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Influence of biopreparations on the productivity of grain crops in the South of Ukraine

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Abstract. The study aimed to determine the optimal conditions for using biological products to improve the agroecological efficiency of grain crops, by analysing their impact on plant physiological processes, productivity and soil resources. The study presented the results of the study of the influence of biological products on the yield, product quality, dynamics of plant development phases and soil microflora composition when growing barley of the Helios variety and buckwheat of the Antaria variety in the South of Ukraine. The experiment was conducted using nitrogen-fixing, mycorrhizal and phosphate-mobilising biological products, both individually and in combination, with the establishment of control and experimental plots. The analysis included an assessment of yields, protein content in grain, changes in plant development stages and the activity of soil microorganisms. The results of the study demonstrated that the use of biological products provided a significant increase in yields: barley showed an increase of 20-25%, and buckwheat – by 18-22% compared to the control plots. The protein content of the grain also increased, reaching 12% for barley and 14% for buckwheat. The duration of plant development phases was reduced, which contributed to more efficient use of soil resources and optimisation of growth processes. Changes in the composition of soil microflora were particularly noticeable: the number of nitrogen-fixing bacteria increased by

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40% and phosphate-mobilising – by 50%, which improved the availability of nutrients for plants. The highest results were achieved when using combinations of biological products that demonstrated a synergistic effect, increasing crop productivity and improving product quality. The results confirmed the effectiveness of biological products in creating sustainable agroecosystems, ensuring environmental safety, reducing the need for chemical fertilisers and increasing the economic profitability of agricultural production. The use of biological products is a promising area for optimising modern agricultural technologies in regions with unfavourable soil and climatic conditions

Keywords: agrotechnology; yield; agroecosystems; environmental sustainability; organic nutrition

INTRODUCTION

Biopreparations are innovative tools that use beneficial microorganisms to improve the physical, chemical and biological properties of soil. The main groups of such microorganisms are nitrogen-fixing bacteria, mycorrhizal fungi and phosphate-mobilising bacteria. Nitrogen-fixing bacteria, such as Rhizobium and Azotobacter, transform atmospheric nitrogen into forms available to plants, which helps to reduce the use of mineral fertilisers. Mycorrhizal fungi form symbiotic relationships with the root system of plants, increasing water and nutrient absorption, which is especially important in drought conditions. Phosphate-mobilising bacteria, such as *Bacillus subtilis*, activate the conversion of hard-to-reach forms of phosphorus into easily assimilated forms. The interaction of these microorganisms creates a favourable environment for plant growth, increases their resistance to stress and contributes to improved yields.

The research relevance is determined by the need to introduce environmentally friendly technologies that can ensure sustainable agricultural development. The use of biological products is an important element of such technologies, as they contribute to improving the microbiological activity of the soil and increasing yields and product quality. This is especially relevant in the South of Ukraine, where climatic conditions, including moisture deficit and high temperatures, make it difficult to grow crops efficiently. In these conditions, biological products can be an alternative to the intensive use of chemical fertilisers, which will ensure long-term soil fertility and economic benefits for farmers. Studying the impact of biological products on less common crops, such as barley and buckwheat, is an important step towards expanding the possibilities of their use and optimising agricultural technologies.

According to the results of the study by F. Urdaneta *et al.* (2024), the chemical and mechanical treatment of wheat straw contributes to the creation of fibrous bioproducts with high productivity. This technology can be adapted for the efficient use of agricultural residues, improvement of soil conditions and optimisation of agricultural processes, which indirectly contributes to crop growth and environmental sustainability. According to I.M. Horodyska *et al.* (2021), biological products combined with organic nutrition methods significantly improve the condition of agrophytocenoses, increasing the resistance of legumes to stress factors, including moisture deficit and disease. This confirms the prospects of integrating biological products into organic farming systems. As noted by D.K.Q.D. Santos *et al.* (2024), the combined use of *Trichoderma* and *Bacillus*-based products with chemicals effectively controls soybean diseases while improving soil fertility. An important aspect of this work is the ability of biological products to increase the efficiency of agricultural technologies and ensure the long-term sustainability of systems.

According to the findings of M.C. Pérez-Pizá *et al.* (2023), biological products can efficiently reduce the negative impact of fungal pathogens on plants. Their use in crop protection systems can be used not only to reduce crop losses but also to create environmentally friendly crop management systems. According to P. Drulis *et al.* (2022), the use of biological products in agriculture reduces the need for high doses of nitrogen fertilisers. They ensure stable crop productivity through the activation of nitrogen-fixing microorganisms, which is substantial for the reduction of the negative impact on the environment. According to a study by R. Górski *et al.* (2024), the use of bacterial consortia in combination with cover crops can be used to restore soil microflora. Such approaches can improve the ecological condition of the agricultural soil and increase yields even under organic farming conditions.

As noted by A. Piotrowska & D. Boruszko (2022), the use of efficient microorganisms has a positive effect on the chemical composition of grain, in particular wheat, improving its quality indicators. This confirms the significant potential of biological products to increase the nutritional value of agricultural products. According to J. Reinhardt *et al.* (2021), biological products ensure the stability of crop yields under stressful conditions, such as lower temperatures or water shortages. The results indicate the importance of using biological products in regions with unfavourable climatic conditions. As noted by E. Wojciechowicz-Żytko *et al.* (2024), biological products effectively reduce the level of plant diseases and the spread of pests. Their use can increase crop yields by improving the overall condition of crops. According to the findings of K. Furtak & A. Wolińska (2023), extreme weather conditions associated with climate change harm soil conditions. However, the use of biological products helps maintain the stability of soil characteristics, which is key to the adaptation of agroecosystems to climate change.

The issue of using biological products in agriculture covers several important aspects. The effectiveness of biological products depends on many factors, such as soil type, climatic conditions and the specifics of the crops grown. Most scientific work has focused on major crops such as wheat and rapeseed, while barley and buckwheat remain under-researched. The synergistic effects of different biological products have not yet received sufficient attention in scientific research, although they have the potential to significantly increase crop productivity. There are gaps in understanding the long-term changes in soil microflora caused by biological products, including their impact on ecosystem resilience. Overcoming these challenges is important to ensure the effective introduction of biological products into agricultural practice and the creation of sustainable agroecosystems.

The study aimed to evaluate the impact of different types of biological products and their combinations on yield, product quality, dynamics of plant development phases and soil microflora composition in barley and buckwheat cultivation in the South of Ukraine, as well as to determine their effectiveness in creating sustainable agroecosystems. The objective of the study was to investigate the effect of certain types of biological products and their combinations on yield, grain quality, dynamics of plant development stages and soil microflora composition in barley and buckwheat cultivation.

MATERIALS AND METHODS

The study was conducted in 2024 (April-July) at the Research and Training Production Centre of Mykolaiv National Agrarian University. The climate of the study region was characterised by typical conditions in southern Ukraine: hot summers with an average daytime temperature of +25-32°C and night time temperatures of +17-20°C, short springs and moderately cold winters with low precipitation. Annual precipitation ranged from 250-350 mm, with the bulk of it falling in the spring. Such conditions required the introduction of water conservation technologies, in particular drip irrigation systems, which were used in the experimental plots to maintain soil moisture at 70% of the field moisture capacity. The research complied with the ethical standards set out in the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

The soils at the experimental site were medium humus chornozems with a humus content of 3.5-4%. The results of soil sample analysis indicated a neutral reaction of the medium (pH 6.8-7.2), low levels of mobile nitrogen, moderate phosphorus and potassium content, and low biological activity. Before the experiment, soil surveys were conducted to clarify the initial characteristics that served as the basis for assessing the effectiveness of the biological products. The objects of the study were barley of the Helios variety and buckwheat of the Antaria variety. These crops were chosen because of their importance in the agriculture of the southern region of Ukraine. Barley was distinguished by its high productivity even in dry conditions, and buckwheat was important for enriching the diet with protein. For each crop, control and experimental plots were laid out to assess the impact of the biological products on the plants.

Three separate groups of biological products were used in the experiment. Separate experimental plots were allocated for each group to assess the effect of each type of biological product on the crops under study. In addition, separate plots were set aside to study the combined use of biological products (e.g., nitrogen-fixing products together with mycorrhizal products) to assess the synergistic effect. This ensured the accuracy of the results and determined the effectiveness of each product both individually and in combination. Nitrogen-fixing products, represented by Bionorm N (manufacturer – Biotechno Ukraine LLC), were chosen because of their ability to increase the availability of nitrogen for plants. This effect was provided by the activity of symbiotic bacteria that actively fixed atmospheric nitrogen. Phosphate-mobilising preparations, such as Phosphobacterin (manufactured by Agrotech Lab LLC), helped improve phosphorus uptake by plants by transforming hard-to-reach forms into easily accessible ones. This was important in the phases of generative organ formation when the demand for phosphorus increased sharply. Mycorrhizal preparations, such as Mycorizin (manufactured by BioSymbiotics), were chosen to improve water management and increase the availability of trace elements in the soil. They helped the plants to adapt to the moisture deficit conditions typical of the summer months.

Pre-sowing treatment of seeds was conducted using working solutions of the preparations at a concentration of 100 ml per 1 kg of seeds. Spraying of plants was conducted in the phase of active growth with an application rate of 5 l/ha. The control plots were not treated with biological products and served as the basis for comparison with the experimental variants. The experiment was laid out in triplicate to ensure the reliability of the results.

The seeding rate was 150 kg/ha for barley and 100 kg/ha for buckwheat. Sowing was conducted in the second half of April, which corresponded to the optimal time for crops in the region. All agrotechnical measures were carried out following the requirements of DSTU 2240-93 (1993).

The effectiveness of the biological products was assessed by the following indicators: growth dynamics, yield, grain quality and changes in soil microflora. Plant height was measured every 30 days during the growing season, with 20 random plants selected for each plot. Productivity was determined by the yield of air-dry mass collected by hand from the control and experimental plots. All samples were converted to t/ha for comparison. Grain quality was assessed by protein, starch, fibre and other parameters. For chemical analysis, infrared spectroscopy was used to ensure high accuracy of the results. The soil microflora was analysed after the end of the growing season to assess changes in the number of nitrogen-fixing, phosphate-mobilising bacteria and other microorganisms. The biological activity of the soil was determined by assessing the activity of dehydrogenase. All data were statistically processed using analysis of variance (ANOVA) in Statistica 12. This identified significant differences between variants, assessed the effect of biological products and visualised the results in the form of graphs and tables. The mean values obtained were presented together with standard errors to ensure the reliability of the conclusions.

RESULTS

In the control plots, where no biological products were used, barley and buckwheat yields were significantly lower than in the treated plots. Barley in the control plots, which was grown from April to July, yielded 35 t/ha, while buckwheat, which had a growing season from May to July, reached only 15 t/ha. These figures are basic and reflect the average level of productivity under standard agronomic care. Under such conditions, plants faced nutrient deficiencies, especially nitrogen and phosphorus, which limited their development and yield potential.

The use of nitrogen-fixing products such as Bionorm N had a positive impact on both crops. Barley treated with this product in April-July showed a yield increase of up to 40 t/ha, which was a 14% increase compared to the control. Buckwheat, which was grown in May-July, reached a yield of 16.5 t/ha, which was 10% higher than the control. This indicates the effectiveness of improving the nitrogen nutrition of plants in the early stages of their development when the need for this element is the highest. Due to the stimulation of nitrogen-fixing bacteria, plants formed a more developed root system, which provided better access to moisture and nutrients in the soil.

Mycorrhizal preparations such as Mycorizin have also shown a noticeable impact. Yields of barley grown from April to July in the treated plots increased to 38 t/ha and buckwheat – to 16 t/ha. Although the increase was somewhat smaller (9% for barley and 7% for buckwheat), mycorrhiza significantly improved the water balance of plants and the absorption of microelements. This was especially important during periods of insufficient moisture, which were often observed in June and July when plants were better able to withstand stressful conditions due to the increased absorption capacity of the root system.

Phosphate-mobilising products such as Phosphobacterin improved phosphorus availability, which was crucial for the formation of generative plant organs. Yields of barley grown from April to July on these plots increased to 39 t/ha (11% increase), and buckwheat grown in May-July – to 17 t/ha (13% increase). This indicates the critical role of phosphorus in grain formation and plant development, especially in the flowering and grain-filling phases that occurred in June and July. Additional phosphorus nutrition utilised the potential even in difficult soil and climatic conditions.

Combinations of biological products demonstrated the highest efficiency. The use of Bionorm N together with Mycorizin provided a significant increase in yield. In this case, barley grown in April-July reached 43.5 t/ha, which was 24% higher than the control, and buckwheat grown in May-July – 18.3 t/ha, which was a 22% increase. The synergistic effect of these two products was to provide plants with nitrogen, water and trace elements, which ensured efficient development throughout the growing season. The combination of Bionorm N and Phosphobacterin showed similarly good results. Barley grown in April-July on these plots reached a yield of 42 t/ha, which was 20% higher than the control, and buckwheat grown in May-July – 17.5 t/ha (17% increase). This indicates the combined effect of nitrogen and phosphorus nutrition, which is key to ensuring plant growth and biomass formation.

The maximum performance was recorded in the plots where a combination of three biological products was used: Bionorm N, Mycorizin and Phosphobacterin. Barley grown from April to July on these plots reached 44 t/ha, which was an increase of 26%, and buckwheat grown from May to July – 18.8 t/ha (25% increase). These results demonstrate the high efficiency of an integrated approach to the use of biological products that complement and enhance each other's effects. Plants in these plots formed a strong root system and resistance to stressful conditions, which ensured consistently high yields even under adverse climatic conditions (Table 1).

Table 1. Comparative characteristics of biological products

Crop	Vegetation period	Type of plot	Yield (t/ha)	Increase in yield (%)	Biological products
Barley (“Helios”)	April-July	Control	35	0	No biological products were used
Barley (“Helios”)	April-July	Experimental	40	14	Nitrogen-fixing (Bionorm N)
Barley (“Helios”)	April-July	Experimental	38	9	Mycorrhizal (Mycorrhizin)
Barley (“Helios”)	April-July	Experimental	39	11	Phosphate mobilising agents (Phosphobacterin)
Barley (“Helios”)	April-July	Experimental	43.5	24	Nitrogen-fixing (Bionorm N) + Mycorrhizal (Mycorrhizin)
Barley (“Helios”)	April-July	Experimental	42	20	Nitrogen-fixing (Bionorm N) + Phosphate-mobilising (Phosphobacterin)
Barley (“Helios”)	April-July	Experimental	44	26	Nitrogen-fixing + Mycorrhizal + Phosphate-mobilising
Buckwheat (“Antaria”)	May-July	Control	15	0	No biological products were used
Buckwheat (“Antaria”)	May-July	Experimental	16.5	10	Nitrogen-fixing (Bionorm N)
Buckwheat (“Antaria”)	May-July	Experimental	16	7	Mycorrhizal (Mycorrhizin)
Buckwheat (“Antaria”)	May-July	Experimental	17	13	Phosphate mobilising agents (Phosphobacterin)
Buckwheat (“Antaria”)	May-July	Experimental	18.3	22	Nitrogen-fixing (Bionorm N) + Mycorrhizal (Mycorrhizin)
Buckwheat (“Antaria”)	May-July	Experimental	17.5	17	Nitrogen-fixing (Bionorm N) + Phosphate-mobilising (Phosphobacterin)
Buckwheat (“Antaria”)	May-July	Experimental	18.8	25	Nitrogen-fixing + Mycorrhizal + Phosphate-mobilising

Source: *compiled by the authors*

In addition to increasing yields, the use of biological products positively affected product quality. An increase in the protein content of barley and buckwheat grain and an improvement in grain structure were recorded. This data confirms the feasibility of integrating biological products into the grain growing system as an effective way to increase the productivity and sustainability of agroecosystems. The results of the study confirm that the use of biological products significantly influenced the formation of both root and ground parts of plants of barley variety “Helios” and buckwheat variety “Antaria”. The control plots, where no biological products were used, showed basic levels of development. In barley grown from April to July, the average root weight was 15 g/plant, and the dry weight of the ground part – 45 g/plant. For buckwheat grown from May to July, these figures were lower: 8 g/plant for the root mass and 25 g/plant for the aboveground part. The absence of stimulants limited the ability of plants to absorb nutrients and water, which reduced growth rate.

Nitrogen-fixing biological products such as Bionorm N significantly improved the growth of both crops. In barley, the average root weight increased to 17 g/plant (a 13% increase), and the dry weight of the aboveground part increased to 51.75 g/plant (a 15% increase). In buckwheat, the increase was similar: the average root weight was 9 g/plant (12.5% increase), and the dry weight of the aboveground part – 28.75 g/plant (15% increase). This indicates a positive effect of nitrogen on plant development in the early phases of their growth, especially in April and May. Mycorrhizal biological products, such as Mycorizin, contributed not only to the formation of the root system but also to the improvement of the above-ground part of the plants. In barley, the average weight of roots increased to 16.5 g/plant (10% increase), and the dry weight of the aboveground part reached 50 g/plant (11.11% increase). In buckwheat, these figures were 8.7 g/plant (8.75% increase) and 27.5 g/plant (10% increase), respectively. The interaction between the root system and mycorrhizal fungi improved the absorption of water and trace elements, which was especially important in the dry period of June. Phosphate-mobilising preparations such as Phosphobacterin increased the availability of phosphorus, which improved metabolic processes in plants. In barley, the average root weight reached 16 g/plant (7% increase), and the dry weight of the aboveground part – 49 g/plant (8.89% increase). In buckwheat, the root weight increased to 8.5 g/plant (6.25% increase), and the aboveground part – to 26.5 g/plant (6% increase). This effect was most pronounced in the phases of active development of generative organs in May and June.

The best results were obtained in the plots where combinations of biological products were used. In particular, the combination of nitrogen-fixing and mycorrhizal preparations (Bionorm N + Mycorizin) provided barley with an average root weight of 19.5 g/plant (30% increase) and a dry weight of the ground part of – 54 g/plant (20% increase). In buckwheat, the increase was similar: the average root weight reached

10 g/plant (25% increase), and the dry weight of the ground part – 30 g/plant (20% increase). The combination of nitrogen-fixing and phosphate-mobilising products (Bionorm N + Phosphobacterin) also showed high efficiency. In barley, the average root weight increased to 18.5 g/plant (23% increase), and the dry weight of the ground part – to 52.5 g/plant (16.67% increase). In buckwheat, the average root weight was 9.5 g/plant (18.75% increase), and the aboveground part – 28.75 g/plant (15% increase) (Table 2).

Table 2. *Root mass growth*

Crop	Type of plot	Average root weight (g/plant)	Root mass increase (%)	The dry weight of the ground part (g/plant)	Increase in dry weight (%)	Biological products	Vegetation period
Barley ("Helios")	Control	15	0	45	0	No biological products were used	April-July
Barley ("Helios")	Experimental	17	13	51.75	15	Nitrogen-fixing (Bionorm N)	April-July
Barley ("Helios")	Experimental	16.5	10	50	11.11	Mycorrhizal (Mycorrhizin)	April-July
Barley ("Helios")	Experimental	16	7	49	8.89	Phosphate mobilising agents (Phosphobacterin)	April-July
Barley ("Helios")	Experimental	19.5	30	54	20	Nitrogen-fixing (Bionorm N) + Mycorrhizal (Mycorrhizin)	April-July
Barley ("Helios")	Experimental	18.5	23	52.5	16.67	Nitrogen-fixing (Bionorm N) + Phosphate-mobilising (Phosphobacterin)	April-July
Barley ("Helios")	Experimental	20	33	55	22.22	Nitrogen-fixing + Mycorrhizal + Phosphate-mobilising	April-July
Buckwheat ("Antaria")	Control	8	0	25	0	No biological products were used	May-July
Buckwheat ("Antaria")	Experimental	9	12.5	28.75	15	Nitrogen-fixing (Bionorm N)	May-July
Buckwheat ("Antaria")	Experimental	8.7	8.75	27.5	10	Mycorrhizal (Mycorrhizin)	May-July
Buckwheat ("Antaria")	Experimental	8.5	6.25	26.5	6	Phosphate mobilising agents (Phosphobacterin)	May-July
Buckwheat ("Antaria")	Experimental	10	25	30	20	Nitrogen-fixing (Bionorm N) + Mycorrhizal (Mycorrhizin)	May–July
Buckwheat ("Antaria")	Experimental	9.5	18.72	28.75	15	Nitrogen-fixing (Bionorm N) + Phosphate-mobilising (Phosphobacterin)	May-July
Buckwheat ("Antaria")	Experimental	10.2	27.5	31	24	Nitrogen-fixing + Mycorrhizal + Phosphate-mobilising	May-July

Source: *compiled by the authors*

The maximum results were recorded when using a three-component combination of nitrogen-fixing, mycorrhizal and phosphate-mobilising preparations. In barley, the average root weight reached 20 g/plant (33% increase), and the dry weight of the ground part – 55 g/plant (22.22% increase). In buckwheat, these figures were 10.2 g/plant (27.5% increase) and 31 g/plant (24% increase), respectively (Fig. 1). This confirms the synergistic effect of the products, which maximises the use of soil resources even under adverse conditions.

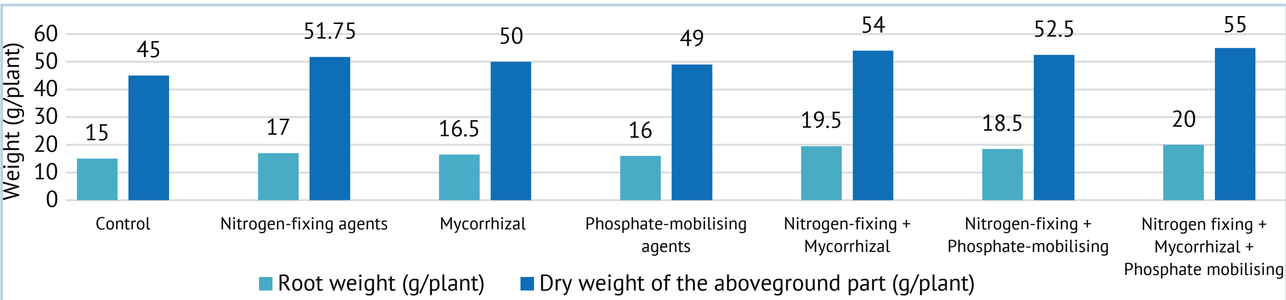

Figure 1. *Growth dynamics of the root system and ground parts of plants*
Source: *compiled by the authors*

Thus, the combined data show that the use of biological products significantly improves the development of both root and above-ground parts of plants, ensuring their resistance to stressful conditions and increasing yields. The use of combined products is a promising area for optimising agricultural technologies. The results of the study show that the use of biological products significantly improved the quality of grains of barley variety Helios and buckwheat variety Antaria. A significant increase in protein content was noted in both crops compared to the control plots, indicating an increase in plant nutrition efficiency and optimisation of their metabolic processes. In the control plots, where no biological products were used, the protein content of barley grain was 10.5%, and in buckwheat – 12.5%. These figures are basic and typical for standard growing conditions without the use of additional stimulants. However, limited nutrition, in particular nitrogen and phosphorus deficiency, limited the ability of plants to synthesise protein, which negatively affected the quality characteristics of the grain.

The use of nitrogen-fixing biological products, such as Bionorm N, increased the protein content of barley grain to 11%, which was an increase of 4.76%. In buckwheat, this figure rose to 13%, which corresponded to a 4% increase. These results demonstrate the effectiveness of nitrogen-fixing bacteria in increasing the availability of nitrogen, which is a key element in protein synthesis. Plants had improved nitrogen nutrition, which is especially important at critical stages of development, such as grain formation in June and July. Mycorrhizal preparations, particularly Mycorizin, also had a positive impact on grain quality. The protein content of barley increased to 11.2%, which was a 6.67% increase compared to the control. In buckwheat, this figure reached 13.2%, which corresponded to an increase of 5.6%. The symbiotic effect of mycorrhiza provided better availability of trace elements, in particular phosphorus and potassium, which contributed to the active synthesis of protein compounds. Phosphate-mobilising products such as Phosphobacterin also contributed to an increase in protein content. In barley, this figure rose to 11.1% (up 5.71%), and in buckwheat – to 13.1% (up 4.8%). The increased phosphorus uptake allowed plants to use this element more efficiently in the synthesis of nucleotides and proteins, which was reflected in the improved grain quality.

The maximum results were obtained in areas where combinations of biological products were used. The combination of nitrogen-fixing and mycorrhizal preparations (Bionorm N + Mycorizin) provided a protein content of 12% in barley (14.29% increase) and 14% in buckwheat – (12% increase). The synergistic effect of the preparations allowed the plants to receive not only improved nitrogen nutrition but also a wide range of trace elements, which increased the efficiency of metabolic processes (Fig. 2).

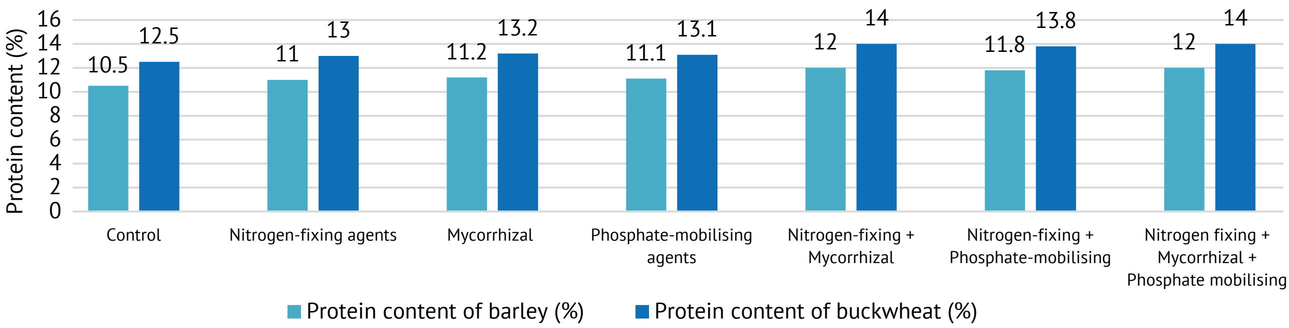

Figure 2. *The impact of biological products on grain quality*

Source: *compiled by the authors*

Thus, the combined data show that the use of biological products significantly improves the development of both root and above-ground parts of plants, ensuring their resistance to stressful conditions and increasing yields. The use of combined products is a promising area for optimising agricultural technologies. In the control plots where no biological products were used, the activity of nitrogen-fixing bacteria remained at a basic level, which limited the soil's ability to provide plants with available nitrogen. Mycorrhizal fungi and phosphate-mobilising bacteria also showed limited activity due to the lack of stimulation of their development. This led to less efficient nutrient uptake and, as a result, reduced the potential for intensive plant growth.

The use of nitrogen-fixing products, such as Bionorm N, increased the number of nitrogen-fixing bacteria, the share of which increased by 15%. This allowed for more active fixation of atmospheric nitrogen and its transformation into a form available to plants. Efficient nitrogen supply is especially important during the phases of intensive plant growth, such as inflorescence formation and grain filling. However, the impact of nitrogen-fixing products alone on mycorrhizal fungi and phosphate-mobilising bacteria was insignificant, indicating the need for combined approaches. Mycorrhizal preparations, particularly Mycorizin, increased the activity of mycorrhizal fungi by 10%. These fungi formed symbiotic relationships with the root system of plants, which significantly improved the availability of water and trace elements. Mycorrhiza also created a favourable environment for other microorganisms, including nitrogen-fixing and phosphate-mobilising bacteria, although their growth was insignificant when using only mycorrhizal preparations.

Phosphate-mobilising biological products such as Phosphobacterin increased the proportion of phosphate-mobilising bacteria by 20%. These microorganisms activated the transformation of hard-to-reach forms of phosphorus into those available to plants, which ensured better phosphorus metabolism. However, the use of phosphate-mobilising preparations alone had a limited impact on other groups of microorganisms, which confirms the importance of synergistic effects from the use of several types of biological products. The combination of nitrogen-fixing and mycorrhizal preparations (Bionorm N + Mycorizin) showed an increase in the activity of nitrogen-fixing bacteria by 25% and mycorrhizal fungi by 15%. The synergistic effect of these two products created optimal conditions for plant development, improving their water regime and providing the necessary nitrogen. At the same time, the activity of phosphate-mobilising bacteria remained at a basic level, indicating the need for additional phosphate nutrition. The combination of nitrogen-fixing and phosphate-mobilising preparations (Bionorm N + Phosphobacterin) provided an increase in nitrogen-fixing bacteria by 20% and phosphate-mobilising – by 30%. This interaction was noted to improve the nitrogen and phosphorus nutrition of plants, ensuring stable development in critical phases (Fig. 3). However, the growth of mycorrhizal fungi was minimal, which reduced the efficiency of water use during dry periods, as evidenced by these data.

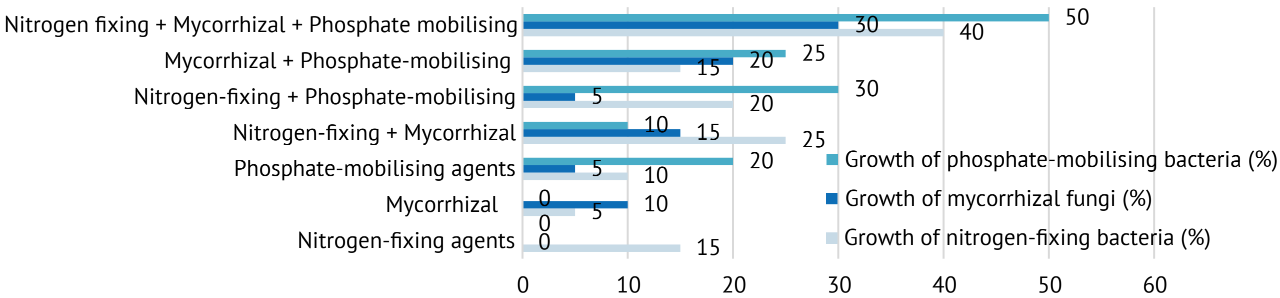

Figure 3. *Changes in the composition of soil microflora when using different biological products*
Source: *compiled by the authors*

The highest rates were recorded when using a combination of three types of biological products: nitrogen-fixing, mycorrhizal and phosphate-mobilising. The share of nitrogen-fixing bacteria increased by 40%, phosphate-mobilising – by 50%, and mycorrhizal fungi – by 30%. This synergistic effect created optimal conditions for soil microflora, which provided plants with all the necessary nutrients. This approach can ensure maximum efficiency of soil resource usage, even under adverse conditions. Changes in the composition of soil microflora indicate that biological products not only improve the availability of nutrients but also contribute to the formation of a sustainable agroecosystem. The increase in the activity of key microorganisms provides a long-term effect, improving soil fertility and reducing the need for chemical fertilisers. The data obtained confirm that the use of combined biological products is an effective tool for increasing crop productivity and creating sustainable farming systems.

DISCUSSION

The results of the study demonstrated the effectiveness of biological products in increasing crop productivity and improving soil conditions. The 20-25% increase in yields of Helios barley and 18-22% increase in yields of Antaria buckwheat in the experimental plots confirms the positive impact of the biological products. This can be attributed to the activation of nitrogen fixation processes and improved phosphorus availability, which created optimal conditions for plant growth. The combination of nitrogen-fixing, mycorrhizal and phosphate-mobilising biological products provided maximum results, emphasising their synergistic effect.

