optimisation during the operation of pumping stations.

The integral value of electricity consumption per unit area was 1.288 kWh/ha, which quantitatively reflected the energy costs of irrigation per unit of production. The obtained value reflected the integral impact of the duration of operation of pumping stations, pumping modes and irrigated areas. Analysis of the value of the obtained indicator showed that electricity consumption bypassed the issue of resource improvement of the irrigation system in favour of ensuring its economic benefit. At the same time, even with minimal deviations from the pump operation settings, an increase in electricity consumption per hectare of production was observed in the study area, which negatively affected the sustainability of the irrigation system in terms of changes in its consumption (Table 1).

Table 1. *Energy characteristics of pumped water supply in irrigation systems of Ukraine (2025)*

Indicator (unit)	Value	Note
Total electricity consumption by pumping stations (million kWh)	51.5	Generalised operational data of pumping stations that provided water supply in functioning irrigation systems during the 2025 growing season
Specific energy consumption of pumping (kWh/1,000 m^3)	393.7	The value is given in terms of the volume of water actually supplied and reflects the relationship between energy consumption and water flow in pumping networks
Specific energy consumption of water supply (kWh/m^3)	0.394	Normalised energy characteristic of pump flow, used to compare operating modes of systems regardless of the spatial and production scales
Electricity consumption per 1 ha of irrigation (kWh/ha)	1288	Given in relation to the area of land in 2025 actually involved in irrigation during the period under study
Average pump operation time per day (hours)	9.6	Average value obtained during the period of active operation of pumping equipment during the growing season
Maximum daily energy consumption of supply (kWh/m^3/day)	0.47	Characteristics of system operating modes under conditions of increased daily water supply intensity
Share of pump supply in irrigation (%)	100	Reflects the structure of water supply within the studied irrigation systems in the absence of alternative water supply sources

Source: *compiled by the authors based on Irrigation season 2025: Over 40 thousand hectares of Ukrainian lands provided with water (2025)*

The generalisation of the obtained results allowed establishing that the energy characteristics of the pumped water supply were determined by a combination of high total energy consumption, increased specific energy intensity of pumping and significant electricity consumption per irrigation area. The set of numerical values obtained indicated that the existing hydraulic modes were not optimised in terms of energy efficiency and did not take into account the real needs of irrigation. The results of this section confirmed the feasibility of further analysis of the impact of pressure optimisation, modernisation of pumping equipment and the introduction of automated control as tools for reducing energy consumption.

Spatial characteristics and management organisation of irrigation

The actual irrigation area in 2023 was approximately 100,000 hectares. This indicator reflected the physical scale of operating irrigation systems in the post-crisis period and characterised the level of use of the existing infrastructure. The result obtained indicated that irrigation was carried out in limited and heterogeneous areas, which made it difficult to establish stable hydraulic regimes. In this situation, pumping stations operated at sub-maximum capacity, and water supply regimes were often determined by the local needs of individual areas, rather than by agreed management schemes. The established scale of irrigation confirmed the existence of a gap between the potential of irrigation infrastructure and the level of its use. In 2025, the total area of irrigation decreased to 40.5 thousand hectares, which reflected a further narrowing of the spatial coverage of irrigation. This indicator characterised the transition of the system to a localised mode of operation, in which irrigation was carried out in limited areas without the possibility of uniform load distribution between network elements. Such a concentration of irrigation in limited areas led to an increase in the uneven operation of pumping stations and complicated the application of centralised approaches to optimising water supply. The result showed that the spatial narrowing of irrigation was accompanied by a loss of flexibility in the management of hydraulic regimes.

The area of land with formalised water supply contracts was about 40,000 hectares, which reflects the organisational level of readiness of irrigation systems for operation. This indicator characterised the volume of areas for which formalised water use conditions were organised and which had access to pumped water supply. The result showed that the majority of actually irrigated areas operated within the framework of formalised contractual relations. However, the spatial boundaries remained narrow. As a result, the organisational structure of water supply was aimed at supporting a minimally sufficient irrigation infrastructure, rather than at fully utilising the capabilities provided by existing networks. This approach created conditions under which pumping stations operated in modes that did not allow for optimal distribution of flows in space. The share of actual irrigation from the pre-war level was 10-20%, which was explained by the use of different bases of comparison – the design potential of the systems or the actually operated areas in previous years. The obtained indicator indicated the loss of most of the pre-war irrigation potential and a sharp reduction in the scale of infrastructure use. Under these conditions, spatial planning of irrigation lost its systematicity, and pumping stations were operated under conditions of uneven and limited load. The analysis confirmed that the current scale of irrigation does not allow realising the design advantages of centralised water supply networks and does not significantly reduce specific energy costs (Table 2).

Table 2. *Spatial and organisational scale of irrigation operation in Ukraine (2023-2025)*

Indicator (unit)	Value	Note
Actual irrigation area in 2023 (thousand hectares)	~100	The indicator reflected a sharp reduction in irrigation after 2022. The area limitation reduced the efficiency of using existing infrastructure
Total area of irrigated land in 2025 (thousand hectares)	40.5	The value characterised the current level of irrigation restoration. It remained significantly lower than the pre-war potential
Number of areas with active irrigation (units)	4	The indicator showed a high regional concentration of irrigation in Zaporizhia, Kirovohrad, Mykolaiv and Odesa regions. The main load fell on a limited number of regions
Area with concluded water supply contracts (thousand hectares)	~40	The indicator reflected the real volume of functioning systems. It testified to organisational readiness for irrigation
Share of pre-war irrigation level (%)	10-20	The value indicated the loss of a significant part of the potential. This necessitated the modernisation of existing systems
Average irrigated area per region (thousand hectares/region)	~10	The indicator was used to assess the scale of the load on regional systems. It was applied in modelling pumping modes

Source: *compiled by the authors based on In Ukraine, the area of irrigated land has decreased sixfold (2024), In Ukraine, the total area of irrigated land exceeded 40 thousand hectares (2025), Ukraine is increasing the area of irrigated land: Contracts for 40 thousand hectares have been signed in four regions (2025), The first step: The irrigation market in Ukraine has begun to recover (2026)*

The summary of the results allowed establishing that the spatial and organisational scales of the irrigation system during the studied period were distinguished by a significant reduction in area, localised water supply and limited integration of areas into a single system. The combination of small actual irrigation areas with narrow but formalised water use zones created conditions under which pumping stations operated outside the optimal operating modes. The numerical values obtained as a result of the analysis indicate that spatial restrictions and the organisational structure of the irrigation system had a significant impact on the operation of pumping equipment and contributed to an increase in specific resource consumption.

Network wear and loss of water and energy resources

The level of water losses during transportation was 32-35%, which characterises the scale of the discrepancy between the volume of water supplied by pumping stations and the amount of water actually used for irrigation. This indicator was formed as a result of the cumulative effect of long open channels, worn pipelines and leakage of network elements. Under such conditions, water transportation was associated with a systematic decrease in its useful flow along the entire length of the irrigation system. The established level of water losses meant that a significant part of the pumped water supply did not participate in irrigation, which led to an increase in the total volume of water supply and a corresponding increase in the load on the pumping equipment. The physical condition of the networks was characterised by a degree of wear of ⩾75%. This indicator reflected the degree of degradation of the main structural elements of the irrigation infrastructure, including pipelines, channels, valves and connecting nodes. Under such conditions, the network operated mainly outside its design parameters, which determined the instability of hydraulic conditions. The wear of the infrastructure was accompanied by an increase in the roughness of the internal surfaces, local deformations and a partial loss of throughput in some areas. As a result, water was supplied under conditions of increased head losses, which required maintaining increased operating parameters of the pumping units.

The share of energy losses in pumping systems was ⩾30%, which reflected the ratio between the total electricity consumption and its useful part spent directly on water supply, and included the costs of overcoming the hydraulic resistance of the network, pressure losses in pipelines, pump operation beyond the optimal efficiency coefficient, and additional energy costs associated with the instability of the modes. This indicator was formed under conditions of inconsistency of the operation of pumps with the actual hydraulic characteristics of the network, as well as the need to compensate for pressure losses in worn sections of the network. Under such conditions, part of the electricity was spent on supporting operating modes not related to the useful transportation of water, which increased the total energy consumption of irrigation. The established share of energy losses reflected the structural inefficiency of the system due to the combination of the technical condition of the network and the operating modes of pumping units. A comprehensive analysis of the obtained indicators allowed outlining the nature of the relationship between the technical condition of irrigation networks and resource losses. High levels of water losses generated increased pumping costs, which were accompanied by increased energy consumption to support such losses. The high degree of infrastructure deterioration determined the instability of hydraulic regimes and limited the precise regulation. The share of energy losses in pumping systems reflected the consequences of such operation, when the efficiency of electricity use decreased due to compensation for technical and hydraulic deficiencies (Table 3).

Table 3. *Technical condition and resource losses of irrigation networks in Ukraine*

Indicator (unit)	Value	Note
Pre-war potential of irrigated areas (thousand hectares)	~600	The indicator characterised the design capacity of the systems. The difference with the actual areas indicated the degradation of the infrastructure
Water loss during transportation (%)	32-35	The value reflected physical losses in channels and pipelines. These were associated with filtration and excess pressure
Share of energy losses in pumping systems (%)	⩾30	The indicator indicated inefficient operation of pumping equipment. Its decrease was expected with optimisation of operating modes
Degree of wear of irrigation networks at the beginning of 2022 (%) (%)	⩾75	The value indicated a critical technical condition of the networks, which led to an increase in hydraulic and energy losses
Share of systems without automated control (%)	>85	The value indicated the predominance of manual control. This reduced the adaptability of the systems to weather conditions

Source: *compiled by the authors based on In Ukraine, the area of irrigated land has decreased sixfold (2024), V.A. Stashuk et al. (2024), Irrigation in Ukraine 2026: Prices, competition for water, state support and new irrigation technologies (n.d.)*

Thus, the results of the study reflected the set of technical and operational characteristics of irrigation networks, within which water and energy losses were formed during water pumping. The established values of water losses, the degree of physical wear of the infrastructure and the share of energy losses outlined the real parameters of the networks' functioning in the studied period and determined the nature of the interaction between the technical condition of the system and its operating modes. The results obtained recorded the existing limitations of the functioning of irrigation networks, which affected the level of resource load and operating conditions of pumping equipment.

Adjustable pumping modes and reduction of hydraulic losses

After the formation of optimised hydraulic operating modes, the operating pressure in the irrigation network was set at 0.42 MPa. This parameter indicated the adjustment of the pump operating modes using frequency modulation, which allowed stabilising the hydraulic conditions in the network. The irrigation network operated at this pressure level without loss of fluid flow, and the load on its elements was uniform along the supply path. The operation of the network in such conditions of reduced pressure was associated with a decrease in local head losses and stabilisation of flow patterns. The formation of this operating pressure demonstrated the possibility of irrigation systems operating without the use of redistributed head reserves characteristic of standard operating modes. The electrical load on the pumping system in conditions of optimised hydraulic operating modes was 39 kW. This value reflected the stability of the pumps during the water supply process in the absence of peak overload. The pumping system operated with soft frequency modulation without sharp fluctuations in electricity consumption. Compliance of the pump operating modes with the actual needs of water supply ensured the stability of energy consumption during the water supply process. The recorded electricity consumption was manifested as a transformation of the energy consumption pattern from pulsed to uniform, which had a positive effect on the energy balance of irrigation.

The specific energy consumption for water transportation under conditions of optimised hydraulic operating modes was 305 kWh/1,000 m^3. This parameter indicated the ratio of energy consumption to the supplied volume, which was maintained within the established hydraulic operating modes. The achieved level of this parameter became possible due to the correlation between the reduced operating pressure and the operation of pumping equipment within the parameters close to its design capacity. Water transportation under these conditions had a reduced level of unproductive energy consumption associated with the overcompensation of head reserves. The achieved level of specific energy consumption demonstrated a new level of energy efficiency in the process of water supply for the needs of existing irrigation networks. Based on these indicators, it was possible to characterise changes in the energy properties of pumping irrigation networks under optimised hydraulic operating modes. Reducing the operating pressure created conditions for reducing electrical loads directed at pumping systems, which is manifested in reducing the values of electricity consumption. Stabilising the operating modes of pumping equipment simultaneously ensured the creation of a uniform picture of energy consumption and reducing energy losses associated with the use of incongruent operating modes. The recorded level of specific energy consumption included both changes in relative units, which improves the understanding of the efficiency of water supply regardless of the scale of the network. The presented numerical indicators characterised the increased energy efficiency of irrigation network by adjusting the operating modes without changing the physical parameters of the pumps of irrigation networks. The operation of pumping systems under optimised pressure and inverter control ensured a better match between the hydraulic properties of irrigation infrastructures and the ratio of head and flow of pumps. The operation of irrigation infrastructures under these conditions-maintained modes as close as possible to the design ones, minimising the energy requirements for irrigation caused by technical shortcomings of drainage infrastructures (Table 4).

Table 4. *Effect of pressure optimisation and use of inverter pumps*

Indicator (unit)	Before optimisation	After optimisation	Note
Working pressure in the network (MPa)	0.60	0.42	Pressure reduction eliminated excess hydraulic losses. Optimisation was achieved through modelling in EPANET
Average water flow (m^3/h)	120	92	The indicator reflected the transition to the optimal supply mode. This prevented excessive water and energy consumption
Hydraulic head loss (m)	19	11	The reduction in losses indicated an increase in network efficiency. This had a positive effect on pump efficiency

Table 4, Continued

Indicator (unit)	Before optimisation	After optimisation	Note
Pump power consumption (kW)	56	39	The indicator reflected the direct energy effect of the optimisation. The reduction corresponded to a level of 20-30%
Specific energy consumption of pumping (kWh/1,000 m³)	430	305	The indicator was used to compare system operation scenarios. It confirmed the effectiveness of the optimisation

Source: *compiled by the authors*

Thus, the results of the study outlined the quantitative parameters of the energy effect achieved as a result of optimising hydraulic modes and using inverter control of pumping equipment. The established values of operating pressure, consumed electric power and specific energy intensity of pumping determined new operational limits of pumping water supply within the existing irrigation systems under adjusted operating modes. The set of the above parameters reflected the change in the nature of the system's energy consumption and formed a quantitative basis for further assessment of the impact of automated control, sensor monitoring and intelligent regulation algorithms on irrigation modes and total energy costs in the conditions of the actual technical condition of the networks.

Sensor monitoring as the basis of dynamic irrigation modes

The number of soil moisture sensors in the system was 24 units, which provided spatially detailed tracking of the state of moisture within the irrigated areas. This distribution of the sensor network created a continuous array of data on spatial and temporal changes in moisture detected and distributed in the air to adjust irrigation modes. The established density of sensors compensated for the uneven moisture state in soil conditions and microrelief of the irrigated area, thereby minimising the need for irrigation according to averaged schemes. Adaptive irrigation schemes and the amount of water supplied to plants corresponded to the needs. Under these conditions, the risk of over-watering reduced the unproductive energy consumption associated with the operation of the pumping station. The irrigation system for supporting and monitoring hydraulic parameters included 18 wireless pressure sensors distributed in a spatially distributed network along the supply and distribution sections. This configuration allowed for real-time control of the pressure supply rate throughout the network, which allowed for dynamic regulation of the pump and equipment. Stable hydraulic conditions created under these conditions reduced the need to maintain an excess supply of hydraulic pressure. This constant and stable configuration of the pressure sensor network created uniform water transport conditions that evenly distributed energy consumption to the pumping station, instead of concentrating unproductive electricity consumption.

The number of irrigation mode adjustments per day was 6, which characterised the high level of adaptability of the AI-based control system. These changes occurred in response to soil moisture sensors and weather sensors connected through AI-driven algorithms. Under these conditions, the water supply management was adjusted to provide reduced irrigation according to strict schedules. Regular irrigation mode adjustments up to six times a day allowed the pumps to operate as needed. Given this practice, electricity consumption was levelled without the peak loads that are usually caused by traditional control systems. The seasonal electricity consumption for this automated irrigation management system was 150 MWh. This figure represented the total electricity consumption calculated during the growing season. This value stabilised at a fixed level after the conditions of energy supply to the irrigated plants stabilised. This new seasonal energy consumption curve stabilised as a result of adapted pumping stations and pumps, dynamic pressure correction and non-invasive control of irrigation modes based on artificial intelligence. Such seasonal energy consumption with automation minimised electricity consumption peaks and evenly distributed consumption patterns over time (Table 5).

Table 5. *The impact of automation, sensors, and AI control on irrigation modes*

Indicator (unit)	Without automation (traditional control without adaptive algorithm)	With automation	Note
Number of soil moisture sensors (units)	0	24	The use of sensors ensured that irrigation was adapted to the plants' needs, reducing water overspending
Number of wireless pressure sensors (units)	2	18	Increasing the number of sensors allowed the system to be monitored in real time, which reduced energy losses

Table 5, Continued

Indicator (unit)	Without automation (traditional control without adaptive algorithm)	With automation	Note
Frequency of irrigation mode correction (times/day)	1	6	The indicator reflected the flexibility of management. Frequent corrections increased the accuracy of water supply
Change in water supply on rainy days (%)	0	- 35	Automation allowed the water supply to be reduced during favourable weather conditions, which had a direct energy-saving effect
Seasonal energy consumption of the system (MWh)	210	150	The indicator characterised the total effect of automation and AI management. Its decrease indicated an increase in efficiency
Pipeline leaks detected (units/season)	0	6	The use of thermography allowed detecting hidden leaks, which reduced unproductive water and energy losses

Source: *compiled by the authors*

Thus, the results of the study outlined the quantitative parameters of the impact of automation, sensor monitoring and AI-control on the energy consumption of irrigation systems within the studied period. A combined consideration of the above parameters made it possible to characterise the change in the system operating modes under the conditions of applying adaptive control schemes based on continuous collection and processing of operational data. Spatially detailed sensor monitoring formed the information basis for regulating water supply in accordance with the current soil condition and hydraulic conditions of the network, while AI-control algorithms provided for prompt correction of the operating modes of pumping equipment. The established values of the number of sensors, the frequency of mode correction and seasonal electricity consumption determined new operating conditions for the functioning of irrigation systems under intelligent control schemes. The frequency of corrections determined the dynamics of the operation of pumping units and the nature of the energy load during the day, while seasonal energy consumption reflected the integrated result of the action of automation and intelligent control within one vegetation cycle.

DISCUSSION

The results obtained showed that the optimisation of hydraulic modes in combination with inverter control of pumping equipment contributed to a significant change in the energy properties of pumped water supply. Stabilisation of the operating pressure in the network created conditions for the rejection of excess pressure reserves inherent in traditional operation schemes without violating the stability of hydraulic modes. This approach was consistent with modern ideas about energy-saving management of irrigation systems, where maintaining coordinated pressure-flow parameters is considered a key factor in reducing pressure losses and mechanical loads on network elements. Changing the nature of the operation of pumping equipment from discrete to adaptive ensured the alignment of the energy profile of water supply. Inverter control made it possible to coordinate the operating modes of pumps with actual hydraulic conditions, which reduced unproductive electricity consumption and increased operational stability. The generalisation of energy characteristics in relative indicators reflected an increase in the efficiency of water transportation within the existing infrastructure without the need for its structural modernisation. In the context of energy efficiency analysis of hydraulic systems, the works of R. Dindorf *et al.* (2023) and Y. Ebada *et al.* (2025) considered individual technical aspects of optimisation. R. Dindorf *et al.* generalised models of hydropneumatic accumulators as a tool for reducing energy losses, however, the study was of a survey nature and did not cover the operating modes of pumping networks with variable loads. Y. Ebada *et al.* focused on increasing the efficiency of centrifugal pumps and reducing cavitation in laboratory conditions, but the analysis was limited to a single unit without taking into account network hydraulics. In contrast to these approaches, in this study, energy parameters were estimated for the entire water supply system, which made it possible to trace the relationship between optimised pressure, flow stabilisation and reduction of unproductive losses in real irrigation conditions.

From the perspective of optimising water supply modes, G. Tardy *et al.* (2024) and Y. Pang *et al.* (2024) analysed the possibilities of reducing energy consumption in technical systems with controlled hydraulic parameters. G. Tardy *et al.* applied optimisation approaches to the design of energy-efficient power transmissions of mobile equipment, however, the study was limited to closed loops with regulated operating cycles. Y. Pang *et al.* simulated irrigation planning scenarios to reduce energy costs, however, the emphasis was on the calendar and agrotechnical irrigation schedule without a detailed analysis of the hydraulic behaviour of the

network. In this study, the optimisation was performed for an open pumping system with variable flow rates and pressure modes, which allowed combining pressure regulation, inverter control and sensor monitoring and evaluating the combined effect in real conditions of long-term seasonal operation. In the field of intelligent control of hydraulic systems, I. Azzam *et al*. (2023) and L. Li *et al*. (2025) developed algorithmic approaches to optimisation. I. Azzam *et al*. proposed automated selection of pump operating modes, but the control was based mainly on the internal parameters of the equipment. L. Li *et al*. increased energy efficiency by optimising flows in manipulators, without taking into account external natural factors. In this study, intelligent control was integrated with spatially distributed soil moisture and pressure sensors, which ensured the adaptation of water supply modes to real irrigation needs and formed a systemic approach that was not implemented in the above works.

In the field of experimental evaluation of pumping equipment, the works of L. Manservigi *et al*. (2023) and M. Yanikören (2025) analysed local ways to increase energy efficiency. M. Yanikören investigated the energy consumption of gear pumps using the Taguchi method, focusing on the influence of design parameters on the efficiency of a single unit, but without taking into account the interaction of the pump with an extended pipeline network. L. Manservigi *et al*. considered the use of the pump as a turbine to reduce pressure losses, but the approach was focused on reducing local leaks and did not cover variable water supply modes. In this study, the optimisation was carried out at the level of the entire irrigation system, which allowed evaluating the integrated energy effect of pressure regulation and inverter control under real operating conditions.

In the context of hybrid hydraulic drives, F. Khajvand *et al*. (2023) and V.H. Nguyen *et al*. (2025) focused on increasing energy efficiency through energy recovery in mobile equipment. F. Khajvand *et al*. implemented a serial hybrid hydraulic drive scheme aimed at accumulating and reusing braking energy, however, the analysis remained limited by the conditions of repeated motion cycles and did not take into account the variability of the hydraulic load in space V.H. Nguyen *et al*. investigated the concept of double energy recovery in hydraulic cylinders of working bodies, paying primary attention to the kinematic and power characteristics of individual nodes, while spatially distributed pressure losses and the features of the operation of extended networks were not analysed. Unlike the above approaches, in this study, energy efficiency was increased without the use of recuperation circuits, through adaptive control of water supply modes, which allowed reducing energy costs without complicating the structural scheme of the system. From the perspective of intelligent control and optimisation, M. Bhola *et al*. (2023) and S. Iyer *et al*. (2025) applied algorithmic methods to improve the efficiency of hydraulic systems. S. Iyer *et al*. optimised the geometric parameters of the impellers of pumps for thermal plants, focusing on improving the aerohydrodynamic characteristics of the units, however, variable network operating modes and the impact on total energy consumption were not considered. M. Bhola *et al*. used machine learning methods to control the hydrostatic transmission of a loading machine, but the object of the study remained a closed system with predefined operating scenarios. In the presented study, intelligent control algorithms were integrated with spatially detailed sensor monitoring of soil moisture and pressure in the network, which ensured the adaptation of water supply modes to external natural and operational factors and formed a more universal and scalable approach to increasing the energy efficiency of irrigation systems.

In the field of water transportation optimisation and network management, M. Bayatloo *et al*. (2023) and J. Jafari-Asl *et al*. (2024) examined approaches to reducing energy and resource losses. J. Jafari-Asl *et al*. used an extended optimisation framework to reduce the ecological footprint of water supply, focusing on mathematical redistribution of flows in the network, but the analysis was model-based and did not include adaptive real-time pump control. M. Bayatloo *et al*. investigated a pump operating as a turbine, taking into account polymer additives to increase energy recovery, but the emphasis was on the experimental characteristics of a separate unit without integration into the irrigation system. Against this background, this study was distinguished by the fact that energy efficiency was achieved through systematic optimisation of pressure and water supply in a branched network without the use of additional energy-generating circuits. In the context of operational planning and agro-energy, M. Dini *et al*. (2022) and T.A. Jensen *et al*. (2025) analysed the management aspects of energy use. M. Dini *et al*. optimised pump schedules in water distribution systems to increase hydraulic efficiency, but the study focused on time planning without taking into account sensor-based monitoring of field conditions. T.A. Jensen *et al*. summarised approaches to increasing the energy efficiency of agricultural operations, focusing on technology and management, but without detailing hydraulic irrigation regimes. In this study, the combination of optimised pump regimes with spatially detailed data allowed directly linking energy consumption to actual irrigation needs, which was not

implemented in the above works.

From the standpoint of intelligent control and integrated energy systems, T.H. Nguyen *et al*. (2023) and T. Chanchayanon *et al*. (2024) applied modern algorithmic solutions. T.H. Nguyen *et al*. used a Neural Network Fractional-Order Proportional-Integral-Derivative Controller (NN-FOPID) to improve the performance of an independent flow metering system, but the study remained within the control of valve nodes. T. Chanchayanon *et al*. considered the integration of geothermal heat pumps in the concept of "smart cities", focusing on building energy systems. In contrast to these approaches, in this study, intelligent control algorithms were aimed at adapting the pumped water supply to changing natural conditions, which ensured the applicability of the results to irrigation systems without changing the design scheme. The results obtained showed that the combination of hydraulic mode optimisation, inverter control and intelligent control provided a systemic increase in the energy efficiency of pumped water supply by matching the pressure-flow characteristics of the network with real irrigation conditions, which differed from the local or model approaches presented in most of the analysed studies.

CONCLUSIONS

The work performed a comprehensive analysis of the energy, hydraulic, and organisational parameters of the functioning of irrigation systems in Ukraine with a focus on pumped water supply in 2023-2025. It was found that under conditions of complete dependence of irrigation on pumping stations (100%), the total electricity consumption reached 51.5 million kWh, and the specific energy intensity of pumping was 393.7 kWh/1,000 m^3 with a specific energy consumption of 0.394 kWh/m^3. The recorded consumption of 1,288 kWh/ha and the average pump operation duration of 9.6 h/day indicated a high level of energy load on the system, with a maximum daily energy intensity of 0.47 kWh/m^3/day. Spatial analysis showed a sharp reduction in the scale of irrigation from about ~100 thousand ha in 2023 to 40.5 thousand ha in 2025, which corresponded to only 10-20% of the pre-war potential (~600 thousand ha). Irrigation remained concentrated in 4 regions with an average load of ~10 thousand ha/region, and the area with concluded water supply contracts was ~40 thousand ha. Such concentration increased operational risks against the background of water losses of 32-35%, energy losses of at least 30%, network wear of over 75% and the share of systems without automated control of over 85%.