Improvement of the root system, in particular an increase in its weight by 30% in barley and 25% in buckwheat, indicates the effective effect of biological products in the early stages of growth. The increase in protein content in barley grain from 10.5% to 12% and in buckwheat from 12.5% to 14% reflects improved plant nutrition, which was ensured by the activation of soil microflora. Significant changes in the composition of soil microflora confirmed the effectiveness of the applied biological products. A 40% increase in the number of nitrogen-fixing bacteria and a 50% increase in phosphate-mobilising bacteria created a favourable environment for plants, reducing their dependence on chemical fertilisers. This improved soil quality, ensuring long-term fertility. Reducing the duration of plant development phases under the influence of biological products, accelerating the transition to generative phases, contributed to more efficient use of natural resources. These results confirm the feasibility of using biological products to increase crop productivity, improve product quality and preserve the environmental sustainability of agricultural systems.

S. Buragienė *et al.* (2023) analysed the impact of biological products on soil physical properties and CO_2 emissions during winter wheat and rapeseed production. Although the authors found that the use of biological products significantly reduced soil density and CO_2 emissions, the study did not focus on yield or crop quality. These results, which show a 20-25% increase in barley yields and an 18-22% increase in buckwheat yields, indicate a wider range of impacts of biological products, including improved product quality (protein content in grain). This broadens the prospects for the use of biological products, adding new arguments in favour of their introduction. P. Rowińska *et al.* (2024) investigated the use of biological products for the decomposition of plant residues. Although the authors noted that these products increase the biological activity of the soil, especially phosphate-mobilising bacteria, their impact on yield and product quality was not directly investigated. These results complement this study, emphasising that the biological products not only activate the microbiological activity of the soil (increasing the number of nitrogen-fixing bacteria by 40% and phosphate-mobilising – by 50%) but also significantly improve the quality and quantity of plants.

P. Kanarek *et al.* (2022) analysed the use of biological products and straw as a strategy to increase the organic carbon content of the soil in spring barley cultivation. Although the authors' study focused mainly on improving the physical and chemical properties of the soil, this data adds an important aspect – the synergistic effect of biological products on yield and product quality. For example, a 14.3% increase in protein content in barley grain under the influence of biological products indicates their direct impact on plant metabolic processes, which is not covered by P. Kanarek *et al.* The study by K. Gleń-Karolczyk *et al.* (2022) analysed the effect of biological products and biostimulants on the health of potato tubers. The authors showed that the use of these products improves the phytosanitary condition of tubers and soil structure, but the study did not address changes in the phases of plant development or the composition of soil microflora, as was done in this study. For instance, in this study, a reduction in the duration of plant development phases indicates optimisation of resource use, which is a key factor for increasing the efficiency of agricultural technologies.

C.A. Kwiatkowski *et al.* (2022) addressed the effect of biological products on the productivity and quality of chamomile grown in an organic system. Although the results showed a positive effect on plant yield and quality, these studies were limited to a specific crop, without a broad analysis of changes in soil microflora. In contrast, the results of this study show a significant increase in key soil bacteria, such as nitrogen-fixing (40% increase) and phosphate-mobilising (50% increase), which leads to increased productivity and quality of grain crops. It is considered in previous work by A. Drobitko *et al.* (2024). O. Abdujalilova & A. Musurmanov (2021) analysed the use of microbiological biological products to increase the yield of winter wheat. Although the authors emphasised the positive impact of biological products on yield, the study did not cover a more comprehensive analysis, including changes in the composition of soil microflora. Compared to this work, the results obtained demonstrate a wider range of effects of biological products, covering biological, physiological and agronomic aspects. This highlights the uniqueness of this study, which is not only aimed at increasing yields but also addresses environmental sustainability and optimising the use of natural resources. K. Lekavičienė *et al.* (2021) examined the impact of biological products on soil and crop residue properties, as well as on machine traction in shallow tillage. Although the authors focused on improving the physical properties of the soil, they did not investigate their impact on product quality or yield. This study complements this approach, as it shows that the use of biological products not only improves soil structure but also increases barley yields by 20-25% and buckwheat – by 18-22%. In addition, the increase in protein content in the grain demonstrates that biological products have the potential to improve the nutritional value of the product. A. Marcinkevičienė *et al.* (2023) analysed the use of sown cover crops and biological products in organic rapeseed cultivation. The authors' results showed the effectiveness of biological products in weed control and yield increase but are limited to one crop and do not consider the possibility of synergistic effects of several types of biological products. This study, which covers barley and buckwheat, demonstrates that combinations of nitrogen-fixing, mycorrhizal and phosphate-mobilising biological products provide the maximum effect, improving both physiological processes and plant yields. For instance, in these experiments, the protein content of barley grain increased from 10.5% to 12%, and in buckwheat – from 12.5% to 14%, which is an important indicator of product quality.

D. Juknevičius *et al.* (2020) studied changes in soil organic carbon content, energy costs and environmental impact of biological products during the cultivation of winter wheat and rapeseed. The authors concluded that biological products contribute to an increase in soil organic carbon levels, reducing energy costs of production. The study also recorded a positive impact of biological products on the soil, including a 40% increase in the number of nitrogen-fixing bacteria and a 50% increase in phosphate-mobilising bacteria. These changes contributed to improved plant nutrition and reduced the need for chemical fertilisers. However, this study additionally demonstrates an impact on crop productivity (increased barley and buckwheat yields) and grain quality (increased protein content), which was not analysed by D. Juknevičius *et al.* (2020). The study by A. Dziwulska-Hunek *et al.* (2022) analysed the quality of cereal seeds treated with effective microorganisms (EM) and red light (RL). The authors showed that the application of EM improves the physiological properties of seeds, such as germination and growth energy. These results, which demonstrate the improvement of plant development phases and acceleration of generative processes, are consistent with the findings of A. Dziwulska-Hunek *et al.* (2022). However, this study goes further, analysing not only the initial stages of growth but also the full cycle of plant development. For example, in barley, a reduction in the duration of the grain-filling phase was recorded, which contributed to faster yields.

The results confirm the effectiveness of biological products in increasing yields, product quality and improving soil microbiological activity. Comparison with other studies shows that this research is distinguished by a comprehensive approach that covers not only the physical and chemical properties of the soil but also the phases of plant development and crop quality. The uniqueness of these results lies in the demonstration of the synergistic effect of various biological products, especially their combinations, on improving the agroecosystem. This makes the proposed technologies promising for implementation in sustainable agriculture, adapted to different crops and environmental conditions.

CONCLUSIONS

The study analysed the impact of biological products on the productivity of cereal crops, in particular barley of the Helios variety and buckwheat of the Antaria variety, under specific conditions in the South of Ukraine. The focus was on assessing yields, product quality, dynamics of plant development phases and changes in soil microflora. The experiment included control and experimental plots where nitrogen-fixing, mycorrhizal and phosphate-mobilising biological products were used, both individually and in combination, to determine the synergistic effect. The results showed that the use of biological products provides a significant increase in grain yields. In barley of the Helios variety, the yield increased by 20-25%, and in buckwheat of the Antaria variety – by 18-22% compared to the control plots. The maximum yields were observed when using combinations of biological products, such as nitrogen-fixing + mycorrhizal and nitrogen-fixing + phosphate-mobilising preparations. This indicates the synergistic effect of their action, which was used to optimise plant nutrition and increase the efficiency of soil resource use.

The quality of the products has also improved significantly. In particular, the protein content of barley grain increased from 10.5% (control) to 12% (trial), and that of buckwheat – from 12.5% to 14%. Such changes are the result of increased availability of nitrogen and phosphorus, activated using biological products. This improved the metabolic processes in plants and had a positive impact on their quality characteristics. The study revealed significant changes in the phases of plant development under the influence of biological products. Reducing the duration of critical phases, such as tube emergence and grain filling, contributed to more efficient use of water and nutrients. In barley, these changes allowed the plants to reach the generative stage earlier, while in buckwheat the ripening period was shortened, which is important for optimising agricultural and technological processes in regions with an arid climate.

Changes in the composition of soil microflora are also worth noting. The use of biological products stimulated a 40% increase in the number of nitrogen-fixing bacteria and a 50% increase in phosphate-mobilising – bacteria. These changes helped improve the availability of nutrients to plants and maintain the stability of the soil ecosystem. The combinations of biological products demonstrated the greatest impact on the activity of microorganisms, creating optimal conditions for the growth and development of crops. The use of biological products also reduces dependence on chemical fertilisers, which is important for ensuring the environmental sustainability of agroecosystems. The combination of nitrogen-fixing, mycorrhizal and phosphate-mobilising products has created an integrated approach to plant nutrition that increases agricultural productivity without harming the environment. Thus, the study confirmed the effectiveness of biological products in increasing the yield and quality of grain crops, optimising plant development stages and improving the condition of soil resources. Further research should address the long-term impact of biological products on soil fertility and their effectiveness for other crops and soil and climatic zones.

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CONFLICT OF INTEREST

None.

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Вплив біопрепаратів на продуктивність зернових культур в умовах Півдня України

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Анотація. Метою дослідження було визначення оптимальних умов застосування біопрепаратів для підвищення агроекологічної ефективності вирощування зернових культур, зокрема через аналіз їх впливу на фізіологічні процеси рослин, продуктивність і стан ґрунтових ресурсів. У роботі представлено результати дослідження впливу біопрепаратів на врожайність, якість продукції, динаміку фаз розвитку рослин та склад мікрофлори ґрунту при вирощуванні ячменю сорту «Геліос» і гречки сорту «Антарія» в умовах Півдня України. Дослід було проведено з використанням азотфіксуючих, мікоризних та фосфатмобілізуючих біопрепаратів як окремо, так і в комбінаціях, із закладенням контрольних і дослідних ділянок. Аналіз включав оцінку врожайності, вмісту білка в зерні, змін у фазах розвитку рослин та активності ґрунтових мікроорганізмів. Результати дослідження показали, що застосування біопрепаратів забезпечило суттєве підвищення врожайності: ячмінь показав приріст на 20-25 %, а гречка – на 18-22 % порівняно з контрольними ділянками. Вміст білка в зерні також збільшився, досягнувши 12 % у ячменю і 14 % у гречки. Відзначено скорочення тривалості фаз розвитку рослин, що сприяло більш ефективному використанню ресурсів ґрунту та оптимізації процесів росту. Зміни у складі мікрофлори ґрунту були особливо помітними: чисельність азотфіксуючих бактерій збільшилася на 40 %, а фосфатмобілізуючих – на 50 %, що покращило доступність поживних речовин для рослин. Найвищі показники було досягнуто при використанні комбінацій біопрепаратів, які продемонстрували синергетичний ефект, підвищуючи продуктивність культур і покращуючи якість продукції. Отримані результати підтвердили ефективність біопрепаратів у створенні стійких агроекосистем, забезпечуючи екологічну безпеку, зниження потреби у хімічних добривах та підвищення економічної рентабельності аграрного виробництва. Використання біопрепаратів є перспективним напрямом для оптимізації сучасних агротехнологій у регіонах із несприятливими ґрунтово-кліматичними умовами

Ключові слова: агротехнології; урожайність; агроекосистеми; екологічна стійкість; органічне живлення

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Role of accounting and control system in taxation of agricultural enterprises under martial law

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Abstract. Under martial law, Ukraine's agricultural sector faces significant challenges, including an unstable tax burden, changes in legislation and difficulties in accounting. The accounting and control system plays a key role in ensuring the transparency of the financial activities of agricultural enterprises, optimising tax liabilities and minimising fiscal control risks. The study aimed to determine the role of the accounting and control system in the taxation of agricultural enterprises during the war and to develop proposals for its improvement. Based on the results of the study, the study defined the role of the accounting and control system in the taxation of agricultural enterprises under martial law and developed practical recommendations for its optimisation. The study provided an analysis of legislative changes, a comparative analysis of tax mechanisms, and the results of a survey of enterprises participating

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in the Territory of High Tax Confidence project. The study established that under martial law, the efficiency of the accounting and control system directly affects the ability of enterprises to fulfil tax obligations, reduce risk of penalties and maintain financial stability. The author proposed approaches to adjusting the accounting and control system to minimise tax risks, reduce the financial burden and adapt to changes in tax regulation. The results of the study can be used by agricultural enterprises to improve the accounting and control system, as well as by government agencies in developing tax initiatives aimed at supporting businesses in crises. Recommendations are aimed at digitalising the accounting system to reduce administrative burden and increase the sustainability of the agricultural sector

Keywords: agricultural enterprises; accounting and control system; taxation; tax regulation; tax compliance manager

INTRODUCTION

During the martial law in Ukraine, agricultural enterprises faced new restrictions as a result of military operations, as well as the need to adapt to new economic conditions, in particular in the field of taxation. There was a need to update the accounting and control system to ensure the effective operation of enterprises in the face of reduced production capacity, loss of property, disruption of supply chains and other difficulties associated with the war. The importance of improving the accounting and control system for tax purposes is of particular importance for agricultural enterprises operating in an environment of increased risk and instability. It is necessary to analyse the theoretical foundations of the accounting and control system, which cover such key aspects as tax planning, financial analysis, internal control and risk management, but are not limited to these elements. They can be used to assess the state of the business and the impact of external factors, including regulatory changes and military losses (Jensen, 2022). The concepts of the accounting and control system and its elements were analysed and numerous studies.

L.O. Marmul (2018) analysed the theoretical and practical foundations of modern transformations of the accounting and taxation system, the state and directions of improving the quality of control and analysed the applied aspects of regulating the socio-economic development of agricultural enterprises. The issue of tax reform under martial law was analysed by S. Oneshko *et al*. (2022). The authors analysed the changes in the tax legislation of Ukraine and their impact on the functioning of enterprises, in the agricultural sector, in the context of military operations. The researchers used a comparative analysis of legislative changes and practical cases to determine the effectiveness of adapting tax procedures to the new conditions. The conclusions highlighted the need for flexibility in the tax system to support businesses in times of instability.

The experience of foreign researchers is important for the adoption of effective accounting, control and financial practices in similar conditions, for adapting to the challenges faced by agricultural enterprises in crisis circumstances (Okafor, 2022; Omodero, 2022). R. Singh (2016) and S. Silajdzic & E. Mehic (2022) assessed the effectiveness of tax policy in advanced economies and emerging markets in attracting foreign direct investment. The authors analysed the relationship between tax rates, investment attractiveness and economic stability, finding that harmonisation of tax mechanisms helps to improve the investment climate. However, to achieve maximum effectiveness, such harmonisation should address the specific conditions of development of individual countries, in the context of economic instability or martial law, which is relevant for Ukraine. The topic is related to the insufficiently studied aspects of the role of the accounting and control system for the purposes of taxation of agricultural enterprises in wartime, in particular, the impact of external tax factors on the organisation of accounting and control of taxation operations.

MATERIALS AND METHODS

To study the peculiarities of the functioning of the accounting and control system for the taxation of agricultural enterprises under martial law, the author uses the method of analysis. The observation method was used to assess the real changes in the organisation of accounting and control and the corresponding changes in the taxation of agricultural enterprises in response to the wartime crisis factors. The methods of specification, grouping, and generalisation were used to achieve the goal and determine the results of the study. An institutional approach was also used to study the legislative and regulatory support for accounting and control of taxation operations of agricultural enterprises, in particular, the legislation of Ukraine regulating the taxation of farmers was analysed. In particular, changes in Tax Code of Ukraine (2010), Law of Ukraine No. 2120-IX “On Amendments to the Tax Code of Ukraine and Other Legislative Acts of Ukraine Regarding the Validity of Provisions for the Period of Martial Law" (2022), Law of Ukraine No. 3219-IX "On Amendments to the Tax Code of Ukraine and Other Laws of Ukraine on Peculiarities of Taxation During the Period of Martial Law" (2023), Order of the State Tax Service of Ukraine No. 444 "On Approval of the Methodology for Conducting Inspections of General Provisions of Tax and Other Legislation of Ukraine, Control over Compliance with Which is Entrusted to Tax Authorities" (2023), Order of the State Tax Service of Ukraine No. 445 "On Approval of the Methodology for Conducting an Audit of the Accuracy, Completeness of Accrual and Payment of Income Tax" (2023), Order of the State Tax Service of Ukraine No. 446 "On Approval of the Methodology for Conducting an Audit of the Accuracy, Completeness of the Accrual and Payment of Value Added Tax" (2023), Order of the State Tax Service of Ukraine No. 322 "On Approval of the Methodology for Verification of the Accuracy, Completeness of Calculation and Payment of Personal Income Tax, Single Contribution to the Compulsory State Social Insurance and Military Tax" (2023), Order of the State Tax Service of Ukraine No. 831 "On Approval of the Methodology for Verification of the Accuracy, Completeness of Accrual and Payment of Excise Tax" (2023).

The areas of support and the main conditions for participation in the Tax Trust Territory project were determined based on information from the official website of the State Tax Service of Ukraine. A group of enterprises in the Mykolaiv Region that were included in the category of taxpayers with a high level of voluntary compliance with tax legislation and included in the project "Territory of high level of tax confidence" was selected for the study to conduct a survey and determine the feasibility and results of implementing such a project. The conclusions obtained became the basis for the development of practical recommendations for improving the accounting and control system for the purposes of taxation of agricultural enterprises under martial law.

RESULTS

The accounting and control system of an agricultural enterprise is an interconnection of successive business operations and actions performed to ensure the completeness and accuracy of information to prepare financial and other forms of reporting and make effective management decisions. These transactions and actions are performed within the framework of accounting and tax accounting. The role of the accounting and control system was of particular importance in recent years, during the martial law period, as a significant number of agricultural enterprises have lost not only the opportunity to harvest in 2022 and further use the available land for their intended purpose but also lost some accounting and reporting information, including without the possibility of its recovery (Sus *et al.*, 2023). This has a direct impact on the fulfilment of tax obligations of agricultural enterprises to timely accrue and fully pay taxes and mandatory payments.

Given the peculiarities of agricultural production, the accounting and control system of agricultural enterprises acquires characteristics and functions that are specific to the agricultural sector (Khadka *et al.*, 2024). For effective decision-making at all levels of enterprise management, the accounting and control system should perform the following functions: 1) information (accounting) – a collection of necessary data according to certain rules and programmes of the accounting and control system, their documentary reflection, processing and transmission of the obtained indicators and data for further use by different user groups; 2) controlling – with the help of which the management personnel checks the received deviations, determines their causes and makes appropriate management decisions to correct the received deviations; 3) analytical – its essence is that it is necessary to process accounting data, process deviations from the planned indicators and necessarily substantiate the cause and effect of economic phenomena. The main task of this function is to ensure an increase in production efficiency and, as a result, to eliminate factors that hinder the development of the enterprise; 4) regulatory – is expressed in the direct impact of the accounting and control system on production, i.e. in its regulation; 5) incentive, the essence of which is that well-established accounting and control not only record the degree of rationality in the use of the enterprise's resources but also encourage their economical and careful use (Dyreng *et al.*, 2019).

Thus, the authors believe that, in addition to these functions, the accounting and control system of an agricultural enterprise during martial law also performs a regenerative and stabilising function. Its essence is to ensure the resumption and/or continuation of the company's activities under martial law, to ensure the fulfilment of all obligations of the company, including tax obligations, as well as all other functions in the face of risks and uncertainty. The purpose of the accounting and control system in taxation is to ensure the accuracy of tax liabilities, control the timeliness and completeness of tax payments, minimise tax risks for enterprises, and promote transparency of financial activities following applicable law. Thus, based on the purpose and functions of the accounting and control system, a model of information support of this system for the taxation of agricultural enterprises has been formed (Fig. 1).

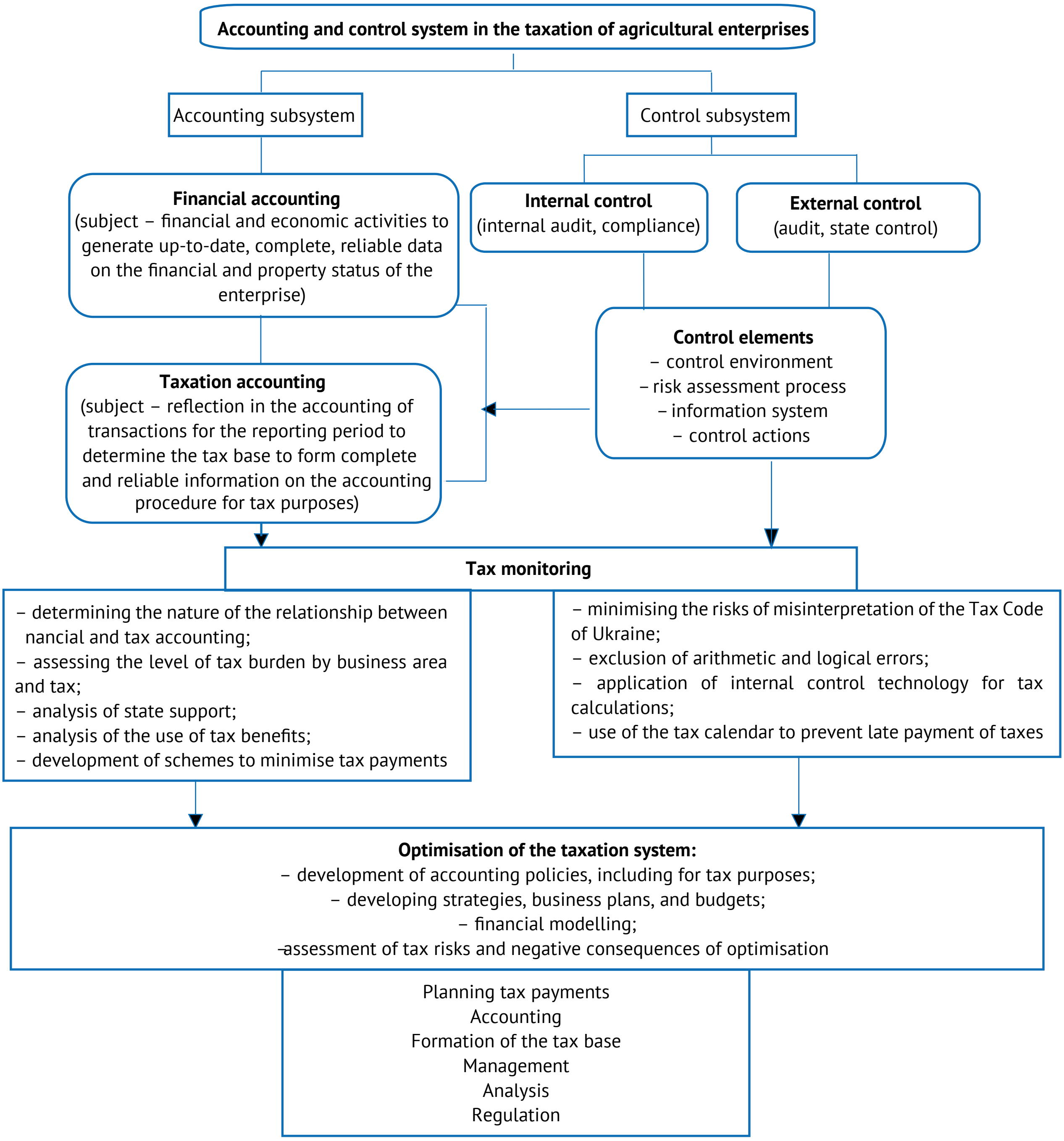

Figure 1. *Accounting and control system in the taxation of agricultural enterprises*
Source: compiled by the authors

The authors believe that one of the most important methods for optimising the taxation system is a properly formed accounting policy of an enterprise, which reduces the tax burden based on legitimate grounds provided for by tax legislation. Accounting policy for taxation purposes is a set of methods and approaches adopted in accordance with the Tax Code of Ukraine (2010) and chosen by the taxpayer to determine taxable items, allocate and record them in the accounts, as well as to record other indicators required for taxation purposes of the company's financial and economic activities. The sectoral characteristics of the agricultural sector directly affect the tax burden of agricultural enterprises (Tkal *et al.*, 2019). The choice of certain variants of accounting elements in taxation depends on a combination of natural and climatic, biological, technical and technological, organisational and economic factors, the organisational model of management and the presence of structural units, sales volumes, branches, subsidiaries, taxation system, forms of settlements with counterparties, and interaction with financial institutions (Shevchuk & Zaitseva, 2018; Butkevich, 2021). The accounting policy for tax purposes is intended to ensure the integrity of the tax accounting system, therefore it should cover all aspects of the process of accounting for settlements with the enterprise's budget. The authors consider it appropriate for agricultural enterprises to form a separate section to the Order on Accounting Policy "Organisation of Accounting for Taxation Purposes". The proposed structure of the section on accounting policy for taxation purposes of agricultural enterprises is shown in Figure 2.

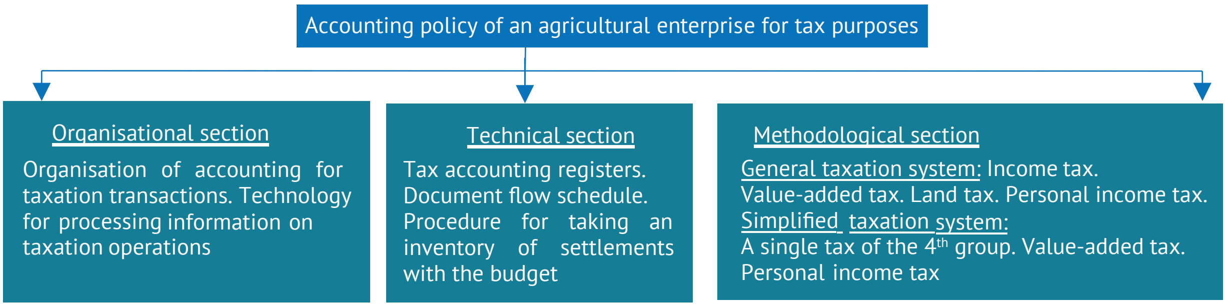

Figure 2. *The proposed structure of accounting policy for taxation purposes of an agricultural enterprise*
Source: *compiled by the authors*

The organisational component of the accounting policy for tax purposes should disclose the methods of accounting for taxation transactions, namely: organising accounting department in terms of taxation operations; composition, forms and methods of forming registers for recording taxation transactions; organisation of document flow. The technical aspect must be ensured: the procedure for settlements with the budget; the procedure for an inventory of budget calculations; regulation of material liability at the enterprise; the procedure for storing tax returns and accounting registers. The methodological aspect of the accounting policy of an agricultural enterprise for tax purposes should be reflected: the taxation system chosen by the company; disclosure of the methodology for accrual, withholding and reporting of tax liabilities in the tax statements following the tax legislation.

The main purpose of establishing a control system as a component of the accounting and control mechanism for tax purposes at an enterprise is to assist management in the effective implementation of its functions. This is achieved by providing recommendations and other information obtained in the course of audits by the controlling officers. Therefore, a clear definition of tax audit methodologies that regulate the procedures for controlling and assessing the accuracy and completeness of tax payments is required. The relevance of such documents is determined by the need to minimise tax risks, optimise the tax burden and ensure legal certainty in relations with tax authorities (McKeehan & Zodrow, 2017). The use of structured methodologies allows companies to plan their activities more efficiently, address the possible tax consequences of financial transactions and fulfil their tax obligations in a timely manner. The application of tax methodologies at the enterprise level includes tax compliance audits, preparation for audits, analysis of the correctness of tax accrual and payment, and implementation of internal control systems (Hou *et al.*, 2024). Such documents help increase the transparency of financial activities, reduce the risk of penalties and facilitate the building of long-term partnerships with government authorities. The methodologies approved by the State Tax Service of Ukraine are an important tool to support tax compliance and ensure fair and efficient tax collection. They provide clear guidelines and instructions for the controlling authorities and contribute to a high level of trust between business and government agencies (Kovalchuk *et al.*, 2021). Their main goal is to establish the correctness and timeliness of the accrual and payment (transfer) of taxes and fees, as well as their reflection in accounting and reporting. Thus, the use of tax control methods is an integral part of the financial management of enterprises, which not only ensures compliance with the requirements of the law but also increases the efficiency of economic activity and provides financial stability. Notably, tax accounting for any business entity, including agricultural ones, has faced many obstacles and difficulties since the first days of the full-scale invasion to ensure the fulfilment of its functions and tasks – from the registration of tax invoices to changes in taxation forms. The external influence of tax factors cannot be levelled by the enterprise but minimising it with the use of an efficiently organised accounting and control system is the real and only way out (Table 1).

Table 1. *Adjustment of the accounting and control system of agricultural enterprises under the influence of tax factors in the conditions of martial law*

Impact of martial law	Changes in taxation	Adjustment of the accounting and control system
Partial restriction or complete impossibility of continuing business activities	Change or termination of tax liability following the Tax Code of Ukraine. If force majeure is confirmed, a company can avoid tax liability	Violation of the going concern principle. Ensuring that the fact of forced mothballing of assets is reflected in the primary, synthetic and analytical accounting; controlling contractual relations; ensuring warranty obligations
Full or partial relocation of the company's activities to safer areas (relocation of the company)*	Changes in the taxation system	Reflecting changes in the management and production structure; accounting and control of expenses for supporting operations in another city
Full or partial change in the direction of business as a result of the relocation of the enterprise	Changes in the taxation system	Adjustment of the classification of economic activities
Full or partial inability to complete (conduct) settlements with counterparties	Adjustment of tax liabilities. Stopping the registration of tax invoices	Consideration of the appropriateness of calculating the allowance for doubtful debts
Total or partial loss of assets	An entity may recognise the loss of assets as an expense. Discontinuation of depreciation. Adjustment of the tax credit with value-added tax (no adjustment is required if it is proved that the asset was lost due to force majeure). Temporary exemption from property tax and land tax	Conducting an inventory with its documentary registration and reflecting its results in accounting
Assistance to the Armed Forces of Ukraine	Reduction of taxable profit in the full amount of transferred property and funds	Accounting and control of products works, and services aimed at assisting the Armed Forces of Ukraine; part of the sales revenue aimed at assisting the Armed Forces of Ukraine
Labour relations and employee settlements	A mobilised employee is not paid a salary, as no work duties are performed	Accounting and control of hiring, dismissal, and leave, including paid leave, remote work, labour guarantees for mobilised employees, etc

Notes: **including the peculiarities of agricultural production, it concerns offices, documentation, employees, equipment, etc*
Source: *compiled by the authors*

Even though martial law significantly affects many agricultural businesses, but not a reason to stop operating, they continue to operate, providing consumers with agricultural products and replenishing the budget by paying taxes and mandatory payments (Kostornoi *et al.*, 2021). One of the areas of support is participation in the project of the State Tax Service of Ukraine called the Territory of High Tax Confidence. The authors emphasise that the project operates during martial law and until the end of the year when martial law is lifted. It is designed for honest taxpayers. A company that does not have an organised and effective accounting and control system cannot be an honest taxpayer a priori. For such honest taxpayers, the specifics of administering taxes, fees and payments were introduced as a new step towards partnership between the state and business. In this context, the state receives tax revenues in full promptly, and business structures have an appropriate reputational status, professional "first aid" and other benefits. These other benefits include: a partial moratorium on documentary unscheduled, scheduled and actual inspections; a significant reduction in the timeframe for conducting desk and documentary checks to obtain a budgetary refund; reducing the timeframe for providing individual tax advice; the possibility of using the services of a personal tax compliance manager to make management decisions on optimising the tax burden, organising internal control to mitigate the risks of tax law violations, etc. Support for taxpayers with a high level of voluntary tax compliance is characterised by targeted, accurate, fast, responsive, relevant, time-sensitive and long-term cooperation. Agricultural enterprises can join the High-Tax Trust Territory project under the conditions set out in Table 2.

Table 2. *Terms of participation of agricultural enterprises in the project "Territory of high level of tax confidence"*

Terms of participation of agricultural enterprises in the project	For legal entities on the general taxation system	For legal entities of group IV single taxpayers (agricultural producers)
Level of income tax payments	Must be equal to or higher than the industry average for the last 4 quarters	X
Level of value-added tax payment	Must be equal to or higher than the industry average for the last 12 reporting periods	Must be equal to or higher than the industry average for the last 12 reporting periods
Average wage	Must be not less than the average salary in the industry in the region multiplied by a coefficient of 1.1 for the last 4 quarters, provided that there are at least five employees	
Difference between the amount of minimum tax liability and taxes paid and land lease expenses	X	Negative value
Land area	X	Owned (under ownership/use), leased land plots – not less than 200 ha
Payment for land and single tax	X	Full compliance with tax obligations
Common requirements	No violations of reporting deadlines; no decision on inclusion in the list of risky VAT payers; no tax and unified social tax arrears; no violations of the deadlines for settlements for export and import transactions in the last 12 months; no sanctions against the taxpayer and/or its founders (participants), ultimate beneficial owners; no bankruptcy or winding-up procedures; the taxpayer and/or its founders (participants), ultimate beneficial owners do not have the citizenship of the state that carries out armed aggression against Ukraine; no changes in the main economic activity over the past 12 months; compliance with the criteria depends on the chosen taxation system; being registered with the State Tax Service for more than 1 year	

Source: *compiled by the authors based on data of Order of the Ministry of Finance of Ukraine No. 495 "On Approval of the Procedure for the Formation and Publication of the List of Taxpayers with a High Level of Voluntary Compliance with Tax Legislation" (2024)*

Business entities in the type of economic activity "Agriculture, forestry and fisheries", which are subject to the general taxation system, practically do not use the opportunities of this tax project. Thus, the List of Taxpayers with a high level of voluntary compliance with tax legislation does not include these business entities in the Mykolaiv Region. As of 1 January 2025, 38 business entities in the Mykolaiv Region were included in this list among those legal entities in the region that are subject to the simplified taxation system of the 4th group for the above type of economic activity. 14 farms, 10 limited liability companies, 5 private agricultural enterprises, 3 agricultural limited liability companies, 2 additional liability companies, 2 subsidiaries, 1 private enterprise and 1 agricultural share company. 92% are engaged in the cultivation of cereals (except rice), legumes and oilseeds. One enterprise each is engaged in growing other annual and biennial crops; growing vegetables and melons, roots and tubers; and breeding dairy cattle.

The authors surveyed the peculiarities of taxation of agricultural enterprises in the Mykolaiv Region under martial law at 30 of the 38 business entities included in the List of Taxpayers with a high level of voluntary compliance with tax legislation. During the project's existence, the surveyed agricultural enterprises used only the service of consulting a personal compliance manager. Thus, 8 respondents contacted the compliance manager with questions about the specifics of taxation and the impact of martial law on the company's taxation system. The authors summarised these issues that were the subject of such consultations. The main ones are: searching for state support instruments that can be used by taxpayers affected by the hostilities (mining of territories, destruction of property, part of the land plots in the occupation zone, etc); on the details and possibility of using the online services offered by the project; adjustments to tax liabilities and financial results resulting from the loss of the ability to complete settlements under signed contracts; on documentation and confirmation of the provision of assistance to the Armed Forces of Ukraine; on the impact on the fulfilment of tax obligations of the fact of partial restriction of business activities.

The authors noted that the respondents who used the above-mentioned service noted the prompt provision of full and detailed consultations in oral and written form. The consultations were substantiated, regarding the current legal and regulatory framework and addressing the specific individual situation and circumstances of a particular company, including its existing accounting and control system. Given the rather significant positive results of the implementation of the Territory of High Tax Confidence project in Mykolaiv Region in terms of the participation of agricultural enterprises, the authors consider it appropriate: to actively disseminate information about the benefits of participation in the High-Tax Trust Territory project among business entities, in particular through professional social groups, newspapers, magazines, webinars, seminars, etc; to consider increasing the level of accessibility of the project for taxpayers; to consider the feasibility of introducing such an advantage for project participants as the possibility of obtaining advice on the preparation of tax reports in the presence of a non-standard situation in financial and economic activities and the professional judgement of managers and accountants within the functioning accounting and control system of the enterprise.

DISCUSSION

The results of the study show a significant impact of the accounting and control system on the taxation of agricultural enterprises under martial law in Ukraine. The study established that in the conditions of war, agrarian enterprises face significant difficulties, to overcome which the author considers the mechanisms of adaptation of the accounting and control system of enterprises, which will allow them to minimise tax risks, optimise and ensure fulfilment of tax obligations. Such measures allow enterprises to maintain financial stability, redirect resources to restore production and adapt to new economic conditions (Verbivska *et al.*, 2023). In the international context, similar support measures have been introduced in other countries during crises. Therefore, to discuss the results of the study, it is worth considering the example of international experience from Germany, where during the COVID-19 pandemic the government introduced a set of tax measures to support the agricultural sector and small businesses in general (Hörner, 2020; Lomachynska *et al.*, 2023). The German Federal Ministry of Finance allowed businesses to defer taxes and reduce advance payments. This was done to reduce the financial pressure on companies that suffered significant losses due to the pandemic. The main condition for receiving such benefits was to prove that the company was directly and significantly affected by COVID-19, without the need to provide a detailed assessment of losses.

This approach of Germany is notable in the context of the current study, as it demonstrates how government tax initiatives can help agricultural enterprises recover faster in times of crisis. Compared to the results obtained in this study, it is possible to conclude that Ukraine also needs more flexible tax support mechanisms, especially under martial law. In particular, the identified recommendations for improving the accounting and control system and introducing automated systems for accounting for damaged assets can provide more prompt information for assessing losses and preparing documents for compensation, which is relevant for Ukrainian enterprises in the context of military operations. Germany has also simplified the procedure for reducing advance tax payments for companies that expected lower revenues in the current year. This differs from the Ukrainian system, which does not have such mechanisms for prompt reduction of tax liabilities, which requires a faster response to economic challenges arising from military operations and other crises. This comparison shows that while both countries have implemented tax support measures in times of crisis, Germany focuses on simplifying administrative procedures and flexibility of the tax system, which allows businesses to receive financial assistance more quickly. In Ukraine, on the other hand, it is necessary to modernise accounting and control processes, which can significantly improve interaction with tax authorities and contribute to a faster recovery of the agricultural sector.

An example of foreign experience is the study by M.A. Arbeláez *et al.* (2019) on the political economy of protecting "sensitive" agricultural products in Colombia. The study analysed mechanisms to support the agricultural sector in the face of economic instability, through the introduction of tariffs and subsidies for key products considered important for national food security. The authors discussed the impact of such measures on the economy, farmers' incomes and the overall sustainability of the agricultural sector. In the current study, parallels can be seen in the context of supporting agricultural enterprises during crisis conditions, such as martial law, through the introduction of fiscal incentives. The difference lies in the emphasis on the role of the accounting and control system, which ensures tax efficiency and transparency of accounting, which is important for Ukraine. An important aspect in the context of the current study is to consider the experience of Israel as a state that has historically faced constant security challenges and economic instability. For decades, Israel has been able to create a unique model of economic development based on flexibility, innovation and efficient use of resources. According to A. Amelin (2022), after numerous conflicts, the country has focused on rebuilding its economy by attracting foreign investment, developing technology, and supporting small and medium-sized businesses. At the same time, J. Zeira (2021) emphasises that Israel's success is largely due to the integration of state policy with market mechanisms that ensure sustainable development even in times of exacerbation. Analysing the similarities with this study, it can be noted that in both cases, the emphasis is on adapting public policy to the conditions of crises, using economic levers such as tax incentives and institutional support for enterprises. Similar to Israel, Ukraine can use innovative approaches to improve the tax system to ensure transparency and efficiency of tax compliance by business entities under martial law. However, a significant difference is that the Israeli economy has a long experience of operating in a conflict environment, while for Ukraine this is a new challenge that requires immediate solutions. In addition, the Israeli focus on the high-tech sector and exports is more pronounced, while Ukraine is aimed at restoring the agricultural sector and ensuring domestic food security. Thus, Israel's experience is a valuable example for understanding possible ways of economic recovery, although approaches should consider the unique features of the Ukrainian context. M. Dubinina *et al*. (2022) addressed the issue of accounting in the European Union (EU). The authors emphasise the relevance of unifying accounting standards through International Financial Reporting Standards. At the same time, the authors determined that the different legal systems of EU countries create difficulties in harmonising accounting approaches. The study also highlights the growing role of digitalisation in accounting processes, which reduces administrative barriers and improves the quality of financial reporting. In contrast to the pan-European context, the current study focuses on the role of the accounting and control system in the taxation of Ukrainian agricultural enterprises during martial law.

G. Kartiko *et al*. (2023) analysed the implementation of the law on the harmonisation of tax legislation in Indonesia, aimed at overcoming the budget deficit and increasing the tax ratio in the context of the COVID-19 pandemic. The researchers applied statutory, conceptual and comparative approaches to assess the effectiveness of the new legislation. They determined that crises cause a significant decline in tax revenues. However, due to the reforms, there was a positive growth of tax revenues by 4.9%, which proved the effectiveness of government measures. The authors emphasised that the harmonisation of tax legislation contributed to a comprehensive and consolidated improvement of tax policy mechanisms. In the context of the current study, this work is relevant, since in both cases the adaptability of the tax system to crisis conditions is assessed: the pandemic in Indonesia and martial law in Ukraine. At the same time, the key differences are determined by the specifics of the crisis phenomena: the current study analysed the impact of military challenges on the agricultural sector, while the study by G. Kartiko *et al*. (2023) addressed pandemic restrictions. In addition, the current study focuses on agricultural enterprises, while in Indonesia the analysis is on the general tax policy. This demonstrates the broader context of tax reforms and emphasises the importance of adapting taxation mechanisms to the unique challenges of each region. Summing up the analysis, it is possible to state that the results of the study demonstrate the significant role of the accounting and control system in optimising the taxation of agricultural enterprises, especially under martial law. Comparison with other studies indicates the interconnectedness of approaches to addressing the negative consequences in the financial and economic activities of enterprises arising from crises, which is especially relevant for business entities in the agricultural sector of Ukraine in the context of the current situation. The study focuses on the peculiarities of accounting and control support of taxation of agricultural enterprises and implementation of mechanisms for its optimisation, including tax monitoring, internal control and adjustment of tax liabilities.

CONCLUSIONS

The conducted research confirmed the critical importance of the accounting and control system for maintaining the tax stability and financial sustainability of agricultural enterprises under martial law. The study showed that wartime challenges, such as loss of assets, forced displacement, interruption of logistics, and rapid changes in legislation, require a flexible and adaptive strategy for organising accounting and control systems. It was determined that companies with an operational accounting and control system are more effective in achieving tax compliance, reducing penalties and maintaining economic sustainability. The research showed that the introduction of tax monitoring technologies, internal audit systems and formalised accounting practices designed for tax purposes significantly reduces fiscal risks. The empirical analysis, which included a survey of agricultural enterprises in Mykolaiv Region involved in the Territory of Tax Confidence project, showed that consulting support and access to personal compliance managers improves understanding of tax obligations and promotes responsible behaviour of taxpayers. The respondents emphasised the importance of individual consultations to solve tax problems related to the loss of property, business interruptions, and state aid.

The authors confirmed the need to make industry-specific changes to accounting procedures, in particular, regarding inventory adjustments, loss reporting, and force majeure document flow. The proposed structural model of martial law accounting and control, together with the clarified section of accounting policies for tax purposes, provides pragmatic assistance to business entities and regulators. Further research directions include a comparative assessment of methods of digitalising accounting systems in times of crisis, with a focus on the use of blockchain technologies for verification and immutability of financial records. A viable area is the creation of predictive models for assessing tax risks with real-time data analytics. In addition, further research should examine the long-term impact of martial law on the establishment of trust-based tax compliance systems in the agricultural sector. Comparative studies with other conflict-affected countries could provide insights into global best practices in taxation and business resilience.

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Роль обліково-контрольної системи в оподаткуванні аграрних підприємств в умовах воєнного стану

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Анотація. В умовах воєнного стану аграрний сектор України стикається зі значними викликами, зокрема нестабільністю податкового навантаження, змінами в законодавчому регулюванні та складнощами у веденні бухгалтерського обліку. Обліково-контрольна система відіграє ключову роль у забезпеченні прозорості фінансової діяльності аграрних підприємств, оптимізації податкових зобов'язань і мінімізації ризиків фіскального контролю. Метою дослідження було визначення ролі обліково-контрольної системи в оподаткуванні аграрних підприємств під час війни та розробка пропозицій щодо її вдосконалення. За результатами проведеного дослідження визначено роль обліково-контрольної системи в оподаткуванні аграрних підприємств в умовах воєнного стану та розроблено практичні рекомендацій щодо її оптимізації. Наведено аналіз законодавчих змін, порівняльний аналіз податкових механізмів та результати анкетування підприємств-учасників проєкту «Територія високого рівня податкової довіри». Встановлено, що в умовах воєнного стану ефективність функціонування обліково-контрольної системи безпосередньо впливає на можливості підприємств виконувати податкові зобов'язання, знижувати ризики штрафних санкцій і зберігати фінансову стабільність. Запропоновано підходи до коригування системи обліку та контролю, що дозволяють мінімізувати податкові ризики, зменшити фінансове навантаження та адаптуватися до змін у податковому регулюванні. Результати дослідження можуть бути використані аграрними підприємствами для удосконалення обліково-контрольної системи, а також державними органами при розробці податкових ініціатив, спрямованих на підтримку бізнесу в умовах кризових ситуацій. Запропоновано підходи до інтеграції цифрових інструментів у процеси управління фінансами підприємств, що дозволяє оперативно реагувати на виклики воєнного стану. Рекомендації спрямовано на діджиталізацію системи обліку для зниження адміністративного навантаження та підвищення стійкості аграрного сектору

Ключові слова: аграрні підприємства; обліково-контрольна система; оподаткування; податкове регулювання; податковий комплаєнс-менеджер

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The effect of biopreparations on the adaptive properties of soybean in organic farming under hydrothermal stress

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Abstract. In the context of organic farming and hydrothermal stress, the use of biopreparations – particularly arbuscular mycorrhiza, rhizobial bacteria, and phytohormonal treatments – has gained special significance as a means of enhancing the adaptive properties of soybean. Their application helps to mitigate the negative effects of abiotic factors and maintain crop productivity. This study aimed to assess the adaptive potential of soybeans under organic farming conditions through the application of mycorrhizal, bacterial, and phytohormonal biopreparations during periods of hydrothermal stress. Based on a field study conducted in the Poltava Region, the influence of biopreparations of various origins on the biochemical, physiological-morphological, and stress-indicative parameters, as well as the productivity of the Khorol soybean variety, was analysed. The application of biopreparations significantly improved biochemical and physiological-morphological indicators, as well as the productivity of soybeans, indicating an improvement in the overall physiological condition of the plants. The highest concentrations of chlorophylls *a* and *b* were recorded in 2023 under the three-component treatment (Mycofriend with Profix and Violar), where the average increase in Chl *a* over the years of research was 42.3%, and Chl *b* was 26.7% compared with the control. The assimilative leaf area reached an average of 29.24 thousand m^2/ha, while yield was recorded at 3.23 t/ha, exceeding the control by 28.9% and 49.0% respectively. In the drought affected 2024 season, the adaptive application of biopreparations contributed to a reduction in leaf surface area loss within the range of 16.4-20.0% and yield reduction of 17.1-20.0%, compared with the control, where losses amounted to 22.1% and 24.4%, respectively. The use of biopreparations under hydrothermal stress in 2024 also resulted in an increase in proline concentration (up to 7.27 mg/g) and a decrease in MDA content (down to 7.14 mg/g), indicating reduced oxidative stress and improved osmoregulation. This effect is attributed to the synergistic action of mycorrhiza formation, nitrogen fixation, and phytohormonal activity. The practical significance of the findings lies in demonstrating the potential of integrated biological treatments to enhance the yield and stress tolerance of soybeans under the conditions of organic farming and climate-related challenges

Keywords: arbuscular mycorrhizal fungi; rhizobial bacteria; phytohormones; chlorophyll; leaf surface area; yield; proline; malondialdehyde

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INTRODUCTION

In the current context of climate instability, agricultural production is increasingly challenged by intensifying hydrothermal stress, which leads to significant disruptions in the physiological and biochemical processes of plants, ultimately reducing their productivity and resilience. The organic farming system, which relies on natural mechanisms of crop growth regulation and protection, is particularly sensitive to such changes. Against this backdrop, the search for agrobiological solutions capable of enhancing plant adaptability to adverse environmental conditions is of growing relevance. Among these solutions is the application of mycorrhizal fungi, rhizobial bacteria and phytohormonal treatments, which can synergistically support the physiological condition of plants, improve nutrient uptake efficiency and modulate stress responses. Investigating the effectiveness of such biopreparations in soybean cultivation under organic farming conditions is of considerable scientific and practical interest, especially in light of the urgent need to strengthen crop adaptability during drought-prone years.

As noted by G. Di Capua & S. Rahmstorf (2023), there is a global trend towards increasing frequency and intensity of abiotic stress factors, which adversely affect the growth, development and productivity of major agricultural crops. Under such conditions, the studies of A. Muhammad *et al.* (2024) have identified disruptions in the physiological and biochemical processes in plants, resulting in suppressed growth compared with optimal cultivation conditions. According to S. Chattaraj *et al.* (2025), this situation is causing growing concern in the agricultural sector and is driving global demand for effective, environmentally safe strategies to mitigate the negative effects of stress factors. In this context, T. Sa (2024) highlighted the ability of beneficial microorganisms to enhance plant resistance to abiotic stress, emphasising the crucial role of plant-microbiome interactions as a fundamental prerequisite for stable agricultural production in the face of climate change.

Alongside these challenges, the growing demand for environmentally friendly products, climate change, biodiversity loss and soil degradation are driving the development of organic farming as a strategy to reduce the anthropogenic pressure on agroecosystems. According to J. Sanders *et al.* (2025), organic farming can contribute to addressing current environmental and resource-related issues and is rightly regarded as a key approach to sustainable land use. Within this system, the use of biological preparations to enhance crop productivity and stress tolerance plays an especially important role. Research by T. Chaika *et al.* (2023) indicated that soybean (*Glycine max* (L.) Merr.), as a leading protein and oilseed crop, holds a central position in the structure of organic production in Ukraine, accounting for 24.7% of the EU's demand. This places Ukraine second among the countries exporting organic soybeans to the European market.

At the same time, as noted by S. Gouli *et al.* (2024), climate change and increasingly erratic moisture conditions during the growing season are critical risk factors, posing a growing threat to crop yields and the overall resilience of agriculture. This highlights the need for effective adaptive solutions to stabilise the productivity of organic soybeans under abiotic stress, as drought conditions can lead to yield losses of up to 100%. In the context of organic farming, the use of arbuscular mycorrhizal (AM) fungi, rhizobial bacteria and phytohormones represents a promising agrobiotechnological strategy, particularly in soybean cultivation. R.K. Ravi *et al.* (2024) reported that AM fungi promote crop growth by enhancing nutrient uptake and play a key role in regulating water balance and improving plant nutrition under adverse conditions. According to the studies of M.P. Inbaraj (2021) and W. Sun & M.H. Shahrajabian (2023), the combined inoculation of soybean with AM fungi and rhizobial bacteria – particularly *Bradyrhizobium japonicum* – enhances the efficiency of biological nitrogen fixation and improves the overall physiological condition of the plants.

In their study, Z. Liao *et al.* (2025) stated that phytohormones play a pivotal role in the system of adaptive mechanisms that counteract drought stress. Acting as endogenous signalling molecules, they coordinate the expression of drought-resistance genes, regulate osmotic balance, modify the architecture of both root systems and aerial plant parts, and induce the biosynthesis of protective compounds, thus enabling a comprehensive physiological adaptation to moisture deficiency. Such biological approaches align with the principles of organic farming by supporting soil fertility and reducing the need for chemical fertilisers, thereby lowering the environmental impact on agroecosystems. As a result, the ecological intensification of crop production through biopreparations – combining the functions of growth stimulators, pathogen antagonists, and stress resistance inducers – represents a promising strategy for improving crop productivity, particularly in soybean cultivation. At the same time, comprehensive studies on the synergistic interaction of arbuscular mycorrhizal fungi, rhizobial bacteria and exogenous phytohormones in soybean agrocenoses under organic farming conditions remain largely unexplored. This highlights the high scientific and practical relevance of the present study, particularly in the context of intensifying hydrothermal stress and the urgent need to enhance the adaptive potential of agricultural crops.

This research aimed to assess the adaptive potential of organically grown soybeans under the influence of mycorrhizal, bacterial and phytohormonal biopreparations across years with differing moisture and temperature conditions. To achieve this aim, the following objectives were pursued: to evaluate the biochemical, physiological-morphological, stress-indicator parameters and productivity of soybean concerning the application of mycorrhizal, bacterial and phytohormonal biopreparations; and to analyse the effectiveness of integrated biological stimulation of soybean stress tolerance under organic farming conditions depending on the climatic conditions of the growing season.

MATERIALS AND METHODS

Experimental research was carried out from May to August during the years 2022-2024 on trial plots located in Khudoliivka Village, Kremenchuk District, Poltava Region. The research was conducted following ethical requirements. Experimental studies on plants, including the collection of plant material, followed institutional and international guidelines. The research also complied with the standards of the Convention on Biological Diversity (1992).

The experimental site is characterised by high environmental quality due to the presence of nearby forest plantations and Lake Sudebske. The soil cover of the trial plots is represented by residual-solonetz chernozem on loess deposits, with a medium level of nitrogen and phosphorus availability and a high potassium content. Agrochemical parameters of the soil were determined in the arable layer (0-20 cm) using a Palintest SK500 multiparameter photometer (Palintest Ltd., United Kingdom). According to the analysis, the soil had the following properties: acidity (pH KCl) – 6.3 (slightly acidic reaction); humus content – 5.2%; total nitrogen – 58.6 mg/kg; available phosphorus – 78.3 mg/kg; exchangeable potassium – 138.4 mg/kg. The total area of the experimental plot was 0.3 ha, with the accounting area covering 0.1 ha.

The research material consisted of the early-maturing Ukrainian soybean variety Khorol, developed by the Soybean Research Institute LLC. Field experiments were conducted in triplicate with randomised placement of treatment variants. Standard agronomic practices for the region were applied during the cultivation process. Soybeans were sown after spring barley as a preceding crop. Sowing was carried out at optimal dates, under the climatic conditions of each research year, to a depth of 5 cm, with row spacing of 38 cm and a seeding rate of 700,000 viable seeds per hectare.

Soil cultivation techniques, adapted to the principles of organic farming, included a sequence of operations: deep autumn ploughing using a mouldboard plough, early spring harrowing with heavy harrows to conserve soil moisture, pre-sowing cultivation with a stubble cultivator, and mechanical weed control through the use of mesh harrows both before and after crop emergence, followed by two inter-row cultivations. To provide biological protection of the crops from pests, *Trichogramma* entomophages were manually released three times at a rate of 100,000-200,000 individuals per hectare, distributed across 50 locations per hectare: before sowing, 30 days after the first application, and additionally if a high level of pest infestation was observed.

The experimental design was implemented as follows: Variant 1 – control (seed and plant treatment with an equivalent volume of water); Variant 2 – seed treatment with Mycofriend®-sc (BTU-Centre, Ukraine), using a diluted solution (1:10) at a rate of 1.5 L/t of seed, applied one hour before sowing; Variant 3 – seed treatment using the dry method with Mycofriend-wp (BTU-Centre, Ukraine) at a rate of 1.5 kg/t. After 30 minutes, seeds were inoculated with Profix® (Certis Belchim, Belgium) using the dry method, 30 minutes before sowing, at a rate of 1.25 kg per 500 kg of seed; Variant 4 – dry seed treatment with Mycofriend-wp at a rate of 1.5 kg/t. During the budding to early flowering stage, plants were sprayed with a diluted solution of Violar® (Innovation Company Bioinvest-Agro LLC, Ukraine) – 100 mL diluted in 200 L of water per hectare; Variant 5 – dry seed treatment with Mycofriend-wp at a rate of 1.5 kg/t. After 30 minutes, seeds were inoculated with Profix using the dry method 30 minutes before sowing at a rate of 1.25 kg per 500 kg of seed. During the budding to early flowering stage, soybean crops were sprayed with the phytohormone complex preparation Violar at a rate of 100 mL/ha, diluted in 200 L of water.

To obtain representative data on the effectiveness of biopreparations in organic soybean cultivation, products with different mechanisms of action on plant physiological processes and various forms of symbiotic interaction were selected. Particular attention was paid to the potential synergistic effects of interactions between components when choosing the biopreparations. In Mycofriend-wp and Mycofriend-sc, synergy is achieved through the mutually reinforcing effects of mycorrhizal fungi and rhizosphere bacteria. Specifically, *Pseudomonas fluorescens* secretes metabolites that stimulate hyphal development in *Glomus sp.*, while the mycorrhizal fungi improve phosphorus availability for *Bacillus* species. The *Bradyrhizobium* strains in Profix exhibit functional complementarity due to differing colonisation dynamics of root tissues and distinct temperature optima for nitrogenase activity, ensuring stable nitrogen fixation across a wide range of agro-ecological conditions. In Violar, synergism is realised through a balanced ratio of phytohormones from various classes, enabling comprehensive regulation of growth and adaptive processes in the plant organism.

Observations of weather conditions and precipitation dynamics were carried out annually during the growing season (May-August), enabling an assessment of the impact of hydrothermal conditions on soybean performance. The degree of moisture during each month of the growing season was evaluated using the hydrothermal coefficient (HTC) developed by G.T. Selyaninov (Koval & Bräuning, 2024). Weather conditions during the 2022-2024 soybean growing seasons were characterised by significant variability in the hydrothermal regime, with a marked deterioration in cultivation conditions in 2024 (Fig. 1).

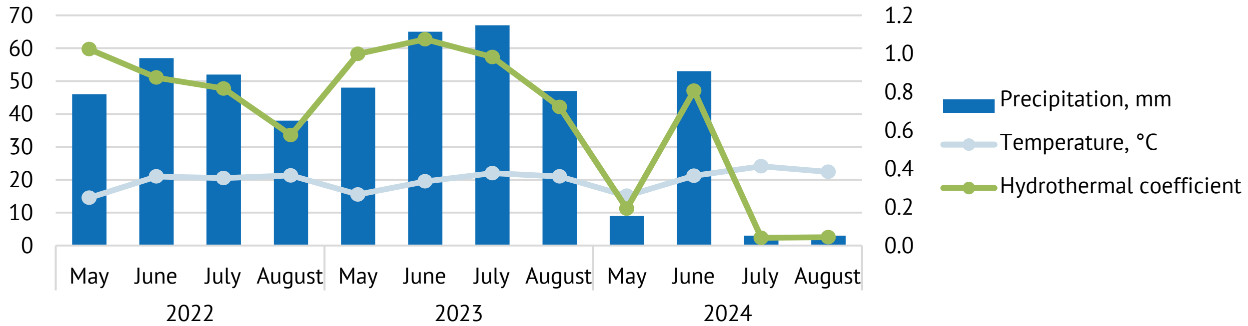


Figure 1. *Dynamics of precipitation, average monthly temperature, and hydrothermal coefficient during the soybean growing season, 2022-2024*
Source: *developed by the authors*

An analysis of HTC dynamics indicates that the 2022 and 2023 seasons provided mostly favourable conditions for soybean growth and development, with HTC values generally ranging between 0.6 and 1.1. In contrast, 2024 was marked by a critical decline in HTC to 0.0-0.2 in July and August, accompanied by a rise in average daily temperatures to 22°C-24°C and a severe precipitation deficit (2-8 mm). This combination of extremely high temperatures and exceptionally low moisture indicates the presence of pronounced hydrothermal stress during the critical phases of soybean development (flowering and pod formation). Under organic farming conditions, this stress was partially mitigated through the use of bacterial preparations from the PGPB (plant growth-promoting bacteria) group, which are capable of stimulating root system development, improving the plant water regime, and inducing physiological and biochemical mechanisms of drought resistance. This contributed to the preservation of the soybean's adaptive potential and the stabilisation of yields, even under conditions of severe hydrothermal stress.

Freshly collected plant material was used to analyse photosynthetic pigments, with pigment extraction carried out in a 96% ethanol solution. The quantitative determination of chlorophyll *a* (Chl *a*) and chlorophyll *b* (Chl *b*) was performed using direct spectrophotometry of ethanol extracts, without prior chromatography. Optical density was measured at wavelengths of 665 nm (for Chl *a*) and 649 nm (for Chl *b*) using a ULAB 108 UV spectrophotometer (ULAB, China). Pigment content in the experimental samples was calculated using the formulas proposed by A.R. Wellburn (1994). To determine the leaf assimilation area, the Easy Leaf Area (n.d.) software was used. The integral indicator of leaf surface area per unit of sown area (m^2/ha) was calculated by multiplying the average leaf area per plant by the number of plants per hectare. The concentrations of proline and malondialdehyde (MDA) in soybean leaf tissues were analysed in accordance with the methodological guidelines developed by M.K. Fatema *et al.* (2023). Soybean yield was determined by fully harvesting the accounting plots manually, following the preliminary cutting of aboveground phytomass.

The significance of the experimental data was assessed using analysis of variance (ANOVA) with the Statistica 12.0 software package (StatSoft Inc., USA, 2013). Mean values and standard deviations (SD) were calculated using Tukey's test ($P < 0.05$) with Bonferroni correction. To test statistical hypotheses regarding functional relationships between the experimental indicators, correlation analysis was carried out using Pearson correlation coefficients. The strength and direction of relationships between variables were interpreted according to the standard scale ($r = \pm0.1$-0.3 – weak; ±0.3-0.7 – moderate; ±0.7-1.0 – strong). The statistical significance of the correlation coefficients was determined at a significance level of $P < 0.05$. Statistical analysis was performed using the Statistica 12.0 software.

RESULTS AND DISCUSSION

The selection of biological products for the experimental study was based on a comprehensive analysis of their composition, with particular attention to the presence of various functional groups of plant growth-promoting bacteria (PGPB) and the specificity of their biological action. Figure 2 presents a summarised scheme of the functional groups of microorganisms included in the selected biopreparations and the directions of their biological activity, which contribute to growth stimulation and enhanced plant resilience.

Thus, the biopreparations chosen for the study represent a representative selection of modern microbial inoculants with diverse mechanisms of action and compositional features, as well as a metabolic biopreparation based on biologically active metabolites. This selection enables a comprehensive evaluation of their effectiveness and supports the development of optimal application strategies in agricultural production. The results of the quantitative analysis of photosynthetic pigments, physiological parameters, productivity, and stress indicators for the soybean cultivar Khorol are presented in Tables 1-3.