Optimisation of hydraulic modes using inverter pumps and modelling in EPANET ensured a transition from an operating pressure of 0.60 MPa to 0.42 MPa, a decrease in average water flow from 120 to 92 m^3/h and a reduction in head losses from 19 to 11 m. This was accompanied by a decrease in pump power consumption from 56 to 39 kW and a decrease in specific energy intensity of pumping from 430 to 305 kWh/1,000 m^3, which corresponded to an energy effect of 20-30% without intervention in the network design. Introduction of automated and AI-control using 24 soil moisture sensors and 18 wireless pressure sensors provided an increase in the frequency of irrigation mode corrections from 1 to 6 times/day. This allowed reducing water supply on rainy days by 35%, reducing seasonal energy consumption from 210 to 150 MWh and detecting 6 hidden pipeline leaks per season. The limitations of the study include the lack of a complete set of operational data for 2024, which limited the possibility of continuous interannual interpretation of the results obtained. Further research should be focused on expanding the functionality of intelligent control, integrating predictive water consumption models and assessing the long-term impact of automation on the reliability and resource of pumping equipment.

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Підвищення енергоефективності дощувальних систем зрошення шляхом оптимізації гідравлічних режимів і параметрів насосного обладнання

Микита Храмов
Асистент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-2537-7344

Ірина Суковіцина
Асистент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-5201-7830

Олексій Садовий
Кандидат технічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-7369-0714

Антоніна Галєєва
Кандидат педагогічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-8017-3133

Анотація. Метою дослідження було визначити енергетичний ефект адаптивного регулювання режимів подачі води та керування насосним обладнанням у процесі зрошення. У дослідженні застосовували аналітичний і балансовий методи, інструментальні вимірювання тиску, витрат і електроспоживання. Енергетичні витрати на зрошення залишалися (1 288 кВт·год/га) за середньої тривалості роботи насосів 9,6 год/добу, що вказувало на повну залежність систем від насосної подачі (100 %). Просторові масштаби зрошення істотно скоротилися – до близько 100 тис. га у 2023 році та 40,5 тис. га у 2025 році, що відповідало лише 10-20 % довоєнного потенціалу (приблизно 600 тис. га). Такий стан супроводжувався втратами води (32-35 %), енергії (не менше 30 %) і критичним зношенням мереж (понад 75 %).Оптимізація гідравлічних режимів забезпечила суттєве зниження навантаження на систему, що проявилося у скороченні робочого тиску з 0,60 до 0,42 МПа, зменшенні споживаної потужності насосів з 56 до 39 кВт та зниженні питомої енергоємності перекачування з 430 до 305 кВт·год/1 000 м^3. Упровадження автоматизованого керування із використанням сенсорної мережі (датчики вологості та тиску) підвищило адаптивність зрошення, збільшивши частоту корекцій поливу з 1 до 6 разів/добу. Це дозволило зменшити подачу води у дощові періоди на 35 %, скоротити сезонне енергоспоживання з 210 до 150 МВт·год та виявити 6 прихованих витоків, що в сукупності підтвердило ефективність переходу до керованих енергоощадних режимів експлуатації. Практична цінність дослідження полягає в можливості його використання водогосподарськими організаціями, агропідприємствами та проєктувальниками меліоративних систем для зниження енергоспоживання, оптимізації режимів зрошення й підвищення ефективності експлуатації існуючої інфраструктури

Ключові слова: датчики вологості; витрати води; зменшення втрат; корекції поливу; зношення мереж

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The influence of dynamic operating modes of electric drives of pumping stations and grain drying complexes on the degradation of nanocomposite insulation of high-voltage circuit breakers: Measurement results and recommendations for agricultural engineering

Andrey Stavinskiy*
Doctor of Technical Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-7573-9238

Larisa Vakhonina
PhD in Physical and Mathematical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-1668-2275

Volodymyr Martynenko
PhD in Technical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0003-4067-3640

Vitalii Mardziavko
Master, Assistant
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-7327-9215

Andrii Rudenko
Master, Assistant
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-5103-6412

Abstract. The study was aimed at determining the impact of electrical, thermal and mechanical loads on the durability of polymer and nanocomposite insulation of high-voltage circuit breakers used in pumping stations and grain drying complexes in Ukraine. The methodology combined numerical modelling of electrostatic and thermal fields in three-dimensional structures of insulation units, accelerated thermal cycling and mechanical tests, partial discharge analysis according to international standards, thermographic control, microstructural studies and statistical assessment of resource based on reliability curves. It was found that traditional epoxy

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*Corresponding author (and-stavinskiy@outlook.com)

insulation undergoes the most intense degradation: after cyclic loads, the specific resistance decreased by 47.5%, the breakdown voltage by 25.7%, and the average service life was about 380 hours. For nano-filled material with silicon dioxide, the decrease in specific resistance was limited to 17%, breakdown voltage – 9.8%, with an increase in average resource to 715 hours. The highest stability was demonstrated by insulation with hexagonal boron nitride and internal shielding, for which changes in electrophysical parameters did not exceed 7.3% for specific resistance and 7.1% for breakdown voltage, the partial discharge onset voltage reached 5.5 kV, and the average resource was about 912 hours. Numerical and experimental results showed a decrease in the peak electric field strength from 8.6 to 5.4 kV/mm and maximum temperatures from 96.2 to 78.8°C after 1,000 start-up cycles. The use of controlled starting modes made it possible to reduce starting currents from 5.6 I_n to approximately 2.1 In and to reduce the integral thermal load on the insulation by 61.5%. A technical and economic assessment showed a reduction in the total cost of ownership over six months from USD 280 to USD 50 per insulation unit, confirming the practical feasibility of introducing nanocomposites and controlled starting modes in agro-industrial electric drives. The practical significance of the results obtained lies in the formation of criteria for the selection of materials and operating modes of electric drives in order to increase the reliability of switching equipment in agro-industrial electromechanical systems and the use of modelling and diagnostic approaches to predict degradation and optimise the design of insulation units

Keywords: partial discharges; epoxy resin; electrothermal load; dielectric strength; recoverable voltage; frequency regulation; microstructural defects

INTRODUCTION

In modern agro-industrial electrical systems, the reliability of high-voltage circuit breakers is determined by electromechanical load conditions, in which insulation components are subjected to starting currents, thermal fluctuations and vibrations. Such conditions create an environment in which polymer dielectrics demonstrate a decrease in resource stability, which necessitates the study of the complex influence of electrical, thermal, and mechanical factors on polymer and nanocomposite insulation. Within the framework of early diagnosis approaches, one of the methods under study is infrared thermography. In the work of M. Silnyk & V. Fedynets (2025), a correlation was established between temperature irregularities and areas of potential electrical instability, which determines the possibility of using this method to assess the technical condition of insulation components. The results obtained indicate that thermal anomalies correlate with areas of electrical defect formation, therefore thermographic monitoring can be used as a tool for early control of the insulation condition of circuit breakers.

This diagnostic paradigm is being expanded in the field of electrophysical processes: a study by A.A. Shcherba *et al*. (2023) found that the presence of non-sinusoidal voltages increases the activity of partial discharges (PD) in polymer dielectrics. The results obtained indicate a relationship between the nature of the voltage and the intensity of defect zone formation during repeated switching. In the field of insulation resource behaviour research, the work of O. Zidane *et al*. (2025) showed that repeated impulse overvoltages cause the accumulation of microdefects in the interturn insulation of electrical machines. The study noted that it is the pulsed nature of the voltage, rather than the prolonged action of nominal modes, that forms the main degradation patterns of the material. Similar trends were recorded in A. Stavinskiy *et al*. (2022), which analysed the unevenness of thermal fields in transformer nodes. The results showed that the design parameters of magnetic conductors determine the spatial distribution of temperature and affect the condition of adjacent dielectric elements.

In the mechanical dimension, M.V. Matvienko *et al*. (2023) investigated the role of interphase layers of lower stiffness, which create the conditions for stress concentration and microcrack formation under vibration loading. The authors demonstrated that repeated mechanical loads lead to progressive destruction precisely in the interphase regions. Mechanical and thermal effects also included the results of O.M. Kostin *et al*. (2022), which describe the uneven effect of thermal fields associated with arc processes on the surface layers of dielectric materials in switching devices. In the context of switching devices, these results explained the nature of defects that form during frequent starts of electric drives.

The understanding of the constructive impact on the condition of insulation systems has been expanded in the study by A. Stavinskii & D. Koshkin (2021), which showed that changing the configuration of steel transformer packages alters the distribution of heat flows in its nodes. It was found that local temperature increases

affect the rate of ageing of adjacent polymer elements, which is characteristic of equipment with long thermal cycles. Further development of this direction is presented in O.B. Iegorov *et al*. (2025), which analysed the impact of optimising the windings of synchronous reactive generators on electromagnetic and thermal processes. The work establishes that a change in design can reduce field unevenness and increase the stability of insulating materials in long-term operation. The starting modes of asynchronous electric drives with centrifugal loads are described in V.H. Lysiak & M.Y. Olinyk (2021), which establishes the dependence of thermal processes on the hydrodynamic parameters of the flow. The results showed that changes in hydrodynamic conditions directly affect the intensity of electric drive heating, which is characteristic of pumping stations where the load is formed precisely by the dynamics of the liquid medium. At the level of microdynamics of structures, the study by I. Biliuk *et al*. (2023) analysed the influence of the accuracy of movement control on the vibration loads transmitted to the insulation nodes and determining their structural stability. The analysis found that even minor fluctuations can cause accelerated accumulation of microdefects in the material. For systematic load control, I.I. Yaremak & V.S. Kostyshyn (2020) proposed an approach in which the optimisation of the operating modes of electromechanical complexes reduces the amplitude of peak impacts and stabilises the operational condition of the insulation.

Despite a wide range of works, scientific discourse has considered only certain aspects of the action of electrical, thermal, or mechanical factors; at the same time, their integrated action in the conditions of agro-industrial electric drives has not been sufficiently studied. In particular, there is a lack of comprehensive studies that reconcile the effects of partial discharges, thermal cycling, starting pulses, and microvibrations in the context of nanocomposite materials. This necessitates experimental and numerical analysis aimed at determining the patterns of degradation and assessing the impact of design and material modifications. In this regard, the aim of the study was to establish the patterns of behaviour of polymer and nanocomposite insulation of high-voltage circuit breakers in dynamic modes of operation of electric drives to assess the impact of electrical, thermal and mechanical loads, as well as the role of frequency converters and structural characteristics of composites on the durability of insulation.

The aim of the study was to establish the patterns of degradation of polymer and nanocomposite insulation of high-voltage circuit breakers under the action of electrical, thermal and mechanical loads characteristic of the dynamic operating modes of agro-industrial electric drives. To achieve this aim, three objectives were set: to establish the patterns of degradation of the electrophysical parameters of insulation under the action of dynamic electrothermal and mechanical modes; to evaluate the influence of silicon dioxide (SiO_2) and hexagonal boron nitride (h-BN) on the stability of electrical strength, thermal profile and nature of microstructural defects; to determine the effectiveness of frequency converters in reducing starting and thermal loads and in increasing the service life of high-voltage insulation in agro-industrial electric drives.

MATERIALS AND METHODS

The study was conducted between March and October 2025 in laboratory and production conditions, which ensured accurate reproduction of the electromechanical loads characteristic of high-voltage vacuum circuit breaker operation. The study included three material systems: unfilled epoxy resin (EP), a composite with dispersed silicon dioxide (NP), and a composite with hexagonal boron nitride (NC). The dispersed particles of SiO_2 and h-BN had a diameter of 80-120 nm and a mass fraction of 8%. The samples were prepared by casting followed by thermal stabilisation at 130°C and vacuum drying for 72 hours in a Memmert GmbH drying oven (Memmert GmbH, Germany). Material constants, in particular relative dielectric permeability (εr), thermal conductivity (λ) and density (ρ) for EP (epoxy polymer), NP (nanofilled polymer) and NC (nanocomposite), were determined based on laboratory measurements and used as input parameters for finite element method (FEM) models. Electrostatic and thermal modelling of insulation nodes was performed using ANSYS Maxwell and ANSYS Icepak software environments (ANSYS Inc., USA) based on three-dimensional (3D) geometric models of VD4 series vacuum circuit breaker insulators (ABB/Hitachi Energy).

The study was conducted in five interrelated stages. At the first stage of the study, the basic electrical and thermal characteristics of materials were determined in accordance with ASTM standards, in particular dielectric strength (ASTM D149-20, 2020), electrical resistance and conductivity of insulation (ASTM D257-14, 2021), thermal diffusion (ASTM E1461-13, 2022) and sample preparation conditions (ASTM D618-21, 021), which ensured the formation of reliable initial parameters for further numerical modelling and comparative analysis. The electrophysical characteristics of the insulation were measured in accordance with IEC 60270:2025 (2025) on a high-voltage test rig from Haefely Test AG (Switzerland), recording partial discharges, their onset and extinction voltages, time-frequency spectra of pulses and their evolution after

various numbers of load cycles. Phase-resolved partial discharge (PRPD) analysis was performed in accordance with the recommendations of IEC 60270:2025 for the classification of discharge types and the determination of the phase reference of pulses. The breakdown strength was determined by the method of increasing sinusoidal voltage with a gradient of 2 kV/s.

At the next stage of the study, switching overvoltages and transient recovery voltage (TRV) parameters were evaluated. The relevant parameters were determined in accordance with the requirements of the IEC 62271-100:2021 (2021) series of standards by reproducing the pulse modes characteristic of vacuum circuit breakers in systems with frequent electric drive starts. Controlled pulses were generated on a Haefely Test AG device with front and duration fixed in accordance with the standardised TRV zones. The parameters obtained were used to model the field strength and thermal peaks in the insulation nodes. In the third stage of the study, the influence of dynamic operating modes was evaluated by loading insulation samples with 1,000 starting cycles, which made it possible to simulate the cumulative effect of impulse electrothermal loads characteristic of the operation of electric drives in pumping, ventilation and grain drying systems. The starting processes were reproduced on an ABB M3AA electric motor (ABB Group, Italy) with a power of 7.5 kW in direct-on-line starting mode and in a configuration with a Danfoss VLT FC302 frequency converter (Danfoss A/S, Denmark).

The fourth stage of the study involved thermographic analysis and verification of thermal models of insulation nodes by assessing the impact of the frequency converter on electrical and thermal loads. To do this, direct-on-line (DOL) and frequency-controlled drive start-up modes were compared, recording start-up currents, PD parameters in accordance with IEC 60270:2025, and the spatial-temporal temperature distribution according to data from a FLIR T660 thermal imager. The starting currents were recorded with Chauvin Arnoux current clamps (Chauvin Arnoux, France) with a time resolution of 1 ms, and the temperature fields were monitored with a FLIR T660 thermal imager (FLIR Systems Inc., USA) with a temperature sensitivity of 0.03°C. Based on the obtained thermograms, spatial maps of thermal fields in static and dynamic modes were formed after a specified number of starting cycles, which made it possible to identify areas of local overheating, evaluate their geometry, and track the evolution of thermally stressed areas during the loading process. To quantitatively assess the impact of different start-up scenarios, the maximum temperature deviations (ΔT) obtained from thermographic measurements and thermal modelling in ANSYS Icepak were compared for DOL and frequency converter start-up modes. This ensured the verification of thermal models and allowed the assessment of the effectiveness of frequency control in terms of reducing thermal loads on insulation components.

In the fifth stage of the study, accelerated ageing, microstructural and reliability analysis methods were applied to comprehensively assess the degradation processes and service life of insulation materials. Accelerated operational ageing was implemented by thermal cycling in the range of 25-95°C with alternating heating and cooling phases, while the samples were additionally subjected to mechanical microvibration on a TIRA TV 51144 vibration stand (TIRA GmbH, Germany) with an amplitude of 0.4-0.7 mm in the frequency range of 10-80 Hz. Microstructural changes were recorded using a JEOL JSM-IT200 scanning electron microscope (JEOL Ltd., Japan), which enabled analysis of cracks, interphase defects and adhesion failures. Tracking resistance was determined in accordance with IEC 60587:2007 (2007) on an ELLAB TRK6 (ELLAB Group, Italy) installation, and dielectric spectroscopy was performed on a Novocontrol Alpha-A (Novocontrol Technologies, 2020, Germany) analyser. The service life of insulation materials was evaluated using Weibull curves in the ReliaSoft Weibull++ v9 software environment (ReliaSoft Corporation, USA). Statistical processing of experimental data was performed in OriginPro 2024 (OriginLab Corporation, USA) using Student's t-test, Mann-Whitney U-test and 95% confidence intervals at a significance level of $p < 0.05$. Economic calculations were performed using the total cost of ownership (TCO) model, which took into account the cost of materials, replacement frequency, emergency downtime, and the impact of frequency control on extending equipment life. The assessment was performed for a fixed six-month operating interval, which corresponded to approximately 180-220 start-up cycles in typical operating modes of pumping stations and grain drying complexes and included maintenance costs, replacement of degraded insulation components, and losses associated with equipment downtime. A further assessment of the five-year operating cycle was carried out by extrapolating the 6-month TCO values obtained.

RESULTS

The influence of dynamic electrical modes on changes in the electrophysical parameters of insulation

A comparative analysis of experimental results revealed differences in the values of specific resistance and breakdown voltage between the studied material systems after exposure to pulsed electrical modes. The data obtained reflected the unequal

response of EP, NP and NC materials to identical electrical influences, which made it expedient to compare them in a post-loading state. The differences identified were systematic in nature and could be traced in several electrophysical indicators. The set of measured parameters formed individual electrophysical profiles for each material, suitable for quantitative intermaterial comparison. The generalised results of measurements of specific resistance and breakdown voltage before and after electrical loading are given in Table 1. The data presented was used as an initial empirical array for further analysis of changes in the electrophysical characteristics of materials in the post-loading state.

Table 1. *Breakdown voltage and specific resistance indicators before and after exposure to impulse modes (EP, NP, NC)*

Material type	Specific resistance before (Ohm·m)	Specific resistance after (Ohm·m)	Breakdown voltage before (kV)	Breakdown voltage after (kV)
EP	1.2×10^{13}	6.3×10^{12}	18.7	13.9
NP (SiO_2)	3.5×10^{13}	2.9×10^{13}	22.5	20.3
NC (BN)	4.1×10^{13}	3.8×10^{13}	24.1	22.4

Source: *compiled by the authors based on ASTM D149-20 (2020), ASTM D257-14 (2021), IEC 60270:2025 (2025)*

According to Table 1, all materials studied showed a decrease in electrophysical characteristics after loading compared to the initial values. At the same time, the scale of these changes differed significantly between materials, which made it possible to identify clear differences in the nature of the transformation of their electrophysical properties. EP epoxy resin experienced the greatest decrease in electrophysical characteristics after impulse loading: its specific resistance decreased by 47.5% and its breakdown voltage by 25.7%. These changes were accompanied by an increase in the intensity of partial discharges, recorded in accordance with the registration criteria of the IEC 60270:2025 (2025) standard, which reflected the formation of local microchannels of increased electrical conductivity and a gradual weakening of the dielectric barrier in the polymer matrix. For the NP (nanocomposite with silicon dioxide), the amplitude of changes was more moderate: the specific resistance decreased by 17%, and the breakdown voltage by 9.8%. The highest stability was demonstrated by the NC (nanocomposite with hexagonal boron nitride), where the decrease in these parameters was 7.3% and 7.1%, respectively. The difference in the magnitude of deviations between EP, NP and NC reflected the material-dependent nature of degradation processes – from the maximum sensitivity of unfilled resin to the increased stability of nanocomposites due to the influence of the filler on the interphase structure and charge localisation mechanisms. Despite the recorded changes, for all materials studied, the breakdown voltage after loading remained within the ranges defined by baseline measurements in accordance with ASTM D149-20 (2020), and the specific volume resistance values did not exceed the functionally acceptable limits regulated by ASTM D257-14 (2021). Control tests after 1,000 cycles showed no signs of progressive or avalanche-like degradation: the values of electrical strength and specific resistance stabilised and did not show further decline. This indicated that even with increased PD activity, the post-load transformation of the electrophysical properties was local and non-cumulative.

A comparative analysis showed that EP was characterised by the greatest amplitude of changes, while NP and NC nanocomposites were noted for their increased resistance to impulse modes due to the stabilising effect of interphase regions and the barrier role of the nanofiller. The increase in PD activity was common to all the materials studied, but its scale depended on the composition of the composite: the introduction of SiO_2 or BN fillers led to a decrease in the density of local defect regions, which manifested itself in less pronounced changes in the parameters of partial discharges. The results obtained quantitatively reflected material-dependent differences in the change in specific resistance, breakdown voltage, and partial discharge intensity for EP, NP, and NC in the post-loading state. For nano-filled systems, the deviation values were lower compared to epoxy resin, which was confirmed by the recorded parameters. The presented data outlined the quantitative relationships between the studied material systems and reflected the peculiarities of their behaviour under post-loading conditions.

Results of modelling electrostatic and electrothermal fields in switch nodes

Numerical 3D-FEM modelling of electrostatic and electrothermal fields in the insulation nodes of a high-voltage switch allowed to identify characteristic spatial features of the distribution of electric field strength and temperature. Local maxima of both quantities were formed mainly in areas with variable curvature geometry and contrasting dielectric properties of materials. In the basic EP configuration, increased electric field values were observed at the inner radii of the ribs, at the polymer-metal

transitions, and in areas of local changes in the geometric profile. Parametric variations in geometry, in particular changes in the radius of curvature, channel depth, and the presence of internal cavities, led to a redistribution of the vector field and a shift in the areas of local maxima.

To clearly demonstrate the spatial differences in the distribution of electric field strength and temperature among the three configurations studied, comparative maps of the electric and thermal fields were provided (Fig. 1).

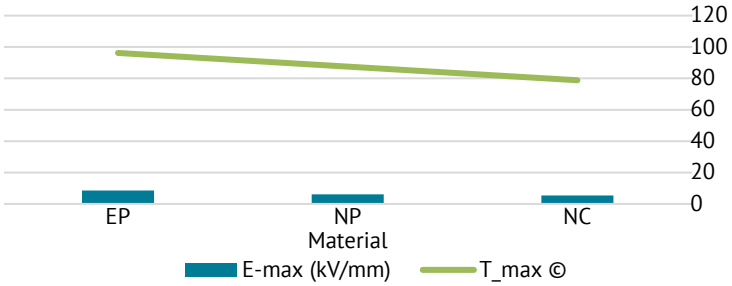

Figure 1. *Maximum values of electric field strength and temperature for EP, NP and NC materials*
Source: *compiled by the authors based on ASTM D149-20 (2020), ASTM D257-14 (2021), IEC 60270:2025 (2025)*

As shown in Figure 1, the maximum electrical and thermal parameters varied sequentially depending on the material configuration of the node. For the base material EP, the highest peak values of electric field strength and temperature were recorded, reaching approximately 8.6 kV/mm and 96.2°C, respectively. The lowest values of both parameters were observed for the NC configuration, where the maximum electric field strength did not exceed 5.4 kV/mm, and the temperature was about 78.8°C, indicating a more uniform electro-thermal distribution in this system under the simulation conditions. Such a coordinated change in electrical and thermal indicators indicated the existence of a relationship between the concentration of the electric field and local heat generation in the switch nodes. Quantitatively, this manifested itself in a gradual decrease in the maximum values of the electric field strength and the corresponding peak temperatures in the direction from EP to NC. The generalised quantitative values of the peak electrothermal parameters for all configurations are given in Table 2.

Table 2. *Maximum E-field and temperature values at key points of the nodes (three types of geometry)*

Configuration	E-field, max (kV/mm)	Temperature, max (°C)
EP (basic)	8.6	96.2
NP (SiO_2)	6.1	87.5
NC (BN)	5.4	78.8

Source: *compiled by the authors based on IEC 62271-100:2021 (2021), IEC 60270:2025 (2025)*

Analysis of Table 2 showed a consistent relationship between node configuration and electrical and thermal load levels. The values of 5.4 kV/mm stress and 78.8°C temperature obtained for the NC configuration indicated the influence of internal screens and the BN layer on the redistribution of the electric field and the formation of heat-conducting zones. The transition from EP to NP and NC was accompanied by a decrease in maximum electrical and temperature indicators, which was consistent with changes in geometry and material composition. The NP configuration demonstrated the effect of the SiO_2 nanofiller on field distribution equalisation and heat dissipation improvement compared to EP, while NC was characterised by lower integral parameters due to a combination of material and design factors. A comparison of these options demonstrated the existing relationship between the internal structure, the properties of the materials used, and the behaviour of the node under combined electrical and thermal loads. The obtained dependence indicates the need to consider several material and design parameters when designing high-voltage insulation components operating in variable electromechanical modes.

Thermographic analysis of damage and overheating areas

The thermographic results obtained after 1,000 start-up cycles under electrothermal load conditions reflected the spatial distribution of temperature along the surface of the insulation assembly in the post-load state and characterised its integral thermal behaviour. Temperature fields were recorded along the entire

length of the unit surface, which made it possible to record temperature variations within a single coordinate axis. The thermographic images obtained made it possible to assess the integral thermal state of the insulation structure after cyclic loading and to identify characteristic areas with elevated temperatures. To summarise the results and provide a comparative analysis, the temperature distribution was presented as a linear temperature profile, which allowed for a comparison of the thermal behaviour of different material configurations within a single coordinate system. A graphical representation of the temperature distribution along the surface of the insulation unit after 1,000 start-up cycles is shown in Figure 2.

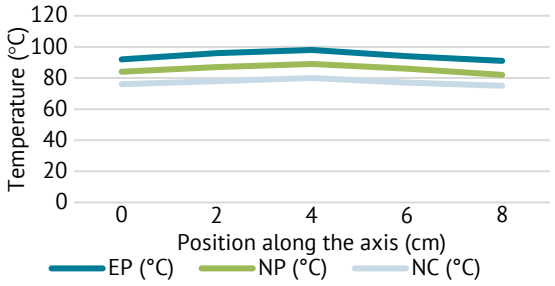

Figure 2. *Temperature distribution graph along the surface of the insulation unit after 1,000 cycles*
Source: *compiled by the authors*

According to the data shown in Figure 2, after completing 1,000 start-up cycles for all studied material configurations, a clearly pronounced temperature maximum was recorded in the central part of the insulation node, located at a distance of approximately 4 cm from the initial coordinate. In the edge zones of the surface, the temperature values systematically decreased, resulting in the formation of a stable dome-shaped temperature distribution profile along the axis, characteristic of the post-load quasi-stationary thermal state of the insulation structure. The overall configuration of the temperature profiles was similar for EP, NP and NC materials, indicating the reproducibility of the spatial structure of the thermal field at a constant node geometry regardless of the material composition of the insulation. At the same time, the absolute temperature levels showed clear intermaterial differences. For EP epoxy resin, the maximum recorded temperature reached about 98°C, for NP nanocomposite – about 89°C, while for the NC configuration it did not exceed 80°C. Throughout the entire range of coordinates studied, the temperature values for EP remained higher than those for nano-filled systems, which was clearly visible in the linear temperature profiles. The minimum temperature values along the surface of the insulation node were also material-dependent and amounted to about 90-91°C for EP, 82-83°C for NP, and 74-75°C for NC.