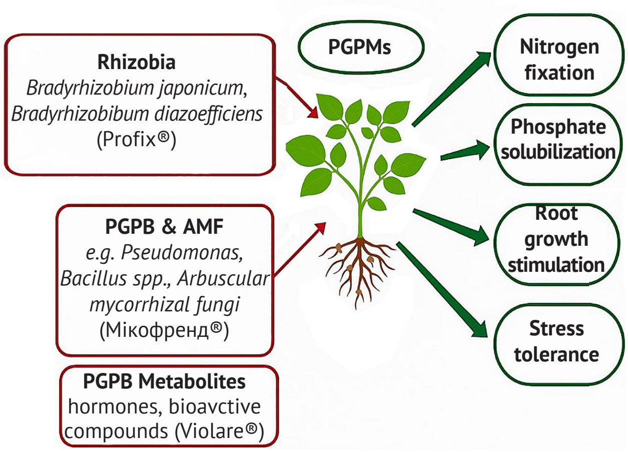


Figure 2. *Effects of PGPMs in soybean*
Source: *developed by the authors*

Table 1. *Dynamics of Chl a and Chl b content in soybean leaves depending on the method of biopreparation application, 2022-2024 (x ± SD, n = 10)*

Biopreparation application	Chl *a*, mg/g			Chl *b*, mg/g		
	2022	2023	2024	2022	2023	2024
Variant 1	2.22 ± 0.066[a]	2.40 ± 0.070[a]	1.78 ± 0.052[a]	0.86 ± 0.029[a]	1.05 ± 0.029[a]	0.68 ± 0.018[a]
Variant 2	2.49 ± 0.068[b]	2.69 ± 0.077[b]	1.99 ± 0.059[b]	0.92 ± 0.026[b]	1.12 ± 0.027[b]	0.73 ± 0.017[b]
Variant 3	2.82 ± 0.082[c]	3.05 ± 0.088[c]	2.26 ± 0.070[c]	0.99 ± 0.028[c]	1.21 ± 0.037[c]	0.78 ± 0.023[c]
Variant 4	2.89 ± 0.088[c]	3.12 ± 0.086[c]	2.31 ± 0.071[c]	1.01 ± 0.029[c]	1.24 ± 0.038[c]	0.80 ± 0.021[c]
Variant 5	3.15 ± 0.089[d]	3.41 ± 0.100[d]	2.53 ± 0.077[d]	1.08 ± 0.030[d]	1.32 ± 0.041[d]	0.86 ± 0.029[d]

Notes: *1. Biopreparation application: Variant 1 – control; Variant 2 – Mycofriend-sc (1.5 L/t); Variant 3 – Mycofriend-wp (1.5 kg/t) with Profix (1.25 kg/500 kg seed); Variant 4 – Mycofriend-wp (1.5 kg/t) with Violar (100 mL/ha); Variant 5 – Mycofriend-wp (1.5 kg/t) with Profix (1.25 kg/500 kg seed) and Violar (100 mL/ha). 2. Letters a, b, c and d indicate mean values that differ significantly within each row of the table (between biopreparation application variants), based on pairwise comparisons using Tukey's test (p < 0.05) with Bonferroni correction*
Source: *developed by the authors*

Based on the data presented in Table 1, a statistically significant positive effect of biopreparations on the accumulation of Chl *a* and Chl *b* in soybean leaves was established. The results of three years of observations indicated that the application of Mycofriend had a beneficial impact on the functional state of the photosynthetic apparatus compared to the control. Specifically, the average increase in Chl *a* and Chl *b* content was 12.2% and 7.0%, respectively, relative to the control. Each successive combination of biological agents in the experimental variants contributed to a further increase in pigment concentration, indicating the presence of a synergistic effect. When Mycofriend was applied in combination with Profix, the average content of Chl *a* and Chl *b* increased by 13.4% and 7.6%, respectively, compared to Mycofriend alone. A similar trend was observed in the variant combining Mycofriend with Violar, where the increase reached 15.9% for Chl *a* and 10.9% for Chl *b*.

The highest pigment levels were recorded in the variant with the three-component treatment, where the average increase in Chl *a* and Chl *b* content reached 26.8% and 18.5%, respectively, compared to the application of Mycofriend alone. These results confirm the high effectiveness of the combined action of biological agents and demonstrate a consistent trend towards increased levels of key photosynthetic pigments in soybean leaves under their influence. The dynamics of the measured indicators over the three-year study period indicate that 2023 was the most favourable year for the development of the photosynthetic apparatus. This is evidenced by the highest recorded values of Chl *a* and Chl *b* under all treatment variants (Table 1): Mycofriend – 2.69 and 1.12 mg/g; Mycofriend with Profix – 3.05 and 1.21 mg/g; Mycofriend with Violar – 3.12 and 1.24 mg/g; Mycofriend with Profix and Violar – 3.41 and 1.32 mg/g, respectively.

In contrast, a noticeable decrease in these values was observed in 2024 across all experimental variants, due to critical hydrothermal stress, which inhibited chlorophyll synthesis. However, even under these unfavourable weather conditions, the combined application of biopreparations led to a significant increase in Chl *a* and Chl *b* content compared to the control: by 11.8% and 7.4% with Mycofriend; by 27.0% and 14.7% with Mycofriend and Profix; by 29.8% and 17.6% with Mycofriend and Violar; and by 42.1% and 26.5% with Mycofriend, Profix and Violar. Thus, the combined use of biopreparations – particularly Mycofriend with Profix and Violar – ensured optimal functioning of the soybean photosynthetic apparatus, even under hydrothermal stress. Analysis of the data in Table 2 revealed clear trends in the influence of biopreparations and weather conditions on leaf surface area and yield of the Khorol soybean variety over the 2022-2024 period.

Table 2. *Dynamics of leaf surface area and soybean yield depending on the method of biopreparation application, 2022-2024 (x ± SD, n = 10)*

Biopreparation application	Leaf surface area, thousand m^2/ha			Yield, t/ha		
	2022	2023	2024	2022	2023	2024
Variant 1	23.40 ± 0.688^a	25.10 ± 0.747^a	19.55 ± 0.571^a	2.24 ± 0.066^a	2.46 ± 0.070^a	1.86 ± 0.059^a
Variant 2	25.99 ± 0.765^b	28.11 ± 0.824^b	22.49 ± 0.688^b	2.73 ± 0.077^b	3.01 ± 0.088^b	2.41 ± 0.070^b
Variant 3	27.63 ± 0.813^c	30.09 ± 0.887^c	24.28 ± 0.718^c	2.93 ± 0.088^c	3.24 ± 0.095^c	2.65 ± 0.077^c
Variant 4	27.81 ± 0.818^c	30.34 ± 0.895^c	24.85 ± 0.736^c	3.02 ± 0.088^d	3.36 ± 0.100^d	2.76 ± 0.082^d
Variant 5	28.92 ± 0.854^d	32.03 ± 0.942^d	26.78 ± 0.788^d	3.15 ± 0.088^d	3.57 ± 0.095^d	2.96 ± 0.088^d

Notes: *1. Biopreparation application: Variant 1 – control; Variant 2 – Mycofriend-sc (1.5 L/t); Variant 3 – Mycofriend-wp (1.5 kg/t) with Profix (1.25 kg/500 kg seed); Variant 4 – Mycofriend-wp (1.5 kg/t) with Violar (100 mL/ha); Variant 5 – Mycofriend-wp (1.5 kg/t) with Profix (1.25 kg/500 kg seed) and Violar (100 mL/ha). 2. Letters a, b, c and d indicate mean values that differ significantly within each row of the table (between biopreparation application variants), based on pairwise comparisons using Tukey's test (p < 0.05) with Bonferroni correction*

Source: *developed by the authors*

The dynamics of changes in leaf assimilatory surface area demonstrate a significant influence of biopreparations, both in comparison with the control and with the application of Mycofriend alone, which resulted in an average increase in leaf surface area of 12.6%. The use of combined treatment schemes – specifically, Mycofriend in combination with Profix and Violar – led to an additional increase in leaf surface area of 7.1% and 8.4% on average, respectively, compared to the Mycofriendonly treatment. The highest values for assimilatory surface area were recorded in the variant involving the combined application of all three biopreparations, averaging 29.24 thousand m^2/ha, which exceeded the Mycofriend-only variant by 14.5%. This confirms the positive impact of integrated biopreparation use and highlights their synergistic effect.

The positive impact of biopreparations is also clearly evident in the yield dynamics. The use of Mycofriend contributed to an average increase in soybean yield of 24.2% compared to the control. Combined application of Mycofriend with Profix and Violar resulted in an additional yield increase of 8.1% and 12.1%, respectively, relative to the Mycofriend-only treatment. The highest yield values over the three-year period were recorded in the variant involving the three-component treatment, which averaged 3.27 t/ha and exceeded the yield achieved with Mycofriend alone by 20.2%. This indicates the substantial effectiveness of their combined use and their synergistic effect. Correlation analysis confirms a direct relationship between the development of the assimilatory surface area and yield formation, and prevailing climatic conditions. In 2024, a decrease in precipitation – particularly during July and August – was associated with a reduction in both leaf area and yield. In 2022, the leaf surface area ranged from 23.4 to 28.92 thousand m^2/ha depending on the treatment (with the minimum in the control and the maximum under the three-component treatment); in 2023, it ranged from 25.10 to 32.03 thousand m^2/ha; and in 2024, from 19.55 to 26.39 thousand m^2/ha.

The increase in leaf surface area in 2023 averaged 8.7% compared to 2022 and closely correlated with the application of biopreparations: in the control plots – 7.3%; with Mycofriend – 8.2%; with the combination of Mycofriend and Profix – 8.9%; with Mycofriend and Violar – 9.1%; and with the combined use of Mycofriend, Profix and Violar – 10.8%. Thus, the application of biopreparations of various types contributed to the activation of morphogenetic processes in the plant organism and the optimisation of the functioning of the soybean photosynthetic apparatus. This was reflected in a progressive increase in the assimilatory surface area and, consequently, a rise in the crop's potential productivity due to the intensification of photosynthetic processes.

The reduction in leaf surface area under the abiotic stress conditions of 2024, compared to the favourable conditions of 2023, varied depending on the biopreparations used: control – 22.1%; Mycofriend – 20.0%; Mycofriend with Profix – 19.3%; Mycofriend with Violar – 18.1%; and Mycofriend with Profix and Violar – 16.4%. These findings confirm the effectiveness of biopreparations in promoting leaf development even under abiotic stress, particularly when all three biopreparations of different natures were used in combination. An analysis of yield under varying weather conditions revealed that the highest levels were recorded in 2023, ranging from 2.46 to 3.57 t/ha, while the lowest were observed in 2024, ranging from 1.86 to 2.96 t/ha – an average decrease of 19.2% compared to the previous year and 10.0% compared to 2022 (Table 2). It is noteworthy that under the favourable conditions of 2023, yield increases were dependent on the application of biopreparations. Specifically, the control variant showed a 9.8% increase compared to 2022, while the use of Mycofriend resulted in a 10.3% increase, Mycofriend with Profix – 10.6%, Mycofriend with Violar – 11.3%, and Mycofriend with Profix and Violar – 13.3%. In 2024, under more stressful conditions for plant growth due to hydrothermal stress, particularly during the critical stages of soybean vegetation, yield reductions compared to 2023 also varied depending on the biopreparation treatment: control – 24.4%, Mycofriend – 20.0%, Mycofriend with Profix – 18.2%, Mycofriend with Violar – 17.9%, and Mycofriend with Profix and Violar – 17.1%.

The observed variation in soybean adaptive responses confirms the role of biopreparations as effective tools for mitigating the effects of abiotic stress and highlights the potential of combined biopreparations to enhance crop stress tolerance under increasingly unstable climatic conditions. According to the data presented in Table 3, there was a clear trend in the concentration of proline and malondialdehyde (MDA) in soybean leaves, depending on both the weather conditions of the study years and the biopreparation treatment schemes. Both indicators are important biochemical markers that reflect plant adaptive responses to stress factors, particularly soil moisture deficit.

Table 3. *Dynamics of proline and MDA content in soybean plants depending on the biopreparation application method, 2022-2024 ($x \pm SD$, $n = 10$)*

Biopreparation application	Proline, mg/g			MDA, mg/g		
	2022	2023	2024	2022	2023	2024
Variant 1	5.10 ± 0.147[a]	5.42 ± 0.159[a]	6.87 ± 0.206[a]	9.40 ± 0.279[a]	9.17 ± 0.272[a]	17.93 ± 0.530[a]
Variant 2	5.72 ± 0.165[b]	5.88 ± 0.177[b]	7.39 ± 0.217[b]	8.19 ± 0.242[b]	7.87 ± 0.236[b]	14.85 ± 0.442[b]
Variant 3	6.12 ± 0.173[c]	6.25 ± 0.186[c]	7.98 ± 0.236[c]	7.26 ± 0.217[c]	6.87 ± 0.206[c]	12.55 ± 0.371[c]
Variant 4	6.28 ± 0.185[d]	6.35 ± 0.188[d]	8.27 ± 0.247[d]	6.92 ± 0.200[d]	6.44 ± 0.191[d]	11.15 ± 0.324[d]
Variant 5	6.51 ± 0.195[e]	6.58 ± 0.202[e]	8.71 ± 0.254[e]	6.28 ± 0.193[d]	5.76 ± 0.170[d]	9.37 ± 0.276[d]

Notes: *1. Biopreparation application: Variant 1 – control; Variant 2 – Mycofriend-sc (1.5 L/t); Variant 3 – Mycofriend-wp (1.5 kg/t) with Profix (1.25 kg/500 kg seed); Variant 4 – Mycofriend-wp (1.5 kg/t) with Violar (100 mL/ha); Variant 5 – Mycofriend-wp (1.5 kg/t) with Profix (1.25 kg/500 kg seed) and Violar (100 mL/ha). 2. Letters a, b, c and d indicate mean values that differ significantly within each row of the table (between biopreparation application variants), based on pairwise comparisons using Tukey's test ($p < 0.05$) with Bonferroni correction*
Source: *developed by the authors*

Over the period from 2022 to 2024, there was a steady increase in proline concentration across all treatment variants, showing a clear dependence on hydrothermal conditions and the applied biopreparations (Table 3). For instance, in the control variant, the average proline content was 5.80 mg/g, while the use of Mycofriend resulted in 6.33 mg/g – an increase of 9.1%. When Mycofriend was applied in combination with Profix and Violar, proline levels increased by 16.9% and 20.2%, respectively, compared to Mycofriend alone. The highest proline concentration was recorded under the three-component biopreparation treatment, with an average annual value of 7.27 mg/g – 14.8% higher than in the Mycofriend-only treatment.

In the moisture-favourable conditions of 2023, the increase in proline concentration was minimal, particularly in the variants with biopreparation treatments: in the control – 6.3%; with Mycofriend – 2.8%; with the combination of Mycofriend and Profix – 2.1%; with Mycofriend and Violar – 1.1%; and with the combined application of Mycofriend, Profix, and Violar – 1.1%. Under hydrothermal stress in 2024, the highest values were recorded (ranging from 6.87 to 8.71 mg/g of fresh weight), along with a significant increase in proline concentration across all treatment variants (on average 28.6%). However, the intensity of this increase varied, reflecting the specific influence of the biopreparations applied: in the control – 26.8%; with Mycofriend – 25.7% (attributed to the protective effect of mycorrhiza); with Mycofriend and Profix – 27.7% (resulting from the activation of both symbiotic systems in response to stress); with Mycofriend and Violar – 30.2% (a synergistic effect of mycorrhiza and phytohormones in regulating osmotic potential); and with the combined application of Mycofriend, Profix, and Violar – 32.4%, which was the highest value, resulting from the integrated activation of all adaptive mechanisms.

Thus, biopreparations activate various adaptive mechanisms: mycorrhiza enhances water uptake, nitrogen fixation improves nitrogen nutrition, and phytohormones regulate metabolic processes. Together, these factors create conditions conducive to the synthesis of increased amounts of proline, an adaptive osmoprotectant, which enables plants to better withstand stress by maintaining cellular water balance. This dynamic in proline content not only demonstrates the successful activation of the plant's defence mechanisms through the use of biopreparations but also confirms their capacity to stimulate a more effective adaptive response to hydrothermal stress. In contrast, the content of malondialdehyde (MDA) (Table 3) showed an opposite trend – a decrease in average values depending on the biopreparation applied. In the control, the MDA level was 12.17 mg/g, whereas with biopreparation treatments it decreased significantly: with Mycofriend – 10.30 mg/g; with Mycofriend and Profix – 8.89 mg/g; with Mycofriend and Violar – 8.17 mg/g; and with the combined application of Mycofriend, Profix, and Violar – 7.14 mg/g.

The temporal dynamics of MDA also revealed a significant increase during the drought conditions of 2024 across all treatment variants, with an average level of 13.17 mg/g, compared with 7.61 mg/g in 2022 and 7.22 mg/g in the more favourable conditions of 2023. In the hydrothermally balanced year of 2023, a reduction in MDA concentration was observed for all treatments relative to 2022: in the control – 2.8%; with Mycofriend – 3.9%; with Mycofriend and Profix – 5.4%; with Mycofriend and Violar – 6.9%; and with the combined application of Mycofriend, Profix, and Violar – 8.3%. The stress conditions in 2024 led to a sharp increase in MDA content, although with varying intensity depending on the treatment compared to 2023: in the control – 96.2%; with Mycofriend – 88.7% (a result of the protective effect of mycorrhiza); with Mycofriend and Profix – 82.7% (reflecting enhanced antioxidant activity due to the function of both symbiotic systems); with Mycofriend and Violar – 72.4% (more effective protection of membrane structures through phytohormonal stimulation of antioxidant systems); and with the combined application of Mycofriend, Profix, and Violar – 62.7% (the highest effectiveness in protecting cellular membranes).

Thus, the biopreparations demonstrated a clear ability to reduce oxidative stress effectively through a range of complementary mechanisms: mycorrhizae improve water supply and mineral nutrition; nitrogen-fixing bacteria enhance nitrogen uptake and the synthesis of protein components of the antioxidant system; and phytohormones (particularly those in Violar) activate both enzymatic and non-enzymatic defence mechanisms. This combined action resulted in reduced lipid peroxidation intensity, as confirmed by the dynamics of MDA content, which decreased under conditions of effective adaptation. This trend corresponded with proline levels and indicated the formation of more efficient antioxidant systems, contributing overall to improved soybean resilience under hydrothermal stress.

To enable deeper analysis of the results and to visualise the variability of the experimental indicators, box plot diagrams were constructed based on statistical data from Tables 1-3 (Figs. 3-5). These plots display medians, interquartile ranges, and extreme values for each treatment variant, offering a multidimensional view of the experimental results and their statistical significance. This graphical format allows for a clear assessment of the distribution of the measured parameters and supports the evaluation of the effectiveness of different biopreparation combinations in relation to key physiological and biochemical indicators as well as crop performance. Such an approach enhances data interpretation and helps reveal patterns that may remain unnoticed in tabular presentation alone.

Analysis of Figure 3(a) revealed a clear trend towards increased Chl *a* content in soybean leaves under the influence of biopreparations. The control variant was characterised by the lowest Chl *a* content (median – 2.2 mg/g) and a narrow range of variation (1.73-2.47 mg/g). Mono-inoculation with the mycorrhizal preparation (variant 2) resulted in a moderate increase in Chl *a* concentration (median – 2.5 mg/g), accompanied by a broader fluctuation range. A marked increase in Chl *a* content was observed with the combined application of mycorrhiza and the rhizobial preparation (variant 3) and with the phytohormonal preparation (variant 4), where the median values reached 2.8 and 2.9 mg/g, respectively. The highest accumulation of Chl *a* was recorded in the triple combination treatment (variant 5), where the median reached 3.2 mg/g and the upper limit exceeded 3.51 mg/g – 26.7% higher compared with variant 2. It is worth noting that the integrated application of the biopreparations not only contributed to an increase in average values but also resulted in a broader variation range. This indicates enhanced adaptive plasticity of the plant photosynthetic apparatus under combined biological treatment and a greater capacity to respond dynamically to environmental factors.

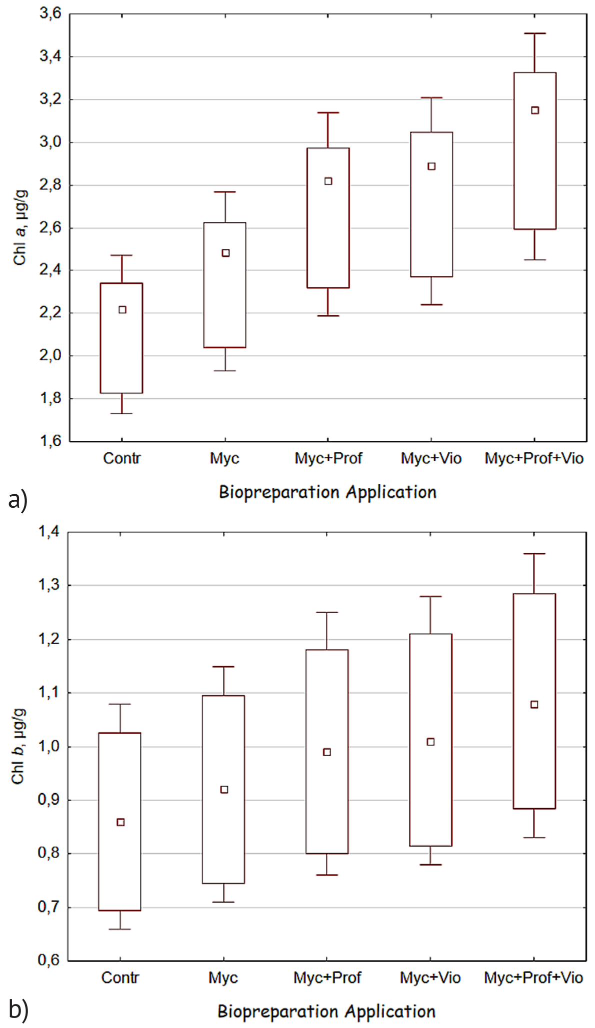


Figure 3. *Effect of biopreparation application on the content of Chl a (a) and Chl b (b) in soybean plants*

Notes: *1) treatment variants: Contr – control (1); Myc – Mycofriend (2); Myc+Prof – Mycofriend with Profix (3); Myc+Vio – Mycofriend with Violar (4); Myc+Prof+Vio – Mycofriend with Profix and Violar (5); 2) the content of Chl a and Chl b in soybean leaves was measured at the flowering stage*

Source: *developed by the authors*

Analysis of Figure 3(b), which illustrates the Chl *b* content in soybean leaves under various biopreparation combinations, reveals a distinct pattern of increasing pigment concentration corresponding to the complexity of the biogenic composition. The control variant exhibited the lowest Chl *b* content (median – 0.86 mg/g) with variability ranging from 0.66 to 1.08 mg/g. Monoinoculation with the mycorrhizal preparation (variant 2) led to a moderate increase in Chl *b* concentration (median – 0.92 mg/g). Increasing the complexity of the treatment by combining mycorrhiza with the rhizobial inoculant (variant 3) or with the phytohormonal preparation (variant 4) resulted in a further rise in pigment activity (medians – 0.99 and 1.01 mg/g, respectively), accompanied by a broader range of variation. The highest accumulation of Chl *b* was observed in the triple biopreparation combination (variant 5), where the median reached 1.08 mg/g and maximum values reached 1.36 mg/g – 18.3% higher compared with variant 2. Notably, this variant also displayed an expanded interquartile range, indicating increased variability in plant response and a possible differentiation in the expression of the synergistic effect under microecological heterogeneity.

Analysis of Figure 4(a), which presents the dynamics of soybean leaf surface area under various biological treatment combinations, reveals clear patterns of variation in this parameter. The control variant exhibited the smallest assimilative surface area (median – 23.4 thousand m^2/ha; range – 18,826.0 thousand m^2/ha), indicating relatively high variability in the experimental data. Application of the mycorrhizal preparation (variant 2) significantly stimulated leaf development (median – 26.0 thousand m^2/ha), exceeding the control by 11.1%, thereby confirming the positive effect of arbuscular mycorrhiza on the formation of the photosynthetic apparatus. Combining mycorrhiza with rhizobial bacteria (variant 3) led to a further increase in leaf surface area (median – 27.6 thousand m^2/ha), while a similar trend was observed in the variant combined with the phytohormonal preparation (variant 4), where the median reached 27.8 thousand m^2/ha. The strongest stimulatory effect was recorded in the triple combination treatment (variant 5), with a median of 28.9 thousand m^2/ha and maximum values reaching 33 thousand m^2/ha, representing a 14.0% increase compared with variant 2.

Notably, the increase in the number of biological agents in the treatment combinations is accompanied by both a rise in average values and an increase in the variability of the experimental indicator. This suggests a complex interaction between the components of the biopreparations and a heterogeneous response among plants of the same cultivar. At the same time, variants 3 and 5 show a tendency towards a narrowing of the interquartile range, indicating greater stability and predictability of the effect when these combinations are used. Additionally, a general trend towards an expansion of the minimum-maximum range (whiskers) of the box plots is observed with increasing treatment complexity, further highlighting the positive influence of bioagents on the parameters of the soybean photosynthetic apparatus.

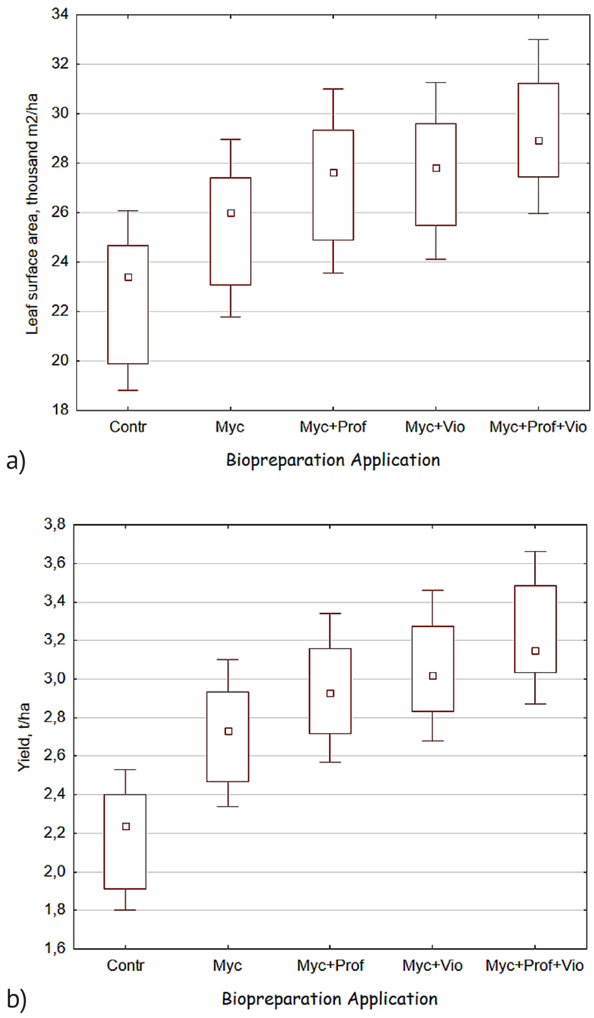


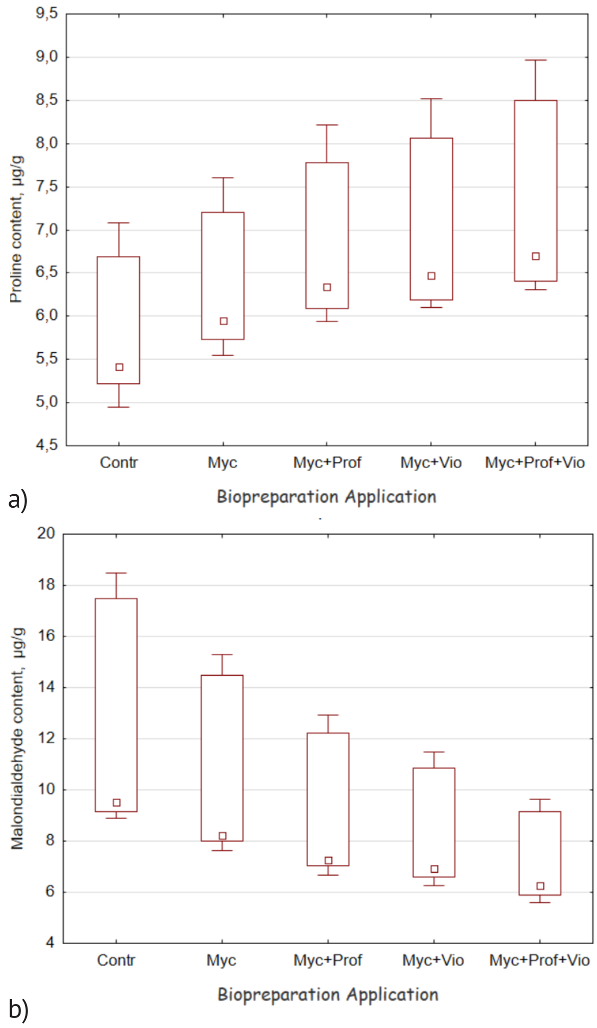
Figure 4. *Effect of biopreparation application on leaf surface area (a) and yield (b) of soybean plants*
Notes: *1) treatment variants: Contr – control (1); Myc – Mycofriend (2); Myc+Prof – Mycofriend with Profix (3); Myc+Vio – Mycofriend with Violar (4); Myc+Prof+Vio – Mycofriend with Profix and Violar (5). 2) the content of the leaf surface area was measured at the flowering stage*
Source: *developed by the authors*

The analysis of the box plot diagram presented in Figure 4(b) illustrates the effect of different biopreparation combinations on soybean yield. The control variant is characterised by the lowest productivity, with a median of approximately 2.2 t/ha and a wide range of variation (from 1.80 to 2.53 t/ha), indicating unstable yield performance in untreated plants. Application of the mycorrhizal preparation (variant 2) results in a significant yield increase, with the median reaching 2.7 t/ha – 21.9% higher than the control – highlighting the crucial role of arbuscular mycorrhiza in enhancing crop productivity. The interquartile range remains moderate, but there is a general shift of the values towards higher levels. The binary combination of mycorrhiza with rhizobial bacteria (variant 3) leads to a further increase in yield, with a median of approximately 2.9 t/ha – 7.3% higher than variant 2 – and an extension of the upper range to 3.34 t/ha. This confirms the synergistic effect of the symbiotic partnership between mycorrhizal fungi and nitrogen-fixing bacteria. The interquartile range is relatively wide, indicating some variability in plant response to this treatment.

The combination of mycorrhiza with the phytohormonal preparation (variant 4) shows an even more pronounced positive effect on soybean productivity, with a median value of approximately 3.0 t/ha – 10.6% higher than variant 2. The interquartile range narrows slightly compared to variant 3, suggesting a more uniform plant response. The highest yield values are recorded with the combined application of all three components (variant 5), where the median reaches approximately 3.2 t/ha, representing a 17.2% increase over variant 2. The upper quartile reaches 3.66 t/ha – the highest value among all treatment variants.

A clear progressive trend can be observed in the increase of both median values and minimum and maximum yield indicators with each additional component of the biopreparations. This reflects the synergistic effect of their combined application on crop productivity. The minimum values (lower extremes) also show consistent growth – from 1.80 t/ha in the control to 2.87 t/ha in variant 5 – confirming the stability of the positive effect of biopreparations even under less favourable conditions. The maximum values (upper extremes) rise from 2.53 t/ha in the control to 3.66 t/ha in variant 5, indicating a high potential for yield improvement when biopreparations are applied in combination.

By integrating data from Tables 1-3 and Figure 3, it can be concluded that the increase in yield results from the overall positive influence of the biopreparations on the physiological condition of soybean plants – particularly the increase in Chl *a* and Chl *b* content, expansion of leaf surface area, enhanced proline synthesis, and reduction in oxidative stress (as indicated by MDA content). The box plot in Figure 5(a) illustrates the changes in proline levels in soybean plants under the influence of different biopreparation combinations. In the control variant, the proline content is relatively low, with a median of 5.4 mg/g and a moderate range of variation (~5.0 to 7.1 mg/g), indicating some variability within the control group. The application of the mycorrhizal preparation (variant 2) contributes to an increase in proline content, with a median of approximately 6.0 mg/g, which is 20.0% higher than the control. The interquartile range is slightly narrower than in the control, suggesting reduced variability.



a)

b)

Figure 5. *Effect of biopreparation application on proline (a) and MDA (b) content in soybean plants*

Notes: *treatment variants: Contr – control (1); Myc – Mycofriend (2); Myc+Prof – Mycofriend with Profix (3); Myc+Vio – Mycofriend with Violar (4); Myc+Prof+Vio – Mycofriend with Profix and Violar (5)*

Source: *developed by the authors*

The combined application of mycorrhiza with rhizobial bacteria (variant 3) results in a further increase in proline concentration, with a median of approximately 6.3 mg/g and an extended variation range reaching up to 8.2 mg/g. This indicates the activation of adaptive mechanisms in plants, along with considerable variability in responses. Even more pronounced proline accumulation is observed when mycorrhiza is used in combination with the phytohormonal preparation (variant 4), where the median value reaches 6.5 mg/g – 8.3% higher than in variant 2. At the same time, the interquartile range narrows compared to variant 3, suggesting a more uniform physiological response among plants. The highest proline accumulation is recorded in variant 5, where all three agents – mycorrhizal preparation, rhizobial bacteria, and phytohormonal supplement – are applied together. The median reaches approximately 6.9 mg/g, which is 15.0% higher than in variant 2 and 27.8% higher compared to the control.

The upper quartile rises to 8.6 mg/g, while the lower extreme increases to approximately 6.0 mg/g, indicating not only an overall enhancement of the adaptive response but also its stability across all treated plants. The overall trend of increased proline content in the variants with biopreparations confirms that the response to hydrothermal stress largely depends on the degree of involvement of symbiotic interactions and the bioregulatory activity of the applied agents. The accumulation of proline, as one of the key osmoprotectants and stabilisers of cellular metabolism, is regarded as an indicator of enhanced plant tolerance to adverse environmental conditions, which may also indirectly influence yield.

The analysis of the box plot diagram in Figure 5(b) reveals clear patterns in the changes in MDA content in soybean plants under the influence of various biopreparation combinations. The control variant is characterised by the highest MDA levels, with a median of approximately 9.5 mg/g and a wide range of variation (8.89-18.47 mg/g), indicating intense lipid peroxidation and the development of oxidative stress in untreated plants. The application of the mycorrhizal preparation (variant 2) significantly reduces MDA content (median ~8.2 mg/g, 13.7% lower than the control) and decreases indicator variability, pointing to the activation of the antioxidant defence system under the influence of mycorrhizal fungi. Although the interquartile range (7.63-15.3 mg/g) remains fairly wide, it is less pronounced compared to the control. The binary combination of mycorrhiza and rhizobial bacteria (variant 3) results in a further reduction in MDA content to a median of approximately 7.3 mg/g, demonstrating the enhanced protective effect of the symbiotic partnership between the two microbial groups. The interquartile range narrows (6.66-12.93 mg/g).

An even more pronounced reduction in MDA levels is achieved with the combination of mycorrhiza and the phytohormonal preparation (variant 4), where the median value reaches approximately 6.9 mg/g – 15.9% lower than in variant 2. This effect is attributed to the stimulation of endogenous antioxidant defence mechanisms by phytohormones. The interquartile range is narrower still, at 6.25-11.48 mg/g. The lowest MDA content is recorded in the triple combination of biopreparations (variant 5), with a median value of approximately 6.3 mg/g – 23.2% lower than in variant 2. This variant also exhibits the narrowest interquartile range (5.59-9.65 mg/g), indicating a stable anti-stress effect resulting from the integrated application of biopreparations. MDA is one of the primary products of lipid peroxidation and is widely used as a marker of oxidative stress in plant tissues. A reduction in its content reflects an increase in antioxidant potential and overall plant stress tolerance. The data obtained confirm that the combined use of biopreparations significantly enhances the ability of plants to withstand stress factors, particularly when mycorrhiza, rhizobial bacteria, and phytohormonal preparations are applied together.

To validate the observed trends and determine the functional relationships between the indicators, a correlation analysis was conducted to provide a deeper insight into the mechanisms of biopreparation action. A strong positive correlation between chlorophyll content (*a* and *b*) and yield ($R^2 = 0.897$, $r = 0.947$, $p < 0.05$) confirms the crucial role of photosynthetic activity in determining plant productivity. A high positive correlation between leaf surface area and chlorophyll content ($R^2 = 0.956$, $r = 0.978$, $p < 0.05$) indicates the interdependence of both quantitative and qualitative characteristics of the photosynthetic apparatus.

In addition, a statistically significant positive correlation was identified between leaf surface area and yield ($R^2 = 0.949$, $r = 0.974$, $p < 0.05$), further confirming the pivotal role of a well-developed photosynthetic apparatus in ensuring high plant productivity. Under the influence of complex biopreparations, a notable increase in the correlation between photosynthetic parameters and yield was observed, indicating an optimisation of internal functional relationships within the plant. Statistical analysis of the experimental data confirmed a statistically significant negative correlation between MDA content and soybean yield ($R^2 = 0.661$; $r = -0.813$; $p < 0.05$), suggesting a considerable inhibitory effect of intensified lipid peroxidation on crop productivity. Moreover, significant negative correlations were found between MDA content and key photosynthetic indicators: Chl *a* ($r = -0.882$; $p < 0.05$), Chl *b* ($r = -0.832$; $p < 0.05$), and leaf surface area ($r = -0.878$; $p < 0.05$). All identified correlations are strong ($|r| > 0.7$) and statistically significant ($p < 0.05$), confirming a close relationship between the intensity of oxidative processes and the functional state of the photosynthetic apparatus.

The obtained results indicate that oxidative stress, as reflected by MDA accumulation, exerts a pronounced negative effect on the formation of structural components of the photosynthetic system and on chlorophyll biosynthesis, which in turn reduces plant productivity. This confirms the critical role of antioxidant protection in ensuring effective photosynthetic activity and in determining yield outcomes. The established correlations may be interpreted as evidence of the synergistic action of biopreparation components on key physiological processes, leading to the development of a balanced donor-acceptor system within the plant and, consequently, to an increase in its productive potential. Such functional relationships are of fundamental importance for understanding the mechanisms underlying crop productivity and may inform the development of strategies for optimising cultivation practices. Thus, under organic farming conditions, achieving high soybean yields remains particularly challenging – even under favourable soil conditions – due to the impact of hydrothermal stress.

To promote the development of resilient agroecosystems for leguminous crops, particularly soybeans, the application of seed treatments with inoculants, arbuscular mycorrhizal (AM) fungi, biostimulants, and hormonal agents is considered highly relevant. This is supported by the findings of M. Nadeem *et al.* (2019) and R. Zia *et al.* (2021). In the present study, pre-sowing application of biopreparations had a positive effect on the physiological and biochemical parameters of the plants, notably contributing to an increase in chlorophyll content, which stimulated the photochemical activity of chloroplasts and enhanced photosynthetic efficiency. Specifically, the use of Mycofriend, Profix, and Violar, in various combinations, resulted in an average increase in Chl *a* and Chl *b* contents by 12.2%-15.9% and 7.0%-10.9%, respectively, compared with the control. This rise in photosynthetic pigment levels was accompanied by an expansion of the leaf surface area by 12.6%-28.9%, reaching 25.53-29.24 thousand m^2/ha, along with a reduction in the adverse effects of hydrothermal stress by 2.1%-5.7% relative to the control. These findings are consistent with those of A. Radzykhovskyi (2019), where the combined application of the biopreparations Rizoline, Rizosave, and Mycofriend led to an increase in leaf area by 5.2%-8.5%. A strong positive correlation was found between chlorophyll content ($r = 0.947$), leaf surface area ($r = 0.974$), and yield level. The yield increase varied depending on the specific biological treatment, ranging from 24.2% to 47.5% (2.72-3.23 t/ha compared with 2.19 t/ha in the control). The relationship between seed treatment and increased soybean biological productivity is also supported by the articles of S. Zimmer *et al.* (2016), M. Leggett *et al.* (2017), and M. Serafin-Andrzejewska *et al.* (2024).

As confirmed by the study conducted by L.B. Martinez-Garcia *et al.* (2013), the effectiveness of mycorrhizal application under various agroecological conditions contributed to yield increases of 15%-40% for soybeans, 20%-70% for maize, 15%-30% for cereal crops, and up to 200% for vegetables. These effects are attributed to the genotypic characteristics of the crops, cultivation conditions, and the efficiency of symbiotic interactions. Similar findings were reported by A. Radzykhovskyi (2019), where the combined use of the biopreparations Rizoline, Rizosave, and Mycofriend resulted in an increase in soybean yield to 4.18-4.23 t/ha, representing a 25.5-27.0% improvement compared with the control. These data confirm the existence of synergy between inoculants and mycorrhizal agents, expressed through enhanced nutrient uptake and increased stress tolerance within agroecosystems.

According to N.A. Milošević *et al.* (2012), soil microorganisms improve plant drought resistance by producing polysaccharides that enhance soil structure, as well as biologically active substances (indoleacetic acid, deaminase, and proline), which support water regime regulation via fungal mycelium. M. Ashraf & M.R. Foolad (2007) also highlight the protective role of proline under water stress conditions. The study confirms an increase in proline concentration during the droughtaffected year of 2024, ranging from 25.7% to 32.4%, depending on the biopreparations applied. These findings are consistent with the results of X. Yang *et al.* (2021) demonstrated that, under drought conditions, the accumulation of osmotically active compounds is positively correlated with plant resilience. According to S.A. Mona *et al.* (2017), inoculation promotes proline accumulation under both normal and stress conditions.

Research by K. Bogati & M. Walczak (2022) indicates that arbuscular mycorrhizal (AM) fungi can reduce MDA content by 32% under moderate drought. The present results support this trend, showing a reduction in MDA levels across treatment variants by 15.4% to 47.5%, with the highest effect observed under triple treatment. The findings demonstrate that, under organic farming conditions and increasing hydrothermal stress, the most effective strategy is the combined application of biopreparations, including rhizobial bacteria, AM fungi, and biostimulants. Their synergistic interaction ensures the development of resilient soybean agrocenoses with high yield potential, as confirmed by experimental data and aligned with findings from other researchers.

CONCLUSIONS

The research findings indicate that the intensification of climate change and the increasing frequency of extreme weather events necessitate a revision of conventional agronomic practices, with the integration of mandatory anti-stress protection measures. Notably high effectiveness in enhancing the adaptive potential of soybeans was observed with the use of the combined formulation of Mycofriend, Profix, and Violar. The application of these biopreparations led to an average increase in Chl *a* and Chl *b* content in soybean leaves of 12.2%-42.2% and 7.0%-26.7%, respectively, compared to the control, with the greatest effect achieved under simultaneous application of all three treatments. Importantly, biopreparation treatment maintained elevated chlorophyll levels even under the hydrothermal stress conditions of 2024. A strong positive correlation was established between the content of Chl *a* and Chl *b* and both leaf surface area ($r = 0.978$) and yield ($r = 0.947$), demonstrating the interdependence between quantitative and qualitative parameters of the photosynthetic system and confirming the critical role of photosynthetic activity in determining plant productivity.

It has been demonstrated that the leaf surface area of soybean plants responds positively to biopreparation treatment, increasing by 12.6%-28.9% compared to the control, with the greatest effect observed under combined application of all biopreparations (29.24 thousand m^2/ha). The use of biopreparations significantly mitigated the effects of hydrothermal stress in 2024, as the reduction in leaf surface area compared to the favourable conditions of 2023 was as follows: control – 22.1%; Mycofriend – 20.0%; Mycofriend with Profix – 19.3%; Mycofriend with Violar – 18.1%; Mycofriend with Profix and Violar – 16.4%. These findings confirm the effectiveness of biopreparations in stimulating the development of the leaf apparatus even under hydrothermal stress, particularly when biopreparations of different origins are applied in combination. A notable positive effect of biopreparations on soybean yield was also recorded, with an average increase of 24.2%-47.5% compared to the control, reaching a maximum of 3.23 t/ha under the combined treatment. In 2024, under more stressful conditions for plant growth due to hydrothermal stress, particularly during the critical stages of soybean vegetation, yield reductions compared to 2023 also varied depending on the biopreparation treatment: control – 24.4%, Mycofriend – 20.0%, Mycofriend with Profix – 18.2%, Mycofriend with Violar – 17.9%, and Mycofriend with Profix and Violar – 17.1%.

It was found that proline accumulation in soybean leaves during the experimental period showed a clear dependence on the hydrothermal regime and the application of biopreparations. Their use resulted in an average increase in proline levels of 9.1%-25.3% compared to the control, and under hydrothermal stress conditions, by 7.6%-32.4% compared to 2023. This indicates the successful activation of the plants' defence mechanisms in response to biopreparations and confirms their ability to stimulate a more effective adaptive response to hydrothermal stress. It was established that the lowest concentrations of MDA were recorded following the application of biopreparations (7.14-10.3 mg/g), whereas the highest level was observed in the control (12.17 mg/g). The stressful conditions of 2024 caused a significant increase in MDA content compared to 2023, although the intensity varied depending on the treatment: control – 96.2%; Mycofriend – 88.7%; Mycofriend with Profix – 82.7%; Mycofriend with Violar – 72.4%; Mycofriend with Profix and Violar – 62.7%.

A statistically significant negative correlation was found between MDA content and soybean yield ($r = -0.81$), Chl *a* content ($r = -0.882$), Chl *b* content ($r = -0.832$), and leaf surface area ($r = -0.878$). Thus, the application of biopreparations – particularly the combination of all three components – contributes to reducing MDA accumulation and enhancing the antioxidant defence of plants, thereby supporting the efficiency of photosynthetic activity and the formation of high yields. Further research should focus on assessing the impact of biopreparations on the hormonal status of plants, which will provide a deeper understanding of the mechanisms underlying soybean stress tolerance and help identify the most effective combination of biological agents for minimising the effects of climate change on agroecosystem productivity under organic farming conditions.

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CONFLICT OF INTEREST

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Вплив біопрепаратів на адаптивні властивості сої в органічному землеробстві в умовах гідротермічного стресу

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Анотація. В умовах органічного землеробства та гідротермічного стресу особливого значення набуває використання біологічних препаратів, зокрема арбускулярної мікоризи, ризобіальних бактерій і фітогормональних препаратів, як інструментів підвищення адаптивних властивостей сої. Їх застосування сприяє пом'якшенню негативного впливу абіотичних чинників і підтриманню продуктивності культури. Метою дослідження було провести оцінку адаптивного потенціалу сої в умовах органічного землеробства за дії мікоризних, бактеріальних і фітогормональних біопрепаратів за гідротермічного стресу. На основі польового дослідження в умовах Полтавської області досліджено вплив біопрепаратів різної природи на біохімічні, фізіолого-морфологічні, стрес-індикаторні показники та продуктивність сої сорту Хорол. Застосування біопрепаратів достовірно підвищувало біохімічні, фізіолого-морфологічні показники та продуктивність сої, що свідчить про покращення загального фізіологічного стану рослин. Найвищі концентрації хлорофілів *a* і *b* спостерігалися за умов трикомпонентної обробки (Мікофренд із Profix і Віолар) у 2023 році, де приріст Chl *a* становив у середньому за роки дослідження 42,3 %, а Chl *b* – 26,7 % порівняно з контролем. Асиміляційна поверхня листків досягала середнього значення 29,24 тис. $м^2$/га, а врожайність – 3,23 т/га, що перевищувало контроль на 28,9 % і 49,0 % відповідно. У посушливому 2024 році завдяки адаптогенному застосуванню біопрепаратів відбулось зменшення втрат площі листкової поверхні в межах 16,4-20,0 % і врожайності – 17,1-20,0 %, тоді як на контролі втрати становили 22,1 % і 24,4 % відповідно. Використання біопрепаратів за гідротермічного стресу 2024 року призвело до зростання концентрації проліну (до 7,27 мг/г) та зниженням вмісту MDA (до 7,14 мг/г), що свідчить про зменшення оксидативного стресу й покращення осморегуляції завдяки синергії мікоризоутворення, азотфіксації та дії фітогормонів. Практичне значення отриманих результатів полягає у розкритті потенціалу комплексної біологічної обробки для підвищення врожайності та стресостійкості сої в умовах органічного землеробства й кліматичних викликів

Ключові слова: арбускулярні мікоризні гриби; ризобіальні бактерії; фітогормони; хлорофіл; площа листкової поверхні; врожайність; пролін; малоновий діальдегід

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Productivity of winter rape depends on the morphostructure of plants in the conditions of the Steppe of Ukraine

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Abstract. The aim of the study was to determine the morpho-structural indicators of the productive organs of winter rapeseed that influence yield, and to establish, on this basis, a strategic direction for the development of a promising assortment for cultivation in the conditions of the Southern Steppe of Ukraine. Using the hybrids Dario, Oriolus, and Blackstone (produced by VNS), a comparative analysis was conducted of the morpho-structure of vegetative and generative plant organs and their influence on yield. It was noted that the seed purity used in the study was 100.0%, and laboratory germination ranged from 91.6% to 94.0%. The total number of shoots at harvest time was largely determined by the biological properties of the hybrid and varied within the range of 9.8 to 15.3 shoots per plant. It was substantiated that the productivity of the crops was primarily determined by the number of pods on first-order branching shoots, which accounted for 75.7-78.5% of the total number of pods, depending on the biological characteristics of the hybrids. The number of pods located on the shoots of zero and second-order branching was minimal, amounting to 12.8% and 9.5%, respectively. The average weight of 1,000 seeds showed no significant difference among the studied hybrids, ranging between 3.69 and 3.81 grams. Differences in yield among the hybrids were determined by a combination of productivity indicators, particularly the total number of pods per plant and the number of seeds per pod. The highest number of pods was observed in the Dario hybrid – 249.4 pods per plant, and the lowest in the Blackstone hybrid – 198.8 pods per plant. The Dario hybrid demonstrated the most optimal plant morpho-structure, contributing not only to the highest yield (4.89 t/ha) but also to the greatest realisation of the hybrid's biogenetic potential (69.9%). Lower comparative indicators were observed in the Blackstone hybrid, with yield and biogenetic potential realisation at 3.11 t/ha (56.6%), respectively

Keywords: rapeseed hybrid; plant morpho-structure; branching; pod; seed; yield

INTRODUCTION

One of the most profitable oilseed crops in Ukraine is rapeseed (*Brassica napus* L.), which is due to the consistently high prices for its seeds and processed products. The expansion of rapeseed production in the Southern Steppe of Ukraine is a promising area of agricultural activity that will help improve the economic efficiency of farms and support the development of bioenergy in the context of climate change. One of the key and

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significant reserves for increasing the efficiency of rapeseed production is the introduction of modern hybrids and varieties that are characterised by high yields and sufficient adaptation to local soil and climatic conditions. The relevance of the research is driven by the need to optimise the assortment of winter rapeseed and is focused on identifying the morpho-structure of productive plant organs that influence yield.

Much of the current scientific research in the field of rapeseed production is aimed at improving the traditionally basic elements of production in different soil and climatic zones of Ukraine. For entrepreneurs, the components of winter rape yield are presented in sufficient detail, taking into account the duration of the phases of plant growth and development at optimal temperatures, pesticide use, disclosure of agrotechnical aspects of production, such as sowing, germination, vegetation period, budding and flowering stages, crop care, ripening, and harvesting. Considering the experimental material obtained, the technological components of commercial crop production are scientifically and reasonably substantiated: the feasibility of a differential approach to soil cultivation, the use of mineral fertilisers, feeding areas, growth regulators, etc.

O.V. Kurach (2021) observed that Ukraine's natural conditions enable the biogenetic potential of winter rape to be realised. Provided the main elements of the technological process are adhered to, it is possible to obtain seed yields of 5.0-6.0 t/ha. However, due to climate change, the average rapeseed yield on many farms is 1.7-2.8 t/ha. M.V. Minkin & G.O Minkina (2023) found that, in southern Ukraine and under natural moisture conditions, the yield of winter rape is 1.5-1.9 t/ha. The agroclimatic and soil conditions in this region allow winter rape to be grown with a yield of 1.8-1.9 t/ha under natural moisture conditions. A.A. Shevchenko & T.O. Vasylinych (2022) also noted that the Odesa Region leads Ukraine in rapeseed production, with a sown area exceeding 100 thousand hectares and a gross harvest accounting for 9.1% of Ukraine's total.

Scientist S.V. Vasylenko (2024) emphasised that the use of new hybrids resistant to adverse factors will significantly increase production productivity. However, in order to obtain stable and high results, it is necessary to introduce innovative technologies that play a significant role in rapeseed cultivation, including paying attention to environmental factors that will reduce the negative impact on the environment by pesticides and mineral fertilisers. Researchers V.M. Bezkorovaynyi & V.V. Moisienko (2024a) noted that in the conditions of the Right-Bank Forest-Steppe, the improvement of only certain elements of the technological process (increasing row spacing) contributed to the production of 3.82-4.45 t/ha of seeds. The best hybrids in terms of yield and individual productivity indicators were the Exception (BAYER) and InVigor 1030 (BASF) hybrids. One of the main indicators that determine the individual productivity of a plant is the presence of generative components. Sparse plant placement allows up to 430-450 pods to be formed per plant, and the average weight of 1,000 seeds is 6.0-6.4 g. A significant reserve for increasing rapeseed yields is the use of bioregulators and fertilisers. S. Muntyan (2024), studying the effect of a nitrification inhibitor (NI) at different rates of nitrogen fertilisers and the application of urea-ammonia mixture on the yield of winter rape seeds, found a significant increase in yield compared to the variant without inhibitors and fertilisers.

At present, the Catalogue of plant varieties suitable for distribution in Ukraine (2025) includes 378 samples of winter rape in the Polissya, Forest-Steppe, and Steppe zones. Scientists O.P. Tkachuk *et al.* (2024) pointed out that such a wide variety of varieties creates some confusion for entrepreneurs in determining the optimal varietal composition. It is also noted that hybrids provide one and a half times higher yields of winter rape seeds than varieties. However, to obtain a high yield, it is necessary to apply much more fertiliser and strictly adhere to the timing of agricultural activities. Researchers A.V. Kostenko *et al.* (2023) noted that winter rape is one of the main technical and fodder crops. Breeding programmes for winter rape are aimed at creating high-yielding, large-seeded varieties and hybrids with wide adaptability to a range of abiotic factors that can fully realise their biogenetic potential in the face of climate change. The aim of this study was to investigate the structure of the productive organs of winter rape, which determine its yield, and, based on the results obtained, to develop strategic recommendations for the development of promising varieties suitable for cultivation in the Southern Steppe of Ukraine.

MATERIALS AND METHODS

The experiment to study the peculiarities of the formation of the morphological structure of winter rape plants of Dario, Oriolus and Blackstone hybrids was conducted at the Educational and Research Centre of Mykolaiv National Agrarian University (NAU) in 2021 and 2022. During the growing seasons 2021-2022 and 2022-2023, the formation of plant morphological structures and their influence on yield were studied. The surveys were carried out on 100 plants (4 replications of 25 plants each). The biometric characteristics of pods and seeds were determined on 400 samples (100 samples in 4 replications). The material for the research was winter rape (*Brassica napus* L.) hybrids Dario, Oriolus and Blackstone. Experimental studies of plants were carried out in accordance with national guidelines (Law of Ukraine No. 4147-IX, 2024).

Dario. A hybrid of winter rape from DSV. It is characterised by intensive development of the root system in autumn. It has genetic resistance to pests, which makes it possible to quickly regenerate damaged plant tissue. Resistant to phomosis due to the RLM 7 gene. Demonstrates excellent indicators of developmental stability and yield. Plants of the hybrid form a strong leaf apparatus of medium size. The maturity group is medium late. The designation group is oilseed. The growing season is 292-320 days. Plant height is 175 cm. It shows a high oil content. Yield potential is 7.0 t/ha. The resistance to cold is 8. Drought resistance is 9. The index of the resistance to lodging is 9. The resistance to major diseases of rapeseed is 8. It is suitable for late sowing. The recommended zone for cultivation is the Forest-Steppe of Ukraine.

Oriolus. A hybrid of winter rape from DSV. It is high-yielding short-stemmed hybrid. It has high stability when grown in different soil and climatic conditions. It effectively uses spring moisture reserves. It has high winter hardiness. It is characterised by early flowering and ripening. The maturity group is medium-late. The designation group is oilseed. The growing season is 292-320 days. Plant height is 165 cm. It obtains high oil content. The yield potential is 6.6 t/ha. The index of the resistance to cold is 8. The drought resistance is 9. The index of the resistance to lodging is 9. The resistance to phomosis is 8. It is suitable for early sowing and for cultivation throughout Ukraine.

Blackstone. A hybrid of winter rape from VNIS. It is a high-yielding short-stemmed hybrid. It has high winter hardiness due to its low tendency to stem growth in autumn, so it is suitable for early sowing. It has a fairly high resistance to lodging and high synchronisation of pod and stem ripening. The maturity group is medium late. The designation group is oilseeds. The growing season is 292-323 days. Plant height is 165 cm. It obtains high oil content. The yield potential is 5.5 t/ha. The index of the resistance to cold is 8.5. The drought resistance is 8.5. The index of the resistance to lodging is 8.5. The resistance to phomosis is 8. It is suitable for cultivation throughout Ukraine.

The agrotechnics of winter rape cultivation was implemented in the experiment in accordance with zonal recommendations for growing oilseeds in the Steppe zone of Ukraine. Rapeseed was sown after peas harvested in late June (third decade). Immediately after harvesting the predecessor, soil preparation for sowing winter rape began which consisted of disking to a depth of 12-15 cm and two subsequent disks to a depth of 5-6 cm. 3 days before sowing, the soil was levelled with a compactor and water-charging irrigation was carried out by sprinkling at the rate of 350 m^3/ha. Sowing of winter rape hybrid seeds was carried out on 29-30 August using a conventional grain seeder SZ-6 with coil seeders for small seeds and a distance of 15 cm between the coulters at the rate of 500 thousand germinating seeds per 1.0 ha to a depth of 2-3 cm. The plots were 300 m^2 (6×50 m) in size and orientated from east to west. Seeds were removed from the seeder cans each time with a vacuum cleaner, after which the seeder passed 100 m without seeds and 300 m with seeds of the next plot. That technological method excluded the possibility of variety mixing which was later confirmed during the crop inspection. Before disking, 100 kg of ammophos (N:P – 12:52) was applied. In the spring, 150 kg/ha of ammonium sulphate (N:S – 21:24) and 300 kg/ha of ammonium nitrate (N:P – 34:0) were applied to the frozen soil. Foliar feeding with boron was carried out twice: in autumn on a well-developed rosette – 1 l/ha (B11 %) and in spring during the budding phase at the same rate. Zinc was applied as part of a complex micronutrient fertiliser on the leaves, g/l (N – 80; MgO – 33; Fe – 4.0; Mn – 13.4; B – 5.4; Zn – 8.0; Cu – 3.0; in spring at a plant height of 20-25 cm at a rate of 1.0 l/ha.

The field for sowing rapeseed was not clogged with weeds, which justified the complete refusal to use herbicides. Growth control was carried out with a preparation with the active ingredient tebuconazole (250 g/l) in autumn at the stage of 6-7 leaves at a rate of 0.6 l/ha, and in spring at a plant height of 20-25 cm for greater shoot branching at a rate of 0.8 l/ha. Fungicidal protection was applied at the beginning of budding with a preparation containing the active ingredient metconazole + pyraclostrobin (130 g/l + 80 g/l) at a rate of 0.7 l/ha. To control the spread of pests, yellow containers – traps – were installed at the demonstration site to determine the thresholds of harmfulness and the timing and effectiveness of insecticide application. Observations of pest reproduction showed that the use of insecticide protection was appropriate. Due to the optimal sowing time and distance from the agrocenoses of cabbage crops, it was sufficient to carry out only one treatment in autumn (a preparation based on chlorpyrifos – 500 g/l + cypermethrin – 50 g/l at a rate of 1 l/ha). In the autumn period, the threshold of harmfulness was exceeded only by the reproduction of rapeseed flea beetle (*Psyllioides chrysocephala*).

In the spring, at the first appearance of rapeseed weevil (*Ceutorhynchus assimilis*) in the traps (III decade of March), the crops were treated with a pyrethroid preparation based on alpha-cypermethrin (100 g/l) at a rate of 0.2 l/ha. When the plants reached a height of

20-25 cm, the crops were treated for the third time with a preparation based on imidacloprid 150 g/l + lambda-cyhalothrin 50 g/l at a rate of 0.15 l/ha. At this time, individuals of cabbage whitefly (*Pieris brassicae*) and rapeseed sawfly (*Athalia rosae*) were observed in the traps. During the budding period, the crops began to be invaded by the rapeseed leaf beetle (*Entomoscelis adonidis*) and the hairy deer moth (*Epicometes hirta*), the latter being extremely widespread, with up to 40 individuals per day being trapped. The fourth insecticide treatment was carried out with a preparation based on chlorpyrifos (500 g/l + cypermethrin). During the flowering period, there was an active infestation of hairy deer and rape leaf beetle, which was controlled by treating the area at night with a mixture of bee-friendly products based on acetamiprid and tau-fluvalinate. After flowering was complete, there was little damage from the cabbage moth (*Plutella xylostella*), cabbage mosquito (*Dasineura brassicae*), and cabbage bug (*Eurydema ventralis*). Irrigation of winter rape crops by sprinkling was carried out according to zonal recommendations. Water-charging irrigation was carried out before sowing (350 m^3/ha). During the growing season, if necessary, artificial moisture was provided by sprinkling, taking into account natural precipitation (350-450 m^3/ha).

The experimental field of Mykolaiv NAU is located in the central agroclimatic region. It is characterised by long warm summers, short winters with little snow, insufficient precipitation, and a large amount of solar radiation. Spring is short (March-April). The average monthly temperature in April is 10.9°C. Summers are long (May-September), dry, hot, and cloudy. The average monthly temperature in July is 24.3°C. Autumn is short (October-November). The average monthly temperature in October is 11.1°C. Winters are short (December-February), with frequent thaws. The average monthly temperature in January is -1.7°C. The sum of active temperatures during the active growing season (above 10.0°C), which lasts 70-200 days, is 2,900-3,600°C. The average duration of the frost-free period is 175-215 days. The southern region of Ukraine is suitable for growing a wide variety of field crops, including winter rape, due to its soil and climatic conditions. Warm winters, long autumns and springs contribute to the full development of growth processes in both spring and winter crops. However, in summer, there is an increase in air temperature and soil surface that exceeds the optimal parameters, which does not allow agricultural plants to realise their biogenetic potential (Vozhegova *et al.*, 2025).

The soils of the experimental field of the NSCP of Mykolaiv NAU are represented by southern chernozems, characterised by moderate nutrient supply and suitable for growing crops. Comparison of the physical and chemical parameters of the soil of the experimental plot with the optimal parameters and grouping of soils by properties established by DSTU 4362:2004 (2005) allowed to conclude that these soils are suitable for growing all crops recommended for the Southern Steppe. The nature of the supply of basic nutrients was as follows: $NO_3 + NH_4$, mg/kg – average; P_2O_5, mg/kg – average; K_2O, mg/kg – very high; Ca, mg-eq/100 g – increased; Mg, mg-eq/100 g – average; humus, % – increased; physical clay content, % – close to optimal; pH (KCl) – 5.7. High sustainable yields in the steppe zone depend on the level of moisture, so in rainfed conditions, measures to increase their productivity should be aimed at accumulating moisture and improving the nutrient regime.