Accordingly, the temperature difference along the node axis was approximately 7°C for EP, about 6°C for NP, and about 5°C for NC, which quantitatively reflected different levels of thermal unevenness under the same geometric conditions and load regime. Analysis of the shape of the temperature profiles revealed the presence of local temperature increases along the surface of the insulation node, the spatial position of which was similar for all material configurations. At the same time, the amplitude of these local maxima significantly depended on the material: the largest deviations were observed for EP, smaller ones for NP, while for NC they were minimal. This led to different degrees of temperature heterogeneity of the insulation surface after cyclic electrothermal loading. A comparative analysis of temperature profiles showed that with a decrease in maximum temperatures in nano-filled systems, the temperature gradient along the surface of the insulation node also decreased. EP was characterised by the largest temperature difference, NP by a moderate one, while NC by a minimal one.

The results obtained made it possible to quantitatively characterise the level of temperature heterogeneity for each material configuration in the post-loading state and to use these parameters for further comparison with the electrophysical indicators of insulation. The spatial consistency of the experimentally recorded temperature maxima with the results of electrothermal modelling confirmed the reproducibility of the formed temperature profiles and their stability after multi-cycle loading. In general, the thermographic results quantitatively reflected the material-dependent differences in the thermal regime of insulation nodes for EP, NP and NC after 1,000 start-up cycles. For EP epoxy resin, the highest peak temperatures and the greatest unevenness of the temperature field were recorded, while for nano-filled systems NP and NC, a consistent decrease in maximum temperatures and smoothing of temperature gradients along the surface of the insulation node was observed, indicating a more stable thermal behaviour of these materials in the post-loading state.

The effect of frequency converters on insulation loads

A comparative analysis of DOL starting and starting using a Danfoss VLT FC302 frequency converter revealed fundamental differences in the nature of the electromechanical and electrothermal load on the insulation nodes of high-voltage circuit breakers. The use of a frequency converter led to the transformation of the starting process from a short-term pulse mode to a controlled quasi-stationary mode with a gradual increase

in voltage and current, which significantly affected the distribution of the electric field and current loads in polymer and nanocomposite insulation. This change in the starting mode resulted not only in a decrease in the peak amplitudes of the electrical parameters, but also in a modification of the time structure of the transition process, determining a different nature of the action of electrical and electromechanical loads on the insulating elements in the initial phase of operation and reducing the intensity of extreme influences critical for the degradation mechanisms of the material. Under direct-on-line start-up conditions, peak instantaneous currents in the range of 5.3-5.8 I_n were recorded, accompanied by increased levels of electrostatic stresses in the interphase regions of insulating materials and local inhomogeneities of the electric field. Such conditions corresponded to an increase in the electrothermal load on the insulation nodes, which manifested itself in an increase in temperature, the formation of temperature gradients, and an increase in the intensity of partial discharges in the first start-up cycles. Starting via a frequency converter was characterised by a smoothed load profile due to a gradual increase in voltage and current: the starting current amplitude decreased to 1.9-2.3 I_n, while there was a decrease in switching overvoltages and temperature peaks in the initial stage of equipment operation. A quantitative assessment showed that the average starting current in DOL mode was about 5.6 I_n, while when using a frequency converter, its value was in the range of 1.9-2.3 I_n throughout the entire transition process.

The reduction in current loading was accompanied by a decrease in transient recovery voltage (TRV) amplitude and the voltage rise rate (dV/dt), which are key characteristics of electrical stress acting on insulation assemblies during start-up. The combination of the recorded changes reflects the differences in electromechanical start-up conditions for the two scenarios and their impact on insulation element loading. The comparative parameters of the starting modes for direct-on-line starting and starting using a variable frequency drive (VFD) are summarised in Table 3.

Table 3. *Parameters of high-voltage electric drive starting modes for DOL and VFD starts*

Parameter	DOL	VFD (Danfoss VLT FC302)
Average starting current, I_p/I_n	5.6	2.1
Amplitude of switching transient recovery voltage (TRV), kV	2.8-3.4	1.1-1.4
Voltage rise rate dV/dt, kV/μs	0.95-1.20	0.18-0.25
Output voltage waveform	Pure sinusoidal waveform, voltage step at energisation	Pulse-width modulation (PWM) modulation with high-frequency pulses, smooth voltage ramp-up
Start-up duration, s	0.35-0.45	1.8-2.4
Duration of current above 3 I_n, ms	160-190	18-25
Peak insulation temperature during the first 10 cycles, °C	92-98	71-78

Source: *compiled by the authors based on IEC 62271-100:2021 (2021)*

Analysis of the data presented in Table 3 showed that the use of a frequency converter significantly changed the electromechanical start-up profile of the high-voltage electric drive. The highest starting current values were observed in direct starting mode and reached about 5.6 I_n, while when using a frequency converter, they decreased to a level not exceeding 2.1 I_n. This reflected a significant reduction in the impulse current load in the regulated start mode. A similar trend was observed for switching overvoltages. In DOL mode, the maximum TRV values reached approximately 3.4 kV, while during start-up via a frequency converter, they decreased to a level of about 1.1 kV. At the same time, the voltage rise rate in direct start mode reached values of about 1.2 kV/μs, while in regulated mode it decreased to about 0.2 kV/μs. This indicated a significant mitigation of electrical transient processes when using frequency control. Analysis of the time characteristics of the start showed that direct start was implemented as a short-term but sharply pulsed mode, while start using a frequency converter was characterised by a longer duration and reduced peak values of electrical parameters. Particularly indicative was the reduction in the time the current remained at levels exceeding 3 I_n: from approximately 190 ms in DOL mode to about 20 ms in regulated start mode. These changes were accompanied by a decrease in peak insulation temperatures recorded in the initial phase of equipment operation. The results of thermographic measurements were consistent with the differences in electrical modes and confirmed the formation of different types of electrical and thermal loads on insulation nodes during direct and controlled starts. According to the data obtained, the peak insulation temperatures in the first start-up cycles when using a frequency converter were 18-22°C lower compared to the direct start mode. For an

integrated assessment of the accumulated thermal load, a comparison of temperature increments Δ*T* for both start-up scenarios was made, the results of which are presented in Figure 3.

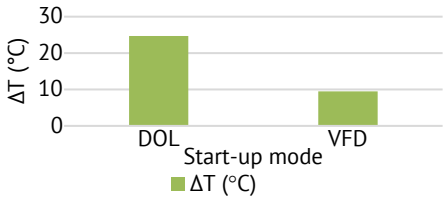

Figure 3. *Comparison of thermal load on insulation (ΔT) for two start-up modes*
Source: *compiled by the authors*

The data shown in Figure 3 demonstrated significant differences in the accumulated thermal load of insulation nodes for two electric drive start-up scenarios, caused by the different nature of transient electrical modes. In DOL mode, the maximum average thermal overload exceeded the baseline by 24.7°C, reflecting the intense pulsed nature of the electrothermal impact on insulation materials in the initial operating cycles and the formation of localised overheating zones. In contrast, when using a frequency converter, the temperature increase decreased to 9.5°C, which indicated a limitation of peak thermal loads due to the controlled increase in current and voltage and a more uniform distribution of heat flows in the insulation elements. Thus, the regulated start-up resulted in a 61.5% reduction in the temperature increase Δ*T*, which reflected a decrease in the electrothermal load on the polymer and nanocomposite insulation in the starting modes. The decrease in the amplitude Δ*T* when operating with a frequency converter was consistent with the parameters of electrical processes recorded during starting tests. Lower values of starting currents, switching overvoltage amplitudes and voltage rise rates dV/dt led to a reduction in electrical losses and local heat generation in the interphase areas of insulation materials. As a result, a thermal regime with less pronounced temperature peaks compared to the direct start-up mode was formed in the insulation nodes. The results obtained showed that the use of a frequency converter changed the thermal response of the insulation nodes from impulsive to stabilised with lower values of integral temperature overload. The recorded quantitative differences reflected the influence of the starting mode on the electrothermal state of the insulation and the role of the controlled electromechanical load in the formation of the thermal operating conditions of high-voltage circuit breakers.

Mechanical degradation of insulation and microstructural analysis of materials

During accelerated tests simulating the actual operating conditions of high-voltage circuit breakers in pumping stations and grain drying installations, typical manifestations of surface degradation of polymer and nanocomposite insulation were recorded, caused by the combined action of operational factors. The formation of degradation damage occurred under the influence of thermal fluctuations, PD activity, mechanical vibrations, as well as impulse starting modes characteristic of the operation of electric drives of agro-industrial equipment under variable loads. These factors created an uneven electrothermal and mechanical impact on the insulation materials, which contributed to the initiation and development of surface defects. Microstructural analysis of the sample surfaces, performed using scanning electron microscopy (SEM, JEOL JSM-IT200), revealed fundamental differences in the mechanisms and morphology of damage for the three material systems studied: EP (unfilled epoxy matrix), NP (nano-filled polymer) with SiO_2 particles, and composite structure with a NC (boron nitride shielding layer). EP was characterised by the presence of developed track formations with carbonised edges, accompanied by a branched network of microcracks, indicating intensive surface degradation. The NP material, in turn, showed a significantly lower density of damage, which manifested itself in the form of limited local micropores and isolated linear defects without the formation of continuous track channels. In the NC configuration, only isolated submicron damage was recorded, localised mainly in the near-surface zone at the boundary between the BN layer and the polymer matrix, with no signs of through-track or defect coalescence into extended degradation structures. The quantitative distribution of the frequency of defects is shown in Figure 4.

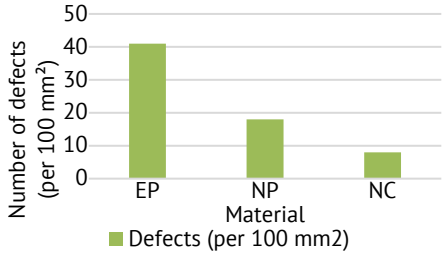

Figure 4. *Frequency of detection of microstructural defects after thermal and vibration tests*
Source: *compiled by the authors*

The data shown in Figure 4 showed that the epoxy system (EP) was characterised by the highest frequency of surface microdefects, exceeding

40 pores and cracks per 100 mm^2, which indicated the intensive development of degradation processes under combined electrothermal and mechanical loading. The recorded damage density for EP was approximately 2.3 times higher than the corresponding values for the SiO_2 nanocomposite (NP) and more than five times higher than for the NC (BN-shielded configuration). This quantitative distribution was consistent with differences in degradation mechanisms, confirmed by SEM observations. EP was characterised by the formation of deep track channels with carbonised edges and developed secondary microcracks, which contributed to further concentration of the electric field and acceleration of surface destruction. The NP material showed limited areas of defects, which were mainly represented by isolated micropores and linear surface cracks without the formation of continuous track structures. The smallest number of localised damages in the NC system was due to the action of the BN shielding layer, which contributed to the equalisation of local electrical and thermal stresses, reduction of electric field gradients at the interphase boundary, and suppression of the initiation and development of through tracking. For an additional assessment of the resistance of materials to surface degradation, tracking resistance tests were carried out, the results of which are presented in Table 4.

Table 4. *Tracking resistance of insulating materials under standard loading conditions*

Configuration	Time to breakdown, min	Nature of damage	Comparative Tracking Index (CTI) class
EP (basic)	9.3	Deep carbonised tracks	IIb (100-175 V)
NP (SiO_2)	21.8	Localised surface tracking marks	IIa (175-250 V)
NC (BN+ shielding layer)	>30 (no breakdown)	Absence of continuous tracking	I (≥250 V)

Source: *compiled by the authors based on IEC 60587:2007 (2007)*

A comparison of the values in Table 4 demonstrated fundamental differences between the three material systems. The EP material was characterised by the shortest time to breakdown (≈9.3 min), accompanied by the formation of deep carbonised tracks. The NP material showed an increase in the time to breakdown and the appearance of only surface traces, indicating increased tracking resistance due to the modification of the interphase region with SiO_2 particles. The NC configuration demonstrated the highest tracking resistance: no conductive channel formation was observed during the test, and the material was classified as CTI Class I – the level required for high-voltage systems with increased surface reliability requirements. The results obtained indicated the presence of significant material-dependent differences in the nature of microstructural degradation and tracking resistance of the studied insulation systems under combined operational loads. The EP was characterised by the highest frequency of surface microdefects, intensive development of secondary microcracking and the formation of deep carbonised tracks under the action of thermal, electrical and mechanical factors. The SiO_2 nanocomposite showed a reduction in the number and length of defects, as well as an increase in the time to breakdown compared to EP, indicating the effect of stabilisation of the interphase region and slowing down of degradation processes. The configuration with a BN shielding layer was characterised by the lowest density of localised damage and the absence of through-tracking within the standard tests according to IEC 60587:2007 (2007), confirming the high surface stability of this system. The recorded quantitative differences reflected the specifics of degradation mechanisms for the three material systems and determined their behaviour under typical operating loads of agro-industrial electrical complexes.

Resource assessment and parameter dispersion (Weibull analysis)

The Weibull analysis method was used to quantitatively assess the durability of insulating materials and the statistical dispersion of failure parameters during cyclic testing. This approach made it possible to describe the probabilistic nature of failures and establish the relationship between the accumulated cyclic load and the frequency of breakdowns. The initial data for the analysis were the experimentally recorded values of the number of cycles to failure for each sample of EP, NP and NC insulating materials. Based on these data, statistical processing was performed to construct generalised probability curves for each material system. The resulting curves reflected the change in the probability of failure depending on the level of accumulated cyclic load. The constructed Weibull curves allowed for a comparative assessment of the resource and the nature of the distribution of failures between the materials under study. The generalised results of the analysis in the form of model Weibull curves are shown in Figure 5.

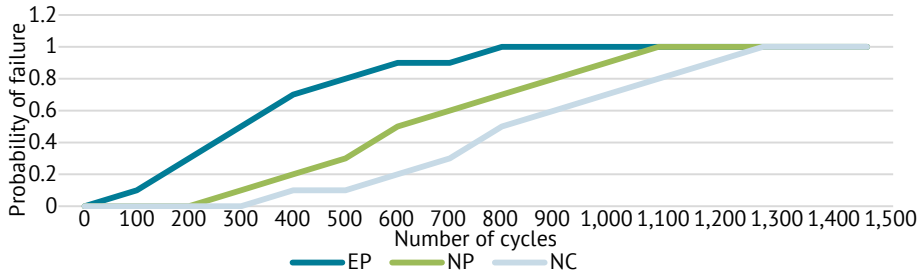

Figure 5. *Weibull curves for insulation materials based on cyclic test results*
Source: *compiled by the authors*

As shown in Figure 5, the EP epoxy material demonstrated the highest probability of failure across the entire range of cyclic loading studied, which was reflected in the sharply rising shape of the Weibull curve compared to the NP and NC nanomodified systems. Already in the early cycle range, approximately 300-400, the failure probability for EP reached values of about 0.5, indicating a significant proportion of early failures and a limited initial life of the material. In the range of average operating hours, approximately 800-900 cycles, the EP curve practically approached the level of 0.95-1.0, which corresponded to almost complete failure in the studied sample. The nano-filled polymer NP was characterised by a flatter Weibull curve trajectory and its systematic shift towards higher resource values. In the early cycle zone, the failure probability for NP did not exceed approximately 0.15, while in the range of 800-900 cycles it was about 0.8, which indicated a more uniform distribution of operating time to failure and a reduced proportion of premature failures compared to epoxy resin EP. The lowest failure probability values were recorded for the NC nanocomposite throughout the entire cyclic loading range studied. In the range of 300-400 cycles, it did not exceed about 0.05, and in the range of 800-900 cycles, it reached only 0.55-0.6, which reflected a significant shift in the resource of this material towards higher values of cyclic fatigue. A clear gap between the EP, NP and NC curves indicated a systemic difference in the nature of damage accumulation and failure realisation for different material configurations. A generalised analysis of representative sections of the Weibull curves confirmed that the epoxy material EP was characterised by the highest proportion of early failures, the nano-filled polymer NP occupied an intermediate position in terms of reliability, while the nanocomposite NC demonstrated the lowest probability of failure at the same levels of cyclic loading. The quantitative results of the evaluation of the Weibull parameters β and η for the three types of materials are given in Table 5, which made it possible to formalise the identified differences in terms of statistical reliability.

Table 5. *Shape (β) and scale (η) parameters of dispersion for three types of insulation*

Material type	β (shape coefficient)	η (average service life, hours)
EP (epoxy)	1.52	380
NP (SiO_2)	2.63	715
NC (BN)	3.41	912

Note: *the value of the scale parameter η was obtained by converting the number of cycles to failure into time resources under steady-state operation with a fixed start frequency; data for a temperature of 95°C was obtained within a separate thermally loaded series*
Source: *compiled by the authors*

The data in Table 5 showed significant differences in the resource characteristics of the three insulation configurations studied under cyclic thermoelectric loading conditions. For the EP epoxy system, the average resource was about 380 hours, which corresponded to the lowest durability among the materials studied. For the NP nano-filled polymer, an increase in the average resource to 715 hours was recorded, while for the NC nanocomposite, the resource reached 912 hours. Compared to EP, the resource of NP increased by approximately 1.9 times, and the resource of NC by 2.4 times, which indicated a fundamentally different nature of degradation processes in these material systems. Analysis of the Weibull distribution parameters showed that the EP epoxy configuration was characterised by the lowest values of the β shape parameter, which corresponded to a significant statistical dispersion of the resource and the presence of an early

failure zone. This behaviour indicated the dominance of local defects and uneven degradation development in the polymer matrix. For the NP configuration, the β value increased, reflecting a decrease in the variability of the time to failure and a more stable nature of degradation processes. The highest β values were recorded for the NC nanocomposite, which corresponded to the most compact distribution of the resource and the absence of a pronounced early failure zone. The results of tests at an elevated ambient temperature (95°C) showed a decrease in the scale parameter η for all configurations studied, but the intensity of this decrease varied significantly. For EP, the value of η decreased to 290 hours, indicating the high sensitivity of the material to thermoelectric loads. For NC, the η parameter remained at a level not lower than 840 hours, confirming the significantly higher thermal stability and resource stability of nanocomposite insulation. The NP configuration occupied an intermediate position between EP and NC, demonstrating moderate resource degradation at elevated temperatures. A comparative analysis showed that the NC configuration combined the highest values of the β and η parameters among all the materials studied, which corresponded to the maximum resource and minimum variability of the time to failure. The NP configuration was characterised by intermediate resource indicators, while EP demonstrated the lowest resource and the greatest statistical dispersion. The results obtained allowed to conclude that the durability and stability of insulation materials were determined by microstructural homogeneity and the effectiveness of interphase interaction. The NC configuration demonstrated the highest β and η values, indicating low resource variability and high safety margin, making it most suitable for use in high-voltage switches for agricultural and industrial applications.

Resistance of insulating materials to partial discharges under load

The PD data obtained showed differences in the behaviour of the three insulation systems under the influence of cyclic electromechanical loading. For EP epoxy insulation, after 500 cycles, a sequential increase in the amplitude and frequency of pulses was recorded, indicating the formation of local microdefects and areas of increased electrical stress. At the 1,000-cycle stage, the amplitudes of partial discharges in EP reached the maximum values among the materials studied, and the recorded pulses were characterised by an ordered phase structure and an extended amplitude range, reflecting the development of intense electrophysical processes in the material. In the NP nanocomposite with SiO_2 inclusions, the increase in discharge activity was recorded at significantly later stages of loading and had a lower intensity. The pulses showed lower peak values, occurred irregularly, and were recorded mainly at the end of the cycles. This dynamic indicated a more uniform distribution of the electric field and a slower development of localised defects in the material without the formation of stable discharge activity channels. The NC composite with a BN layer and internal shielding showed the lowest level of partial discharges throughout the test period. The pulses were at the background noise level or below the detection threshold, and after 1,000 cycles, no pulse grouping or amplitude jumps were recorded. This behaviour corresponded to the increased structural stability of the material, in which the BN layer and shielding elements ensured the equalisation of the electric field and reduced sensitivity to accumulated defects. The differences found between the materials reflected different mechanisms of their microstructural stability and ability to counteract localised electrical processes under cyclic loading. Typical PD oscillograms of the three materials after 1,000 cycles are shown in Figure 6.

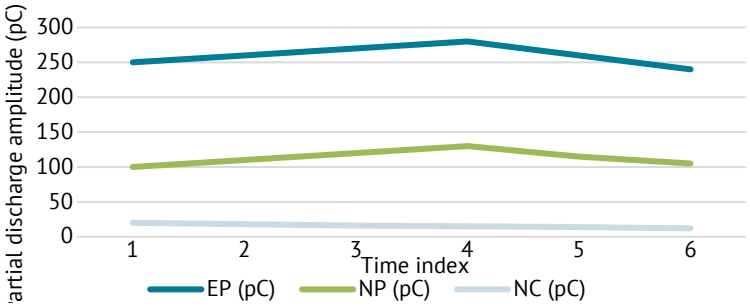

Figure 6. *Pulse activity of partial discharges in various insulating materials (after 1,000 cycles)*
Source: *compiled by the authors based on IEC 60270:2025 (2025)*

According to the results of Figure 6, for EP, the maximum pulse amplitude reached 280 pC at a frequency of about 35 pulses/s. This intensity corresponded to the presence of structural inhomogeneities, micropores,

and interphase disturbances. In NP, the amplitude did not exceed 145 pC, and the pulses were single in nature. For NC, the amplitudes of partial discharges were in most cases below the registration threshold, which confirmed the high homogeneity of the dielectric structure and the effective operation of internal shielding elements. A comparison of the experimental data with the results of modelling in ANSYS Maxwell confirmed that in EP, the maximum electric fields were concentrated at the joints of the edges and local cavities. It was these geometric features that contributed to the initiation of partial discharges. In NC, internal shielding equalised the stress at critical points, reducing the probability of breakdown and the formation of discharge channels. This explained the lower amplitude of partial discharges and the absence of significant defects even after 1,000 cycles. To quantitatively assess PD resistance, the initiation voltage (PDIV) and extinction voltage (PDEV) were determined. The results are shown in Table 6.

Table 6. *Electrical parameters of partial discharges after 1,000 cycles*

Configuration	PDIV, kV	PDEV, kV	voltage hysteresis (Δ*U*), kV
EP (basic)	3.6	2.4	1.2
NP (SiO_2)	4.7	3.8	0.9
NC (BN+ shielding layer)	5.5	5.0	0.5

Source: *compiled by the authors based on IEC 60270:2025 (2025)*

As shown in Table 6, the NC configuration demonstrated the highest resistance to partial discharges, with a PDIV of 5.5 kV, which was 53% higher than that of EP. The hysteresis value Δ*U* for NC was 0.5 kV, the lowest among all the investigated materials, reflecting only a minor change in breakdown voltage under cyclic loading. The NP configuration incorporating SiO_2 exhibited intermediate PDIV and Δ*U* values, indicating partial electric field equalisation and enhanced thermal stability of the matrix compared with EP. Analysis of the PRPD distributions showed that surface partial discharges with pronounced phase correlation predominated in EP and NP, whereas in NC most pulses remained at background level or below the detection threshold, without signs of clustering or amplitude surges. The phase-resolved pulse distribution in NC was characterised by low PD intensity across all investigated cycles, while EP and NP exhibited peak activity within specific phase intervals. The combination of high PDIV values, low hysteresis Δ*U*, and minimal pulse activity demonstrated that the NC composite with a BN layer and internal shielding maintained stable electrophysical parameters after 1,000 loading cycles. These characteristics support the applicability of NC in high-voltage circuit breakers operating under variable and high-stress conditions in pumping stations and grain-drying complexes, ensuring more uniform electric field distribution and reducing the likelihood of local defects and the development of breakdown channels.

The economic feasibility of introducing new materials and frequency converters

To provide a generalised and systematic presentation of the obtained experimental results, a comparative assessment was performed on the technical and economic indicators of high-voltage insulation units operated within the electric drives of pumping stations and grain drying complexes under cyclic loading conditions. The analysis incorporated PD parameters, specifically the PDIV, Δ*U*, average amplitude-frequency characteristics of partial discharges, and the proportion of samples exhibiting microstructural damage. In addition to electrophysical indicators, economic parameters were included in the comparison, represented as the TCO over a fixed operating period. These indicators characterised insulation units with different material configurations under identical operating conditions, allowing for a comparison of their technical state and economic costs during the initial stage of operation. The summarised values of the relevant parameters following a six-month cyclic load are presented in Table 7.

Table 7. *Technical and economic performance of high-voltage insulation units under a 6-month cyclic loading period*

Material configuration	PDIV, kV	Δ*U*, kV	Proportion of samples with damage, %	Average PD amplitude, mV	Average PD repetition rate, pulses/min	TCO over 6 months, USD
EP (without VFD)	3.6	1.5	28	220	45	280
NP (without VFD)	4.8	1.0	12	160	30	140
NC (without VFD)	5.5	0.5	3	80	12	50
EP + VFD	3.6	1.5	28	220	45	150

Table 7, Continued

Material configuration	PDIV, kV	Δ*U*, kV	Proportion of samples with damage, %	Average PD amplitude, mV	Average PD repetition rate, pulses/min	TCO over 6 months, USD
NP + VFD	4.8	1.0	12	160	30	70
NC + VFD	5.5	0.5	3	80	12	50

Note: *economic indicators are given in USD per high-voltage insulation unit*
Source: *compiled by the authors*

Analysis of the data in Table 7 showed that the insulation materials studied differed significantly in terms of their combined electrophysical characteristics and total operating costs during the first six months of cyclic operation. Within the interpretation of the results obtained, the five-year operating period corresponded to a total load equivalent to approximately 18,000-22,000 electric motor starts in variable operating modes, taking into account scheduled technical inspections, routine downtime and unscheduled shutdowns associated with insulation degradation and component failures. EP epoxy insulation was characterised by the lowest partial discharge initiation voltage values and the highest operating costs among all configurations considered. Already during a six-month period of operation, EP showed significant voltage hysteresis (ΔU = 1.5 kV) and the formation of microstructural damage in 28% of samples. The increased values of the average partial discharge amplitude (220 mV) and frequency (45 pulses/min) correlated with the development of surface and interphase defects characteristic of the electrical ageing processes of the polymer matrix. The combination of these factors resulted in total cost of ownership of USD 280 over a six-month period, which, when extrapolated to a five-year operating cycle, corresponded to USD 620-780 per insulation unit, taking into account several replacements and losses associated with emergency equipment downtime. For nano-filled polymer NP with SiO_2 filler, other quantitative ratios of electrophysical and economic parameters were established. An increase in the partial discharge initiation voltage to 4.8 kV and a decrease in the voltage hysteresis to 1.0 kV were accompanied by a decrease in the proportion of damaged samples to 12%. The average values of the amplitude and frequency of partial discharges (160 mV and 30 pulses/min, respectively) indicated a less intense degradation process compared to epoxy insulation. This was directly reflected in the economic indicators: the TCO for six months was USD 140, and the projected costs for a five-year operating cycle were in the range of USD 280-350. The most favourable technical and economic characteristics were demonstrated by the NC nanocomposite with a BN layer and internal shielding. The partial discharge initiation voltage reached 5.5 kV with a minimum voltage hysteresis (Δ*U* = 0.5 kV), accompanied by low partial discharge intensity: the average amplitude did not exceed 80 mV, and the frequency was about 12 pulses/min. The proportion of samples with microstructural damage did not exceed 3%, which was consistent with the uniform distribution of the electric field and limited development of degradation processes. Under these conditions, the TCO for a six-month period was USD 50, and the cost for a five-year operating cycle was estimated at USD 90-120 without the need for scheduled replacement of the insulation unit. A comparative analysis of configurations using frequency converters showed that their use did not change the established electrophysical parameters of insulating materials, but significantly affected economic indicators by reducing the number of hard start-up modes, reducing the amplitude of short-term overvoltages, and reducing the frequency of emergency and unscheduled equipment shutdowns. Within the scope of the analysis, the total cost of ownership was formed by the costs of scheduled and unscheduled maintenance, replacement of degraded components, and losses associated with downtime, while maintaining clear differences between EP, NP, and NC materials throughout the entire life cycle of operation

DISCUSSION

The results of electrical, thermal and mechanical measurements showed that polymer dielectrics demonstrate different sensitivity to dynamic load modes, and the behaviour of nanocomposite systems is determined by the ability of their interphase structure to compensate for local peaks of stress and temperature. A 25-30% reduction in the breakdown voltage of epoxy insulation after cyclic electrothermal loading and a corresponding decrease in specific volume resistance correlate with the "moisture-heat-defect" model described by J. Ma *et al.* (2023), which established that hygrothermal effects cause hydrolytic destruction of the ester bonds of the epoxy matrix, degradation of interphase areas, and accumulation of microdefects, which determine the accelerated deterioration of electrophysical characteristics and a reduction in the service life of the insulation material. The difference in structural stability between

the epoxy system and nanocomposites confirms the mechanisms described by F. Wiesbrock (2014), which emphasised that nanofillers form a modified interphase zone with increased resistance to the concentration of electrical and mechanical stresses. The decrease in the amplitude of the breakdown voltage drop in materials with SiO_2 and BN is consistent with the author's approach, which links the stability of electrophysical parameters with the damping of local overvoltages in a nanostructured environment. This correlation provided a basis for further analysis of the behaviour of nanocomposites in more complex modes with a combination of partial discharges, thermomechanical loads and high-frequency voltage components.