The weather conditions during the experimental work were at the level of long-term averages: the amount of precipitation was 350-400 mm, and the average monthly air temperature during the growing season of winter crops was 11.4°C. At the same time, in some years, the main hydrothermal indicators differed significantly from the long-term average. The growing season of 2021 was relatively cool but rainy. The average annual air temperature was 10.3°C, which is 1.1°C less than the long-term average. The 2023 was warmer. The cumulative air temperature exceeded the long-term average by 9.5°C, but precipitation was at the level of the long-term average. Certain plant growing seasons differed significantly from the long-term average in some years. The autumn period favoured the growth and development of vegetative organs with biochemical and morphological parameters that ensure the plant's adaptation to adverse weather conditions in winter. The air temperature regime in September-November 2021-22 during the initial growing season of winter rape was generally favourable for growth processes. The average monthly air temperature ranged from 15.4-15.8°C in September to 5.3-6.1°C in November, while the long-term average was 5.5°C. Total precipitation in 2021 was much higher than the long-term average. At the same time, in 2022, it was a quarter less than the long-term average. In 2023, the total amount of precipitation during the year was at the level of the long-term average. The average amount of precipitation during 2021-2023 was at the level of long-term averages. The dynamics of precipitation during the year had a specific uneven character. In the autumn period (September-November, 2021-2022), the average precipitation was 100.0 mm, 140.4 mm, while the normal precipitation was 102 mm.

Taking into account the moderate air temperatures for the season, winter rape plants developed well, which to some extent prevented their damage in winter.

In the spring (March-May), compared to the average (122 mm), there was a significant difference in the dynamics of precipitation compared to the long-term average. In the spring of 2022, only 71.4 mm fell, while in 2023 it was 198.0 mm, or 2.8 times more. Thus, natural moisture significantly influenced the formation of the leaf apparatus, the growth of the productive part of the plant during the entire period of active vegetation. The air temperature regime during the study period had, in general, a smaller deviation from the average. The average long-term air temperature was 11.4°C, the average temperature for the period of the experiment in 2021-2023 was 11.1°C, or the deviation for individual years was 0.3-1.1°C, or 6.1-10.7%. In winter, negative low air temperatures did not cause plant death, as they most often fluctuated around 0°C. Thus, the weather conditions during the experiment were at the level of long-term averages, although significant deviations were observed in some periods of plant growth and development. The influence of factors that suppress plants was not detected. Additional artificial irrigation as needed contributed to the maintenance of optimal hydrothermal conditions in the agrocenosis of winter rape.

RESULTS

The quality of field crop seeds, including winter rape seeds, significantly impacts field germination, growth energy, and the formation of the synthetic apparatus during the initial stage of plant growth. The average weight of seeds used for sowing is also important. This indicator determines the amount of reserve nutrients, positively affecting seed germination. The average weight of F1 hybrid seeds intended for sowing was 6.63 g/1,000 seeds, a fairly high value for winter rape (Table 1).

Table 1. *Sowing qualities of winter rapeseed (average for 2021-2022)*

Hybrid	Average seed weight, 1,000 seeds/g	Purity of seeds, %	Germination of seeds, %	Sowing suitability of seeds, %
Dario	7.03	100.0	93.2	93.2
Oriolus	6.60	100.0	91.6	91.6
Blackstone	6.26	100.0	94.0	94.0
Medium	6.63	100.0	92.9	92.9
NIR05	0.98	-	-	-

Source: *created by the authors*

A variety of parental forms were involved in the breeding process, which influenced not only the biometric characteristics of the plants, but also the morphological traits of the seeds, including their shape, size, and weight. The highest seed weight was recorded in the hybrid Dario, amounting to 7.03 g per 1,000 seeds. The average seed weights of the Oriolus and Blackstone hybrids were comparable, at 6.60 g/1,000 seeds and 6.26 g/1,000 seeds, respectively. However, the variation in average seed weight among the hybrids was relatively low, ranging from 4.02 to 3.72 g, or 9.1-9.4% of the mean value.

Accordingly, to achieve a uniform density of productive plants per unit area, the sowing rate should be adjusted proportionally and should not exceed the average rate by more than 10.0%. A substantial number of winter rapeseed hybrids of foreign origin (Germany, France, the Netherlands, Czech Republic) are utilised in commercial production. Breeding companies supplying the Ukrainian market provide seeds that are fully compliant with agricultural standards: they are calibrated, cleaned, and treated. Laboratory analysis confirmed that the seed purity in the experiment was 100.0%, while germination rates ranged from 91.6% to 94.0%, thus meeting the requirements for first-class seed material. Given the high sowing quality of the seeds, there is no justification for increasing the calculated seeding rate for any of the hybrids examined. Consequently, the sowing rate was set at 500,000 viable seeds per hectare, corresponding to 3.13-3.52 kg/ha.

Considering the fact that winters in Ukraine are relatively mild, with the southern region being no exception, no damage to winter rapeseed plants due to low temperatures was recorded during the winter period. The onset of vegetation resumed 8-10 days earlier than the average long-term norms. The dynamics of rapeseed phenophases was slightly ahead of schedule, taking into account the accumulation of positive temperatures in the initial period of vegetation. During the seed ripening period, more than 97.0% of winter rapeseed plants have a well-developed central stem. There is no branching in the upper part of the stem, with first-order branches extending from the lower part of the stem, and second-order branches extending from them. In the upper part, only flowers are located on the 0^{th} order branch, and later – pods. Observations have shown that the biological characteristics of the hybrid significantly influenced the condition and nature of the morphostructure of the entire above-ground part of winter rapeseed. However, some specificity is evident in a number of indicators (Table 2).

Table 2. *The branching pattern of winter rapeseed plants during the harvest period (average for 2022-2023)*

Hybrid	Number of shoots, per plant	Including the order of branching of pieces/plants		
		0th	1st	2nd
Dario	15.3	1.0	10.4	3.9
Oriolus	12.1	1.0	8.7	2.4
Blackstone	9.8	1.0	7.1	1.7
Medium	12.4	1.0	8.7	2.7
NIR05	1.01	-	0.74	0.22

Source: *created by the authors*

The highest ability to form early-maturing axillary buds in the basal part of the shoot of the 0th order of branching was observed in the Dario hybrid and amounted to 10.4 pieces per plant, the lowest – in the Blackstone hybrid (7.1 pieces per plant). A similar trend between hybrids was observed in the formation of early-maturing buds on shoots of the 1st order of branching, which contributed to the growth of shoots of the 2nd order of branching – 3.9 pcs/plant and 1.7 pcs/plant, respectively. Ultimately, the total number of shoots of all orders of branching on which pods are formed was highest in the Dario hybrid, reaching 15.3 per plant, and lowest in the Blackstone hybrid (9.8). An important component of winter rapeseed productivity is the number of pods per plant (Table 3).

Table 3. *Yields of winter rapeseed hybrids during the harvest period (averages for 2022-2023)*

Hybrid	Number of pods, pieces/plant	Including the order of branching of pieces/plants		
		0th	1st	2nd
Dario	249.4	28.7	194.5	26.2
Oriolus	219.5	31.6	166.2	21.7
Blackstone	198.8	25.3	158.0	15.5
Medium	222.5	28.5	172.9	21.1
Deviation, %	10.1-11.2	11.5-14.4	75.8-79.5	7.8-10.5
NIR05	15.92	2.16	13.08	1.53

Source: *created by the authors*

The largest number of pods was observed in the Dario hybrid, amounting to 249.4 pods per plant, and the smallest number was observed in the Blackstone hybrid, amounting to 198.8 pods per plant. Among the hybrids studied, the morphostructure of pod placement also had its own characteristics. On the shoots of the 0th branching, there were on average 12.8% of pods of the total number. The number of pods on the shoots of the 1st order of branching was the largest and amounted to 77.7%. Taking into account the branching of hybrids, the proportion of pods on the shoots of the 2nd order of branching was the smallest – 9.5%. The tendency of pod placement on shoots of different branching orders in the studied hybrids was almost the same. It should be noted that the main number of pods was located on shoots of the 1st order of branching and accounted for 75.0-79.5% of the total number. That is, the biological characteristics of the crop were manifested, and the differences between the studied hybrids were insignificant. Thus, the overall localisation of pods on shoots is related to the structure of the shoots: a larger number of shoots on the plant led to an increase in the number of pods on the plant. When considering the "load" borne by the pods on individual shoots of various branching orders, a certain regularity is also observed: the largest number of pods per shoot is observed on shoots of the 1st order of branching, and the smallest on shoots of the 2nd order of branching, as the least developed. The variation in the indicator studied was also insignificant and ranged from 18.7 to 22.2 pieces for shoots of the 1st order of branching and from 6.7 to 11.1 pieces for shoots of the 2nd order of branching. Compared to the "load" of pods per shoot of the 0th order of branching, an increase in the order of branching leads to a decrease in the number of pods per shoot, respectively 28.5-19.8-7.8 pieces. The number of pods formed on one plant has a significant impact on the formation of crop yield, but it should also be taken into account that the average weight of seeds and their number in a pod also significantly affect this indicator (Table 4).

Table 4. *Yield structure of winter rapeseed (averages for 2022-2023)*

Hybrid	Seeds, pcs		Seed Weight, g		
	per pod	per plant	pod	per plant	per 1,000 seeds
Dario	21.1	5,262.3	0.0785	19.55	3.72
Oriolus	18.8	4,126.6	0.0716	15.72	3.81
Blackstone	16.9	3,359.7	0.0624	12.41	3.69
Medium	18.9	4,205.2	0.0708	15.73	3.74
HIP	1.18	-	0.0063	-	0.265

Source: *created by the authors*

The average pod length ranged around 50.0 mm, which corresponds to the typical pod size of the hybrid, as indicated by the breeder. The number of seeds per pod ranged from 16.9 to 21.1. There was no significant difference in the average seed weight among the hybrids, which ranged from 3.69 to 3.81 g per 1,000 seeds. However, taking into account the number of pods per plant and the number of seeds per pod, there was a difference in the productivity of individual plants. For example, the Dario hybrid produced 19.55 g per plant, the Oriolus hybrid – 15.72 g per plant, and the Blackstone hybrid – 12.41 g per plant. Due to the biological characteristics of the hybrid, which determine the formation of the plant's morphological structure, the total seed mass differed significantly, with the difference between the highest and lowest values ranging from 24.3% to 57.5%.

As a result, it was established that the yield of winter rapeseed depended not only on the genetic potential of the hybrid but also on the meteorological conditions during the years of the study. A prolonged autumn vegetation period promoted the development of the root system and the formation of the leaf apparatus. During the winter period, there were no severely low temperatures that could have damaged the plants. The most challenging was the spring period, when ambient temperatures-initiated vegetation, but there was no possibility to conduct additional irrigation. The most favourable hydrothermal conditions for winter rapeseed occurred in the spring (April) and early summer (June) of 2023. Precipitation contributed to creating a comfortable microclimate near the ground surface, which positively affected the formation and functioning of the assimilation apparatus (BBCH growth stages: 3 – elongation of the main stem; 5 – pod formation). During this period, key processes in winter rapeseed plants were observed, such as stem growth, leaf formation, emergence of flower stalks, flowering, and the development of full pods. Overall, the proper and timely implementation of key cultivation practices for winter rapeseed, taking into account the region's climatic features, contributed to yields ranging from 2.52 to 5.41 t/ha (Table 5).

Table 5. *Yield of winter rapeseed hybrids depending on biological characteristics, t/ha*

Hybrid	Years of research			Deviation		Yph, t/ha	Rbp, %
	2022	2023	Average	t/ha	%		
Dario	4.37	5.41	4.89	+0.96	124.43	7.0	69.9
Oriolus	3.51	4.35	3.93	0.00	100.00	6.6	59.5
Blackstone	2.52	3.70	3.11	-0.82	79.13	5.5	56.5
Medium	3.47	4.49	3.98	+0.05	101.27	6.3	63.2
HIP	0.28	0.33					

Notes: *Yph – yield potential of the hybrid, t/ha; Rbp – ratio of the actual yield of the hybrid to its yield potential*
Source: *created by the authors*

As a result of the research, varying adaptive responses of winter rapeseed hybrids to high temperatures and relatively low air humidity during the summer period were identified. The Dario hybrid demonstrated the best realisation of its biogenetic potential. It showed the highest number of shoots of all branching orders – 15.3, the highest number of pods per plant – 249.4, and 21.1 seeds per pod. These conditions contributed to the highest yield, which averaged 4.89 t/ha over the two years of the study. The lowest comparative photometric indicators were recorded in the Blackstone hybrid, which in turn resulted in the lowest yield – 1.78 t/ha (or 63.4%) less than that of the Dario hybrid.

Taking into account the average yield potential of the studied hybrids, as indicated by the originators, and comparing it with the results of the research, it becomes evident that under the conditions of the Southern Steppe of Ukraine, they were able to realise, on average, 63.2% of their genetic potential. However, it should be noted that the winter rapeseed seeds used for the experiment were obtained from "DSV-Ukraine", a subsidiary of Deutsche Saatveredelung AG (DSV), based in Lippstadt, Germany. It can be assumed that the variability range of traits such as tolerance to high temperatures and low air humidity in the parental lines was insufficient for the resulting hybrids to fully realise their potential in this arid region.

DISCUSSION

Effective agricultural management in modern conditions largely depends on the identification and scientifically grounded direction of enterprise activities. A crucial aspect is the prioritisation of product realisation, including its export potential. Researchers M.I. Bakhmat & I.V. Sendetskyi (2020) noted that rapeseed accounts for approximately 10% of global oilseed production, ranking third in terms of cultivation volume. One of the tasks aimed at improving the organisational and economic indicators of the agricultural sector involves comprehensive measures to expand the production of oilseed crops, including rapeseed, which is highly profitable and promising.

O. Kulakova (2023) indicated that rapeseed production in European Union countries is projected at 20.2 million tons with a yield of 3.33 t/ha. The significant increase in global demand for rapeseed seeds is primarily associated with the substantial development of alternative bioenergy. I.V. Smirnova & V.M. Galaban (2024) noted that global rapeseed production in 2024/25 is forecasted by experts to exceed 88.34 million tons. The high demand for vegetable oils used for biofuels and lubricants significantly strengthens the crop's position in the international market, and the creation of modern high-yield hybrids provides a significant impetus for expanding its cultivation areas. S. Kyrychok (2022) emphasised that rapeseed is also an important forage crop, with green mass yields in winter intermediate crops reaching 34-36 t/ha, equivalent to 36-38 feed units. Additionally, rapeseed serves as a phytosanitary crop in crop rotations with a high concentration of cereal grains.

Ukraine possesses favourable soil and climatic conditions for obtaining stable yields of winter rapeseed across most of the Forest-Steppe, Western Polissia, and parts of the Northern Steppe, provided that technological aspects of production are adhered to. The expansion of rapeseed seed production in Ukraine directly depends on the crop's assortment. At the time of planning and establishing the experiment, the Catalogue of plant varieties suitable for distribution in Ukraine (2025) listed 129 varieties and hybrids of winter rapeseed, including 77 recommended for cultivation in the Steppe zone. By 2025, this number has increased to 378 winter rapeseed samples, with nearly half recommended for cultivation in the Steppe zone. The experiment involved winter rapeseed hybrids from the "DSV" breeding centre, which may be promising for cultivation under irrigation conditions.

According to research by A. Plotnitska *et al.* (2020), regardless of the direction of rapeseed breeding, special attention was paid to creating hybrids and varieties with increased potential productivity through the optimisation of the morphological structure of plant organs and their functioning. Varieties of different geographical origins differ in adaptive and productive characteristics. For instance, differences in plant overwintering ranged from 0.5-3.0%, carbohydrate accumulation in the root neck from 0.2-0.8%, resistance to downy mildew from 7.0-21.3%, alternaria from 15-34.2%, phoma from 6.1-11.0%, yield from 0.15-0.41 t/ha, 1,000-seed weight from 0.02-0.37 g, oil content by 2.0%, and erucic acid content by 0.2 μmol/g. Ultimately, hybrids and varieties should be characterised by high and stable yields over the years, high oil and protein content, drought and winter hardiness. Preference is given to early-maturing hybrids resistant to pod shattering, lodging, and diseases and pests, with broader ecological adaptability. For the southern region of Ukraine, requirements for adaptive hybrids include drought and winter hardiness (Markova *et al.*, 2025).

In this context, studying the features of morphological structure formation and productivity of new winter rapeseed hybrids under the conditions of the Southern Steppe of Ukraine is relevant. Winter rapeseed hybrids from the "DSV" producer are characterised by intensive root system development in the initial growth phases according to the BBCH scale and possess genetic resistance to pests. Their biological characteristics allow for the formation of a well-developed leaf apparatus and a deeply penetrating root system during the autumn period before the onset of unfavourable conditions, which ultimately contributes to good plant adaptation to extreme hydrothermal conditions occurring in December-February (Muntyan *et al.*, 2024). The winter hardiness of the hybrids studied in the experiment was rated at 9 out of 10 points. Balanced development of the above-ground part of the plant and a well-developed root system also determines sufficient drought resistance during the summer period of active vegetation (9 out of 10 points). Already in the autumn period, during phase 2 – development of lateral shoots (20 – lateral shoots absent) according to the BBCH scale of winter rapeseed development, prerequisites for the development of lateral shoots in the axils of true leaves are laid, and in phases 21-29, lateral shoots begin to form. In phase 3 – elongation of the main stem (30 – beginning of stem growth), the 0-order branching stem begins to grow (according to the BBCH scale – main stem).

In comparative tables of rapeseed hybrids, indicating their features, primarily agronomic and morphological characteristics, disease and stress resistance, important indicators include average yield over years of testing and potential yield. For the group of VNIS hybrids (Blackstone, Grim, Parker, Redstone, Trump, Hulk, etc.), the potential yield is 7.0-7.2 t/ha, yield over years of testing – 4.7-5.2 t/ha, with the realisation of biogenetic potential reaching 65.3-73.9%. Over the years of testing, the yield of hybrids presented in the studies ranged from 2.52-5.41 t/ha, and the realisation of hybrid yield potential – 56.5-69.9%. In the southern region, under the conditions of adhering to the main elements of the technological process, average yield indicators and realisation of the biogenetic potential of hybrids were at the level of indicators presented in reference literature. High rapeseed productivity, according to M. Parkhomets *et al.* (2023), is associated with the creation of regional zones of concentrated winter form cultivation, allowing for the effective use of soil-climatic and material-technical resources and effective agrotechnical measures.

According to research by O. Klyachenko (2021), the realisation of the biomorphological potential of winter rapeseed hybrids and varieties is based on creating a balanced morphological structure of plants. It should be noted that the natural accumulation of reproductive organs on shoots of different branching orders, considering the photosynthetic apparatus, has a certain pattern. As a rule, winter rapeseed develops a sufficiently developed single shoot – the 0-order branching shoot (Zabarniy & Zabarna, 2024). As records showed, 25.3-31.6 pods formed in its upper part. In the axils of leaves on the 0-order branching shoot, 7.1-10.4 first-order branching shoots formed, on which 158.0-194.5 pods were counted, averaging 19.9 pods per shoot. On first-order branching shoots, 1.7-3.9 second-order branching shoots formed, with 15.5-26.2 pods on them. Thus, the distribution of pods depending on the branching order of shoots follows the trend: 0-order – 12.8%, 1st order – 77.7%, 2nd order – 9.5%. The number of seeds, their weight, and yield distribution by branching character generally follow the same pattern as the pod distribution on the plant.

The conditions of plant cultivation significantly influenced the formation of generative organs. In the conditions of the Western Forest-Steppe of Ukraine, Ukrainian selection rapeseed varieties (Pegas, Solo, Smaragd, Stilutsa) performed well, with seed yields of 3.94-4.03 t/ha. Plants had 115-119 pods, including 59-60 on 0-order branching shoots. V.M. Sendetskyi *et al.* (2023) indicate that in plots without fertiliser application, the number of pods was 89-95 pcs/m², and with the application of $N_{210}P_{135}K_{165}$ – 99-105 pcs/m². V.M. Bezkorovaynyi & V.V. Moisienko (2024b) noted that with a row spacing of 30 cm, modern winter rapeseed hybrids can form an average of 419.1 to 444.0 pods per plant. The formation of the morphological structure of winter rapeseed in the conditions of the Western Forest-Steppe and the Southern Steppe has significant differences because, in the Southern Steppe, the cultivation technology of winter rapeseed must utilise moisture-conserving elements of technology, which significantly reduces the risk of its production. To model the optimal distribution of a plant's productive organs, it is necessary to reasonably generalise the following indicators: determine the optimal number of first-order branches per plant and the distribution of pods on them; justify the feasibility of stimulating the growth of second-order branches and placing pods on them (Nikochuk & Mykolaichuk, 2025).

Research has shown that only 40-60% of plants form yield on second-order branches, and the average number of pods per such branch ranges from 6.7 to 11.1. By the time of rapeseed harvest, the optimal plant parameters that promote the realisation of genetic potential and determine yield can be regulated through technological process components, including plant spacing, the use of growth regulators, scientifically justified fertiliser application rates, and improvement of the water-air regime in the crop biocenosis.

CONCLUSIONS

The winter rapeseed seeds obtained for the study showed high sowing and varietal quality indicators and met the standards required for first-class seed. The weather conditions of the Southern Steppe of Ukraine are generally suitable for growing winter rapeseed. However, there was an insufficient amount of natural precipitation during the plant's vegetation period, especially in the early stages of growth and development, as well as during flowering and fruit-setting phases. To improve hydrothermal conditions during critical vegetation periods, additional irrigation is necessary, taking into account soil moisture and the physiological state of the plants.

A biological characteristic of the crop allows for the development of first- and second-order lateral shoots during the spring period. The total number of shoots developing on a plant, depending on the hybrid, ranges from 9.8 to 12.3, with first-order branches comprising the largest share of the structure (68.0-72.4%). The winter rapeseed hybrids had a sufficiently developed reproductive component, enabling the formation of 198.8-249.4 pods per plant. The majority of pods were located on the first-order shoots (75.8-79.5% of the total), which largely determined the yield. The average seed weight (per 1,000 seeds) among the studied hybrids varied slightly, ranging from 3.69 to 3.81 g. Yield was determined by the weather conditions during the experiment and the biological characteristics of the hybrid. Under the conditions of the southern region, the realisation of the biogenetic potential of the winter rapeseed hybrids was at the level of 56.5-69.5% of the potential yield, amounting to 2.52-5.41 t/ha.

The highest yield during the experiment was observed in the Dario hybrid. The biomorphological characteristics of the plants that determined yield were as follows: total number of shoots per plant – 15.3, including 10.4 first-order shoots; total number of pods per plant – 249.4, including 194.5 on first-order shoots; average weight of 1,000 seeds – 3.72 g; average yield over the experiment – 4.37-5.41 t/ha; realisation of biogenetic potential – 62.4-77.3%. The lowest yield during the experiment was observed in the Blackstone hybrid. The plant biomorphological indicators that determined productivity were as follows: total number of shoots per plant – 9.8, including 7.1 first-order shoots; total number of pods per plant – 198.8, including 58.0 on first-order shoots; average weight of 1,000 seeds – 3.69 g; yield over the experiment – 2.52-3.1 t/ha; realisation of biogenetic potential – 45.8-67.3%.

Targeted efforts aimed at forming a balanced ratio between vegetative and reproductive plant organs (total number of shoots per plant, number of 0-1-2 order shoots, number of pods per shoot, their optimal combination in the shoot/pod ratio, seed weight per pod) through the implementation of adaptive technological elements-such as the use of growth regulators and the application of micro- and macroelements during the rosette leaf and lateral shoot development stages (BBCH growth stages 20-30) – require further research.

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Продуктивність ріпаку озимого залежно від морфоструктури рослин в умовах Степу України

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Анотація. Метою досліджень було визначення показників морфоструктури продуктивних органів ріпаку озимого, які впливають на врожайність і встановлення на їх основі стратегічного напрямку формування перспективного сортименту для вирощування культури в умовах Південного Степу України. На прикладі гібридів ріпаку Даріо, Оріолус, Блекстоун – (ВНІС) представлена порівняльна морфоструктура вегетативних і генеративних органів рослин і її вплив на урожайність. Відмічалося, що чистота насіння, яке використовували в дослідженні, склала 100,0 %, лабораторна схожість – 91,6-94,0 %. Загальне число пагонів на період збирання урожаю визначалася значною мірою біологічними властивостями гібриду і коливалась в межах 9,8-15,3 штук/рослину. Обґрунтовано, що продуктивність посівів визначалась передусім наявністю стручків на пагонах 1-го порядку галуження, що складало в структурі врожаю – 75,7-78,5 % від їх загальної кількості залежно від біологічних особливостей гібридів. Кількість стручків, розміщених на пагонах 0-го і 2-го порядків галуження була незначною і складала 12,8 % і 9,5 % відповідно. Середня маса 1 000 насінин між досліджуваними гібридами відрізнялась не суттєво і коливалась в інтервалі 3,69-3,81 г. Різниця у величинах урожайності між гібридами визначалася за комплексними показниками продуктивності, зокрема, загальною кількістю стручків на рослині і кількістю насінин в стручку. Найбільша кількість стручків була у гібрида Даріо – 249,4 шт./рослині, найменша – у гібрида Блекстоун – 198,8 шт./рослині. Оптимальна морфоструктура рослин виявилась у гібрида Даріо, що сприяла не тільки отриманню найвищого урожаю (4,89 т/га), але й реалізації в найвищому ступені біогенетичного потенціалу гібриду (69,9 %). Нижчі порівняльні показники були виявлені у гібрида Блекстоун, урожайність і реалізація біогенетичного потенціалу склали відповідно 3,11 т/га (56,6 %)

Ключові слова: гібрид ріпаку; морфоструктура рослин; галуження; стручок; насіння; урожайність

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Conceptual models of state support for agriculture: From direct producer support to financing general agricultural services

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Abstract. Since the concept of state support for agriculture in Ukraine is not perfect and requires improvement, given the limited financial capabilities of the country during a full-scale invasion and post-war recovery, the aim of the article was to find an optimal model of state support based on the experience of countries with a highly developed agricultural sector. The features of conceptual models of state support were considered through indicators of structural and dynamic analysis and assessments of the effectiveness of budget support in the EU, Canada, New Zealand, the USA, and Ukraine. The premise of the study was an analysis of the overall imbalance level of state support directions for agriculture, according to the results of which none of the countries had a balanced approach to regulating the agricultural sector. It was established that the reason for the highest levels of imbalance in the EU was the undisputed dominance of producer support and, in the USA – consumer support, simultaneously with a low priority of financing for agricultural knowledge and innovations in both countries. A hybrid model of state support turned out to be a feature for Ukraine since dissimilar directions prevailed during different periods of turbulence. Given the assessment of the effectiveness, Ukraine should use the Canadian model in the short term, which, although similar to the EU, supports farmers on a much smaller scale and has a relatively upper focus on general services for the agriculture, in particular inspections and controls and knowledge and innovations. It was established that in the long term, the priority is to adapt the New Zealand approach with the absolute dominance of investments in infrastructure, research and technological development, which ensures maximum economic effect and competitiveness of the industry. The findings of the study can be used by the Ukrainian authorities, in particular the Ministry of Agrarian Policy and Food, to improve state support programmes for agriculture by adapting effective financing models based on international experience and taking into account the economic and resource realities of the country

Keywords: agricultural sector; Ukraine; imbalance level of state support; efficiency; value of agricultural products; agricultural knowledge and innovation; New Zealand

INTRODUCTION

Since each country has specific natural and climatic, economic conditions and financial capabilities, which affect the determination of state agrarian policy priorities, the structure, directions, and types of agricultural support have significant differences. Since Ukraine needs to implement a well-founded and consistent concept of state intervention in the development of the strategically major agricultural sector, deepening research into the

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balance of state support, its effectiveness, and its impact on agricultural production is a component of ensuring its long-term prosperity, which is especially important for the post-war recovery of Ukraine. The agricultural sector of Ukraine plays a critical role in shaping economic security and ensuring balanced development, being one of the strategically important sectors of the national economy. However, the criticality of the challenges that agricultural producers have faced daily over the past decades has steadily increased during the period of martial law.

L. Vdovenko (2022), studying the instruments of state financial support under martial law and the problems that faced Ukrainian agriculture, emphasised their negative impact on the development of the industry. In the author's opinion, the concept of state support was not ideal, as it required a change in the vector of agricultural policy due to the aggravation of the issue of food security not only at the national but also at the global level. Economist Impact (2023) data reinforced this conclusion since there was a decrease in the food security level in Ukraine in 2022. The country lost 13 positions and took 71st place out of 113 assessed countries, compared to 58th in 2021. R.V. Ivanov *et al*. (2024) also emphasised the importance of supplementing state support mechanisms, analysing the exporters' behaviour in the case of a disruption of one of the chief logistical supply chains under martial law.

Russian military aggression, the consequences of which are damage to granaries, greenhouses, farms, and machinery, rising prices and a decrease in production and income due to logistics disrupted by the war, and the destruction of irrigation and port infrastructure, became the most significant problem and threat to agricultural activity, as was emphasised in the study by H. Cherevko (2022). Its negative impact on agriculture should be levelled or mitigated by implementing a complex of budgetary, price, tax, scientific, credit, and foreign economic instruments implemented within the framework of state agrarian policy. However, S. Kolotukha *et al*. (2019) noted that the wrong priorities of state agricultural policy are one of the factors causing the decline in agricultural production. Even though the authors' study was aimed at identifying key problems in the financial provision of farming enterprises, the principal attention was still focused on analysing the growth of agro-industrial production and the loans provided to it. Although lending to agricultural producers is a means of influencing the crisis in the sector, applying only this support measure without alternative approaches that demonstrate effectiveness based on international experience narrows the possible ways of reforming the support model. Thereby, state support measures must be justified and contribute to the maximum achievement of the planned results to ensure rational agricultural sector regulation. Despite the importance of state support, the existing agro-protective mechanisms of state support in Ukrainian legislation, according to K. Hryhorieva (2024), were rather declarative. Although the author analysed the essence of state support types for agriculture through the prism of the evolutionary development of the regulatory framework, the study results insisted on the need for conceptual reform of agro-protective measures, which have become urgent since 2022.

D. Shelenko *et al*. (2023), when justifying the concept of state support for the development of agricultural producers, concluded that it should include a set of targeted measures that would contribute to agricultural production development and encourage the introduction of intensive technologies. For these reasons, the current model of state support requires adjustment and improvement, which is especially important in the context of rapid changes in systemic security challenges. V. Lavruk & N. Pokotylska (2019) proposed a conceptual model of the strategy of state financial support for livestock enterprises in Ukraine, which was an essential step given its permanent stagnation and lower development rates compared to crop production. However, given the weak diversification of plant production, which consists of the dominance of grain crops, it is substantial to develop models of effective state regulation of the agricultural sector in general.

The focus of the study by M. Gumeniuk & D. Nemish (2024) was to assess the main organisational and economic problems of the agricultural sector development during martial law and post-war reconstruction in Ukraine. Analysing the strategic directions of state support for small producers, the authors also focused on the importance of its increase to overcome the crisis phenomena faced by small farms. Despite the probable inability of small producers to solve problems independently without state intervention, the study did not sufficiently reveal the effectiveness of existing state support measures, especially in conditions of strict budget constraints that will persist in the post-war reconstruction period. Based on this, proposing a sound policy for small business development, a comparative analysis of Ukraine with countries whose agricultural sector demonstrates high productivity without excessive support, New Zealand in particular, would be of additional value.

According to I. Dinis (2023), agricultural policy was becoming particularly meaningful for the Ukrainian government due to the increase in expenditures on supporting producers by UAH 4 billion in 2025 compared to the previous one. In the article, the authors studied the effectiveness of state support, in particular subsidies, loans, and tax breaks, in ensuring the development of agricultural enterprises in Ukraine and increasing their competitiveness. Comparing forms of state support with the experience of Canada, it was determined that Ukraine should carefully analyse successful approaches to the financial resources distribution of other countries to adopt them and innovatively solve problems. However, despite the Canadian case used, the analysis of the state support model in Ukraine and the level of its balance compared to other conceptually different models operating in countries with highly developed agriculture (for example, in the EU, the USA, or New Zealand) remained insufficiently disclosed, which limits the formulation of balanced recommendations for Ukraine.

T.O. Kharchenko (2022) studied the structure of state financial and economic support for the agricultural sector of Ukraine, comparing it with a set of countries around the world based on generalised statistical indicators developed by the Organization for Economic Co-operation and Development (OECD), namely the Total Support Estimate (*TSE*), Producer Support Estimate (*PSE*), Consumer Support Estimate (*CSE*), General Services Support Estimate (*GSSE*). Even though it enabled shaping the view of the state support level and its dynamics, the study did not focus on distinguishing its conceptual features (orientation on producers, consumers, or general services for the agricultural sector) and the effectiveness of each state support model. It, in turn, limits the possibilities of forming recommendations on the optimal vector of transformation of the state support system, which would ensure the agricultural sector development of Ukraine in the short and long term.

Since the concepts of state support followed abroad have not been given due attention, an interstate comparison of support features for the agricultural sector, considering its effectiveness under each conceptual model, remained relevant. For these reasons, the purpose of the study was to identify conceptual models of state support for agriculture and analyse their impact on the effectiveness of agricultural production in Ukraine, the EU, New Zealand, Canada, and the USA, as well as to identify promising areas of state intervention that can be adapted by Ukraine in the short and long term in conditions of limited financial capabilities.

MATERIALS AND METHODS

The features of state total support for agriculture (*TSE*) in the EU, Ukraine, New Zealand, Canada and the USA were considered by analysing its individual directions. To determine the dominant types of state support (x_{ij}), which had the largest share in country *j* among the *i*-th number of types ($i = \overline{1.14}$), presented in Table 1, samples were formed according to data from the Organisation for Economic Co-operation and Development (OECD, 2023) in 2010-2022.

Table 1. *Types of state support (x_i) in the structure of total support directions (TSE) of the agricultural sector in country j*

Variable	Types	The essence of state support measures within the type
	Producer Support Estimate (PSE_j)	
x_{1j}	Support based on commodity output	A set of measures that create a gap between domestic market prices and marginal prices for a given agricultural product or are based on its current production
x_{2j}	Payments based on input use	Payments provided to reduce the cost of variable inputs; investment costs in buildings, equipment, plantations, drainage, soil quality; costs of technical, accounting, phytosanitary and other services
x_{3j}	Payments based on current area planted / animal numbers / receipts / income, production required	Payments provided per hectare of crops or livestock, income tax benefits
x_{4j}	Payments based on non-current area planted / animal numbers / receipts / income, production required	Payments provided for the average level of production over a certain period, for a set number of farm animals
x_{5j}	Payments based on non-current area planted / animal numbers / receipts / income, production not required	Subsidies for historical crop area without mandatory cultivation, fixed number of farm animals
x_{6j}	Payments based on non-commodity criteria	Payments related to environmental or social initiatives, specific non-commodity products, one-off payments to all farmers
x_{7j}	Miscellaneous payments	Payments for which there is insufficient information to classify them in the above categories
	General Services Support Estimate ($GSSE_j$)	
x_{8j}	Agricultural knowledge and innovation system	Financing of research and development, knowledge transfer through agricultural education, training, advisory and consultancy services to farmers
x_{9j}	Inspection and control	Financing of inspections of domestic products, border inspections, control of pests and diseases in crop or livestock production, state expenditures on veterinary and phytosanitary services

Table 1, Continued

Variable	Types	The essence of state support measures within the type
x_{10j}	Development and maintenance of infrastructure	State investments in irrigation and drainage networks, storage facilities, port facilities (docks, elevators), wholesale markets, land cadastres, seed registers
x_{11j}	Marketing and promotion	Financing of promotion of agricultural products (advertising campaigns, participation in international fairs)
x_{12j}	Cost of public stockholding	Covering costs associated with state reservation of agricultural products
x_{13j}	Other miscellaneous general support payments	Financing of services for which information is insufficient to classify them in the above categories
Consumer Support Estimate (CSE_j)		
x_{14j}	Consumer support	Supporting consumers by lowering prices for agricultural products through subsidies or domestic food aid programs

Notes: *the volumes of state support were measured in millions of US dollars*
Source: *OECD (2023)*

The prerequisite for studying conceptual models of state support for agriculture in the above-mentioned countries was the assessment of the balance of its components. For this purpose, the formed pairs (*PSE/GSSE*, *CSE/GSSE*, *CSE/PSE*) were used, which fully characterised the uniformity of the distribution. Since the ideal balance was the equality of the proposed ratio to 1, the imbalance level of state support directions in country was determined using the Euclidean distance (D_j) from the reference point (*1,1,1*) in three-dimensional space:

$$D_j = \sqrt{\left(\frac{PSE_j}{GSSE_j} - 1\right)^2 + \left(\frac{|CSE_j|}{GSSE_j} - 1\right)^2 + \left(\frac{|CSE_j|}{PSE_j} - 1\right)^2}. \quad (1)$$

In order to take into account the negative impact of *CSE* on consumer prices and incomes, which could not be ignored, for the EU, New Zealand, Ukraine, and Canada its values were absolute, since using the value without a modulus would lead to a distorted picture with the illusion of the absence of consumer subsidies, even when the state carried out significant interventions. Based on the obtained values, the directions of state support were balanced if $D_j = 0$. In cases where $D_j > 1$, the model of the studied country fell into the zone of significant imbalance with a focus on one direction at the expense of others. Since the group assessment of the overall imbalance level of state support directions only showed how far the country has deviated from the balance, a number of criteria were used for an in-depth analysis of state support models, grouped into two substantive categories. The first included indicators of the structural and dynamic analysis of *TSE*, which allowed for assessing the dominant directions and types of state support in each of the countries and their change in 2017-2022 compared to 2011-2016. The corresponding prevalence rates (KP_j), constructed and interpreted according to the same scheme, were used to determine the main reason for state support imbalance (priority of support for producers, consumers, or general services). In particular, the prevalence of direct support over consumer support and financing of general measures for the agricultural sector ($KP_{j(PSE)}$) was determined by the formula:

$$KP_{j(PSE)} = \frac{PSE_j}{(|CSE_j| + GSSE_j)}, \quad (2)$$

where CSE_j – estimated consumer support by module to neutralise absorption of its negative impact by the direction *GSSE*. Since, in this case, the ratio of each direction of support (*PSE*, *GSSE*, *CSE*) to the sum of the other two was considered, and each of the three components occupied the same share, the threshold value of dominance was 1/2. Thus, if $KP_j > 1/2$, then the specified direction prevailed over the other two. Otherwise, the components considered did not play a key role in the state support model. The elasticity of direct producer support ($E_{(PSE/TSE)}$) concerning to total support in country j showed how much direct support increased in 2017-2022 compared to 2011-2016 in response to the growth of *TSE* and is determined by the formula:

$$E_{j(PSE/TSE)} = \frac{\%\Delta PSE}{\%\Delta TSE}. \quad (3)$$

If both indicators showed negative growth (EU, Ukraine, Canada), then if $E_{(PSE/TSE)} > 1$ – *PSE* showed a faster rate of decline than *TSE*; $0 < E_{(PSE/TSE)} < 1$ – *PSE* was declining more slowly than *TSE*. If both indicators showed positive growth (New Zealand, USA), then $E_{(PSE/TSE)} > 1$ meant that the support policy was becoming more farmer-centric in 2017-2022; at $0 < E_{(PSE/TSE)} < 1$, *PSE* growth occurred at a slower rate, which indicated a shift in the priority of direct support for farmers towards other directions of support.

In addition, the criteria that demonstrated the conceptual differences of the models included the average share of *PSE* in the structure of gross farm receipts (GFR) and its shift in 2017-2022 compared to 2011-2016, the average share of financing for agricultural knowledge and innovation (x_8) over the entire period under study (2010-2022) and the top 5 dominant types of state support (x_{ij}) over the past five years. It facilitated the assessment of the dependence of farmers' incomes on state support and the level on which the country relied, developing the agricultural sector through knowledge, technology, and innovative approaches. To clearly present them, visualisation of the evolution of direct state support shares in the structure of gross farm receipts and the structure of general support for the agricultural sector with an emphasis on financing for agricultural knowledge and innovation was used.

The second category included indicators of the preliminary assessment of total budget support (*TBSE*), which allowed for the determination and comparison of the effectiveness of each of the models. Unlike *TSE*, *TBSE* reflected purely budgetary expenditure aimed at supporting the agricultural sector. The starting point, which showed the current efficiency level in absolute terms, was the rate of budget support return (*RTBSE*) in country *j*. It gave an idea of how much agricultural output ($ValueAP_j$) was generated for each unit of state budget support ($TBSE_j$) on average in 2010-2022 and was determined by the formula:

$$RTBSE_j = \frac{ValueAP_j}{TBSE_j}. \tag{4}$$

In addition to the rate of budget support return, to understand its trend, the change rate of $RTBSE_j$ was determined – the growth rate (α_{1j}) in the univariate regression model using time *t* as the independent variable. If $\alpha_{1j} > 0$, then the return from budget support $RTBSE_j$ demonstrated gradual growth, however, extreme values indicated sharp changes in state agricultural policy and transformation of the state support model. The final indicator that made it possible to summarise the flexibility of the relationship between the level of budget support and the result was the elasticity of agricultural product value ($E_{j(VAP/TBSE)}$), which showed how much the change in budget financing ($\%\Delta TBSE_j$) in 2017-2022 compared to 2011-2016 stimulated the change in the resulting variable ($\%\Delta ValueAP_j$). If $E_{j(VAP/TBSE)} > 1$, an increase in budget support led to a faster growth in the value of agricultural products, which meant high efficiency and a multiplier effect. If $E_{j(VAP/TBSE)} < 1$, the state's financial resources were used less efficiently, and the elasticity value < 0 was a sign of structural problems in the agricultural sector, and the value of the products inversely depended on state intervention measures. The proposed comprehensive assessment allowed for narrowing the search space for optimal models of state support for Ukraine, focusing only on relevant concepts, the adaptation of which will bring the most effective and stable results in the short and long term.

RESULTS AND DISCUSSION

According to the OECD (2023) methodology, one of the state support directions for agriculture is the Producer Support Estimate (*PSE*), which reflects the annual monetary value of gross transfers and is provided by governments directly to agricultural producers, generally in the form of subsidies or partial reimbursement, maintaining the stability of farmers' incomes. In turn, the General Services Support Estimate (*GSSE*) characterises those forms of state intervention that provide broad benefits to the farming sector through infrastructure development, financing for research and development, education, inspections, or control. It means that the amount of state funding in this area does not directly change either revenues or expenditure at the level of individual agricultural agents. Consumer Support Estimate (*CSE*) is the third direction of state support, within which domestic food aid programs are implemented for consumer nutrition in cash or product forms. The total annual monetary value of all gross transfers by the directions (*PSE*, *GSSE*, and *CSE*) is embodied in the estimated total support (*TSE*) indicator. It regards not only actual budget expenditures reflected in the government accounts but also indirect hidden measures, such as market price support or tax benefits (foregone state budget revenue).

In the EU, Ukraine, New Zealand, Canada, and the USA, state support for agriculture had significant differences, which primarily consisted of the priority of its various directions and the stability of the state agricultural policy strategy. Considering the analysis of the Euclidean distance, which allowed for estimating the deviation of direct support for producers (*PSE*), general support for the agricultural sector (*GSSE*), and consumer support (*CSE*) from the reference point with coordinates (*1,1,1*) in three-dimensional space, none of the studied countries had a balanced approach to regulating the agricultural sector (Fig. 1). Instead, depending on economic conditions, political decisions and priorities, the mentioned countries demonstrated different models of state support for agriculture with the dominance of some directions over others.

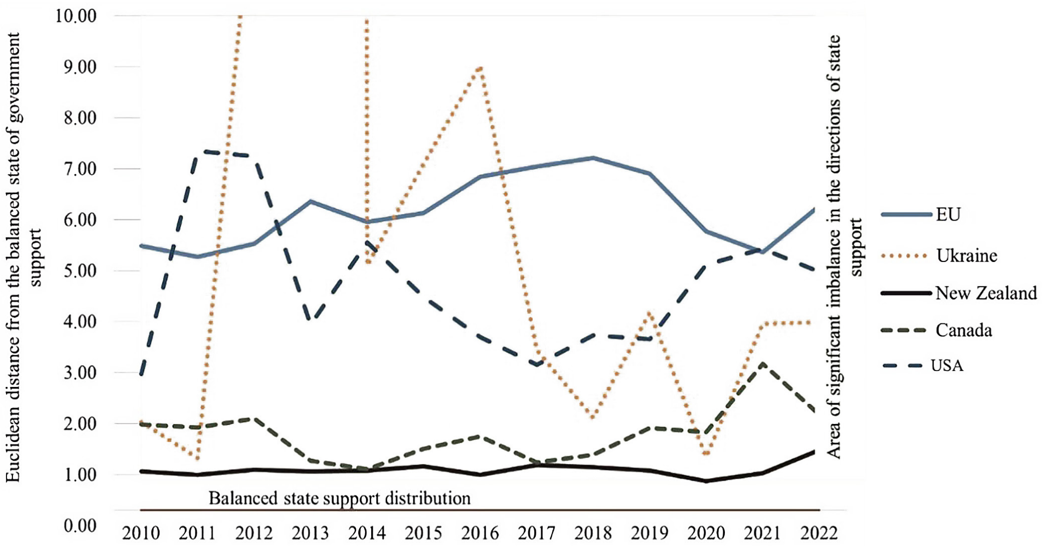

Figure 1. *Imbalance of state support to agriculture in 2010-2022: contrast of the EU compared to New Zealand*
Notes: *Euclidean distance values for Ukraine in 2012 (12.85) and 2013 (500.68) were not shown in the graph to maintain a comparable scale*
Source: *constructed by the author according to OECD (2023) data*

The EU was characterised by the relatively highest overall level of imbalance in 2017-2022 ($D = 6.43$). The relative decrease in imbalance in 2020-2021 was due to the increase in *GSSE* volumes compared to *PSE* during the active phase of the pandemic, especially in the agricultural knowledge and innovation system (x_8), as well as infrastructure development (x_{10}), compared to the pre-pandemic period of 2016-2019. Stable ratios of other components indicated the unchanged orientation of their policy of active subsidies and direct support for farmers, although its volumes decreased by 1.03% annually during 2010-2022. Analysis of the prevailing direction gave grounds to argue about the absolute dominance of direct support since $KP_{PSE} = 3.31 > KP_{CSE} > KP_{GSSE}$ in 2017-2022.

The USA, like the EU, was characterised by a significant level of imbalance ($D = 4.34$) in the corresponding period, which was especially growing in 2011-2012 and 2020-2022. Its reason was a sharp jump in *CSE* compared to *GSSE* in order to strengthen state food assistance to consumers in times of crisis and the secondary nature of the overall development of the agricultural sector. Although their state support model was characterised by high flexibility with moderate direct support for producers ($KP_{PSE} = 0.64$), according to the analysis, the dominant direction was consumer support ($KP_{CSE} = 1.01$), which allowed for smoothing market fluctuations and guaranteeing food security for citizens. For these reasons, *CSE* was characterised by the highest average annual growth rate, which was 7.01%, the volumes of which increased from 32,982.19 million US dollars in 2010 to 74,400.12 million US dollars in 2022, significantly exceeding annual growth in other directions – *PSE* (+3.07%), *GGSE* (+2.62%).

According to the criterion of imbalance of state support for agriculture in 2017-2022, Ukraine was next after the EU and the USA ($D = 3.17$). Its characteristic feature was the lack of a stable strategy due to the influence of external factors related to military aggression, both economic and political upheavals. Extreme values of deviations from the balance in 2012-2013 were associated with a sharp drop in *PSE* against the background of record volumes of *GSSE* (774.79 million US dollars in 2012) and *CSE* (1,342.18 million US dollars in 2013). During the crisis periods of the hybrid war (2014-2022) and the full-scale Russian invasion starting in 2022, accompanied by a decline in state support, the main priority for the government remained to ensure the ability of consumers to purchase goods (at lower prices compared to those offered in a completely competitive sector).

Based on the analysis of the prevailing trends, a reliable conclusion was that Ukraine is characterised by a hybrid model of agricultural support since KP_{PSE} (0.79) ≈ KP_{CSE} (0.75). In various turbulent periods, direct producer (2010-2011, 2018-2020) and consumer support (2012-2017, 2021-2022) dominated in Ukraine against the background of a small level of financing of general services for the agricultural sector (in 2010-2022 $KP_{GSSE} = 0.29 < 0.5$), the volumes of which decreased annually by 6.85% in the studied period.

An equally significant reason for the volatility of the KP_{PSE} ratios was the sharp fluctuations of one of its components – market price support (MPS), which, according to descriptive statistics, had a variation range of 3,808.25 million US dollars: from (-3,124.31) million US dollars in 2011 to 683.94 million US dollars in 2019. The peak of KP_{PSE} in 2018-2020 was associated precisely with the positive effect of this type of direct producer support because only in the specified period did Ukrainian farmers sell products to the foreign market at prices that were 0.05-2.00% higher than the world ones. It indicated the protection of Ukrainian producers by the state's foreign trade policy, which was insufficient in 2010-2017 and 2021-2022. Compared to other studied countries, whose national producers were constantly protected from foreign competition and sold products in 2010-2022 at prices higher than the world average, only in Ukraine did the state support of market prices (through taxes, export restrictions, or prices for agricultural products on the domestic market to protect consumers and other regulatory actions) have a predominantly negative effect and, as a result, led to a decrease in the income of Ukrainian farmers.

For the Canadian model of state support, the imbalance level was moderate compared to the EU, the US, and Ukraine ($D = 1.95$). Apart from the peak in 2021, triggered by a sharp increase in *PSE* compared to *GSSE* in response to the COVID-19 pandemic, Canada demonstrated consistency in the priority of state support directions, as its ratios were among the most stable. An analysis of the dominant directions gave grounds to argue about the absolute dominance of direct support ($KP_{PSE} = 1.15$), although on a slightly smaller scale than in the EU, with a negligible level of support for the general development of the agricultural sector ($KP_{GSSE} = 0.24$) and state intervention in consumer support ($KP_{CSE} = 0.39$). In addition, the annual growth rates of *PSE* and *GSSE* were negative in 2010-2022, amounting to (-1.38%) and (-2.09%), respectively.

Unlike Canada, the growth rate of general services expenditure (*GSSE*) for the agricultural sector in New Zealand was positive and amounted to 1.14%. According to the balance criterion, the ratio of different of state support directions in the New Zealand model was closest to the reference point of the Euclidean space ($D = 1.13$). The absence of sharp fluctuations indicated the invariance of its conceptual model, which consisted of a low level of both *PSE* and *CSE*, focusing only on general services to the agricultural sector ($KP_{GSSE} = 2.32$). In addition, in 2022, New Zealand further reduced direct state support by 59.53%: from 172.22 million US dollars in 2021 to 69.69 million US dollars with a simultaneous reduction in state intervention in the formation of consumer market demand. By prioritising funding for agricultural knowledge and innovation (x_8), product inspection and control (x_9), and infrastructure development and maintenance (x_{10}), New Zealand is implementing a model of state support that ensures sustainability, low market distortions, and producer self-sufficiency. Minimising direct producer support, the experience of institutional support for the agricultural sector by New Zealand can serve as a guideline for reforming the strategy of Ukraine's agricultural policy, which is becoming especially relevant in conditions of limited budgetary resources.

An equally significant criterion was the dependence degree of producers' incomes on state support and the level of autonomy, which were calculated to deepen the research of conceptual models of state support for agriculture in the studied countries. The share of direct state support in gross farm receipts in the EU, although it showed a downward trend, which might be associated with the reform of the Common Agricultural Policy (CAP), nevertheless remained significant: from 19.34% in 2010 to 15.10% in 2022 (Fig. 2). Analysis of direct producer support structure indicated that one of the elements of ensuring the stability of the agricultural sector's income in the EU was payments based on both current (x_3) and non-current (x_5) area planted and the number of animals, since their share in the *TSE* structure was over 57.02% in 2017-2022. However, the assessment of shifts showed that while the share of payments by type x_3 increased by 5.69 pp in 2022 compared to 2010, the share of x_5 showed a decrease of 7.33 pp, which was the maximum in the structure. Other components, although relatively smaller, provided an average of 6.33% of farmers' income in 2010-2022.

Thus, the top 5 dominant types of state support for the agricultural sector by their average share in the *TSE* structure in 2017-2022 in the EU were payments based on non-current area planted, number of animals, receipts, income that does not require production (x_5) – 36.90%, payments based on current area planted, number of animals, receipts, income that requires production (x_3) – 20.13%, support based on commodity output (x_1) – 15.78%, payments based on input use (x_2) – 13.52%, agricultural knowledge and innovation system (x_8) – 6.37%. While the share of state support in the structure of producers' incomes was decreasing, and the value of agricultural products was increasing in 2020-2022, the dependent variable is assumed to be more influenced by market or external factors (COVID-19 pandemic, rising world food prices, or war in Ukraine) than by direct state support.

In contrast to the EU model, New Zealand had seen a consistently low share of direct state support in the structure of farmers' incomes in 2010-2022: from 0.63% in 2010 to 0.32% in 2022 (Fig. 3). It is due to radical reforms implemented almost 40 years ago that were aimed at minimising farmers' dependence on state funding and reorienting the agricultural sector to function depending on market conditions. The decline in the share of producer payments in the structure of gross farmer receipts from 19.36% in 1986 to less than 1% in 2010-2022 was accompanied by a significant increase in the value of agricultural products (+563.85%): from 3,304.93 million US dollars in 1986 to 21,939.70 million US dollars in 2022.

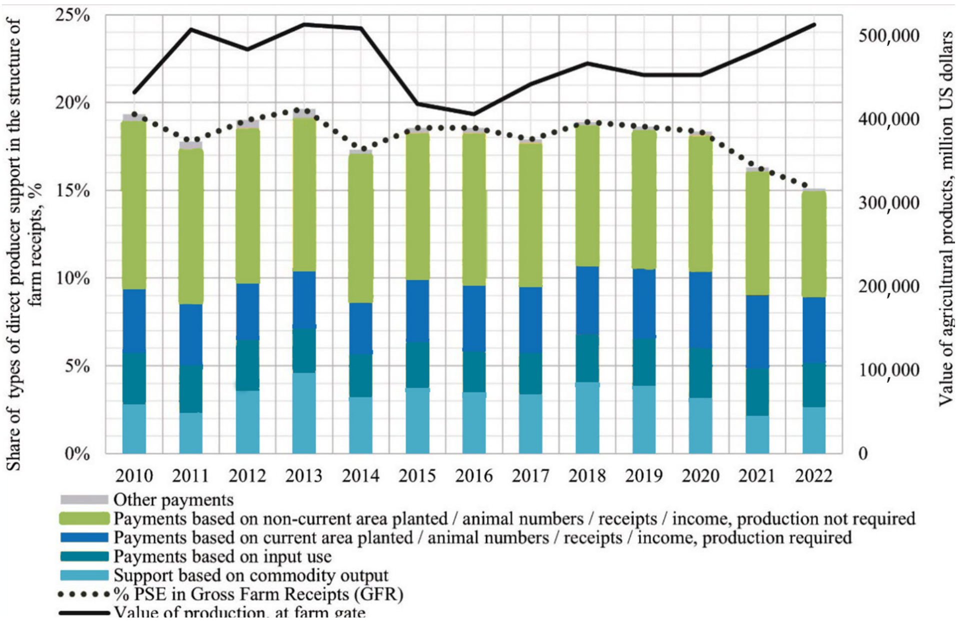

Figure 2. *The share of direct state support in the structure of gross farm receipts in the EU and the value of agricultural products in 2010-2022*

Source: *constructed by the author according to OECD (2023) data*

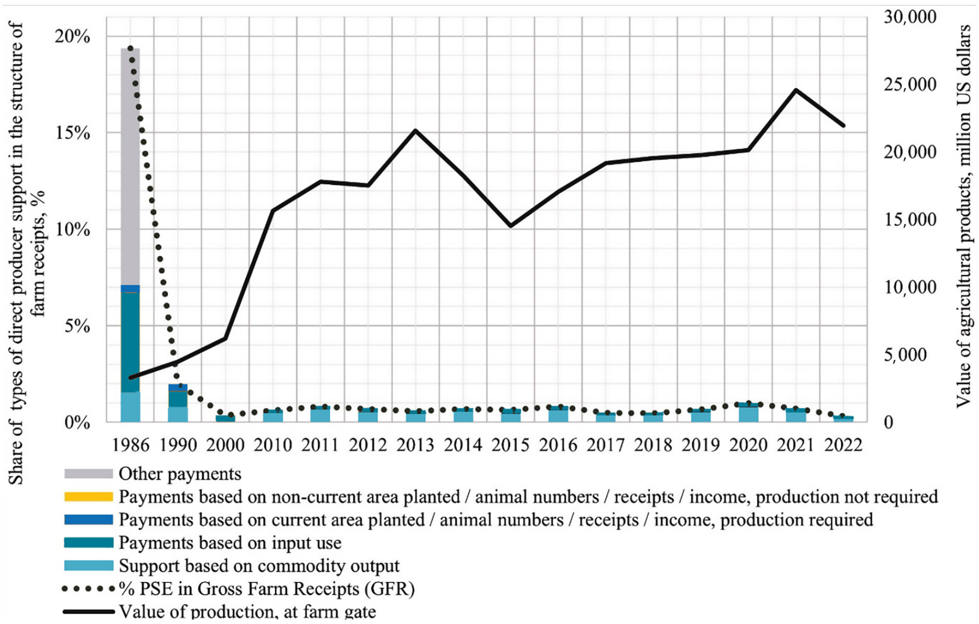

Figure 3. *The share of direct state support in the structure of gross farm receipts in New Zealand and the value of agricultural products in 2010-2022*

Notes: *the dynamic series was expanded to demonstrate the radical changes in the model of state support in 1986-2010*

Source: *constructed by the author according to OECD (2023) data*

Analysis of structural shifts in 2010-2022 indicated that despite the dominance of producer support through protectionist measures (x_1) in the structure of direct support (*PSE*), its share decreased by 10.41 pp, which was not accompanied by a simultaneous decrease in the value of products, that is, New Zealand producers were self-sufficient and competitive at the global level without active state intervention. Thanks to adaptation to market conditions and the use of effective business models, which had required more than one or several years, the New Zealand agricultural sector is thriving due to the growth of its competitiveness, which does not depend on state support volumes. It proved that a sharp reduction in subsidies and direct payments to farmers did not lead to a regression in agriculture development. So, the top 5 dominant types of state support to the agricultural sector by their average share in the *TSE* structure in New Zealand in 2017-2022 were agricultural knowledge and innovation system (x_8) – 34.40%, inspection and control (x_9) – 34.40%, support based on commodity output (x_1) – 17.33%, development and maintenance of infrastructure (x_{10}) – 6.79%, payments based on input use (x_2) – 4.86%.

Analysis of the share of direct payments in the structure of agricultural producers' receipts in Ukraine in 2010-2022 (Fig. 4) indicated the hybrid nature of its state support model: in 2010-2013, it was close to the traditional model of the EU and Canada, demonstrating an average relatively high value (5.48%). However, Russian intervention and full-scale invasion caused its chaotic and forced transition to a certain extent to New Zealand's model, with a share on average less than 1% in 2017-2022.

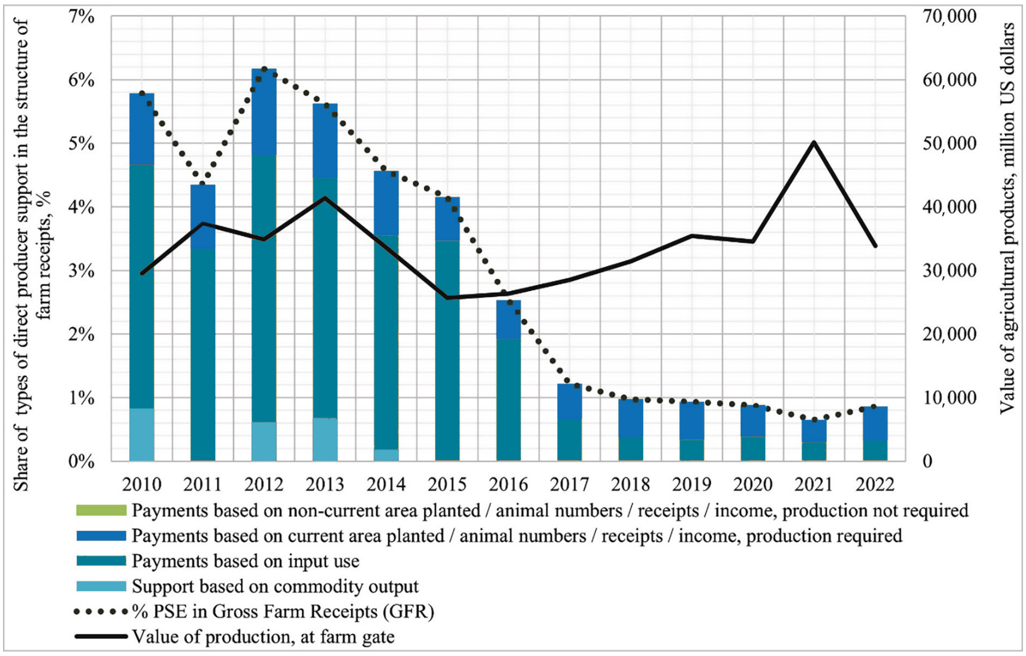

Figure 4. *The share of direct state support in the structure of gross farm receipts in Ukraine and the value of agricultural products in 2010-2022*

Notes: *support based on commodity output (x_1) was presented without taking into account the impact of market price support (MPS) since its negative values make it impossible to correctly calculate the specific weight of types of state support in the structure*

Source: *constructed by the author according to OECD (2023)*

In 2010-2022, the state support model showed changes, but the share of payments based on input resources (x_2) decreased the most (by 29.66 pp). At the same time, similar to the EU and Canada, the share of payments provided per hectare of crops or livestock (x_3) increased in Ukraine by 18.39 pp, which gave grounds to argue about common trends in the state support models of these three countries. Thus, the top 5 dominant types of state support for the agricultural sector by their average share in the *TBSE* structure in Ukraine in 2017-2022 were payments based on current area planted, number of animals, receipts, income requiring production (x_3) – 33.75%, payments based on input use (x_2) – 25.59%, inspection and control (x_3) – 24.25%, agricultural knowledge and innovations (x_8) – 13.46%, support based on commodity output (x_1) – 17.33%, other miscellaneous general support payments (x_{13}) – 1.45%.

The share of direct state support in the structure of gross receipts of Canadian farms was closest to the EU, amounting to 13.76% in 2010-2012 (Fig. 5). The relatively high level of subsidies and payments decreased sharply to about 8-10% starting from 2013, probably due to the implementation of the new agricultural and agri-food policy Growing Forward 2 (Gulab & Lhermie, 2025). Analysis of the direct support structure showed that over 61% in 2017-2022 in the structure of *TSE* fell on payments based on commodity output (x_1) and payments based on current area planted, number of animals, receipts, income requiring production (x_3).