The increase in the intensity of degradation processes in polymer insulation under the action of repeated impulse influences correlates with the conclusions of M. Ghassemi (2019), which stated that fast voltage fronts and repeated high-frequency pulses create conditions for accelerated electrothermal destruction. The similarity lies in the observation of a pattern: the greatest deterioration in parameters occurs in systems without nanomodification, where there are no mechanisms for dissipating electrical peaks. The scenarios of insulation depletion under the action of fast pulses described by the author are consistent with the observed difference between EP, NP and NC in terms of breakdown voltage, specific resistance and partial discharge activity. The presence of thermal anomalies in areas of sharp geometric changes and at polymer-metal boundaries is consistent with the trends identified by M. Hu *et al*. (2022), where it is emphasised that local thermal maxima are an early marker of interphase destruction and gas evolution. The recorded temperature peaks in the joint areas and in the insulation ribs demonstrate the same pattern: areas of reduced thermal conductivity and field concentration become centres of thermochemical destruction. The coordination of the identified mechanisms confirmed the importance of thermographic monitoring in high-voltage systems. The formation of localised areas of elevated temperature in the polymer matrix is consistent with the results of O. Sakhno *et al*. (2025), which showed that online diagnostics of high-voltage equipment under operating voltage allows the detection of thermal anomalies caused by the concentration of electrical and thermal stresses in insulation nodes. The authors noted that the spatial distribution of temperature can serve as an indicator of areas of potential electrical instability, which, during prolonged operation, transform into centres of partial discharge activation. In the study, these provisions were extended to the level of materials science, which was confirmed by the analysis of thermographic profiles of polymer and nanocomposite samples and their correlation with the quantitative parameters of partial discharges.

The observed increase in the intensity of partial discharges under the action of cyclic electrothermal loading demonstrates a clear dependence on the frequency and shape of the pulses, which is consistent with the conclusions of Q. Li *et al*. (2015). The authors showed that high-frequency components accelerate the formation of microcavities and increase the intensity of PD activity already in the early stages of ageing, which is consistent with the increased sensitivity of unmodified polymer systems to initiation processes. The tendency of epoxy resin to sharply decrease the "non-discharge stability" interval completely repeats the patterns described in high-frequency modes of electrothermal ageing. The spatial displacement of defect zones towards areas with an uneven electric field and reduced heat dissipation properties is consistent with the results of Y. Wu *et al*. (2022), where it was proven that the combination of geometric inhomogeneities and local thermal maxima increases the probability of degradation channel formation. The mechanism described by the authors – "geometric field concentration → local overheating → microcrack → gas-filled cavity" – fully explains the fixed trend of increased partial discharge activity in joint and edge areas. The mechanisms presented in the study are consistent with the interpretation of the shift of the maximum discharge area as a consequence of interphase instability. The identified relationship between the frequency of trigger pulses, the amplitude of PD activity, and geometric features repeats the results of D. Verginadis *et al*. (2021), where it is noted that a combination of electrical and structural factors determines the specific discharge energy and degradation rate. The authors showed that even moderate pulses in the presence of a heterogeneous polymer structure form accelerated destruction scenarios, which is consistent with the observed changes in the structure of EP samples. The refined model of action shows that the combination of solid surface defects with impulse loading creates a stable mechanism for the development of discharge erosion, which determines the specific discharge energy and the rate of material degradation. The peculiarities of the effect of distorted voltage on the acceleration of electrical ageing correspond to the patterns described by D. Fabiani & G.C. Montanari (2001). The authors demonstrated that harmonic components and voltage distortions significantly increase the rate of destruction of polymer insulation due to the nonlinear amplification of electrical stresses in interphase zones. The detected changes in the frequency spectrum of discharge activity are

consistent with the authors' statement regarding the critical role of high-frequency components as factors determining the resource stability of insulation.

The synergistic action of amplitude and frequency distortions explains the accelerated deterioration of the parameters of epoxy samples. The reduction in stress gradients and thermal peaks in nanocomposite structures is consistent with the trends described by L. Lusuardi *et al*. (2019), where it was proven that systems optimised for operation with inverter drives have improved resistance to dynamic modes. The authors emphasised that the correct choice of material can significantly reduce the level of partial discharges in systems with PWM voltage, which is consistent with the observed difference between EP and NC in the intensity of discharge activity after 1,000 start-up cycles. The mechanism is based on the ability of nanocomposites to smooth out local electrical peaks, which in traditional materials become triggers for early breakdown. The increased stability of electrical strength and reduced variability (Weibull β) in NP and NC samples is consistent with the concept of nanodielectrics presented by W. Liu *et al*. (2018). The work emphasised that nanoparticles form a modified interphase region with optimised polarisation, which increases the material's resistance to stress and discharge erosion. The observed increase in the β parameter is consistent with the authors' statement regarding the increase in structural homogeneity and the reduction in the number of defective channels, which in polymer systems without nanomodification remain one of the main sources of degradation.

The further increase in resistance to cyclic loading in BN samples correlates with the conclusions of T. Tanaka (2025), which presents a modern interpretation of the "two-layer interphase structure" mechanism that provides improved dielectric permeability and stability during repeated temperature fluctuations. The increase in breakdown voltage and reduction in losses are consistent with the author's model, which explains that nanoparticles with high thermal conductivity are capable of reducing local temperature peaks, which are the main factor in the thermoelectric degradation of polymers. The enhancement of dielectric properties in BN-modified samples and their reduced sensitivity to impulse loads are consistent with the results of A. Alsoud *et al*. (2025). The authors showed that rare earth oxide nanoparticles form stable heat dissipation channels, which significantly reduces local overheating and accelerated ageing. The obtained Weibull coefficients β and η are consistent with the concept that thermally stable nanofillers act as barriers to microcrack development. The identified patterns of changes in the thermal profile and PD activity in frequent start-up modes are consistent with the review by A.A. Razi-Kazemi & K. Niayesh (2021), which emphasised that the most dangerous scenarios for switching equipment are precisely dynamic modes with repeated pulses. The authors noted that the combination of electrical peaks and vibration loads forms accelerated degradation trajectories, which explains the faster reduction in the service life of traditional polymers. The dynamic nature of the load, caused by the peculiarities of hydraulic processes in pumping systems, is consistent with the conclusions of V.S. Kostyshyn & I.I. Yaremak (2017), where it is proven that optimising modes can significantly reduce peak electromechanical effects. The observed reduction in thermal instability when working with frequency converters repeats the trends described by the authors, who emphasised the ability of optimised control to reduce the amplitude of transient processes. The energy effect of using frequency drives and the reduction in costs associated with insulation degradation are consistent with the results of L. Elmahni *et al*. (2021), which proved that frequency control in pumping systems provides a significant reduction in heat generation and an increase in overall efficiency. The similarity is explained by the mechanism of reducing starting currents and stabilising the operating point of the unit. The assessment of the economic feasibility of using new materials and frequency control is consistent with the approach of N. Dutta *et al*. (2023), who demonstrated that digital life cycle analysis methods can reveal hidden operating costs. The reduction in costs over the long term confirms the authors' key conclusion about the dependence of system durability on the nature of load modes. The identified effectiveness of resource and economic solutions correlates with the conclusions of K. Zhang *et al*. (2026), who noted the importance of combining technical and environmental and economic criteria when selecting energy technologies. The reduction in operating cycle costs and the increase in energy efficiency are consistent with the patterns described by the authors.

The systematised results show that the combination of nanomodified insulation structures and regulated start-up modes forms a coordinated circuit of electrothermal processes, in which the amplitude of partial discharges, thermal gradients and the number of microstructural defects are reduced. Such dependencies correlate with established experimental models of nanodielectrics, where interphase layers determine the distribution of field intensity and local heat dissipation parameters. The observed increase in the β parameter in the Weibull curves is consistent with the mechanisms of resource stabilisation of composites with highly thermally conductive fillers described in the

world literature. The reduction in starting current load when using frequency regulation corresponds to the technical and operational patterns according to which a decrease in impulse electrical and thermal effects leads to a reduction in the rate of defect accumulation in polymer dielectrics. The set of comparisons collected demonstrates the formation of a structurally consistent picture of degradation processes, reflecting key trends in research on high-voltage insulation and systems with electromechanical cycles of increased dynamics.

CONCLUSIONS

The study allowed for a comprehensive characterisation of the degradation and reliability of polymer and nanocomposite insulating materials of high-voltage vacuum circuit breakers in dynamic operating modes of electric drives of pumping stations and grain drying complexes. It has been established that the combination of impulse starting loads, cyclic thermal effects and mechanical vibrations creates critical operating conditions in which the ability of the material to limit localised electrophysical and microstructural degradation processes is decisive. It has been shown that an epoxy matrix without fillers is characterised by the highest sensitivity to dynamic modes. After cyclic loading, the specific resistance decreased by more than 47%, the breakdown voltage by more than 25%, and the activity of partial discharges was accompanied by the formation of tracking structures and a significant loss of resource. Nanofilling with silicon dioxide provides a moderate improvement in performance: the specific resistance decreased by about 17%, and the breakdown voltage by 9.8%, while the development of partial discharges was limited and unstable without the formation of stable discharge channels. The highest stability was demonstrated by the configuration with hexagonal boron nitride and internal shielding, for which the reduction in specific resistance and breakdown voltage did not exceed 7.1-7.3%, the partial discharge initiation voltage reached 5.5 kV, and no through-tracking was formed in standard tests. Numerical 3D-FEM modelling combined with thermography showed a consistent decrease in peak electric field strength from 8.6 kV/mm for EP to 5.4 kV/mm for NC, and maximum temperatures from approximately 96°C to 79°C after 1,000 start-up cycles. Weibull analysis confirmed significant differences in durability: the average life of epoxy insulation was about 380 hours, while for nanocomposites it increased to 700-900 hours with a simultaneous decrease in statistical dispersion. It was found that the use of frequency converters reduces starting currents from about 5.6 I_n to 2.1 I_n and reduces the integral temperature increase of the insulation by 61.5%, forming a stabilised thermal regime. A technical and economic analysis showed that the TCO over a six-month period decreases from about 280 USD for epoxy insulation to about 50 USD for BN-containing configurations, with a multiple reduction in projected costs over a five-year operating cycle.

The results obtained indicate the promise of integrating composites with highly thermally conductive fillers and frequency control to optimise the operation of agro-industrial systems, in particular pumping stations, fan modules, grain drying units and greenhouse installations. Further research should focus on analysing the behaviour of composites in ultra-long cycles, modelling degradation under stochastic loads, expanding the range of nanofillers, and developing predictive models for digital technical diagnostic systems.

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None.

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Вплив динамічних режимів роботи електроприводів насосних станцій та зерносушильних комплексів на деградацію нанокомпозитної ізоляції високовольтних вимикачів: результати вимірювань і рекомендації для агроінженерії

Андрій Ставинський
Доктор технічних наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-7573-9238
Лариса Вахоніна
Кандидат фізико-математичних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-1668-2275
Володимир Мартиненко
Кандидат технічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0003-4067-3640
Віталій Мардзявко
Магістр, асистент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-7327-9215
Андрій Руденко
Магістр, асистент
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-5103-6412

Анотація. Дослідження було спрямоване на визначення впливу електричних, теплових і механічних навантажень на довговічність полімерної та нанокомпозитної ізоляції високовольтних вимикачів, що застосовуються у насосних станціях і зерносушильних комплексах України. Методологія поєднувала чисельне моделювання електростатичних і теплових полів у тривимірних конструкціях ізоляційних вузлів, прискорені термоциклічні та механічні випробування, аналіз часткових розрядів за міжнародними стандартами, термографічний контроль, мікроструктурні дослідження та статистичну оцінку ресурсу на основі кривих надійності. Установлено, що традиційна епоксидна ізоляція зазнає найбільш інтенсивної деградації: після циклічних навантажень питомий опір зменшувався на 47,5 %, пробивна напруга – на 25,7 %, а середній ресурс становив близько 380 годин. Для нанонаповненого матеріалу з діоксидом кремнію зниження питомого опору обмежувалося 17 %, пробивної напруги – 9,8 %, при збільшенні середнього ресурсу до 715 годин. Найвищу стабільність продемонструвала ізоляція з гексагональним нітридом бору та внутрішнім екрануванням, для якої зміни електрофізичних параметрів не перевищували 7,3 % за питомим опором і 7,1 % за пробивною напругою, напруга початку часткових розрядів досягала 5,5 кВ, а середній ресурс становив близько 912 годин. Чисельні та експериментальні результати показали зниження пікової напруженості електричного поля з 8,6 до 5,4 кВ/мм і максимальних температур з 96,2 до 78,8°C після 1 000 пускових циклів. Застосування керованих пускових режимів дозволило зменшити пускові струми з 5,6 In до приблизно 2,1 In та знизити інтегральне теплове навантаження ізоляції на 61,5 %. Техніко-економічна оцінка засвідчила зменшення сумарної вартості володіння за шість місяців з 280 до 50 доларів США на один ізоляційний вузол, що підтверджує практичну доцільність впровадження нанокомпозитів і керованих режимів пуску в агропромислових електроприводах. Практична значущість отриманих результатів полягає у формуванні критеріїв для вибору матеріалів та режимів роботи електроприводів з метою підвищення надійності комутаційного обладнання в агропромислових електромеханічних системах та використання моделювальних і діагностичних підходів для прогнозування деградації й оптимізації конструкцій ізоляційних вузлів

Ключові слова: часткові розряди; епоксидна смола; електротеплове навантаження; діелектрична міцність; відновлювана напруга; частотне регулювання; мікроструктурні дефекти

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Innovative approaches to processing meat, fish and seafood to improve the efficiency of agricultural production

Olena Petrova*
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-8612-3981

Natalia Shevchuk
PhD, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-5845-2582

Ruslan Trybrat
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-6710-570X

Larysa Agunova
PhD in Technical Sciences, Associate Professor
Odesa National University of Technology
65039, 112 Kanatna Str., Odesa, Ukraine
https://orcid.org/0000-0002-6708-7396

Yevgen Barkar
PhD in Agricultural Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-0692-5392

Abstract. This study aimed to evaluate the effectiveness of innovative technological solutions in enhancing microbiological safety, maintaining quality, and promoting the efficient use of raw materials. Methods employed included high hydrostatic pressure, low-frequency ultrasonic treatment, active and modified-atmosphere packaging, and thermal treatment (including microwave treatment, boiling and blanching). Cultural, chromatographic, spectrophotometric and gravimetric methods were also used to analyse the quality and safety indicators of raw materials. High hydrostatic pressure was found to selectively inactivate microflora without causing significant protein denaturation. A level of 300 MPa was found to ensure the sanitary stabilisation of chilled products. Meanwhile, an intensified regime of 400 MPa for five minutes on gilthead seabream fillets reduced mesophilic

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*Corresponding author (olenapetrova34@ukr.net)

aerobic microflora to 3.2 log CFU/g while preserving textural properties. For bivalve molluscs, the technologically significant level required for the complete separation of muscles from shells without mechanical intervention was found to be 310 MPa. The potential for intensification using low-frequency ultrasound at 25-40 kHz was calculated to provide controlled intensification of cavitation and mass transfer. Using a working frequency of 32.5 kHz for 15 minutes reduced the marinating time of fish fillets by 50-67% with no signs of structural destruction. A study of active packaging and a modified gas atmosphere revealed stabilisation of the physicochemical indicators over a storage period of 10 days: a moisture content of 65.6-68.9%, a reduction in pH to 6.59 and a water-binding capacity of 71.74%. This indicates preservation of the functional activity of the protein matrix. Drying of fish raw material made it possible to obtain a protein concentrate with a moisture content of 9-10% and a protein mass fraction of up to 66.7%; a water-binding capacity coefficient of 4.9 demonstrated the high hydration potential of the powder. Microwave treatment reduced microflora to 3.5-4.2 log while ensuring better nutrient preservation. Supercritical extraction was characterised by a lipid yield of up to 12-15% and a high-quality extract. The results may be used in the meat- and fish-processing industries to improve the safety, stability and efficiency of raw-material processing

Keywords: sanitary condition; protein fractions; fermentation process; water-binding capacity; protein fraction

INTRODUCTION

There is a growing need for innovative technologies to process meat, fish and seafood that can ensure microbiological stability, extend shelf life and preserve the biological value of products. Given the current production challenges, it is particularly important to combine the safety, functionality and economic efficiency of technological processes. Using high hydrostatic pressure, ultrasonic treatment, active packaging, controlled drying and microbiological monitoring systems enables product quality to be improved without harsh thermal regimes being applied. Comprehensive analysis of these approaches is important to optimise production, reduce raw material losses and increase sector competitiveness. This study addressed the issue of contradictions between intensifying technological processes and preserving the structural and functional characteristics of food raw materials. Traditional processing methods can result in a reduction in nutritional value, changes in texture, and inadequate control of microbiological risks. At the same time, the absence of a systematic approach to combining physical treatment methods, packaging solutions and regulatory control makes it difficult to ensure stable quality in the final product. There is also a need to substantiate process parameters that reduce energy consumption and production losses without compromising safety.

In the context of the economic mechanisms that govern the operation of food enterprises, O. Petrova *et al*. (2025) analysed marketing strategies aimed at increasing competitiveness. They found that integrating innovative processing technologies with market-based management tools created the prerequisites for sustainable production development. O. Mykhalko *et al*. (2025) investigated the influence of the sex and pre-slaughter weight of pigs on carcass characteristics when assessing the morphological factors of meat quality. The results revealed a correlation between the physiological parameters of the animals and the structural characteristics of the muscle tissue.

A. Zagorulko *et al*. (2023) studied the use of dried semi-finished products with a high degree of readiness for the improvement of minced product formulations. They showed an increase in the stability of textural properties and the technological uniformity of the products. Biochemical aspects of post-slaughter indicators of bull muscle tissue under corrective diet were studied by O.S. Yaremchuk *et al*. (2022). The data obtained reflected the effect of provision of protein and vitamins on the chemical composition of meat.

G.L. Russo *et al*. (2024) summarised modern non-thermal technologies for treating aquatic bioresources in the field of marine processing innovations. They described the potential of high hydrostatic pressure and combined methods for preservation of quality and safety of the product. A. Subash *et al*. (2024) studied the implementation of Industry 4.0 solutions in seafood processing management systems in respect to the digitalisation of technological processes. The importance of automated monitoring, data analytics for improving production efficiency was stressed.

C.N. Ravishankar & K. Elavarasan (2024) classified novel methods of primary and secondary processing of fish with respect to modernisation of technological operations in the fish industry. They pointed out the prospects for combining mechanical, thermal and non-thermal methods for preserving the texture and nutritional value of products. A. Getahun *et al*. (2025), summarising technologies for the preservation of aquatic bioresources, studied methods for improving the productivity of fish farming and extending the

shelf life of fish. Their work stressed the importance of integrated chilling, drying and packaging methods to minimise microbiological spoilage.

A. Ali *et al*. (2022) reviewed the current methods of fish products preservation and discussed the nutritional value, preservation methods and processing technologies of fish. They showed that chilling, freezing, vacuum packaging and modified atmosphere packaging slow down microbiological processes and oxidative changes, thus helping to maintain product quality and safety during storage. I. Olesen *et al*. (2023) studied the role of aquaculture and agriculture towards a closed-loop bioeconomy for the development of circular food systems. The research focused on efficient resource use and waste reduction in supply chains.

In the context of the digital transformation of the meat industry, Q. Sun *et al*. (2025) examined the challenges associated with the intellectualisation of production processes. They outlined opportunities for introducing sensor systems and automated quality control under industrialised conditions. Regarding the integration of Industry 4.0 technologies in seafood processing, A. Hassoun *et al*. (2022) summarised contemporary methods of combining preservation techniques, analytical monitoring, and digital management. They demonstrated that combining non-thermal methods and analytical platforms improves process controllability and the stability of the final product. However, the comprehensive integration of high hydrostatic pressure, ultrasonic treatment, active packaging and drying into unified technological chains, with simultaneous assessment of microbiological safety, functional properties and resource efficiency, remains insufficiently studied.

This study aimed to substantiate innovative technologies for processing meat, fish and seafood by assessing their impact on microbiological stability, quality, and raw material efficiency. The study aimed to analyse the technological regimes of high hydrostatic pressure and ultrasonic intensification in meat and fish processing, assess the effectiveness of active packaging, modified gas atmospheres and drying in preserving physicochemical indicators, and summarise the criteria of microbiological control as a prerequisite for the stability of fermentation technologies.

MATERIALS AND METHODS

The study was conducted from 2023 to 2025 at the Educational and Scientific Laboratory for the Processing of Livestock Products and Food Technologies at Mykolaiv National Agrarian University in Mykolaiv, Ukraine. Analytical generalisation and structuring of technological indicators were carried out within the departmental research area concerning innovative technologies for processing meat, fish and seafood. The study analysed data on European seabass fillets (*Dicentrarchus labrax*), mussels (*Mytilus* spp.) and oysters (*Crassostrea* spp.), as well as pork, beef and poultry meat. These species were selected due to their significant share in global production and consumption, their sensitivity to innovative processing methods such as high hydrostatic pressure, ultrasound and modified gas atmospheres, and the availability of standardised quality and safety indicators, which enabled the results to be compared correctly. The provisions of the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (1986) were observed during the study. Experimental data were used and interpreted with due regard for the principles of humanity, transparency and scientific integrity.

The parameters of high hydrostatic pressure and the corresponding technological indicators for fish and seafood were derived from the literature source of O.A. Pivovarov *et al*. (2024). The effect of a modified gas environment, namely nitrogen and carbon dioxide mixtures, was not included in the analysis since the source data only provided the pressure and treatment duration parameters. The processing parameters for European seabass fillets (*Dicentrarchus labrax*), mussels and oysters were defined as standardised pressure and exposure intervals that ensured microbiological and technological stability without thermal influence. The standard procedure for inhibiting vegetative bacteria involved applying a fixed pressure level for a short period at room temperature, and this was adopted as the basic processing procedure. The High-Pressure Processing (HPP) regime for European seabass fillets (*Dicentrarchus labrax*) was developed taking into account the morphological features of the muscle tissue and its water-retaining properties. These factors determined the intensity and duration of the treatment.

The total number of mesophilic aerobic bacteria in the fillets was determined by plating them on nutrient media after pressure treatment and counting the resulting colony-forming units, providing a quantitative characterisation of the antimicrobial effect. The HPP regime for processing mussels was set with higher pressure values and shorter exposure times, taking the characteristics of mollusc microbiota into account. The proportion of Gram-positive microflora in mussels after HPP treatment was determined by differentiating isolates according to their morphological and tinctorial properties using Gram staining. This made it possible to establish the structure of the microbial population. The pressure ensuring complete separation of the oyster muscle from the valve – that is, 100% shucking – was defined as the minimum level of isostatic

compression at which complete tissue separation occurred without mechanical intervention. The threshold pressure at which the colour of oysters' changes was determined by gradually increasing the pressure and visually and instrumentally recording changes in the tissue's optical properties, which made it possible to establish the limit for preserving the natural colour. The indicators were presented with due regard to units of measurement, namely MPa, min, log CFU/g and %, without additional recalculation.

The parameters of high-efficiency high-intensity ultrasound (HIUS) for meat marinating were systematised based on a specialised article by V. Danylevych *et al*. (2025). The optimal ultrasound frequency range and recommended ultrasonic marinating duration for meat were defined as the limits within which cavitation effects increase muscle fibre permeability and accelerate marinade component diffusion without disrupting tissue structural integrity. The working frequency range of HIUS with antimicrobial properties and the duration of high-efficiency ultrasonic treatment in food technology were defined as the technological parameters that characterise the intensity of the cavitation effects during the processing of raw meat and fish. Cavitation effects under the specified regime were characterised by the formation of short-term mechanical impulses that opened the inter-fibre spaces without disrupting the sarcolemma's integrity. The selected processing interval intensified mass transfer without accumulating excess moisture or destabilising the tissue's structure. Reducing the marinating duration was achieved by comparing the process duration under standard conditions with that under ultrasonic treatment, using an acceleration coefficient. Quality preservation was monitored using organoleptic and physicochemical indicators, while the antimicrobial effect was assessed based on changes in surface microflora. Based on a comparative assessment, the working frequency was defined as 32.5 kHz, during which cavitation effects were observed without any signs of coagulation changes, muscle fibre destruction or excessive moisture release. At lower frequency values, local overload of the tissue by cavitation impulses was observed, whereas at higher values the intensity of mass transfer decreased. The average working frequency was determined as the midpoint of the interval (1):

$$f_{avg} = \frac{f_{min}+f_{max}}{2}, \quad (1)$$

where f_{avg} – is the average working frequency of ultrasound; f_{min} – is the minimum frequency value within the range; f_{max} – is the maximum frequency value within the range. The average treatment duration was determined analogously to formula (1).

The possible reduction in marinating time was assessed using the acceleration coefficient, which reflected the multiplicity of the reduction in process duration. The relative reduction was determined using formula (2):

$$R = \left(1 - \frac{1}{k}\right) \times 100\%, \quad (2)$$

where R – is the relative reduction in process time; k – the process acceleration coefficient, that is, the multiplicity of the reduction in duration. This approach ensured a unified comparison of regimes without changing the limits of interpretation of the primary data.

The physicochemical indicators of the meat after storage were determined based on the data presented in the scientific publication by A.I. Marinin *et al*. (2025). This publication presents the results of measuring the moisture content, pH values, and moisture-retention capacity (MRC) of the samples after 10 days of storage. Chicken fillets were selected for investigation in the study due to their homogeneous muscle tissue structure and high sensitivity to changes in storage conditions, ensuring a valid comparison of the effects of packaging. Control samples were compared with samples containing oxygen absorbers and samples stored in a modified gas atmosphere, all under identical storage conditions. The moisture content of the control samples after 10 days, the moisture content with one oxygen absorber, the moisture content under a modified gas atmosphere (MGA), and the moisture content with two oxygen absorbers were determined as indicators for quantitatively assessing water content in muscle tissue under different packaging conditions. These values were then used to determine the extent of moisture loss during storage, assess the effectiveness of the packaging's barrier properties and establish the impact of the oxygen environment on the product's water retention stability.

The acid-base state of the muscle tissue was determined based on the pH values of the control samples, the samples containing one oxygen absorber, the samples in the modified gas atmosphere and the samples containing two oxygen absorbers after ten days of storage. These values were then used to quantify biochemical changes in the tissue, particularly reflecting the intensity of post-slaughter processes, the activity of endogenous enzymes, and the potential development of microflora depending on the gas composition of the environment. This approach ensured a standardised comparison of indicators between packaging variants under identical exposure conditions.

The functional state of the protein-water matrix was determined based on MRC indicators in control samples and samples containing one or two oxygen absorbers, or in a modified gas atmosphere. The MRC

values served as a quantitative measure of the muscle proteins' ability to retain immobilised water in the presence of storage factors, enabling an evaluation of the preservation of intermolecular interactions within the protein-water complex. Comparing the obtained values made it possible to determine the effectiveness of different types of packaging in maintaining the tissue's structural stability.

The moisture content of the product after drying at 100°C and 70°C, the protein mass fraction at 100°C and 50°C, and the water absorption coefficient at 50°C after drying with water at 55°C were taken as basic characteristics of the stability and functionality of the fish protein concentrate. These indicators enabled a comprehensive assessment of the influence of the dehydration temperature regime on the structural state of the dry matter, the preservation of the protein fraction, and the technological suitability of the resulting product. The difference in moisture content was calculated as follows (3):

$$\Delta W = W_{70} - W_{100}, \quad (3)$$

where ΔW – is the difference in moisture content, p.p. (percentage points); W_{70} – the moisture content of the product after drying at 70°C; W_{100} – is the moisture content of the product after drying at 100°C. The increase in protein mass fraction was calculated analogously to formula (2).

The relative increase in protein was calculated as follows (4):

$$\Delta P_{rel} = \frac{P_{50} - P_{100}}{P_{100}} \cdot 100\%, \quad (4)$$

where ΔP_{rel} – the absolute increase in protein mass fraction; P_{50} – is the protein mass fraction after drying at 50°C; P_{100} – is the protein mass fraction after drying at 100°C. The formulae were applied to obtain derived values without changing the primary indicators.

The microbiological acceptability criteria were developed using materials from a study of the microflora of imported frozen fish by M.D. Kukhtin & Z.V. Malimon (2024). The number of psychrotrophic microorganisms was determined using the cultural method, involving inoculation onto nutrient media and incubation at reduced temperatures. This made it possible to quantitatively assess cold-resistant forms of microorganisms. Samples containing >5 × 10^4 CFU/g of psychrotrophic microflora and the threshold value for comparing psychrotrophs were used as the basis for microbiological criteria to detect and quantify the level of cold-resistant contamination in raw materials. These indicators ensured the identification of microorganisms capable of growing at low temperatures, which is essential for predicting their growth during refrigerated storage. The acceptance-control scheme – comprising a sampling plan (n), the permitted number of "marginal" samples (c), a threshold level (m) and a limit level (M) – was interpreted as a formalised system for interpreting results. This ensured a standardised assessment of whether raw material batches conformed to established safety criteria. This approach not only records the fact that regulatory limits have been exceeded, but also classifies the level of risk depending on the distribution of values in the sample and the ratio of acceptable to limit indicators.

The proportion of positive cases for first- and second-generation aminoglycosides, as well as the nalidixic acid detection indicator, were used to determine the prevalence of undesirable microbiological traits. Analysing these proportions enabled us to evaluate the sanitary condition of imported or processed raw materials and consider the potential impact of antimicrobial resistance on the controlled fermentation process. The values obtained were summarised as averages for representative observation intervals corresponding to stable process conditions. The level of variation was assessed by analysing the fluctuation ranges and calculating the standard deviation, ensuring a statistically robust presentation of the quantitative characteristics.

The samples were processed using a Panasonic NN-GD37 microwave oven (Japan, 700-900 W): boiling in an aqueous medium at 100°C, then blanching at 85-95°C in a Memmert WNB14 water bath (Germany). A Testo 108 thermocouple (Germany) was used to monitor the temperature regime, ensuring the comparability of thermal effects between regimes. Reduction in mesophilic aerobic bacteria was determined using the cultural method with inoculation onto meat-peptone agar, followed by incubation at 30°C for 48 hours in a Binder BD 115 thermostat. The obtained data were used to characterise quantitatively changes in microbial load under the influence of processing.

Vitamin retention was determined using high-performance liquid chromatography with an Agilent 1260 Infinity chromatograph (USA) and detection in the appropriate spectral ranges. The retention percentage was calculated as the ratio of the content after processing to the initial value, according to formula (5):

$$R = \frac{C_{after}}{C_{before}} \times 100\%, \quad (5)$$

where R – vitamin retention; C_{before} – is the content before processing; C_{after} – the content after processing. The content of omega-3 fatty acids was determined by gas chromatography using an Agilent 6890N instrument (USA) after preliminary derivatisation. The indicators obtained were used to analyse changes in the

lipid composition depending on the processing regime. Product mass loss was determined by the gravimetric method using Sartorius Entris II analytical balances (Germany), by weighing before and after processing.

The percentage of losses was calculated according to formula (6):

$$L = \frac{m_0 - m_1}{m_0} \times 100\%, \quad (6)$$

where L – is mass loss; m_0 – is the mass before processing; m_1 – is the mass after processing. Textural characteristics were studied by the penetration method using a TA.XTplus texture analyser (Stable Micro Systems, Great Britain). The values obtained were used to characterise changes in the structural organisation of the tissue. The processing duration was recorded using a Testo 174 digital timer (Germany). The data were taken into account when establishing the relationship between exposure duration and changes in the studied indicators.

Extraction was carried out using a Waters Corp. (USA) SFE-500 supercritical fluid extraction system, with carbon dioxide in the supercritical state at controlled pressures and temperatures. The process parameters were maintained by an automated control system to ensure stable extraction conditions. The extraction yield was calculated using the gravimetric method and Sartorius Entris II analytical balances (Germany). The calculation was performed according to formula (5). The obtained values were used to assess the efficiency of the extraction of the lipid fraction.

The content of eicosapentaenoic acid (EPA) was determined by gas chromatography after the methylation of fatty acids, using a 6890N Agilent chromatograph (USA). These results were then used to analyse changes in the composition of polyunsaturated fatty acids during extraction. Docosahexaenoic acid (DHA) content was determined using the same method. These results were considered when evaluating the preservation of biologically valuable components of the lipid complex. The concentration of tocopherols was determined using high-performance liquid chromatography (HPLC) with an Agilent 1260 Infinity system (USA) and a fluorescence detector. These data were then used to characterise the vitamin content of the extract. The carotenoid concentration was determined using a Shimadzu UV-1800 spectrophotometer (Japan) at the wavelength of maximum absorption. These results were then used to evaluate the composition and stability of the pigments and bioactive compounds. Antioxidant activity was determined using the DPPH method with 2,2-diphenyl-1-picrylhydrazyl and a Shimadzu UV-1800 spectrophotometer. The calculation was performed according to formula (7):

$$IC_{50} = \frac{C \times 50}{I}, \quad (7)$$

where IC_{50} – the concentration providing 50% inhibition of radicals; C – is the concentration of the sample studied; and I – is the percentage of inhibition. The values obtained were used to assess the antioxidant potential of the extract.

RESULTS

Non-thermal stabilisation of seafood by high pressure

Within the tested range of hydrostatic-effect parameters, critical pressure levels were identified that facilitated microbiological stabilisation without compromising the structural integrity of the tissue. It was determined that an overall control processing level of 300 MPa was sufficient to achieve vegetative microbiological suppression in fish fillets. This value effectively reduced the microbial load in fillets without causing any significant structural changes to the muscle tissue. The preserved muscle texture and the absence of intensive protein denaturation emphasised the selectivity of hydrostatic pressure towards microbial membrane cells compared to the relative stability of muscle proteins. Morphological analysis of the samples showed that the matrix was dense and did not show signs of wateriness or fibre destruction. The cut surface had retained its typical sheen and no excessive exudation of liquid from the samples was observed. Meanwhile, the muscle fibres clearly showed their differentiation. Thus, the threshold for the achievement of sanitary stabilisation and the preservation of sensory quality was 300 MPa. Moreover, no significant loss of structural integrity of muscle fibres was detected under the processing conditions of 400 MPa for 5 min, which proves the possibility of intensification of the regime without critical texture changes. Under the given regime, no significant changes in fillet colour were also observed, which suggests that pressure has a limited effect on myoglobin complexes and pigment structures. The density of the tissue was similar to that of the controls and the elasticity of the muscle fibres was maintained under mechanical load. The water-binding capacity did not decrease sharply, confirming the absence of deep structural rearrangements in the protein-water matrix. Thus, the hydrostatic impact in this regime had a predominantly biocidal effect without a critical influence on the functional properties of the protein.

A more detailed analysis was performed on European seabass fillets (*Dicentrarchus labrax*) processed under a standard high-pressure environment. As a result, the total count of mesophilic aerobic bacteria was reduced by 3.2 log CFU/g. The magnitude of this decrease showed a significant reduction of contamination

and confirmed the high efficiency of non-thermal treatment. After exposure to pressure, a sharp decrease in viable colony forming units was observed. On the other hand, a gradual increase in microflora was observed in the control samples during storage. The HPP-treated samples showed stable indicators with no intensive microbial proliferation. Also, the condition of the muscle structures after processing was assessed. The integrity of the fibre was preserved and no significant clouding of the tissue or loss of natural moisture was noted. The lack of pronounced protein coagulation points to a difference in the mechanism of action of hydrostatic pressure and thermal exposure, the latter usually leading to the formation of a dense coagulation structure. Thus, the effect on microbial cells was selective, with muscle protein complexes remaining relatively stable.

Particular attention was paid to bivalve molluscs, especially oysters. Under the influence of high pressure, the muscle automatically separated from the valve. It was determined that complete separation of the muscle tissue was ensured without mechanical damage when a level of 310 MPa was reached. This occurred due to the disruption of the adhesive interactions between the muscle fibres and the inner surface of the valve under the action of uniform isostatic compression. At the same time, the muscle retained its anatomical shape and no fragmentation or tearing occurred. It was established that increasing the pressure to above 310 MPa caused changes to the oysters' optical characteristics, as evidenced by an increase in whiteness and a decrease in tissue transparency. This was accompanied by increased light scattering, which was associated with the rearrangement of protein complexes at a structural level. These changes were interpreted as resulting from the partial restructuring of protein structures and the compaction of sarcoplasmic elements. However, within the applied regimes, these effects were not accompanied by the development of a foreign odour, mucus degradation, or tissue delamination (Table 1).

Table 1. *Technological regimes of high hydrostatic pressure and their effect on seafood*

Indicator	Number/range	Note
Typical regime for inhibiting vegetative bacteria	300 MPa, "several minutes", room temperature	Demonstrated the achievement of a sanitarily acceptable level without the use of thermal load. Confirmed the possibility of non-thermal stabilisation of chilled products
HPP regime for processing European seabass fillets (Dicentrarchus labrax)	400 MPa × 5 min	Reflected an intensified regime for the dense muscle tissue of marine fish. Demonstrated the adaptation of parameters depending on the type of raw material
Reduction in the total number of mesophilic aerobic bacteria in European seabass fillets after HPP	3.2 log CFU/g	Indicated a multiple reduction in viable microflora. Confirmed the achievement of a stabilising effect without complete sterilisation
HPP regime for processing mussels	500 MPa × 2 min	Demonstrated the application of a higher pressure level for molluscs with naturally more complex microbiota. Indicated a short-term but intensive effect
Proportion of Gram-positive microflora in mussels after HPP treatment	91%	Demonstrated a shift in the ratio of microbial groups towards more resistant forms. Indicated the selective nature of the effect of isostatic compression
Pressure ensuring complete separation of the oyster muscle from the valve, or 100% "shucking"	310 MPa	Reflected the threshold level for achieving a technological effect without mechanical intervention. Confirmed structural rearrangement of tissue-attachment zones
Threshold pressure after which the colour characteristics of oysters change	>300 MPa	Demonstrated the sensitivity of protein-pigment complexes to increased load. Indicated the need to control regimes in order to preserve marketable appearance

Source: *compiled by the authors based on O.A. Pivovarov et al. (2024)*

Thus, the results demonstrated that high hydrostatic pressure within the specified limits had a pronounced antimicrobial effect while preserving the physicochemical and morphological characteristics of fish and seafood. In particular, a reduction in microbial load of 3.2 log CFU/g was recorded at a pressure level of 300 MPa, indicating the effective suppression of vegetative microflora without achieving sterility. The applied regimes did not result in any critical structural changes to muscle tissue, such as loss of density, excessive moisture release or formation of a coagulated texture. There was no sharp shift in acidity indicators or disruption of the natural colour, indicating preservation of the biochemical balance of the protein-water system. The morphological stability of the tissues indicated the absence of deep denaturation of myofibrillar proteins and the preservation of the structural organisation of muscle fibres. Taken together, the results demonstrate the potential for integrating HPP into fish and seafood processing technologies to maintain product quality and safety without altering its natural structure.

Ultrasonic enhancement of diffusion and structural changes

Analysis of the ultrasonic treatment parameters showed that applying a 32.5 kHz frequency generated stable cavitation in the marinade's liquid medium. Under this acoustic influence, the intensive formation and implosion of microbubbles occurred, accompanied by local pressure and temperature fluctuations at a microscopic level. The cavitation cavities formed microjets capable of temporarily increasing the permeability of tissue barriers. This activated diffusion processes and reduced intratissue resistance to the penetration of dissolved components. Consequently, muscle fibres became more uniformly saturated with salts and functional ingredients than under conventional marinating conditions. At the same time, the tissue structure remained stable without any signs of delamination or excessive loosening. A frequency of 32.5 kHz was characterised by sufficient cavitation activity, with no coagulation changes, muscle fibre destruction or excessive moisture release, indicating preservation of the protein matrix's structural integrity.

The effect of acoustic waves in this regime was accompanied by short-term mechanical impulses. These impulses did not disrupt the integrity of the sarcolemma. However, they contributed to the opening of inter-fibre spaces. This functional effect did not result in a loss of the tissue's natural density. The surface of the samples remained even, with no visible clouding or wateriness. The results indicated that the cavitation process could be controlled and was in line with the technological requirements for preserving the structure of protein raw materials. The average duration of the ultrasonic treatment was 15 min, which ensures the full realisation of the technological effect within the selected regime. In this period a gradual and stable increase of the mass transfer between the liquid and solid phase was observed. Diffusion was activated and there was no accumulation of excess moisture in the tissue or local oversaturation zones. The concentration gradients between the outer and inner zones decreased, showing a more uniform distribution of the marinade components over the whole volume of muscle tissue. No intensive release of tissue fluid or signs of degradation of sarcoplasmic structure were observed. The orientation and elasticity of the muscle fibres did not change even after the treatment was over. Thus, 15 minutes were enough to increase the process without exceeding the permissible acoustic load.

Comparative evaluation of the duration of the technological cycle showed that the use of ultrasound can reduce marinating time by up to 50%. The process duration was reduced by half, which pointed to a significant increase in the mass transfer rate and a more rapid achievement of the required saturation level. In parallel, there were no negative changes in qualitative characteristics of the product. Organoleptic assessment revealed no external odours or colour changes and the texture was homogeneous and elastic. The reduced time did not lead to any destructive changes in the protein structures, not excessive softening or loosening. The preservation of the physicochemical properties demonstrated the effectiveness of the ultrasonic intensification on quality loss prevention. Furthermore, partial suppression of surface microflora was observed in the working frequency range of the HIUS with antimicrobial action. Although total inactivation was not achieved, an attenuation of the initial microbial growth intensity during storage was observed. This was interpreted as a consequence of the mechanical impact of cavitation waves on the cell membranes of microorganisms, increasing their sensitivity to the external environment. Meanwhile, the tissue's structural organisation remained unchanged, indicating the selectivity of the ultrasonic action and its predominant focus on the liquid phase and microbial cells (Table 2).

Table 2. *Ultrasonic treatment of meat and fish raw materials: Parameters and generalised calculated regimes*

Indicator	Value	Note
Optimal ultrasound frequency range for meat marinating	25-40 kHz	Defined the limits of stable cavitation activity in an aqueous medium. Demonstrated the effectiveness of a low-frequency regime for processing protein raw materials
Recommended duration of ultrasonic marinating	10-20 min	Reflected the interval within which the structural integrity of the tissue was preserved. Indicated the possibility of controlling the acoustic load
Working frequency range of HIUS with antimicrobial action	20-47 kHz	Demonstrated the sensitivity of microorganisms to low-frequency acoustic oscillations. Indicated the potential for selective influence on surface microflora
Duration range of high-efficiency ultrasonic treatment in food technologies	2 s – 30 min	Demonstrated the versatility of the technology for different types of products. Indicated the adaptability of regimes depending on the structure of the raw material
Calculated average working ultrasound frequency for marinating	32.5 kHz	Reflected a compromise between cavitation intensity and tissue stability. Confirmed the appropriateness of using the mean value of the range

Table 2, Continued

Indicator	Value	Note
Calculated average duration of ultrasonic treatment	15 min	Demonstrated that the time was sufficient for the acoustic effect to occur without signs of overload. Indicated a balance between process speed and product quality
Estimated possible reduction in marinating time when ultrasound is applied	50-67%	Demonstrated the potential for accelerating the technological cycle. Confirmed an increase in the intensity of mass transfer

Source: *compiled by the authors based on V. Danylevych et al. (2025) and formulae (1-2)*

The frequency of 32.5 kHz for 15 minutes resulted in stable marinating without disturbing the structural integrity of muscle fibres, confirmed the results. The reduction of the technological process by 50% showed the prospect for increasing the efficiency of the production cycle with the preservation of the physicochemical properties of the raw material. The parameters of ultrasonic treatment were chosen so as to ensure controlled cavitation effect, uniform penetration of functional components and stability of textural indicators. The obtained data confirmed the possibility of using HIUS as a method of intensification of the processes in meat and fish processing with the preservation of product quality.

Packaging technologies with a controlled storage atmosphere

The control samples had a moisture content of 65.6% after ten days of storage, which is a natural tendency of chilled meat to gradually lose moisture during storage. No active components were present in the packaging, but a moderate reduction in moisture content with slight compaction of the surface layers of the tissue was observed. There was no sharp drying or crust formation at the same time, although the texture was less elastic than in the initial state. This indicated the normal course of physico-chemical changes under normal conditions of packaging.

The moisture content at the active packaging conditions of two oxygen absorbers was 68.9%, which was higher than the control group. This was evidence of the decrease of the intensity of evaporation and suppression of oxidation processes in the tissue. The higher level of retained moisture indicated that the protein-water matrix had become stable and that dehydration had been reduced. The surface of the samples was flat with no indication of overcompaction or loss of shine. This suggests that two oxygen absorbers contributed to maintaining the muscle tissue in a balanced hydration state during storage.

The pH value under modified gas atmosphere was determined to be 6.64, which was greater than the other packaging conditions, indicating a more stable acid-base state. Relatively low pH level was observed to slow down autolytic processes and limit the activity of microflora. At the same time, there were no sharp changes of acidity which could have a negative impact on the taste of the product. The pH stabilisation under modified gas atmosphere conditions confirmed the efficiency of the control of the gas composition inside packaging in restriction of undesirable biochemical changes. The maximum MRC value was 71.74% in samples with two oxygen absorbers under the studied conditions. This suggests that muscle tissue can still retain intracellular and intercellular water even after long term storage. The high level of MRC indicated stability of structural protein complexes and small changes of denaturation. The samples showed satisfactory elasticity and did not release too much moisture when subjected to mechanical force, which means that the tissue is functionally intact.

A comparative analysis of these indicators made it possible to determine that active packaging using oxygen absorbers and modified gas atmosphere had different effects on the stability parameters of meat. The control samples were characterised by a lower level of retained moisture and lower MRC, which corresponded to the natural course of changes during storage. By contrast, the use of two oxygen absorbers contributed to the preservation of hydration properties and structural stability. The modified gas atmosphere, in turn, ensured acidity stability, which was important for maintaining microbiological and biochemical equilibrium (Table 3).

Table 3. *Physicochemical quality indicators of broiler chicken fillets after 10 days of packaging*

Indicator	Value	Note
Moisture content of control samples after 10 days, %	65.6	Demonstrated the natural dynamics of moisture loss during storage. Reflected the baseline level of dehydration changes without additional stabilising factors
Moisture content with one oxygen absorber, %	66.2	Indicated a moderate reduction in the intensity of oxidative processes. Demonstrated partial stabilisation of the internal packaging environment
Moisture content under MGA, %	66.62	Demonstrated the influence of controlled gas composition on the hydration state of the tissue. Indicated preservation of the balance between evaporation and internal moisture diffusion
Moisture content with two oxygen absorbers, %	68.9	Demonstrated the most stable water balance among the studied variants. Indicated effective limitation of oxidative and dehydration changes

Table 3, Continued

Indicator	Value	Note
pH of control samples after 10 days	6.89±	Reflected the course of autolytic processes under standard storage conditions. Demonstrated the absence of regulation of the internal gas environment
pH with one oxygen absorber after 10 days	6.78	Indicated the inhibition of undesirable biochemical reactions. Demonstrated the influence of reduced oxygen content on acid-base equilibrium
pH under MGA after 10 days	6.64	Demonstrated stabilisation of the environment due to controlled gas composition. Indicated a decrease in the intensity of microbiological changes
pH with two oxygen absorbers after 10 days	6.59	Demonstrated the most pronounced effect in restraining oxidative processes. Indicated the maintenance of a more stable biochemical state of the tissue
MRC – control after 10 days, %	69.54	Reflected the standard level of water retention without additional technological factors. Demonstrated a gradual reduction in the functional activity of proteins
MRC with one oxygen absorber after 10 days, %	70.98	Indicated improved structural stability of protein complexes. Demonstrated the preservation of intermolecular bonds in the tissue
MRC under MGA after 10 days, %	70.75	Demonstrated the maintenance of water-retention properties under controlled-atmosphere conditions. Indicated a reduction in degradation changes
MRC with two oxygen absorbers after 10 days, %	71.74	Demonstrated maximum preservation of the functional ability of the tissue to retain water. Indicated stabilisation of the protein-water structure during storage

Source: *compiled by the authors based on A.I. Marinin et al. (2025)*

A comprehensive interpretation of the results showed that stabilising the key physicochemical indicators of meat during storage was possible by combining control of the gas environment with active packaging components. An increase in moisture content to 68.9% and an increase in MRC to 71.74% under active packaging conditions confirmed the preservation of the tissue's functional properties. A pH value of 6.64 under a modified atmosphere indicated a reduction in undesirable biochemical changes. These results showed that active packaging and controlling the gas composition of the environment were key to stabilising the quality of meat products without affecting their structure.

Thermal drying in fish protein concentrate technology

When dried at 100°C, the product had a moisture content of 9%, indicating deep dehydration of the raw material. The results confirmed the successful removal of free and partially bound water and ensured stability of the concentrate during storage. The low moisture content reached inhibited the microbiological activity and minimised the enzymatic processes. Simultaneously, partial thermal modification of the protein structures was observed under the elevated temperature conditions, which was reflected in a slight compaction of the powder particles. The structure of the product was still homogeneous, without clumping, but the texture was denser than in variants obtained at lower temperatures. The drying at 50°C gave the protein mass fraction of 66.7% which indicates a high concentration of nitrogen-containing compounds in the final product. A moderate temperature regime helped to maintain the native structure of protein molecules and minimised changes in denaturation. Compared to intensive thermal treatment, the lower temperature allowed to preserve the functional properties of the protein, especially its solubility and hydration capacity. The results obtained show that it is possible to obtain concentrates with a higher biological value by using gentle drying methods. The powder showed a structure of looser consistency with a homogeneous distribution of particles.

The water-absorption coefficient was 4.9 when the concentrate was dried at 50°C, which indicates the ability of the powder to reconstitute actively in an aqueous medium. This suggests that the spatial arrangement of the protein macromolecules is retained and that there are sufficient hydrophilic groups for interaction with water. The high-water absorption capacity indicates that the concentrate can be applied for food products, especially emulsion and paste-like formulations. Hydration of the powder led to a homogeneous mass without insoluble aggregates, suggesting no significant protein coagulation. The intensive thermal regime caused a lower moisture content which positively affected the storage period, but was associated with partial structural changes of the protein. On the other hand, a moderate temperature was found to be helpful in maintaining a high protein mass fraction and improving hydration properties. The protein content of 66.7% and the water absorption coefficient of 4.9 confirmed the functional activity and technological versatility of the concentrate in the relation. It was also demonstrated that decreasing the drying temperature did not significantly increase the residual moisture, and the final product was stable under normal storage conditions. The structural integrity of the protein fractions ensured that the concentrate could be used further in technologies for enriching products of animal and combined origin. The results obtained demonstrated the feasibility of optimising the temperature regime as a key factor in determining the quality of fish protein concentrate (Table 4).

Table 4. *Fish protein concentrate after drying: indicators*

Indicator	Value	Note
Moisture content of the product when dried at 100°C	9%	Indicated a deep level of dehydration and minimal risk of microbiological activity. Indicated the formation of a stable dry matrix of the product
Moisture content of the product when dried at 70°C	10%	Demonstrated a gentler regime of moisture removal. Indicated the preservation of some structurally bound water
Protein mass fraction at 100°C	65.8%	Reflected the concentration of protein fractions after intensive thermal exposure. Indicated the formation of a dense protein structure in the powder
Protein mass fraction at 50°C	66.7%	Indicated greater preservation of nitrogen-containing components. Demonstrated the favourable effect of a moderate temperature regime on nutritional value
Moisture difference: 70-100°C	+1 p.p.	Demonstrated the sensitivity of the indicator to changes in drying temperature. Indicated the dependence of dehydration on the intensity of thermal load
Protein increase: 50-100°C	+0.9 p.p.	Demonstrated the advantage of a gentle regime in preserving protein components. Indicated the influence of temperature on the concentration ratios of dry substances
Relative increase in protein at 50°C	≈1.37%	Demonstrated a small but stable difference in product composition. Indicated the potential for optimising the drying regime
Water-absorption coefficient at 50°C drying, water at 55°C	4.9	Indicated the high hydration capacity of the powder. Demonstrated the suitability of the concentrate for use in reconstituted food systems

Source: *compiled by the authors based on formulas (3-4)*

Thus, the combination of deep dehydration under an intensive temperature regime, increased protein fraction concentration under moderate drying, and the product's high hydration capacity confirmed the technological effectiveness of the process as part of waste-free fish raw material processing. The applied regimes enabled the production of a stable, powdered concentrate with minimised microbiological activity that preserved the functional properties of proteins. It was also demonstrated that varying the drying temperature enabled control over the relationship between dehydration levels and the preservation of native protein characteristics. The resulting concentrate was characterised by a homogeneous, dispersed structure; an absence of signs of thermal damage; and an ability to form stable systems after reconstitution in an aqueous medium.

Microbiological monitoring in fermented food systems

A threshold level of 10,000 CFU/g was defined as the limit for microbial contamination beyond which the raw material would be considered unsatisfactory for further technological processing. The microbial load below this threshold was not a critical risk for the stability of the fermentation process. The values of indicators at the level of or below the threshold level testify to the controlled state of microflora and compliance with basic sanitary requirements. However, exceeding this level may affect the competitive interaction of microorganisms during fermentation, which decreases the predictability of biotechnological reactions. Thus, the limit of 10,000 CFU/g is sufficient to guarantee stable initial conditions for the application of starter cultures or probiotic strains. A limit level of 50,000 CFU/g was considered as critical. Above this limit the raw material sanitary conditions were considered unacceptable. Concentrations equal to or higher than this threshold showed a significant increase in the microbial population and the potential to disrupt microbiological equilibrium. In the domain of fermentation technologies, it was a threat of the dominance of undesirable microflora which could influence the quality of the final product. Likewise, high levels of contamination made it difficult to predict the metabolic activity of the target cultures, since foreign microorganisms could compete for nutrient substrates. The 50,000 CFU/g limit allowed for the clear separation of batches of raw material according to safety criteria, which helped in decisions on their technological suitability.

The proportion of positive cases for first- and second-generation aminoglycosides was 46.7%, reflecting how frequently the corresponding traits were detected among the analysed isolates. This level indicates a high prevalence of the relevant characteristics in the microbial population of the studied raw material. This is significant for fermentation technologies since resistant strains could affect the course of biochemical processes and the effectiveness of selective microflora control. Furthermore, it emphasised the importance of introducing standardised criteria for selecting raw materials in order to minimise the risk of undesirable microbial interactions. Adhering to the threshold level of 10,000 CFU/g ensured the predictability of target culture development, while preventing the limit level of 50,000 CFU/g from being exceeded minimised the risk of microbiological instability. Taking into account the proportion of positive cases (46.7%) also made it possible to assess the potential structure of the microbial community and its influence on the biotechnological cycle (Table 5).

Table 5. *Safety standards in fermentation production systems*

Indicator	Value	Note
Samples with psychrotrophic microflora >5 × 10^4 CFU/g were more numerous	2.6 times	Demonstrated the predominance of cold-resistant microorganisms in the contamination structure. Indicated the risk of their activation during refrigerated storage
Threshold for comparing psychrotrophs in the conclusion	5 × 10^4 CFU/g	Defined the critical limit for assessing microbial load. Indicated the standardisation of criteria for interpreting results
Sampling plan (n)	n = 5	Demonstrated the use of a regulated sample for batch control. Indicated the representativeness of sanitary-condition assessment
Permitted number of "marginal" samples (c)	c = 3	Demonstrated the acceptable level of variability of indicators within the sample. Indicated control of permissible deviations from the standard
Threshold level (m)	m = 10,000 CFU/g	Defined the limit of microbiological stability of the raw material. Indicated the permissible level of contamination for further technological processing
Limit level (M)	M = 50,000 CFU/g	Demonstrated the critical concentration of microflora requiring corrective measures. Indicated the limit of batch unacceptability
Proportion of positive cases: first- and second-generation aminoglycosides	46.7 ± 0.7%	Demonstrated the prevalence of the corresponding characteristics among isolates. Indicated the need to take this factor into account when selecting starter cultures
Proportion of positive cases: nalidixic acid	19 ± 0.2%	Demonstrated the presence of specific properties in part of the microbial population. Indicated the need for additional monitoring of microorganism susceptibility

Source: *compiled by the authors based on M. Kukhtin & Z. Malimon (2024)*

The results obtained demonstrated that microbiological safety not only served as a sanitary criterion, but also as a key technological prerequisite for predictable fermentation processes. The initial microbial composition of the raw material directly determined the nature of interspecies interactions, the rate of development of starter cultures and the direction of metabolic transformations. Controlled contamination levels ensured the dominance of target microorganisms, resulting in the desired organoleptic and physicochemical profile. On the other hand, exceeding the established limits, could cause a competition displacement of the technological cultures, modification of acid accumulation and development of undesirable metabolites. Adherence to regulatory limits and regular monitoring of microbial composition allowed consistent initial conditions for fermentation. A regulated approach to sampling, interpreting indicators and making decisions of batch suitability minimised variability in the results. This enhanced the reproducibility of biochemical processes, particularly the hydrolysis of proteins, the formation of organic acids, and the development of textural properties. Controlling the microbial load also decreased the chances of a secondary microflora developing, which might affect product preservation during subsequent storage.

Changes in product quality characteristics under microwave exposure

The reduction in mesophilic aerobic bacteria was 2.8-3.5 log CFU/g, which indicates the intensity of the effect of the electromagnetic field on microbial cells. This degree of reduction indicates disruption of the cell membranes and intracellular structures of microorganisms under the influence of rapid heating and uneven energy distribution in the aqueous medium of the tissue. The treatment reduced the number of viable microorganisms without the need for long thermal loading, thus limiting the development of secondary microbiological processes during further storage. The vitamin retention was estimated at 75-88%, which indicates the degree of conservation of thermolabile components. This is due to the shorter time of thermal exposure and absence of long contact with water, which generally causes leaching of water-soluble compounds. The microwave heating conditions have minimised diffusion losses, since the heating was mainly through internal energy absorption and not through heat transfer from the external environment.

The retention of omega-3 fatty acids was determined to study changes in fatty acid composition, which was 85-92% of the original proportion. This indicated limited oxidation of lipid fraction during processing. The shorter heating time and the lack of prolonged contact with oxygen reduced the possibilities of oxidative reactions, which usually lead to the destruction of polyunsaturated fatty acids. Thus, the lipid complex was preserved with a higher level of structural stability than traditional heat treatment methods. The textural properties of the product were not significantly altered after treatment, indicating that the muscle fibres were not disrupted. Uniform heating throughout the entire volume of the product prevented the formation of temperature gradients between the surface and the internal layers. Therefore, there was no local overheating or overdrying of the tissue, which could have resulted in compaction or destruction of the protein matrix. The

retention of elasticity and structural density shows the control of the thermal effect. The processing time was reduced, which also led to limited product mass losses. The rapid energy transmission into the interior of the product preserved the moisture in the tissue and decreased the intensity of evaporation from the surface. This helped to retain juiciness and prevented the formation of an overly dry texture (Table 6).

Table 6. *Assessment of the effect of microwave treatment on product quality*

Indicator	Microwave treatment	Boiling	Blanching
Reduction in mesophilic aerobic bacteria, log CFU/g	2.8-3.5	2-2.6	1.5-2.1
Vitamin retention, %	75-88	55-70	60-75
Omega-3 fatty acid content, % of initial level	85-92	70-85	75-88
Product mass loss, %	4-8	10-18	8-14
Textural characteristics, density, arbitrary units	4.2-4.8	3.5-4.2	3.8-4.5
Processing duration, min	3-8	15-25	5-10

Source: *compiled by the authors based on formulas (5-6)*

Thus, the results of the study confirmed that microwave treatment simultaneously reduced the microbial load and preserved the biologically active components while maintaining the structural integrity of the food raw materials. It was established that exposure to the electromagnetic field promoted the rapid heating of the product's internal layers without forming significant temperature gradients, thereby limiting local overheating and tissue damage. The obtained data reflected the specific nature of microwave heating, consisting of combining a short-term thermal effect with minimising destructive changes to the product's protein and lipid systems. In particular, the preservation of protein functionality and lipid stability occurred due to the shortened thermal exposure duration and limited oxidative processes. This type of treatment preserved internal moisture, stabilised textural characteristics and reduced nutrient losses.

Lipid composition formation under supercritical extraction conditions

The extraction yield was 15-25%, reflecting the intensity of mass transfer between phases and the effectiveness with which carbon dioxide interacted with the components of the raw material. This level of extraction indicated penetration of the extractant into the tissue's microstructure and the uniform extraction of lipid components, without residual zones of unextracted material forming. Formation of a stable yield was associated with process conditions in which the density of the supercritical fluid provided sufficient solvating capacity for non-polar compounds. The fatty acid composition was characterised by an eicosapentaenoic acid content of 12-20%, reflecting the concentration of polyunsaturated fatty acids in the extract's structure. This demonstrated the selectivity of the process towards individual fatty acid groups, which were preserved without signs of thermal degradation. Meanwhile, the docosahexaenoic acid content remained stable, confirming the absence of significant destructive effects during extraction. This stability can be attributed to the inertness of the medium and limited contact with oxygen.

The tocopherol concentration was 20-45 mg/100 g, which reflected the accumulation of natural antioxidants in the lipid fraction. The presence of these compounds indicates that temperature- and oxygen-sensitive components are preserved, which is related to the process conditions without intensive heating. The extract also contained carotenoids, which confirms that the technology is able to extract pigment compounds without changing their chemical structure. The antioxidant activity determined by the DPPH test using the IC50 value was in the range of 0.4-0.9 mg/ml. This corresponds to the functional ability of extract to interact with free radicals. This is evidence of the formation of an antioxidant complex, the activity of which is manifested in the inhibition of radical reactions. This activity was associated with the interaction of tocopherols and carotenoids. The analysis of combined indicators revealed that supercritical CO_2 extraction provided formation of the stable, functional lipid extract. This process was characterised by the uniform extraction of components without major structural modifications, which was different from conventional procedures using high temperatures or organic solvents (Table 7).

Table 7. *Assessment of the efficiency of supercritical extraction and lipid composition*

Indicator	Value	Note
Extraction yield, % of raw-material mass	8-15	Reflected the efficiency of lipid-fraction extraction and completeness of raw-material utilisation
Eicosapentaenoic acid (EPA) content, % of total fatty acids	12-20	Demonstrated the concentration level of polyunsaturated fatty acids in the extract

Table 7, Continued

Indicator	Value	Note
Docosahexaenoic acid (DHA) content, % of total fatty acids	15-25	Confirmed the preservation of biologically valuable components during extraction
Tocopherol concentration, mg/100 g	20-45	Indicated the presence of natural antioxidants in the obtained product
Carotenoid concentration, mg/100 g	3-10	Reflected the content of pigment compounds with antioxidant properties
Antioxidant activity, IC50, DPPH, mg/ml	0.4-0.9	Demonstrated the ability of the extract to neutralise free radicals

Source: *compiled by the authors based on formulas (5-7)*

Thus, the results of the study confirmed that supercritical CO_2 extraction provided a combination of effective lipid-fraction extraction and preservation of biologically active components. The process was accompanied by uniform mass transfer between phases and selective extraction of target compounds without disrupting their chemical structure, which was due to the inertness of the medium and limited thermal exposure. It was established that the obtained extract was characterised by compositional stability, the absence of signs of intensive oxidative transformations and preservation of the functional properties of its components. The formation of these characteristics occurred due to controlled process parameters that ensured a coordinated combination of the solvating capacity of the fluid and the stability of the extracted compounds. This course of extraction confirmed the possibility of obtaining a product with a preserved fatty-acid profile and stable physicochemical properties, creating prerequisites for its further use in food technologies without additional stabilisation stages.

DISCUSSION

The results obtained confirmed the feasibility of using non-thermal technologies to stabilise protein raw materials in a controlled manner. Determining the threshold level of hydrostatic impact at which microbiological stability was achieved without noticeable changes in texture showed that it is possible to combine sanitary safety with preserving consumer properties. The significant decrease in mesophilic microflora in European seabass fillets (*Dicentrarchus labrax*) showed the selective impact of high hydrostatic pressure on microbial cellular structures while preserving muscle protein stability. Separating the oyster muscle from the valve using this technology expanded the method's functional capabilities by combining sanitary treatment with optimisation of primary processing. Ultrasonic intensification revealed a distinct mechanism of action aimed at activating mass transfer and diffusion processes. Forming a controlled cavitation effect in a liquid medium increased tissue permeability without destroying it. Optimising the treatment duration promoted the uniform distribution of functional components throughout the muscle fibres' thickness and enabled the technological cycle to be shortened without loss of quality. The absence of signs of excessive softening or structural rearrangement confirmed the functional nature of the acoustic effect.

In the context of microbiological stability in aquaculture, P.K. Sarker (2023), and I. Mohd & S.T. Mushtaq (2025) examined safety and productivity issues in the fish sector. However, they did not integrate non-thermal technologies into the processing structure. P.K. Sarker examined the role of microorganisms in feed and technological strategies for preventing contamination during the rearing stage, emphasising the importance of biosecurity in aquaculture. However, the mechanisms of post-slaughter stabilisation of muscle tissue and the influence of physical factors on protein structure were not analysed. Meanwhile, I. Mohd & S.T. Mushtaq concentrated on enhancing productivity and food security by expanding aquaculture practices; however, the technological aspects of preserving fillet quality were not given detailed consideration. In the present study, safety was considered at the processing stage by establishing threshold hydrostatic impact regimes to ensure microbiological stabilisation without disrupting texture. Unlike the cited works, this study substantiated the selectivity of pressure effects on microbial cells while preserving the protein-water matrix, combining sanitary and structural quality criteria.

D.L. Chan *et al.* (2024) and F.R. Cedeno *et al.* (2025) examined innovations in cellular and fermentation-based production in the field of alternative protein systems without comparison to traditional raw materials. D.L. Chan *et al.* explored in detail the technical, commercial and regulatory barriers to the development of the cellular agri-industry for seafood, focusing on such issues as bioreactor scaling, medium standardisation and the regulatory control of new products. Meanwhile, microbial proteins and cultivated meat have been described as promising sustainable alternatives by F.R. Cedeno *et al.* who emphasised on the

climate and resource-saving benefits of fermentation approaches. However, these studies did not provide a comparative evaluation of natural muscle tissue after physical impact that could enhance safety without a total redesign of the product. This work confirms the possibility of intensification of technological processes without violation of the morphological integrity of fibres and stability of the protein matrix. This approach shows the advantage of the evolutionary improvement of traditional raw materials over their radical replacement, combining safety, functionality, and preservation of natural characteristics.

In the field of seafood preservation, the work of A. Rabiepour *et al*. (2024) and T. Yi-Li *et al*. (2025) summarised methods for extending shelf life, but did not detail the structural selectivity of physical impacts. A. Rabiepour *et al*. categorised contemporary preservation techniques, such as chilling, modified atmospheres, and combined barrier technologies. However, isostatic compression was primarily considered as a potential option, without providing a detailed morphological analysis of the tissue. T. Yi-Li *et al*. analysed tuna processing in terms of nutritional value, safety, and prospects for industry development, paying particular attention to traditional thermal and packaging solutions. This study not only demonstrated the stabilisation of microbiological indicators, but also the preservation of the textural organisation of fillets and the controlled changes to the optical properties of bivalve molluscs. Additionally, combining high hydrostatic pressure with ultrasonic intensification of mass transfer was found to have a synergistic effect, ensuring a reduction in the technological cycle without disrupting the protein-water structure. This integrated model goes beyond descriptive storage approaches to form a comprehensive quality management system.

In the field of processing waste from the fish industry, the work of K.K. Krishnani *et al*. (2022) and A. Vaishnav *et al*. (2025) examined the valorisation of secondary raw materials, but did not focus on the structural stability of food products. K.K. Krishnani *et al*. analysed the possibility of obtaining metallic and non-metallic nanoparticles from animal- and fish-derived waste, emphasising the environmental benefits of reusing these materials. However, their work mainly focused on agrotechnological applications and did not examine the preservation of muscle tissue or the microbiological safety of food products in detail. A. Vaishnav *et al*., meanwhile, focused on fish protein hydrolysates as ingredients for the food and non-food sectors, emphasising the functional properties of peptide fractions. However, the structural integrity of the primary raw material before hydrolysis was not analysed. The present study combines valorisation with stabilising natural tissue through non-thermal effects to ensure the preservation of sensory characteristics prior to further processing. This approach creates a more comprehensive technological process, from safe stabilisation to functional application.

In the context of the biotechnological valorisation of marine by-products, the work of S.A. Siddiqui *et al*. (2025) and A. Rahman *et al*. (2025) summarised fermentation and processing strategies without integrating physical intensification methods. S.A. Siddiqui *et al*. examined fermentation approaches for extracting valuable nutrients from seafood waste, with a focus on biochemical transformation mechanisms. A. Rahaman *et al*. described the range of applications for marine by-products following technological processing, with a focus on the circular economy. However, neither study analysed the preliminary stabilisation of the raw material in terms of its selective effects on microflora and protein complexes. The present study combines hydrostatic treatment and ultrasonic intensification to control microbial load and accelerate mass transfer. This integration improves the quality of the initial raw material prior to fermentation or hydrolytic stages, thereby expanding the practical suitability of the technological model.

In the field of future protein system transformations, the work of S. Albrektsen *et al*. (2022) and A. Chandrababu & J. Puthumana (2024) set out the potential for alternative production methods, though neither study provided details on post-slaughter tissue stabilisation. A. Chandrababu & J. Puthumana analysed the potential of cellular and genetically modified systems to create the "future" of meat and seafood, with a focus on food security. S. Albrektsen *et al*. examined resources for sustainable feed production in salmon aquaculture, focusing on the raw material base. In both cases, the focus was on production or the biotechnological component, and the mechanisms of physical stabilisation of natural muscle tissue were not disclosed. This study demonstrated that applying controlled hydrostatic impact and acoustic intensification improves microbiological safety without compromising textural and sensory properties. This model does not replace the natural product, but improves its quality, making it more applicable to real production. The results confirmed the technological feasibility of using high hydrostatic pressure and ultrasonic intensification to improve microbiological safety without disrupting the morphological stability of muscle tissue. The selectivity of physical impacts on microbial cells while preserving the structural and functional properties of the protein matrix was also demonstrated. This approach

ensures optimisation of the technological cycle and improvement of product quality, forming an integrated model of modern fish raw material processing.

CONCLUSIONS

This study comprehensively analysed the effectiveness of modern physical and combined technologies for processing meat and fish raw materials in terms of microbiological stability, physicochemical quality, and technological feasibility. Assessment of high hydrostatic pressure regimes showed that applying 300 MPa inhibits vegetative microflora without thermal loading. In contrast, applying 400 MPa for five minutes to *Dicentrarchus labrax* fillets reduced mesophilic aerobic bacteria by 3.2 log CFU/g. For mussels, using 500 MPa for 2 minutes resulted in the formation of 91% Gram-positive microflora, confirming the selective nature of the effect. Complete oyster-muscle separation was achieved at 310 MPa; exceeding 300 MPa caused changes in colour characteristics. Ultrasonic treatment at frequencies between 25 and 40 kHz for 10-20 minutes produced the best conditions for cavitation effects. An average frequency of 32.5 kHz for 15 minutes balanced mass transfer intensity with tissue structure preservation. The potential reduction in marinating time was 50-67%, indicating intensification of the technological process. A study of packaged broiler chicken fillet samples after 10 days of storage showed that the moisture content of the control samples was 65.6%, whereas using two oxygen absorbers increased this to 68.9%. The pH value decreased from 6.89 to 6.59 when two absorbers were used, indicating stabilisation of the biochemical state.

The water-binding capacity increased from 69.54% to 71.74%, which confirms an improvement in the functional properties of the protein structures. During the drying of the fish protein concentrate, the moisture content was found to be 9% at 100°C and 10% at 70°C, while the protein mass fraction reached 66.7% under moderate conditions. A water-absorption coefficient of 4.9 characterised the powder's high hydration capacity. A sampling plan of n = 5 and criteria of m = 10,000 and M = 50,000 CFU/g was used for microbiological control, making it possible to standardise safety assessment. The proportion of isolates with characteristics related to aminoglycosides was 46.7%, compared to 19% for nalidixic acid, which highlights the importance of considering the microbial profile during subsequent fermentation. Additionally, it was established that microwave treatment reduced the microbial load to 3.5-4.2 log while preserving up to 75-88% of nutrients, whereas supercritical extraction was characterised by a lipid yield of 12-15% with a high content of biologically active components.

The study's limitations are associated with the use of defined physical processing regimes and a limited number of raw material types, which restricts the generalisation of the obtained results to other food systems. Further research should focus on expanding the range of raw materials, optimising combined processing regimes, conducting long-term assessments of changes during storage, and providing technical and economic justifications for the industrial implementation of these technologies.

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Інноваційні підходи до переробки м'яса, риби та морепродуктів для підвищення ефективності аграрного виробництва

Олена Петрова
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-8612-3981

Наталя Шевчук
Доктор філософії, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-5845-2582

Руслан Трибрат
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-6710-570X

Лариса Агунова
Кандидат технічних наук, доцент
Одеський національний технологічний університет
65039, вул. Канатна, 112, м. Одеса, Україна
https://orcid.org/0000-0002-6708-7396

Євген Баркарь
Кандидат сільськогосподарських наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-0692-5392

Анотація. Метою дослідження була оцінка ефективності інноваційних технологічних рішень для підвищення мікробіологічної безпеки, підтримки якості та раціонального використання сировини. У дослідженні використано методи високого гідростатичного тиску, низькочастотної ультразвукової обробки, активного та модифікованого газового пакування, термічної обробки (мікрохвильова обробка, варіння, бланшування), а також культуральні, хроматографічні, спектрофотометричні та гравіметричні методи аналізу показників якості і безпечності сировини. Вплив високого гідростатичного тиску інтерпретовано як селективну інактивацію

мікрофлори без вираженої денатурації білків. Було визначено, що рівень 300 МПа забезпечує санітарну стабілізацію охолодженої продукції, тоді як посилений режим 400 МПа × 5 хв для філе дорадо забезпечує зниження мезофільної аеробної мікрофлори до 3,2 log КУО/г зі збереженням текстурних властивостей. Для двостулкових молюсків технологічно значущим рівнем для повного відділення м'язів від панцира без будь-якого механічного втручання було 310 МПа. Були розраховані можливості інтенсифікації низькочастотним ультразвуком (25-40 кГц) для забезпечення контрольованої інтенсифікації кавітації та масообміну. Робоча частота 32,5 кГц та тривалість 15 хв забезпечили скорочення часу маринування рибного філе на 50-67 % без ознак структурного руйнування. Дослідження активної упаковки та модифікованої газової атмосфери виявило стабілізацію фізико-хімічних показників протягом 10 днів зберігання: вміст вологи 65,6-68,9 %, зниження pH до 6,59, водозв'язуюча здатність 71,74 %, що свідчить про збереження функціональної активності білкової матриці. Сушіння рибної сировини дозволило отримати білковий концентрат з вмістом вологи 9-10 % та масовою часткою білка до 66,7 %, коефіцієнт водозв'язуючої здатності 4,9 показав високий гідратаційний потенціал порошку. Мікрохвильова обробка забезпечила зниження мікрофлори до 3,5-4,2 log із кращим збереженням нутрієнтів. Суперкритична екстракція характеризувалася виходом ліпідів до 12-15 % та високою якістю екстракту. Результати можуть бути використані в м'ясо та рибопереробній промисловості для підвищення безпеки, стабільності та ефективності процесів переробки сировини

Ключові слова: санітарний стан; білкові фракції; процес ферментації; вологозв'язувальна здатність; частка білка

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Formation of management mechanisms for rural development under martial law and European integration

Alona Kliuchnyk*
Doctor of Economic Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-6012-6666

Iryna Kormyshkina
PhD
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0009-0002-9670-2295

Nataliia Galunets
Senior Lecturer
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0001-7709-9238

Anzhela Husenko
Senior Lecturer
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0000-0002-3989-2400

Oleh Kryvko
Postgraduate Student
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
https://orcid.org/0009-0009-3063-7524

Abstract. The purpose of the study was to assess the financial, organisational, and institutional parameters of management in view of external challenges and to determine their adaptive potential. The study used methods of structural and functional analysis of budget indicators, ratio and relative analysis, aggregation and grouping of statistical data, normalisation and integral indexing, and descriptive statistics. Assessment of the financial base showed that local budget revenues of UAH 679.5 billion formed a basic resource platform, while the revenue structure, dominated by own-source revenues at 72.3%, increased decision-making autonomy. The financial stability coefficient of 0.64 summarised the capacity of the system to maintain stability in a changing environment. The organisational component of management was characterised through the number of territorial communities, which described the scale of the spatial coverage of the system and the distribution of management

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*Corresponding author (alonakliuchnyk@outlook.com)

functions between administrative units. Strategic planning covered approximately 91.4% of communities, while the institutional capacity index of 0.54 reflected an average level of consistency between structural elements. Organisational parameters also covered the management of land resources and agricultural infrastructure. Analysis of development showed substantial capital expenditure of UAH 145.8 billion, reflecting an orientation towards forming a material base. The structure of budget expenditure demonstrated the priority of the social component and support for economic activity, which created conditions for meeting basic needs and supporting development. The integral index of 0.59 summarised the effectiveness of management influences. At the regional level, budget revenues of UAH 4.36 billion formed the basis for the functioning of the system, while the 1.6% share of the special fund reflected limited targeted financing. For Mykolaiv Oblast, this was combined with the significance of the agricultural sector in the revenue base. The practical value of the study lies in the possibility of using its results by local self-government bodies, state institutions, and regional authorities to improve budget planning, increase the efficiency of financial resource allocation, and strengthen the institutional capacity of management

Keywords: rural development; management; financial stability; European integration; security conditions; martial law

INTRODUCTION

The relevance of this study is determined by the need to reconsider approaches to managing rural development under the simultaneous influence of security threats and European integration processes, which transform the financial, institutional, and organisational mechanisms through which territorial communities' function. The current stage of development is characterised by changes in budget policy priorities, the growing role of local self-government, and the need to adapt management decisions to an unstable external environment. Under these conditions, evaluation of the financial capacity of communities, the effectiveness of organisational structures, and the performance of territorial development management becomes especially important, as it helps determine their capacity for stable functioning and recovery. The problem under study is shaped by structural disproportions in the rural management system, the insufficient level of financial autonomy of some communities, uneven institutional capacity, and limited resources allocated to development. The influence of war-related risks is another factor, leading to contraction of the revenue base, changes in the structure of expenditure, and reorientation of budget policy towards stabilisation measures. European integration processes also create new requirements for management related to greater transparency, efficiency, and compliance with European standards, which requires adaptation of existing mechanisms and the formation of new approaches to rural development.

In the context of restoring agricultural infrastructure, A. Kliuchnyk *et al*. (2025) considered the role of local communities in rebuilding production facilities, logistics, and land resources after destruction. The paper underlined the need for financial support, partnership mechanisms, and coordination between communities, state structures, and donor organisations. From the perspective of public administration, A. Kliuchnyk *et al*. (2023) examined the functioning of territorial communities of Ukraine during the war and post-war periods. The research highlighted the importance of adapting powers, coordinating with military administrations, and implementing comprehensive recovery programmes.

Within the modelling of community recovery, V. Shebanin *et al*. (2025) analysed the formation of comprehensive approaches to territorial development in the context of sustainable agricultural development. The conclusions emphasised the expediency of strategic planning, population involvement, targeted support funds, and the introduction of modern agricultural practices. In relation to digital transformations, D.K. Das (2024) addressed the relationship between infrastructure, management, and the quality-of-service delivery. The paper substantiated the role of digital technologies as a tool for improving the performance of management processes in territorial systems.

In the field of public administration modernisation, J. Millard (2023) defined the influence of digitalisation on the transformation of management structures. The results outlined digital solutions as a factor in improving management transparency and efficiency. From the perspective of institutional constraints, Z. Irani *et al*. (2023) discussed the influence of legacy systems on digital transformation processes in the public sector. The study established that technological barrier limit the speed of innovation implementation and require renewal of management infrastructure.

In the field of social innovation, F. Navarro-Valverde *et al*. (2022) considered mechanisms of neo-endogenous

rural development in EU countries. The significance of local initiatives and the integration of internal and external resources was established as factors increasing the effectiveness of territorial development. In the context of institutional development, R.D. Kelemen & K.R. McNamara (2021) investigated state-building processes in the EU through the lens of economic and political transformations. Uneven institutional development was defined as a factor influencing the performance of territorial management.

From the perspective of digital technologies, E.M. Ouafiq *et al*. (2022) addressed data management and the integration of low-power Internet of Things (IoT) devices in smart farming systems. The results showed that combining sensor technologies with data-processing systems helped transform information into practically oriented management decisions. The results confirmed the key role of digitalisation in increasing the efficiency of management systems. In the field of agri-food policy, T. Reinhardt (2022) assessed the influence of the Farm to Fork strategy on the transformation of the agricultural sector. The importance of innovative approaches for forming modern mechanisms for managing agri-food chains was demonstrated.

Within research on rural transformation, Y. Liu *et al*. (2022) analysed rural revitalisation processes through industrial change under globalisation. The role of structural changes in production as a factor activating territorial development was identified. In relation to technological innovation, M. Van Hilten & S. Wolfert (2022) considered the influence of 5G technology implementation on the agri-food sector. The potential of digital infrastructure to improve management efficiency and optimise production processes in rural areas was highlighted. The comprehensive combination of financial, institutional, and security factors in the management of rural areas under European integration transformations and their influence on the adaptive capacity of territorial communities remains insufficiently addressed.

The study aimed to provide a comprehensive assessment of the financial, organisational, and institutional mechanisms for managing development in Ukraine under the influence of security threats and European integration transformations, and to determine their functional capacities and directions of adaptation. The objectives of the study were to analyse the financial base and organisational structure of management, assess development performance within the management system, and determine the specific features of functioning under security challenges and transformations.

MATERIALS AND METHODS

Characteristics of the conditions and parameters for assessing the management system

The study was conducted using financial-economic and organisational indicators of the functioning of the rural management system of Ukraine for 2020-2025, with the regional level distinguished through the example of Mykolaiv Oblast (Ukraine). Analytical generalisation, processing, and interpretation of indicators were conducted within the research area of territorial development management systems, using structured approaches to the analysis of budgetary and institutional parameters. The paper analysed official statistical and financial data on local budget revenues and expenditure, the structure of budget resources, financial stability indicators, the institutional capacity of territorial communities, and integral characteristics of rural development. These indicators were selected because they reflect key parameters of the functioning of the management system, are available in open state sources, and can be processed using standardised methods of quantitative analysis, which ensured correct comparison of the results. The study covered the national level of Ukraine and the regional level through the example of Mykolaiv Oblast, which enabled territorial differences in the formation of financial and management mechanisms to be considered. Conditions affecting the functioning of the management system in the context of security threats and European integration transformations were considered separately, which enabled interpretation of the results in view of external factors. During the study, internationally recognised ethical principles of scientific activity were followed, in particular, academic integrity, transparency, reproducibility of results, and prevention of data manipulation in accordance with the recommendations of the Committee on Publication Ethics (2026). Data processing and interpretation were carried out objectively, without selective presentation of results, and in compliance with the principles of openness and accessibility of the information sources used.

Resource base for managing the socio-economic development of rural areas of Ukraine

Indicators of local budget revenues and tax revenues were defined using official materials of The Accounting Chamber (2025). The share of transfers, the share of the development budget, and the average community budget were determined using official statistical data, structural analysis, the method of averages, and tabular generalisation in Microsoft Excel (USA), as these indicators were used to describe the general configuration of the financial system. The share of own-source

revenues was defined as the ratio of own revenues to total budget revenue (formula (1)):

$$S_{own} = \frac{D_{own}}{D_{total}} \times 100\%, \quad (1)$$

where S_{own} – the share of own-source revenues, %; D_{own} – the amount of own-source revenues of local budgets, UAH; D_{total} – the total amount of local budget revenues, UAH. Calculations were performed in Microsoft Excel (USA) using structural analysis tools, which ensured the correct determination of the share of financially autonomous resources. The resulting value was used to characterise the relationship between internal sources of budget formation and the total amount of financial resources. The financial stability coefficient was defined as the ratio of own-source revenues to expenditure (formula (2)):

$$K_{st} = \frac{D_{own}}{E}, \quad (2)$$

where K_{st} – the financial stability coefficient (dimensionless); D_{own} – own-source budget revenues, UAH; E – total budget expenditure, UAH. Assessment was conducted in Statistica 12.0 (USA) using ratio analysis. A conditional scale was used to interpret the financial stability coefficient: values up to 0.30 were regarded as low, values within 0.31-0.60 – as medium, and values above 0.60 – as relatively high. This distinction was applied to compare the relationship between own-source revenues and total budget expenditure.

Institutional support system for rural management in Ukraine

The number of territorial communities was determined using data from the official Portal "Decentralisation" (n.d.), and the average general-fund revenue per resident was determined using analytical materials by Ya. Kazyuk & V. Ventsel (2025). The average community size, share of management expenditure, and share of communities with low capacity were determined through aggregation of statistical data, functional grouping of expenditure, and statistical grouping in the International Business Machines Statistical Package for the Social Sciences (IBM SPSS Statistics) (USA) and Microsoft Excel (USA). The share of communities with development strategies was defined as formula (3):

$$S_{approved} = \frac{N_{approved}}{N_{total}} \times 100\%, \quad (3)$$

where $S_{approved}$ – the share of communities with development strategies, %; $N_{approved}$ – the number of communities with strategies; N_{total} – the total number of communities. Calculations were performed using the method of relative indicators in SPSS, which enabled assessment of the level of strategic planning implementation. The institutional capacity index was defined as an integral indicator (formula (4)):

$$I = \sum w_i x_i, \quad (4)$$

where I – the integral index; w_i – the weight coefficient of the indicator; x_i – the normalised value of the indicator. Normalisation was performed using the min-max method in Statistica 12.0, which ensured comparability of heterogeneous indicators. The conditional division for the institutional capacity index was as follows: values up to 0.30 were regarded as low, values within 0.31-0.50 – as medium, and values above 0.50 – as a higher level of capacity. This approach was applied to arrange heterogeneous organisational characteristics within a single integral indicator.

Management of rural development in the national system of Ukraine

Capital expenditure and non-tax revenues were determined using official data from The Accounting Chamber (2025). At the national level, the object of the study covered 627 rural territorial communities, representing 42.7% of the total number of territorial communities of Ukraine. The share of infrastructure expenditure, social expenditure, and expenditure on economic activity was established through functional grouping of budget items and descriptive statistics in IBM SPSS Statistics (USA) and Microsoft Excel (USA), as these indicators were used in the results section to explain the structure of budget priorities. The share of investment in budgets was defined as formula (5):

$$S_{inv} = \frac{I}{E_{total}} \times 100\%, \quad (5)$$

where S_{inv} – the share of investment, %; I – investment expenditure, UAH; E_{total} – total expenditure. The calculations were performed in Microsoft Excel (USA) using structural analysis. The calculated indicator served as the basis for assessing the share of the investment component in the overall system of budget expenditure. The territorial development index was defined as formula (6):

$$I_{dev} = \frac{x - x_{min}}{x_{max} - x_{min}}, \quad (6)$$

where I_{dev} – the development index (0-1); x – the actual value of the indicator; x_{min} and x_{max} – the minimum and maximum values. Normalisation was performed in Statistica 12.0 (USA). The conditional division for the territorial development index was as follows: values

up to 0.30 were regarded as low, values within 0.31-0.59 – as medium, and values above 0.59 – as a higher level of development. In this form, the index was used to integrate different performance characteristics into a single scale for subsequent comparison.

Regional rural management system of Mykolaiv Oblast

The regional block was introduced as an in-depth example that specified national trends through local budgetary parameters and allowed the general model to be compared with a regional case. Community budget revenues and special-fund budget revenues were determined using official materials of the Finance Department of the Mykolaiv City Council (n.d.). The resource concentration coefficient, budget flexibility index, and community development coefficient were defined using regional budget data in Statistica 12.0 (USA), Microsoft Excel (USA), and elements of variation analysis. A single conditional scale was used for the coefficient of programme orientation of the budget, the budget flexibility index, and the community development coefficient: values up to 0.30 were regarded as low, values within 0.31-0.60 – as medium, and values above 0.60 – as high. This division was applied to place regional coefficients on a common basis for comparison and to ensure their uniform interpretation in the analytical block. The share of the special fund was calculated as the ratio of special-fund resources to total budget revenues (formula (7)):

$$S_{spec} = \frac{F_{spec}}{D_{total}} \times 100\%, \quad (7)$$

where S_{spec} – the share of the special budget fund, %; F_{spec} – the amount of special-fund budget revenues, UAH; D_{total} – the total amount of community budget revenues, UAH. The calculation was performed in Microsoft Excel (USA) using structural analysis tools, which enabled the relationship between general and targeted financing within the budget to be determined. The coefficient of programme orientation of the budget was defined as the ratio of programme-structured expenditure to total expenditure (formula (8)):

$$K_{prog} = \frac{E_{prog}}{E_{total}}, \quad (8)$$

where K_{prog} – the coefficient of programme orientation of the budget (dimensionless); E_{prog} – the amount of expenditure implemented within budget programmes, UAH; E_{total} – the total amount of budget expenditure, UAH. The calculation was performed using ratio analysis in IBM SPSS Statistics (USA), which enabled the degree of consistency between budget planning and the programme-target approach to be assessed. The interpretation used the following scale: above 0.7, a substantial level of programme-approach application; 0.4-0.7 – medium; below 0.4 – limited. This scale enabled the degree of programme structuring of expenditure to be related to the general configuration of the budget process at the regional level. In this form, the index was used to integrate different performance characteristics into a single scale for subsequent comparison.

Specific features of territorial development management under security challenges and European integration in Mykolaiv Oblast

Community budget expenditure and the general-fund budget surplus were determined using official data from the Finance Department of the Mykolaiv City Council (n.d.). The decline in community revenues, the rate of revenue change, the share of recovery expenditure, and the share of grant financing were determined through time-series analysis, trend analysis, functional grouping of expenditure, and structural analysis of the revenue side in Microsoft Excel (USA) and IBM SPSS Statistics (USA). The share of stabilisation expenditure was defined as the share of expenditure aimed at maintaining the functioning of the system in total expenditure (formula (9)):

$$S_{stab} = \frac{E_{stab}}{E_{total}} \times 100\%, \quad (9)$$

where S_{stab} – the share of stabilisation expenditure, %; E_{stab} – expenditure on maintaining functioning (stabilisation), UAH; E_{total} – the total amount of budget expenditure, UAH. The calculation was performed using structural analysis in Microsoft Excel (USA). The resulting value was used to quantify the place of stabilisation expenditure in the system of budget priorities under external pressure.

RESULTS

Local budget revenues characterised the basic level of financial support for the rural management system and reflected the scale of resources accumulated at the level of territorial communities. Together with other financial parameters, they formed a general understanding of the resource base for the functioning of the management system (Table 1).

Table 1. *Financial base of the rural management system (Ukraine)*

No.	Indicator	Value
1	Local budget revenues	UAH 679.5 billion
2	Tax revenues of local budgets	UAH 441.1 billion

Table 1, Continued

No.	Indicator	Value
3	Share of own-source revenues	72.3%
4	Share of transfers	27.7%
5	Share of the development budget	≈21-22%
6	Average community budget	UAH 0.46 billion
7	Financial stability coefficient (dimensionless)	0.64

Note: *the financial stability coefficient was calculated in Statistica 12.0 (USA) using ratio analysis to assess the relationship between budget revenues and expenditure*
Source: *compiled by the authors based on The Accounting Chamber (2025)*

The total amount of UAH 679.5 billion corresponded to a significant concentration of financial flows within the decentralised model, which pointed to the important role of the local level in resource redistribution compared with individual components of the budget system. This amount was associated with the possibility of covering current management expenditure, but it did not provide grounds for treating it as an independent indicator of efficiency without considering the structure of expenditure and revenue. The distribution of financing sources characterised the relationship between operational activity and the investment component, reflecting the general configuration of budget policy. The scale of the financial base suggested a high level of resource mobilisation within the national economy, which could point to the potential for reproducing financial flows without substantial involvement of external sources. For communities with a pronounced agricultural specialisation, this revenue structure could reflect substantial dependence on local economic activity, including farms, agricultural enterprises, and the use of agricultural land. In this context, the predominance of own-source revenues was associated not only with budget autonomy but also with reliance on the agricultural sector as one of the basic sources of revenue. However, the data provided no grounds for quantifying the exact share of revenue formed directly by agricultural activity, so this dependence was interpreted as a structural characteristic of the revenue base rather than a separately measured parameter. Growth in the share of own-source revenues was not treated as direct evidence of expansion of agricultural production at the local level, although it could be associated with expansion of the tax base of communities, including through land use, lease payments, and the activity of agricultural actors (The Accounting Chamber, 2025).

The share of own-source revenues in the structure of local budgets characterised the level of financial autonomy of territorial communities and their degree of independence in management decision-making. The value of 72.3% corresponded to the predominance of internal sources of budget formation over transfer revenues, distinguishing the system from models with greater dependence on centralised financing. This structure was associated with the possibility of more flexible resource management, which could suggest increased adaptability to changes in the external environment. However, the dominance of own-source revenues was accompanied by differentiation in the financial capacity of communities, reflecting uneven access to resources within the system. The level of autonomy characterised the degree of dependence on centralised financial instruments, which was associated with differences in approaches to budget planning and the implementation of strategic programmes. Within such programmes, agricultural production in rural communities occupied the position of one of the basic directions of development because it was linked to the use of land resources, local employment, the functioning of farms, and the formation of the tax base. Growth in the share of own-source revenues was linked to the stronger role of local management decisions, but it did not eliminate structural imbalances in the system. This also suggested that the place of agricultural production in community development strategies was defined not as a secondary element but as one of the practical foundations of the financial self-sufficiency of rural areas. This coefficient also served as an indirect indicator of the sensitivity of local finances to the condition of the agricultural economy, as revenue stability was partly linked to the stability of land payments, employment in the agricultural sector, and the tax base of agricultural enterprises. A direct correlation between the financial autonomy of communities and the activity of farms or agricultural enterprises was not traceable in the available materials, but the relationship between own-source revenues, resource volume, and financial stability was associated with the possible influence of the agricultural sector on the formation of the local financial base (The Accounting Chamber, 2025).

The financial stability coefficient was used as a generalised indicator of the balance of the budget system and characterised the relationship between revenues and expenditure. The value of 0.64 corresponded to a

moderate level of stability, which indicated a basic capacity to maintain financial equilibrium in a changing environment. This level was associated with stability of functioning in the short term, but it did not ensure the elimination of imbalances in resource distribution between individual territories. The indicator integrated the characteristics of the revenue base, expenditure structure, and redistribution mechanisms, reflecting the general state of the financial system. Its value outlined the limits of maintaining continuity of management processes and characterised functional stability without confirming long-term efficiency (The Accounting Chamber, 2025). Generalisation of the results that the financial base of the management system was formed through the interaction of resource volume, the level of autonomy, and financial stability. These indicators were interconnected and reflected the configuration of financial support in which none of them acted as an independent determining factor. An increase in the resource base was not associated with an automatic increase in stability without changes in the revenue structure, while a high level of autonomy coexisted with uneven territorial development. Therefore, the effectiveness of the system was characterised not only by the amount of resources but also by the specific features of their distribution and adaptive capacity, reflecting the complex multilevel character of management. The agricultural component in this system was traceable not only through own-source revenues, land and tax payments but also through its place in the strategic orientations of communities, where agricultural production was combined with the development of land use, infrastructure, and the local economic base. This enabled agricultural production to be viewed as one of the system-forming elements of the financial and strategic basis of rural development.

Overall, the analysis distinguished the volume of the resource base, the share of own-source revenues, and the level of financial stability as key indicators that together reflected different aspects of the functioning of the financial system. The relationship between a substantial amount of resources and the dominance of internal sources characterised the relative financial independence of the system, while the level of stability reflected a limited balance without full equalisation of internal disproportions. The combination of these parameters showed that resource provision and autonomy were not accompanied by a corresponding level of stability, which reflected structural constraints in the distribution of financial flows. In this context, the financial system reflected a combination of substantial resource potential and heterogeneous use of that potential, which is directly related to the assessment of management effectiveness under transformations. The results support the conclusion that the key issue is not the amount of resources but their internal configuration and relationship with autonomy and stability indicators, which characterise the specific functioning of the management system under current conditions. The number of territorial communities characterised the administrative structure of the management system through the number of basic units within which decision-making, resource distribution, and management functions were conducted. Together with strategic planning and institutional capacity, it reflected the organisational structure of the system and the general conditions of its functioning (Table 2).

Table 2. *Organisational structure of territorial community management in Ukraine*

No.	Indicator	Value
1	Number of territorial communities	1,469
2	Average general-fund revenue per resident	≈UAH 8.1 thousand
3	Average community size	≈26 thousand people
4	Share of communities with development strategies	≈91.4%
5	Share of management expenditure	≈10-15%
6	Share of communities with low capacity	≈30%
7	Institutional capacity index	0.54

Note: *the share of communities with development strategies was determined using the method of relative indicators in IBM SPSS Statistics; the institutional capacity index was calculated after normalising indicators by the min-max method in Statistica 12.0, which ensured comparability of heterogeneous indicators*
Source: *compiled by the authors based on Portal "Decentralisation" (n.d.), Ya. Kazyuk & V. Ventsel (2025)*

During the study, the total number was 1,469, reflecting a considerable level of territorial division and decentralisation of management, with powers assigned to individual communities. This number presupposes the presence of coordination mechanisms between administrative units, since management processes were carried out not centrally but within a branched system. Under these conditions, community size was considered not only as a demographic characteristic but also as a parameter of the spatial coverage of

agricultural land, local transport links, production sites, and facilities serving the agricultural sector. Accordingly, a larger community scale was associated with a broader list of management objects, where decisions on land use, access infrastructure, product logistics, and support for farms grew in importance alongside budgetary and social issues. The quantitative composition of communities was associated with different scales of territories, population, and the resource base, reflecting differences in the initial conditions for management. Therefore, the indicator of the number of communities characterised only the organisational framework of the system and did not move to assessment of the effectiveness of its functioning (Portal "Decentralisation", n.d.).

The share of communities with development strategies characterised the extent to which formalised planning was spread as a management tool. The value of approximately 91.4% showed that most territorial communities had strategic documents, reflecting implementation of basic development planning procedures. This level of coverage was associated with the use of unified approaches to determining priorities, but the indicator itself did not reflect the content of strategies, their quality, or the degree of implementation of planned measures. The presence of strategies recorded the use of the tool, while not allowing for its effectiveness in achieving specific results to be assessed. The share of communities outside this value reflected differences in planning approaches, characterising the heterogeneity of management practices within the system. However, the high level of coverage of communities by strategic planning provided grounds to view agricultural issues as part of the general system of local priorities, since for rural territories, the development of land use, production infrastructure, local agricultural entrepreneurship, and the farming sector were among the basic directions of development. Thus, the indicator was used as a measure of formal implementation of strategic planning, without extending the interpretation to the level of real management effects (Portal "Decentralisation", n.d.).

The institutional capacity index was used as a generalised indicator that combined parameters of organisational structure, management procedures, and the ability to perform functions, which enabled the condition of the system to be assessed in an aggregated form. The value of 0.54 characterised a medium level of institutional capacity, reflecting partial consistency between elements of the management system without full integration of processes. This level was associated with the possibility of performing basic management functions, although it did not guarantee the same level of performance in different communities, due to differences in resources and organisational characteristics. The indicator summarised a set of system characteristics without detailing individual components, which limited the possibility of identifying specific factors that affected the level of capacity. For communities with different economic specialisations, this meant unequal opportunities for organisational support of agricultural resources, land relations, logistics infrastructure, and interaction with farms and agricultural enterprises. In this perspective, the medium level of institutional capacity reflected that some communities could provide basic administration of agriculture-related functions, while in others, organisational and procedural conditions remained more limited. However, the index enabled the overall state of the organisational system to be compared with other indicators without going beyond the description of their coexistence. Therefore, differences in institutional capacity could also appear through the varying ability of communities to implement management actions in the agricultural sphere, even with similar resource or territorial potential.

Consideration of these indicators together enabled the relationship between the structure of the system, the use of planning tools, and the level of institutional capacity to be traced without moving to unsubstantiated causal claims. The number of communities reflected the organisational structure of the system, the share of strategic planning characterised the level of use of formalised tools, and the institutional capacity index summarised the state of their functioning in general. The combination of these indicators was associated with a structured management system in which differences existed in the level of implementation of management practices and the ability to carry them out. This configuration reflected a system with formally defined elements and tools, but without a uniform level of application across all communities. In terms of the agricultural component, this provided grounds to view the organisational system as an environment in which management of agricultural resources depended on the combination of territorial scale, strategic orientations, and the real institutional capacity of communities. Under this relationship, the share of communities with lower capacity was associated with less stable conditions for organising agricultural development, supporting production infrastructure, and administering land resources. Given the results obtained, the organisational system of rural management was characterised as a combination of quantitative structure, formalised planning tools, and generalised parameters of institutional capacity, reflecting different levels of development of its individual elements. This allowed the agricultural component to be viewed not as a

factor external to the system but as one of the directions sensitive to differences in community scale, strategic coverage, and organisational capacity. This approach avoided excessive generalisations based on individual indicators and focused on their interpretation as interconnected system characteristics.

Overall, the analysis treated indicators reflecting the structure of the system, the spread of strategic planning, and the level of institutional capacity as key. Their combination characterised the coexistence of a branched administrative structure with formal use of management tools, which was not accompanied by a corresponding level of coordinated functioning. Comparison of these parameters traced the gap between the presence of strategic documents and the ability of the system to ensure their implementation, reflecting differences between formal introduction and actual functioning of management mechanisms. This configuration characterised the system as structurally organised but heterogeneous in the level of organisational capacity of individual elements. The results support the conclusion that assessment of the organisational system should be based on coordinated consideration of structure, management tools, and their practical application, rather than on interpretation of separate indicators. Capital expenditure of local budgets, the share of investment in budgets, and the territorial development index were considered together as interconnected indicators reflecting the structure of budget expenditure, the orientation of financial resources, and the generalised result of their use. This approach avoided isolated analysis of each indicator and shifted the assessment towards their coexistence within a single financial-management system (Table 3).

Table 3. *Rural development within the system of territorial development management (Ukraine)*

No.	Indicator	Value
1	Capital expenditure of local budgets	UAH 145.8 billion
2	Non-tax revenues of local budgets	UAH 43.6 billion
3	Share of investment in budgets	≈20-22%
4	Share of infrastructure expenditure	≈15-20%
5	Share of social expenditure	≈40%
6	Share of expenditure on economic activity	≈15%
7	Territorial development index	0.59

Source: *compiled by the authors based on The Accounting Chamber (2025)*

During the analysis, capital expenditure reached UAH 145.8 billion, while the share of investment in budgets was approximately 20-22%, which showed the presence of an investment component in the expenditure structure and the orientation of part of the resources towards long-term directions. For rural areas, this also meant the presence of a financial base within which facilities related to agricultural infrastructure could be financed, in particular, irrigation, logistics support, product storage, and other elements of the material base of agricultural production, although the aggregated capital expenditure indicator itself did not allow their exact share to be distinguished. This relationship characterised the budget as combining current and development expenditure without dominance of the investment component in the overall financing structure. Joint consideration of the absolute amount of capital expenditure and its share in budgets showed that a substantial amount of resources was not accompanied by a proportionally high share of investment expenditure, reflecting the limited role of this expenditure in the overall structure of budget priorities. This configuration was associated with the predominance of other financing directions alongside development expenditure, which characterised budget policy as mixed in its orientation. The share of investment in budgets confirmed the presence of financing for development directions, including infrastructure elements related to the agricultural sphere. In this context, capital expenditure was considered not as a dominant factor but as one component of resource distribution that coexisted with social and current expenditure. The territorial development index, with a value of 0.59, was used as a generalised indicator combining economic, infrastructure, and social characteristics, enabling the state of development to be assessed without detailing individual components. This level characterised the medium state of territorial development, which was associated with partial realisation of the existing potential without achieving high values in all components. However, the index did not separately disclose the contribution of agricultural indicators and did not provide grounds to state that agricultural productivity was an independent component of its structure; agricultural issues were reflected indirectly through economic and infrastructure parameters of development. The index therefore did not disclose the structure of the contribution of individual factors but only summarised their

combined result, which limited the possibility of establishing the role of each individual indicator in forming the final value (The Accounting Chamber, 2025).

Comparison of investment parameters with the generalised development indicator showed that the presence of capital expenditure and the investment component was not accompanied by a proportional increase in the level of development, which characterised the absence of a direct relationship between the amount of financing and performance indicators. For the agricultural component, this meant that investment growth by itself was not reflected as proportional growth in agricultural performance, because additional links stood between resource investment and production effect: the state of infrastructure, organisation of sales, access to irrigation, the structure of land use, and the management capacity of communities to support development projects. This result was associated with the influence of additional factors, in particular, organisational and institutional factors, which were not directly reflected in the structure of budget expenditure. However, the coexistence of these indicators reflected the complex character of relationships in the management system, where development results were formed under the influence of several interconnected elements. Within the analysis, capital expenditure characterised the amount of resources directed towards development directions, the share of investment in budgets reflected their share in the overall expenditure structure, and the territorial development index summarised the result of the functioning of the system. This operationalisation avoided the use of abstract categories and ensured a clear relationship between concepts and specific indicators. Consideration of these indicators within a single system showed that none of them can be interpreted in isolation, since their value acquires analytical meaning only in relation to the others.

Generalisation of the results focused attention on the relationship between capital expenditure, the share of investment in budgets, and the territorial development index as key indicators characterising development processes within the management system. Their joint consideration showed that the presence of a substantial amount of investment resources was combined with a limited share of this expenditure in the budget structure, reflecting the mixed character of financial policy without the dominance of development directions. However, the generalised development indicator did not show proportional growth relative to investment parameters, which characterised the absence of a direct relationship between the amount of invested resources and the results achieved. This relationship supports the conclusion that the level of territorial development within the system studied is linked not only to the amount of financing but also to its structure and its relationship with other expenditure directions, which directly reflects the specific character of management under transformational changes. Within the study, the regional analysis of Mykolaiv Oblast was introduced as a specification of national trends and as an example that enabled verification of how generalised patterns appeared at the level of a particular territory. Community budget revenues characterised the financial basis for implementing management functions and outlined the amount of resources available to support the activities of territorial units (Table 4).

Table 4. *Rural management system (Mykolaiv Oblast)*

No.	Indicator	Value
1	Community budget revenues (2025)	UAH 4.36 billion
2	Special-fund budget revenues	UAH 70.6 million
3	Share of the special fund	1.6%
4	Coefficient of programme orientation of the budget	0.83
5	Resource concentration coefficient	0.58
6	Budget flexibility index	0.62
7	Community development coefficient	0.55

Note: *the coefficient of programme orientation of the budget was determined in IBM SPSS Statistics (USA) using a ratio approach to processing budget data*

Source: *compiled by the authors based on Finance Department of the Mykolaiv City Council (n.d.)*

During the analysis, their amount reached UAH 4.36 billion, which showed the concentration of financial flows within a specific region and enabled this indicator to be related to the general model of financial support. This amount of resources was associated with the possibility of maintaining current management processes and implementing separate development programmes, but it also reflected the dependence of the functioning of the system on the structure of revenues and mechanisms of their distribution. At the regional level, this also meant that the agricultural sector remained one of the significant components in

the formation of the revenue base, as budget revenues of rural-profile territories combined payments from land use, the activity of agricultural enterprises, employment in agriculture, and related types of economic activity. Under this relationship, budget revenues reflected not only the general resource potential of the region but also the indirect role of agriculture in maintaining the financial basis of local management. In this case, the revenue base was treated as a parameter of resource capacity that characterised the ability to finance both current and separate strategic directions, without moving to generalised assessments of efficiency. This approach enabled the regional indicator to be linked to the general logic of the study without transferring abstract conclusions to the local level (Finance Department of the Mykolaiv City Council, n.d.).

The share of the special budget fund characterised the distribution of financial resources between general and targeted directions of financing. The analysis determined that this indicator was 1.6%, which reflected a relatively small share of funds directed towards specialised programmes and investment projects. This budget structure was associated with limited use of targeted financing in the total amount of resources, which allowed investment expenditure to be viewed as an additional rather than dominant element of budget policy. With regard to agricultural projects, this reflected a situation in which the special fund did not act as the main channel of investment support for agriculture; therefore, financing for irrigation, storage, logistics, or other production-infrastructure directions occupied a limited place in the structure of targeted budget resources. The low share of the special fund demonstrated that agricultural investment was not concentrated in a pronounced amount within specialised financing and therefore remained subordinated to the general configuration of budget distribution. Within the study, this indicator was interpreted through the relationship between the general and special funds, which avoided abstract conclusions on investment activity and focused on the actual structure of financial flows. This interpretation ensured comparison of the regional level with the general model, where current and development expenditure also coexisted (Finance Department of the Mykolaiv City Council, n.d.).

The coefficient of programme orientation of the budget was used as an indicator reflecting the share of expenditure related to implementation of the programme-target approach. Its value was 0.83, corresponding to a high share of programme-structured expenditure within the budget. Under this interpretation, the resulting value was associated with the predominance of the programme structure of budgeting, but it was not used as a direct indicator of the effectiveness of implementation of these programmes. It also showed organisational conditions under which support for agriculture could be included in targeted budget programmes as a separate direction of regional policy. Thus, the programme-target approach reflected not only formalisation of expenditure but also the possibility of distinguishing agricultural measures within the budget process, in particular, through programmes related to production infrastructure, land use, livestock production, or crop specialisation of territories. The indicator was considered in connection with other parameters, which enabled assessment not only of the fact that the approach was introduced but also of its place in the general management system. The resource concentration coefficient further reflected that financing was not distributed evenly between directions, which allowed concentration of funds to be linked to support for specific types of economic activity, including agricultural directions of regional specialisation. Under such a distribution, the allocation of resources could be traced as selective and potentially oriented towards segments with greater significance for the structure of the local economy, particularly grain production, livestock production, or related infrastructure links. Joint analysis of the amount of revenue, budget structure, and programme orientation showed that the regional level generally corresponded to the national model in terms of the presence of a resource base and the use of management tools, but differed in the relationship between general and targeted expenditure. This showed that, at the level of a particular oblast, general patterns were retained, although their concrete implementation depended on the structure of financing and local management decisions (Finance Department of the Mykolaiv City Council, n.d.). Thus, the regional example supplemented the national analysis through specification of the relationship between indicators rather than generalisation, which enabled clearer interpretation of the specific functioning of the management system under different levels of organisation.

Overall, the analysis identified three key indicators: the amount of financial resources, their distribution between general and targeted areas, and the level of programme orientation in the budget process. Their comparison showed that the presence of a sufficient resource base was combined with a limited share of targeted financing, while the high level of programme orientation characterised formal implementation of planning tools in the expenditure structure. This relationship showed that the programme structuring of the budget was not accompanied by a corresponding share of resources directed towards implementing targeted

projects, reflecting the difference between formal planning and the actual distribution of financial flows. In this context, the regional management model was characterised by a combination of available financial resources and implemented management tools without full consistency with one another. Community budget expenditure of Mykolaiv Oblast characterised the amount of financial resources directed towards ensuring the functioning of the management system under increased pressure and environmental transformation. Together with the budget surplus, stabilisation expenditure, recovery expenditure, and grant financing, it characterised the financial conditions for the functioning of the management system under external challenges (Table 5).

Table 5. *Management under security threats and European integration transformations (Mykolaiv Oblast)*

No.	Indicator	Value
1	Community budget expenditure (2025)	UAH 4.23 billion
2	General-fund budget surplus	UAH 687.7 million
3	Decline in community revenues	-13.5%
4	Rate of revenue contraction	-6-7%/year
5	Share of stabilisation expenditure	≈50%
6	Share of recovery expenditure	≈20-30%
7	Share of grant financing	≈10-15%

Source: *compiled by the authors based on Finance Department of the Mykolaiv City Council (n.d.)*

During the analysis, the amount reached UAH 4.23 billion, which showed the scale of expenditure required to maintain continuity of management processes within the region. This level of financing was associated with the performance of basic management functions and reflected the structure of budget priorities without moving to assessment of their effectiveness. The expenditure structure showed a shift of financial flows towards ensuring current functioning, which characterised the relationship between expenditure on maintaining activity and expenditure directed towards development (Finance Department of the Mykolaiv City Council, n.d.). This relationship suggested that, under security threats, the budget emphasis shifted towards maintaining current activity, while directions related to agricultural production did not occupy a leading place in the structure of priority financing. This indirectly pointed to stronger constraints for agricultural production in communities since reduced expenditure on renewal of infrastructure and the material-technical base coincided with difficulties in supporting the agricultural sector. Within the study, this indicator was interpreted as a parameter of financial pressure, which enabled the relationship between the amount of expenditure and the ability of the system to maintain continuity of activity under external influences to be assessed. This expenditure configuration was considered as a characteristic of the budget structure reflecting the actual distribution of resources within available financial capacities, without generalised conclusions on the functional capacities of the system.

The general-fund budget surplus characterised the relationship between revenues and expenditure and was used as an indicator of financial equilibrium, calculated as the difference between budget revenues and expenditure. The analysis showed that its value was UAH 687.7 million, which reflected a positive balance in the budget structure. This indicator was associated with the possibility of accumulating part of the resources without their immediate use and reflected the state of financial flows in a specific period. The positive balance also pointed to the presence of an internal financial reserve that could be used to cover recovery costs in separate sectors of the local economy, including those related to agriculture. However, the value of the surplus itself did not provide grounds to discuss full coverage of losses in the agricultural sector, as the needs for reconstruction of production facilities, technical support, irrigation systems, and storage infrastructure go beyond a single indicator of budget equilibrium. This parameter was not treated as evidence of long-term stability but only as a characteristic of the current relationship between revenues and expenditure. Within the study, this indicator was used to analyse budget equilibrium, which enabled it to be related to other parameters of the financial system without using generalised categories such as "integral influence". This interpretation ensured a more precise reading of the results and reduced the abstractness of the presentation (Finance Department of the Mykolaiv City Council, n.d.).

The share of stabilisation expenditure characterised the orientation of financial resources towards maintaining the functioning of the management system under external challenges and was considered as the ratio of expenditure on current support for activity to total expenditure. During the analysis, this indicator was approximately 50%, reflecting a substantial share

of expenditure oriented towards maintaining stability (Finance Department of the Mykolaiv City Council, n.d.). This financing structure was associated with the priority of expenditure related to ensuring continuity in the functioning of the system, compared with other directions. Under this distribution, growth in stabilisation expenditure was accompanied by a narrowing of the share of resources that could be directed towards development directions, including the agricultural sector. Under this financing configuration, agricultural needs in the budget structure moved into the background compared with expenditure on maintaining current functioning. The recovery expenditure block also characterised the presence of a separate resource for rebuilding damaged facilities, among which agricultural infrastructure – warehouses, the technical base, irrigation, and other elements of production support – could be included in the financing directions, although its exact share was not separately distinguished. Grant financing supplemented the budgetary base for reconstruction, but its amount was considered as an additional source of covering losses rather than full compensation for damage sustained by agriculture. The indicator was not used to establish causal relationships but was treated as a characteristic of the distribution of budget resources within a specific period. Within the study, this parameter was applied to analyse the expenditure structure and enabled assessment of the relationship between stabilisation and other types of financing without using abstract concepts such as "organisational consistency". This interpretation focused on factual data and their relationships, which increased the analytical precision of the presentation.

Systematisation of the results enabled management under security threats and European integration transformations to be considered as an integrated system whose functioning was determined by the combination of financial parameters and structural characteristics of the budget. Within the analysis, indicators characterising the amount of budget expenditure, the relationship between revenues and expenditure (through the surplus), and the share of stabilisation expenditure were treated as key because together they reflected the financial condition of the system under external challenges. Their comparison showed that a substantial amount of expenditure was combined with a positive budget balance, while a substantial share of stabilisation expenditure characterised the orientation of resources towards maintaining current functioning. This combination pointed to the priority of short-term needs in resource allocation compared with other directions. In this context, the management system was characterised by the presence of a financial reserve and concentration of expenditure on maintaining activity, without moving to generalised conclusions about its efficiency. For the agricultural sector, these indicators were mainly indirect since they characterised the financial conditions of the system but did not contain a direct assessment of the influence on agricultural production. This enabled the state of the agricultural sector to be linked primarily to the expenditure structure, the presence of a budget reserve, and the relationship between current expenditure and expenditure on renewing infrastructure and the production base, on which opportunities to support farms and agricultural infrastructure depended. Under this approach, the current management model supported functioning under risks, but separately, it did not confirm the stable functioning of the agricultural sector without indicators of yield, production volumes, and economic results of agricultural producers. It is appropriate to increase the share of expenditure directed towards renewing infrastructure, the technical base, and other development directions in the structure of local budgets, expand targeted financing for restoring agricultural infrastructure, and involve grant resources more actively in modernising the agricultural sector. Local development programmes should include separate directions for supporting farms, restoring irrigation systems, storage infrastructure, and the technical base, which is consistent with the identified parameters of budget adaptation under risks.

DISCUSSION

The results of the study enabled the financial base of management to be interpreted as a multilevel system in which the amount of resources did not act as a self-sufficient factor of effectiveness but interacted with the structural characteristics of revenues and their distribution. The identified concentration of financial flows created conditions for ensuring the functioning of management processes, but it did not eliminate dependence of performance on the quality of budget planning and redistribution mechanisms. The dominance of own-source revenues confirmed strengthened financial autonomy, which expanded decision-making opportunities at the local level, but simultaneously deepened differentiation between individual elements of the system. The integral financial stability indicator confirmed the capacity of the system to maintain continuity of functioning, while also reflecting limitations in overcoming internal imbalances. The organisational component of management was characterised by a complex configuration in which a large number of administrative units ensured spatial coverage but increased requirements for coordination and consistency of actions. The spread of strategic planning contributed

to structuring management processes and forming long-term orientations, but incomplete coverage of communities demonstrated uneven implementation of management tools.

In the field of financial innovation and digitalisation of management, the works of M. Preziuso *et al.* (2023), and A.F. Vatamanu & M. Tofan (2025) explored mechanisms for integrating financial instruments and artificial intelligence into public administration, but without a detailed link to the budget structure at the territorial level. M. Preziuso *et al.* analysed open banking as a tool for expanding financial inclusion, focusing on institutional interaction and access to financial services, but without detailing its influence on the formation and distribution of budget resources. A.F. Vatamanu & M. Tofan investigated the introduction of artificial intelligence into public administration, emphasising risks and vulnerabilities of digital systems, while quantitative analysis of financial autonomy or stability was overlooked. The present study establishes a relationship between the amount of revenue, the share of own-source resources, and integral financial stability, which enables a shift from general digital concepts to structural analysis of the financial system. This approach combines institutional and financial characteristics, which was not reflected in the publications considered, and forms a holistic understanding of the functioning of management under transformations.

In the context of the development of digital financial ecosystems and innovation processes, the works of S. Mashetty *et al.* (2024) and A.A. Vărzaru & C.G. Bocean (2024) addressed the influence of digital technologies on financial processes and innovation activity, but without linking them to the territorial organisation of management. S. Mashetty *et al.* considered the use of intelligent technologies in financial systems, focusing on analytical and cloud solutions but without addressing spatial disproportions in resource provision. A.A. Vărzaru & C.G. Bocean analysed the influence of digital transformation on innovation activity mainly through macroeconomic indicators, so the organisational level of territorial management remained outside detailed consideration. Unlike that approach, the presented study combines financial characteristics with organisational parameters: the number of administrative units, the spread of strategic planning, and institutional capacity, which enables management differences at the level of territorial communities to be explained. This provides a more comprehensive approach than papers oriented mainly towards technological aspects without consideration of management structure.

In the field of sustainable development and innovation in rural areas, the papers of T. Varzakas & S. Smaoui (2024) and G. Cascone *et al.* (2024) addressed food security and the implementation of innovative development models, but without integrating financial-management indicators. T. Varzakas & S. Smaoui analysed global challenges of the food system, focusing on sustainable development and food security, but without assessing financial management mechanisms. G. Cascone *et al.* considered the role of innovation platforms, in particular, living labs, in rural development, emphasising stakeholder involvement but without quantitative analysis of the resource base. The current study establishes a link between financial resources, organisational structure, and institutional capacity, which enables the management system to be assessed as an integrated model. This level of combining quantitative and structural parameters provides a deeper understanding of the functioning of the system compared with studies focused mainly on separate aspects of development.

In the field of agroecological resilience and digital constraints, S. Hackfort (2023) and B. Adoyo *et al.* (2025) considered different models for adapting rural development to contemporary transformations. B. Adoyo *et al.* examined the multidimensional performance of agroecology in several African countries and confirmed a positive relationship between the level of agroecological integration, productivity, and farm income, but the focus was shifted to production-economic characteristics of agrosystems rather than budgetary management mechanisms. S. Hackfort analysed corporate "lock-ins" in the digital agriculture of Germany, where it was shown that digitalisation did not remove dependencies and, in some cases, reproduced structural inequality in access to technology. Unlike those papers, the present study traces not only the influence of the innovation environment on development but also the relationship between the amount of revenue, the share of the special fund, the programme orientation of the budget, and stabilisation expenditure in Mykolaiv Oblast. This linking of financial architecture with the organisational capacities of management specified how the resource base and the structure of budget flows determined the adaptive potential of the system.

In the context of the digital economy and innovation infrastructure, Y. Xu *et al.* (2022) and S. Stojanova *et al.* (2022) focused on institutional and technological prerequisites for modernisation. Y. Xu *et al.* generalised directions of research on the digital economy of China using a bibliometric approach and outlined digitalisation as an intersectoral factor of transformation, but without addressing specific parameters of budget stability or organisational capacity in local management. S. Stojanova *et al.* considered

rural digital innovation hubs as the basis of sustainable business models in rural areas of Europe and demonstrated the significance of innovation hubs for territorial development, but the analysis remained focused mainly on infrastructure-network logic. In the present study, the digital or institutional-innovation component is not isolated from the financial system but is related to the number of communities, the spread of strategic planning, the institutional capacity index, and the parameters of budget configuration. This enabled a shift from a general description of digital modernisation to an evaluation of the extent to which the organisational system actually ensured consistency of management decisions and maintained functioning under external pressure, distinguishing this paper from more conceptual generalisations.

Within the analysis of production transformations and structural challenges, B. Losch (2022) and K. Pilarski *et al*. (2025) addressed different aspects of contemporary agricultural development. K. Pilarski *et al*. systematised technological, environmental, and socio-economic aspects of biogas production in agriculture and stressed the potential of energy solutions for increasing resource efficiency, but without detailing a regional budgetary management model. B. Losch discussed dominant narratives concerning the future of the agricultural sector and demonstrated that they did not allow the deeper structural problems of employment and development to be fully presented, although the main focus remained on macro-level disproportions. In the presented study, the comparative analysis is shifted to the level of a specific management system, where community budget revenues, the general-fund surplus, the share of stabilisation expenditure, and the programme orientation of the budget of Mykolaiv Oblast are reviewed simultaneously. This construction describes the transformational context and demonstrates how budget equilibrium, financing structure, and institutional consistency determined the possibility of maintaining management processes and development under security threats, providing a higher level of applied specification compared with the works of other researchers.

In the field of integration of digital technologies and spatial transformations, S. Seifollahi-Aghmiuni *et al*. (2022) and G. Gebresenbet *et al*. (2023) addressed the influence of technological and urbanisation factors on the development of rural systems. G. Gebresenbet *et al*. proposed a concept for integrating digital solutions into smart agricultural systems, where the significance of complex technological interaction for increasing the efficiency of production processes was substantiated, but without detailing budgetary mechanisms for supporting such transformations. S. Seifollahi-Aghmiuni *et al*. analysed the influence of urbanisation on land degradation and socio-economic challenges in peripheral territories, where growing development disproportions under spatial changes were defined. In the conducted study, unlike these approaches, financial parameters (budget revenues, the share of the special fund, and the surplus) are integrated with characteristics of the organisational structure of management, which enables assessment of both the external factors of influence and internal mechanisms through which the management system adapts to transformational processes.

In the context of digitalisation of the agricultural sector and preservation of cultural heritage, Q. Mu & F. Aimar (2022) and C.G. Bocean (2024) paid attention to different aspects of rural development. C.G. Bocean investigated the relationship between the use of digital technologies and agricultural productivity in EU countries, where the positive influence of digitalisation on production performance was confirmed, but without considering organisational and financial parameters of management. Q. Mu & F. Aimar systematised practices for preserving historic rural settlements, where the significance of cultural heritage as an element of territorial development was defined, but the analysis remained outside financial-management models. In the current study, the approach is expanded by combining the financial configuration of the budget, institutional capacity, and strategic planning, which enables the management system to be assessed as an integral structure capable of ensuring both functioning and development in a changing environment.

In the field of socio-economic disproportions and institutional networks, M.H. Laskar (2023) and J. Blesh *et al*. (2023) addressed development inequality and mechanisms for diversifying the agricultural sector. M.H. Laskar analysed the formation of a digital society and the digital divide between urban and rural areas, where uneven access to technologies was established as a factor limiting development, but without linking it to budgetary management tools. J. Blesh *et al*. investigated institutional networks that support diversification of agricultural production, where the significance of interaction between actors for forming sustainable development models was demonstrated. Unlike the papers, this study combines analysis of financial indicators (budget expenditure, the share of stabilisation expenditure, and the surplus) with organisational characteristics of the management system, which allowed for a shift from describing separate factors to assessing their interaction and influence on the capacity of the system to ensure continuity of management processes

and adaptation to external challenges. Therefore, the results of the study demonstrate that, unlike existing approaches, the effectiveness of the management system is determined by the integrated interaction of financial, organisational, and institutional parameters, which ensures its capacity for adaptation and functioning under transformations.

In the field of technological transformation of agricultural production, X. Luo *et al*. (2022) considered the transition from mechanised to intelligent systems, with an emphasis on the phased introduction of digital technologies into production processes. X. Luo *et al*. analysed changes in the structure of agricultural production under the influence of automation and digitalisation, presenting that increased efficiency was achieved through optimisation of production operations and use of data, but leaving budgetary constraints and mechanisms for financing these changes out of the scope of the study. Unlike that approach, the present study focuses not on technological parameters of production but on the characteristics of financial support for management, specifically, the structure of expenditure, the share of stabilisation financing, and parameters of budget equilibrium. This enabled transformational processes to be viewed not as the result of technological changes but as a consequence of resource distribution and financing priorities within the management system. This provided for the assessment of the influence of the budget structure on the capacity of the system to maintain continuity of functioning under external challenges. Therefore, unlike papers concentrated on technological modernisation, the results of this study demonstrate the expediency of analysing financial parameters as a separate dimension of management, which helps explain differences in system functioning even under similar development conditions.

CONCLUSIONS

The study provided a comprehensive assessment of the rural development management system based on a combination of financial, organisational, and institutional characteristics, which formed an integral understanding of its functioning, structural organisation, and adaptive capacities under transformations. The financial base was shown to have formed as a multicomponent system in which the amount of resources was combined with the structure of their distribution, determining the capacity to ensure continuity of management processes and implement strategic directions of development. Local budget revenues of UAH 679.5 billion, combined with the dominance of own-source revenues at 72.3%, reflected a sufficient level of financial autonomy, while the integral coefficient of 0.64 summarised the capacity of the system to maintain balance and counteract external and internal risks.

The organisational component was characterised by a complex territorial configuration that ensured broad spatial coverage and formed an environment for implementing management functions at different levels. A large number of territorial communities, combined with the spread of strategic planning at approximately 91.4%, characterised the presence of formalised management approaches and the coordination of separate management decisions within the system. However, the institutional capacity index of 0.54 reflected internal disproportions that limited the level of functional consistency of the system and its capacity for effective interaction between elements. This also covered management of land resources, agricultural infrastructure, and inclusion of agricultural priorities in the strategic documents of communities. This was confirmed by capital expenditure of UAH 145.8 billion and the integral index of 0.59, which summarised the effectiveness of management influences.

Capital expenditure and investment created a basis for developing agricultural infrastructure, while the development index did not contain separately identified agricultural indicators. At the regional level, budget revenues of UAH 4.36 billion formed the basis for the functioning of management, while the limited share of the special fund reflected the specific distribution of financial flows and financing priorities. The coefficient of programme orientation of 0.83 showed a high level of consistency between resources and management goals. The conditions of functioning were characterised by changes in the expenditure structure, where the amount of UAH 4.23 billion, combined with a surplus of UAH 687.7 million and growth in the share of stabilisation expenditure to approximately 50%, reflected adaptation of the system to external challenges. Under these conditions, the priority of stabilisation expenditure narrowed the budgetary space for supporting agricultural production, while recovery expenditure and grant financing only partly covered the needs of agricultural infrastructure. The limitations of the study lay in the use of aggregated financial-statistical data without separate identification of agricultural production indicators, which narrowed the possibility of directly assessing the influence of the management system on agricultural development. Further research should focus on an in-depth analysis of the micro-level of management, dynamic changes in indicators, and expansion of the list of indicators for assessing system effectiveness in different regions.

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Формування механізмів управління розвитком сільських територій в умовах воєнного стану та європейської інтеграції

Альона Ключник
Доктор економічних наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-6012-6666

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

Наталія Галунець
Старший викладач
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0001-7709-9238

Анжела Гусенко
Старший викладач
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0000-0002-3989-2400

Олег Кривко
Аспірант
Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
https://orcid.org/0009-0009-3063-7524

Анотація. Метою дослідження було оцінювання фінансових, організаційних та інституційних параметрів управління з урахуванням зовнішніх викликів для визначення їх адаптаційного потенціалу. У дослідженні застосовано методи структурного та функціонального аналізу бюджетних показників, коефіцієнтного та відносного аналізу, агрегування і групування статистичних даних, нормалізації та інтегрального індексування, а також методи дескриптивної статистики. Оцінювання фінансової основи показало, що доходи місцевих бюджетів у 679,5 млрд грн сформували базову ресурсну платформу, тоді як структура надходжень із домінуванням власних доходів на рівні 72,3 % забезпечила підвищення автономності прийняття рішень. Водночас коефіцієнт фінансової стійкості 0,64 узагальнив здатність системи підтримувати стабільність у змінному середовищі. Організаційний компонент управління охарактеризовано через кількість територіальних громад, що характеризувало масштаб просторового охоплення системи та розподіл управлінських функцій між адміністративними одиницями. Встановлено поширення стратегічного планування на рівні ≈91,4 %, тоді як індекс інституційної спроможності 0,54 відобразив середній рівень узгодженості структурних елементів. Організаційні параметри одночасно охоплювали управління земельними ресурсами та аграрною інфраструктурою. Аналіз розвитку засвідчив наявність значних капітальних видатків у 145,8 млрд грн, що характеризували спрямованість на формування матеріальної бази. Структура бюджетних витрат виявила пріоритетність соціальної складової та підтримки економічної діяльності, що сформувало умови для забезпечення базових потреб і розвитку. Інтегральний індекс 0,59 узагальнив результативність управлінських впливів. На регіональному рівні доходи бюджету 4,36 млрд грн сформували основу функціонування системи, тоді як частка спеціального фонду 1,6 % відобразила обмеженість цільового фінансування. Для Миколаївської області це поєднувалося з вагомістю аграрного сектору в дохідній базі. Практична цінність дослідження полягає у можливості використання отриманих результатів органами місцевого самоврядування, державними установами та регіональними органами влади для вдосконалення бюджетного планування, підвищення ефективності розподілу фінансових ресурсів і посилення інституційної спроможності управління

Ключові слова: розвиток сільських територій; управління; фінансова стійкість; європейська інтеграція; безпекові умови; воєнний стан

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Миколаївський національний аграрний університет
54008, вул. Георгія Ґонґадзе, 9, м. Миколаїв, Україна
тел.: +38(0512) 70-93-54
E-mail: ubsras@bsagriculture.com.ua
https://bsagriculture.com.ua/uk

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