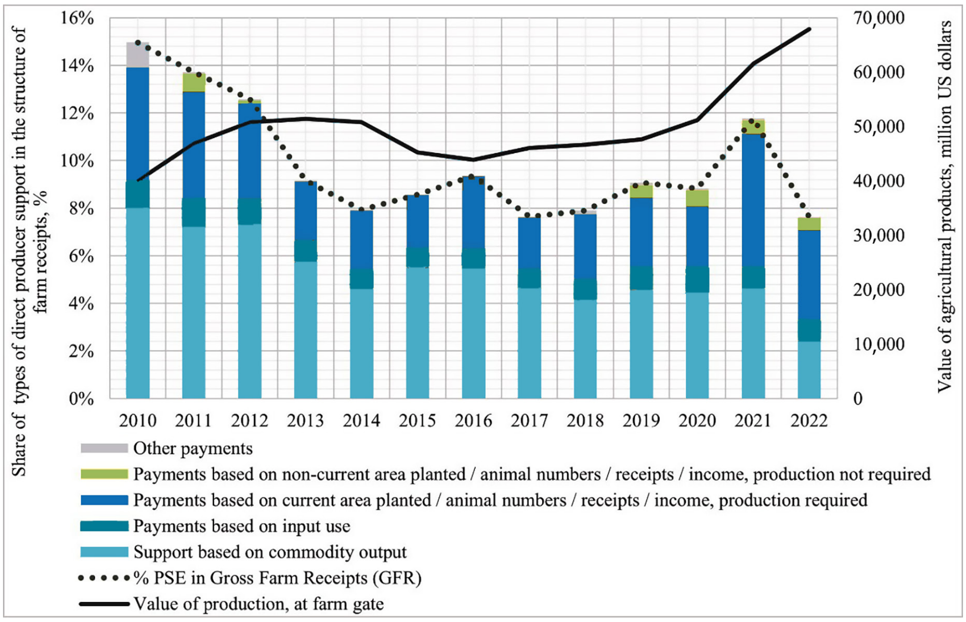

Figure 5. *The share of direct state support in the structure of gross farm receipts in Canada and the value of agricultural products in 2010-2022*
Source: *constructed by the author according to OECD (2023) data*

However, the analysis of structural shifts in 2010-2022 detailed their multidirectional dynamics: while the share of x_3 increased by a record 13.88 pp (similar to the EU and Ukraine), the share of x_1 decreased by 15.72 pp, the structural shifts of which were common with the New Zealand model. This reduction in support for protectionist measures for agricultural producers within the framework of the MPS did not lead to a sharp decrease in the value of products, and the nominal producer protection coefficient (NPC) retained its consistently high value compared to the studied countries, indicating that Canadian farmers sold competitive products at prices that were on average 5-6% more expensive than the world average in 2010-2022. Thus, the top 5 dominant types of state support for the agricultural sector by their average share in the *TSE* structure in Canada in 2017-2022 were support based on commodity output (x_1) – 34.07%, payments based on current area planted, number of animals, receipts, income requiring production (x_3) – 27.15%, inspection and control (x_9) – 11.34%, agricultural knowledge and innovation system (x_8) – 9.91%, payments based on input use (x_2) – 7.88%.

Compared to Canada, the share of direct support in the structure of farmers' receipts in the USA was somewhat smaller and ranged from 7% to 9% (Fig. 6). Its highest values, observed in 2018-2021, were the result of state compensation to farmers affected by the Trump administration's trade disputes with China, Canada, Mexico, and the EU, after which a new special program for compensation of losses related to COVID-19 began (Belasco & Smith, 2022). Despite this, compared to the level of direct producer support in the EU, there was still enough space for market mechanisms to function. Analysis of structural shifts in 2010-2022 showed an increase in the share of payments based on current area, number of animals, receipts, and income requiring production (x_3) by 9.00 pp, which was about 16.60% in the *TSE* structure in 2017-2022. At the same time, the share of state support type x_1 decreased by 6.48 pp, providing only 0.45% of gross receipts of American farms in 2022. Among other direct support measures, no less important was the financing of payments based on the input use (x_2), which accounted for almost a tenth of all total support (*TSE*).

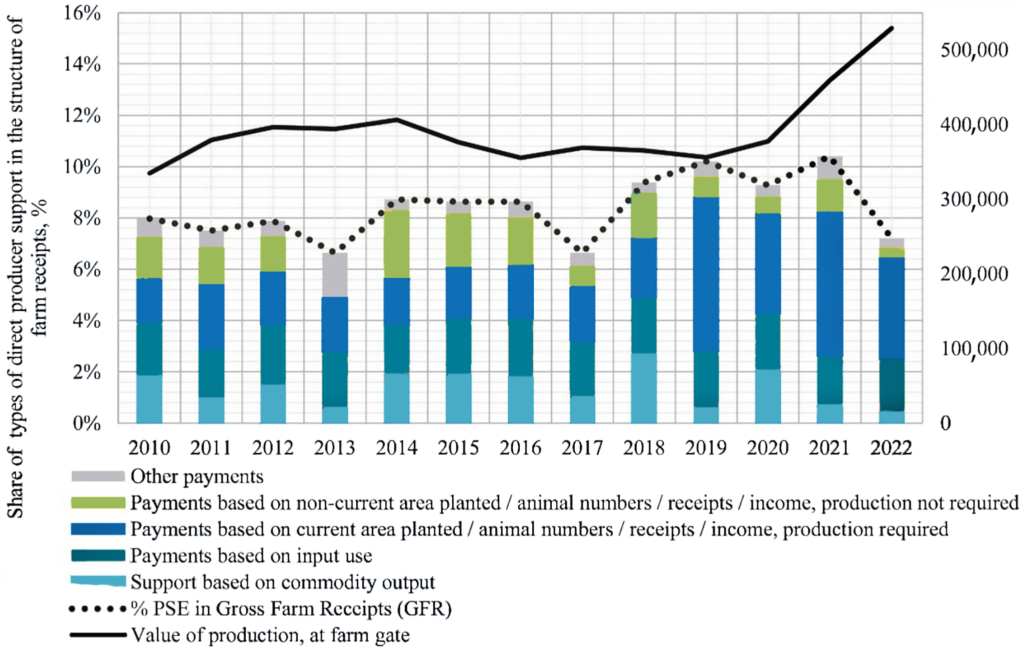

Figure 6. *The share of direct state support in the structure of gross farm receipts in the USA and the value of agricultural products in 2010-2022*
Source: *constructed by the author according to OECD (2023)*

Thus, the top 5 dominant types of state support for the agricultural sector by their average share in the *TSE* structure in the USA in 2017-2022 were consumer support (x_{14}) – 47.44%, payments based on current area planted, number of animals, receipts, income requiring production (x_3) – 16.60%, payments based on input use (x_2) – 8.84%, support based on commodity output (x_1) – 5.37%, payments based on non-current area planted, number of animals, receipts, income requiring production (x_5) – 3.94%.

An additional difference in the state support models of the EU and New Zealand was the variation in the financing of the agricultural knowledge and innovation (x_8). In the EU, despite the decrease in total support (*TSE*) on average from 118,447.07 million US dollars in 2011-2016 to 109,022.56 million US dollars in 2017-2022, the share of support for research and development, agricultural education, training and extension, on the contrary, increased from 5.72% to 6.37% in the same periods (Fig. 7). Although the volume of direct producer support dominated in the structure, accounting for almost 87.64% over the last five years, the agricultural knowledge and innovation system is most likely to play an important role in determining the development of the EU agricultural sector, even with a relatively small share, which had a linear growth trend from 2010 to 2022.

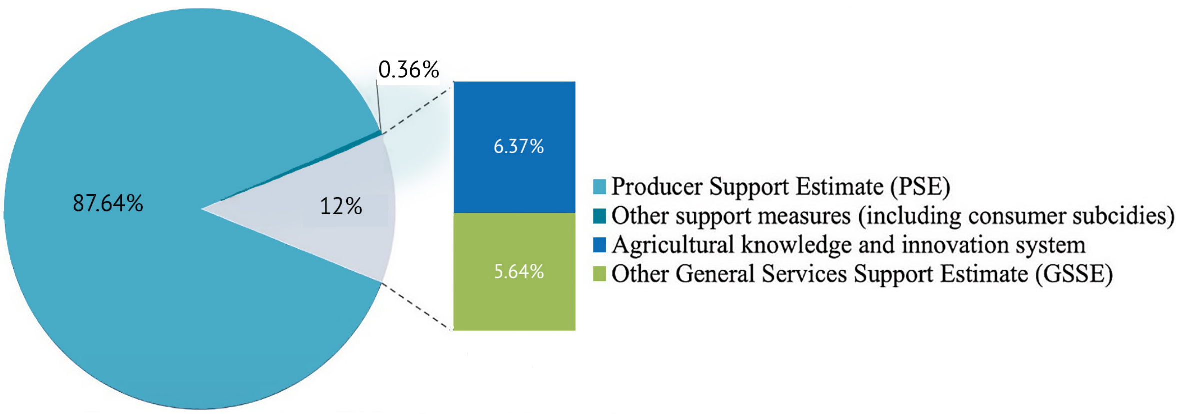

Figure 7. *The ratio of state support for producers and general services for the agrarian sector in the EU with an emphasis on financing agricultural knowledge and innovation*
Notes: *the amounts of funding for state support directions were averaged for 2017-2022 and determined in the TSE structure*
Source: *constructed by the author according to OECD (2023) data*

In Ukraine, despite a record decrease in total budget support (*TBSE*) by an average of 73.91% (from 2,082.54 million US dollars in 2011-2016 to 543.43 million US dollars in 2017-2022), the share of financing for agricultural knowledge and innovation (x_8) increased from 9.29% to 13.46% in the corresponding periods (Fig. 8). At the same time, there was an increase in the volume of financing for other general types of support for the agricultural sector (primarily inspections, pest and disease control, expenditures on veterinary and phytosanitary services (x_9)): from 9.59% to 27.20% in the same years. It indicated a slight shift in the government's focus on supporting general services for the agricultural sector (*GSSE*), as their share in 2022 increased by 21.93 pp compared to 2010.

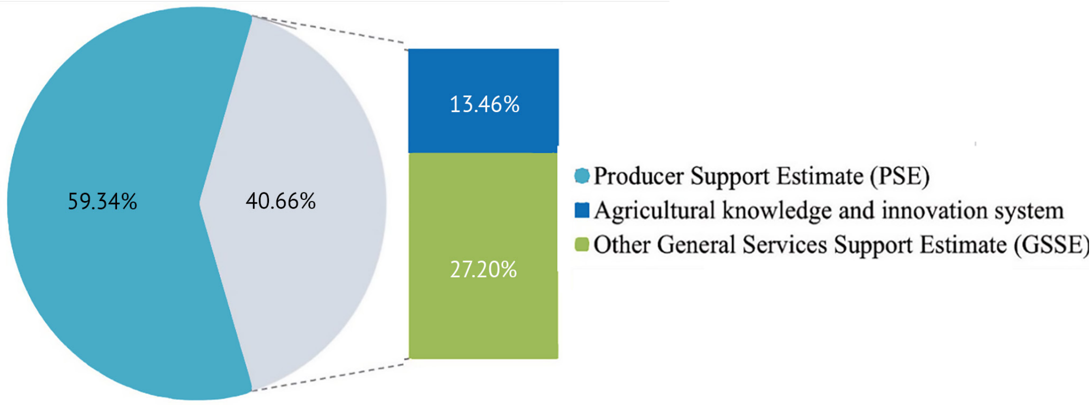

Figure 8. *The ratio of state support for producers and general services for the agrarian sector in Ukraine with an emphasis on financing agricultural knowledge and innovation*

Notes: *the amounts of funding by state support directions were averaged for 2017-2022 and determined in the structure due to the negative impact of market price support (MPS) and consumer support (CSE), which makes it impossible to correctly calculate the specific weight of types of state support in the TSE structure*

Source: *constructed by the author according to OECD (2023) data*

Thus, the model of state support in Ukraine had familiar features with the New Zealand concept in 1990-2000, which was in this period at the stage of transformation to a more balanced one, combining both short-term support for producers and supporting long-term development factors. But in addition to the fact that New Zealand did not subsidise consumers (x_{14}), another difference was that the competitiveness of Ukrainian products has not yet been able to compensate for the reduction in subsidies and other direct payments, although it should also be taken into account that the agricultural sector of Ukraine is forced to operate in much harsher conditions – against the backdrop of armed aggression. New Zealand had seen a modest increase in total support (*TSE*) in 2017-2022, at 3.15% compared to 2011-2016. However, its structure still reflected a model of agricultural support with minimal government intervention, which is aimed at creating long-term competitive advantages (productivity and quality) with an emphasis on funding knowledge and innovation rather than short-term support for producers.

The growth of *TSE* occurred primarily due to an increase in payments based on input use (x_2) and an increase in financing of other general services for the agricultural sector (in particular, control and inspection (x_9) from 39.84% in 2011-2016 to 41.19% in 2017-2022 (Fig. 9). At the same time, there was an increase in the value of agricultural production of 17.22% and reached an average of 20,859.71 million US dollars in 2017-2022. On the one hand, it does not deny the effectiveness of certain state support types, for which the amount of funding has increased. On the other hand, the increase in agricultural production could have occurred due to favourable market or foreign economic factors since New Zealand, like Ukraine, is a major agricultural product supplier to the world market, playing a crucial role in ensuring global food security.

According to the data obtained (Fig. 10), compared to New Zealand, Canada placed less emphasis on supporting agricultural knowledge and innovation (x_8) and financing general agricultural services, but they still outweighed the corresponding shares calculated for the EU. Despite the strong element of state intervention to ensure farmers' financial stability in times of crisis, compared to 2010, the share of x_8 increased by 0.69 pp in 2022, which indicated potentially larger volumes of support for the development of agricultural knowledge and innovation in the near future.

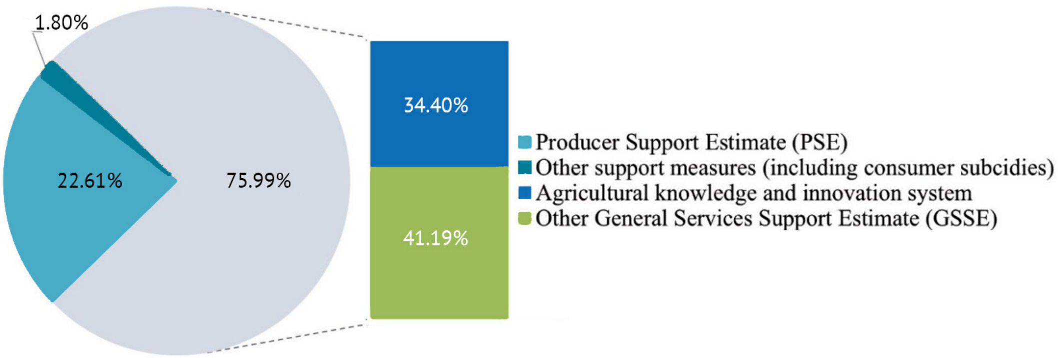

Figure 9. *The ratio of state support for producers and general services for the agrarian sector in New Zealand with an emphasis on financing agricultural knowledge and innovation*
Notes: *the amounts of funding for state support directions were averaged for 2017-2022 and determined in the TSE structure*
Source: *constructed by the author according to OECD (2023) data*

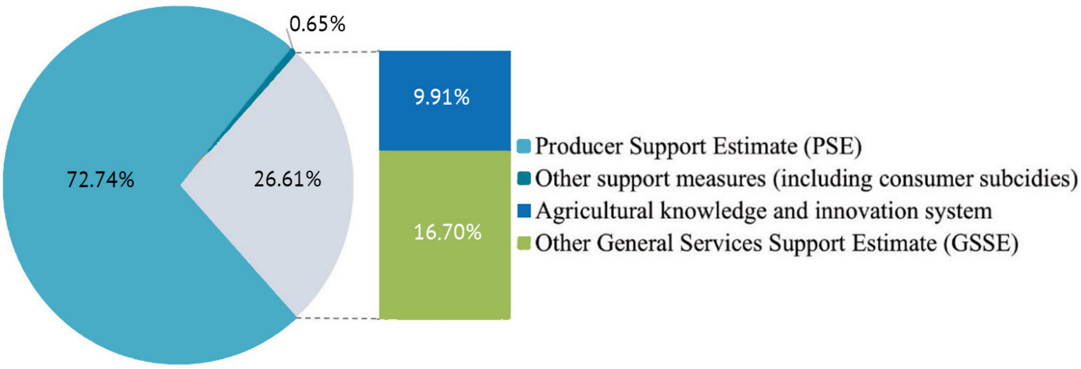

Figure 10. *The ratio of state support for producers and general services for the agrarian sector in Canada with an emphasis on financing agricultural knowledge and innovation*
Notes: *the amounts of funding for state support directions were averaged for 2017-2022 and determined in the TSE structure*
Source: *constructed by the author according to OECD (2023) data*

The model of state support for USA agriculture contrasted perhaps the most with the models of other countries according to the criterion of the share of agricultural knowledge and innovations (x_8) since its average value in 2017-2022 was not only the smallest (2.59%) but also demonstrated a gradual decrease, since in 2022 its specific weight decreased by 0.74 pp compared to 2010 (Fig. 11).

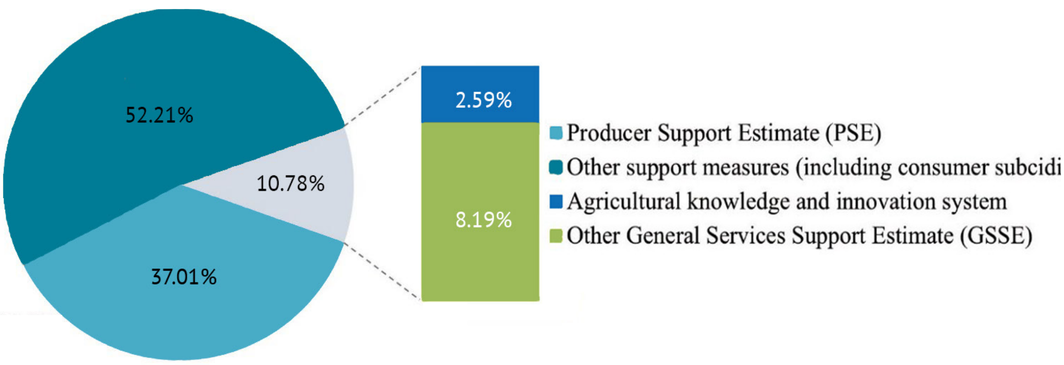

Figure 11. *The ratio of state support for producers and general services for the agrarian sector in the USA with an emphasis on financing agricultural knowledge and innovation*
Notes: *the amounts of funding for state support directions were averaged for 2017-2022 and determined in the TSE structure*
Source: *constructed by the author according to OECD (2023) data*

Against the background of a reduction in funding for general services to the agricultural sector, which was different from the practices observed in the EU, Canada, and Ukraine models, the focus of state agricultural policy in 2017-2022 in the USA was the support of effective agro-logistics and transport infrastructure (x_{10}), which reached about 4% of the volume in the financing structure. The uniqueness of the USA support model was confirmed by the replacement of direct intervention in the farmers' production process with consumer subsidies for food products. By stimulating consumer demand, the USA indirectly supports agricultural producers while distorting market competition between them less. Based on the elasticity of direct producer support, in the EU (0.89) and Canada (0.50), the reduction of *PSE* was slower than *TSE*. At the same time, in the EU, although support for farmers remained the most substantial component of the model, direct producer support accounted for the reduction of *TSE* in 2017-2022 by (-7.96%) compared to 2011-2016 (-7.11%). For these reasons, the share of other indirect types of state support was increasing, financing the agricultural knowledge and innovation system (x_8) in particular. For Ukraine, $E_{(PSE/TSE)}$ = 1.09, which, with negative increases in both indicators, indicated a greater reduction in *PSE* expenditures against the background of a general decrease in total support.

While in the USA model (0.91), the bulk of the *TSE* increase (+21.28%) was directed towards supporting the stability of producer incomes (+19.35%), for New Zealand, the consistent conclusion was the weak dependence of production support on the total: with a 1% increase in *TSE*, only 0.27% was directed in this path. Analysis of the absolute efficiency level and its change over time – the rate of budget support return (*RTBSE*) and the rates of its change (α_{1j} in univariate regression models) – demonstrated a low (*RTBSE* = 4.86), although relatively stable return on *TBSE* in the EU in 2010-2022.

In turn, the extremely high change rate for Ukraine (α_1 = 6.17) indicated a transformation of the state support model, the reduced volumes of which did not have a proportional impact on the value of agricultural products. The rate of budget support return in New Zealand was the highest (*RTBSE* = 44.43), demonstrating a gradual and stable growth rate. While the USA had the lowest agricultural output per unit of budget support, which tended to decrease (-0.10), Canada demonstrated a stable agricultural policy with a moderate rate of return, which increased similarly to New Zealand.

Thus, based on the different stages of the above analysis, it was possible to distinguish four conceptual models of state support, which were presented in Table 2. Based on the analysis of $E_{VAP/TBSE}$, Ukraine should change the strategy of state agricultural policy since the current combined model of state support was characterised by negative elasticity ($E_{VAP/TBSE}$ = -0.10). Its inefficiency lies in the fact that an increase in the volume of general budget support was accompanied by a decrease in the value of agricultural products and vice versa. Given the strong market reaction, the Canadian model, with a moderate producer priority, and the New Zealand model, with a priority for financing general services to the agricultural sector, can be a reference point for Ukraine. New Zealand had the most effective model of state support since even small amounts of funding directed to infrastructure, innovation, and quality control had a high effect on the value of agricultural products. Canada also had a high value of elasticity (1.75), which, although smaller compared to New Zealand (5.47), nevertheless indicated the effectiveness of budget support and its multiplier effect.

Table 2. *Comparison of conceptual models of state support for the agricultural sector in the EU, Canada, Ukraine, New Zealand, and the USA from the standpoint of its final beneficiaries*

Criterion/ Model/ Country	Model 1 with the priority support of direct producer support		Model 2 – hybrid/ balancing	Model 3 with the priority support of general services for the agricultural sector	Model 4 with the priority of consumer subsidies
	EU	Canada	Ukraine	New Zealand	USA
Indicators of structural and dynamic analysis of total state support (*TSE*)					
PSE Prevalence rate (KP_{PSE}) in 2017-2022	3.31	1.15	0.79	0.25	0.64
$E_{PSE/TSE}$ in 2017-2022 compared to 2011-2016	0.89	0.50	1.09	0.27	0.91
Average share of *PSE* in the GFR structure in 2010-2022	18.10%	9.93%	2.98%	0.66%	8.39%
Shift in the average share of *PSE* in the GFR structure in 2017-2022 compared to 2011-2016	-0.95%	-1.42%	-3.65%	-0.10%	0.84%
CSE Prevalence rate (KP_{CSE}) in 2017-2022	0.15	0.39	0.75	0.15	1.01

Table 2, Continued

Criterion/ Model/ Country	Model 1 with the priority support of direct producer support		Model 2 – hybrid/ balancing	Model 3 with the priority support of general services for the agricultural sector	Model 4 with the priority of consumer subsidies
	EU	Canada	Ukraine	New Zealand	USA
GSSE Prevalence rate (KP_{GSSE}) in 2017-2022	0.12	0.24	0.30	2.32	0.13
Average share* of financing for agricultural knowledge and innovation in 2010-2022	6.04%	10.55%	11.38%	35.42%	2.61%
Top 5 dominant types* of state support in 2017-2022	X_5, X_3, X_1, X_2, X_8	X_1, X_3, X_9, X_8, X_2	$X_3, X_2, X_9, X_1, X_{13}$	$X_8, X_9, X_1, X_{10}, X_2$	$X_{14}, X_3, X_2, X_1, X_5$
Indicators of preliminary assessment of the total budget support effectiveness (*TBSE*)					
The rate of budget support return (*RTBSE*) in 2010-2022	4.86	11.66	39.66	44.43	4.35
Change rate (α_1) of the	0.08	0.23	6.17	0.57	-0.10
$E_{VAP/TBSE}$ in 2017-2022 compared to 2011-2016	0.13	1.75	-0.10	5.47	0.24
Impact on the value of agricultural products	Stable gradual growth due to the support of farmers' incomes		Disproportionate fluctuations that do not depend on state support	Stable active growth due to market self-regulation and high competition	Unstable growth due to fluctuations in consumer subsidies

Notes: **for Ukraine were determined in the TBSE structure due to the negative impact of market price support (MPS) and consumer support (CSE), which makes it impossible to correctly calculate the specific weight of the state support types in the TSE structure*

Source: *compiled by the authors*

The EU state support models, which focused on producer incomes, and the USA, with an emphasis on consumer subsidies, demonstrated less effectiveness: while for every 1% increase in *TBSE*, the value of agricultural products in the EU increased by only 0.13%, in the USA the elasticity was 0.24%. The results of the correlation analysis (Table 3) demonstrated a weighty statistical relationship between the preliminary estimates of effectiveness and the state support conceptual models: high statistical significance at the 0.05 level showed that the prevalence of support for general services to the agricultural sector (*GSSE*) and investments in the agricultural knowledge and innovation system (x_8) had a strong positive relationship with the elasticity of agricultural product value. It meant that, unlike other components of the state support structure, *GSSE*, in general, and x_8 were key factors in increasing the value of agricultural products, in particular.

Table 3. *Dependence of the elasticity of agricultural output value on the state support structure: results of correlation analysis*

Variables		*PSE* Prevalence rate	Average share of *PSE* in the GFR structure	*CSE* Prevalence rate	*GSSE* Prevalence rate	Average share of financing for agricultural knowledge and innovation (X_8)	Overall level of state support imbalance (*D*)
The elasticity of agricultural output value in 2017-2022 compared to 2011-2016	Pearson Correlation	-0.47	-0.55	-0.56	0.95*	0.94*	-0.74
	Sig. (2-tailed)	0.42	0.34	0.33	0.01	0.02	0.16

Notes: **correlation was statistically significant at the 0.05 level*

Source: *designed by the author*

Despite the lack of significance of other statistical relationships, the current analysis could formulate a working hypothesis that reducing the overall imbalance between state support directions has a positive impact on its effectiveness in the context of the elasticity of agricultural product value. In further studies, this hypothesis can be tested on a sample that includes a larger number of countries. Considering the state support structure through the prism of its key beneficiaries, the EU and Canada had a common model of state support, directing most of its volumes to farmers in the form of subsidies, grants, and other mechanisms with a relatively huger focus of the Canadian scheme on general services for the agricultural sector, in particular inspections and controls (x_9) and the system of knowledge and innovations (x_8). State support concepts in New Zealand and the USA had a radically different orientation. The differences in their models made it possible to determine priority in the provision of general services to the agricultural sector and consumer subsidies, respectively.

Ukraine demonstrated a hybrid model, balancing between different state support directions. Despite the fact that the vector of the conceptual model development was not clearly defined due to state intervention in ensuring demand and food security against the background of armed aggression, the dynamics of *PSE* share in the GFR structure and the positive trend of KP_{GSSE} are likely signs of the priority of agricultural development in general in the long term. During the period of full-scale invasion and post-war reconstruction, given the significant destruction of the production capacities, housing and construction funds, and limited budgetary resources, the use of EU or USA models with significant direct financing of producers or consumers is inexpedient due to the significant burden on the state budget and its low efficiency, established on the basis of a preliminary assessment. However, during a period of full-scale invasion, the use of another extreme approach – the New Zealand model – creates significant risks to the stable functioning of the agricultural sector due to the lack of prerequisites for high productivity, developed infrastructure, and limited access to external markets.

Comparing conceptual models of state support in countries with highly developed agriculture provides a deep understanding of farming sector development strategies and the identification of the most effective approaches in different economic environments. I. Furman (2021) analysed the model of state support for agriculture in Ukraine, focusing on its distribution by budget programs, compared to the size and structure of state support in developed countries – Australia, Canada, the USA, France, and China. This approach is similar to that presented in the study, as it aimed to influence the formation of effective state policy in Ukraine based on best international practices. In the author's opinion, overcoming crisis phenomena through state support measures, which are reliable pillars for agricultural activity, strengthens food security. However, the comparison of world models in the article I. Furman (2021) was carried out without using unified criteria, focusing only on one indicator of the amount of state support per 1 ha of arable land, which, although might indicate the level of budget intervention, did not cover all the structural features of state support (indicators of structural and dynamic analysis of total state support) and did not allow for an assessment of its effectiveness (indicators of preliminary assessment of the total budget support effectiveness), which were proposed in Table 2.

Even though the assessment of the economic effectiveness of state support in the agricultural sector could be carried out using economic and mathematical modelling, in the study by V. Rusaniuk (2021), among several proposed methods, one of the efficiency criteria was the ratio of the volume of sold products to the volume of funds allocated to support agricultural production entities. This approach is logical, based on the principles of resource efficiency, with the indicator of the efficiency of used fixed assets in particular, utilised in the article by I. Umantsiv *et al*. (2021) as the ratio of the output volume in the sector to the unit cost of fixed assets. Since state support, like fixed assets, is a resource that affects the production potential of the industry, the proposed indicators in Table 2 enabled an initial assessment of the effectiveness of state support models. However, unlike V. Rusaniuk (2021), in the current study, agricultural output was calculated per unit not of direct producer support but of total budgetary support, which also considered the volume of general support – agricultural knowledge and innovations, inspections and control, infrastructure.

In addition, involving countries such as the EU, Canada, New Zealand, and the USA in the comparative analysis instead of Australia or China was more appropriate for Ukraine since their agricultural sector is export-oriented and has a high level of competitiveness in world markets, and therefore, their proven state support measures will contribute to the sustainability of the Ukrainian agricultural sector in the case of adaptation against the background of economic and climate instability. P. Yukhymenko *et al*. (2021) believed that when developing a new ideological platform for state support for the agricultural sector, the focus should be shifted from agroholding groups to small businesses. Investigating the principles of forming a model of state support for the farming sector of Ukraine in 2020 against the background of global trends, they proposed to take as a basis the priorities of the EU Common Agricultural Policy. The same idea was present in the study by S. Rogach *et al*. (2019), who having studied the experience of financial support in the EU, argued that Ukraine should take their model as a guideline since high amounts of funding ensure high results in agricultural production. Additional arguments in favour of adopting the EU concept within the framework of state policy, according to the authors, were not only Ukraine's European integration aspirations but also the effectiveness of state support measures in the context of solving social and environmental problems and intensification of the entrepreneurial activity development in rural areas. E. Erjavec *et al*. (2021), studying the process of accession of the Western Balkan countries to the EU, generally considered the possibility of providing significant state support to be an implicit prerequisite for the accession of candidate countries to the EU.

Despite the arguments presented by the authors, the current study found that the EU has the highest level of imbalance in state support areas in 2017-2022 ($D = 6.43$) due to the absolute dominance of producer support, which, as a result, turned out to be a less efficient model compared to other countries, given the increase in the value of agricultural products by only 0.13% in the case of a 1% increase in *TBSE*. For these reasons, the statement of I. Mitchell & A. Baker (2019) was justified partially, as they believed that hundreds of billions of euros spent on agricultural subsidies did not contribute to the agricultural sector development and need to be used more effectively in the context of increasing instability, negative consequences of climate change and migration.

Thus, Ukraine's adaptation of the EU model with a significant level of producer subsidies was not recommended, which correlates with the conclusion of G. Pruntseva (2020), who suggested that a substantial amount of subsidies and benefits is not a guarantee of farm profitability and achievement of key goals. Since the mechanism of direct support for producers' incomes is widely used in the EU, which Ukraine is focusing on when building its economic and political system in the context of integration, Europe relies on powerful financial capabilities that Ukraine does not have, especially in the context of a full-scale invasion.

Although the agricultural sectors of Canada and the USA are also competitive and export-oriented, and production growth occurs due to structural changes, innovations, modern technologies, and developed infrastructure, the study demonstrated significant conceptual differences in their models. Although the Canadian model prioritised funding for producers, which made it similar to the EU, it was one of the most balanced ($D = 1.95$), also supporting the development of agricultural knowledge and innovation, inspections and controls, and other general support measures, which accounted for more than 25% of the funding structure in 2017-2022. It is consistent with the position of the Canadian Chamber of Commerce (2024), which emphasised that the continued high productivity and sustainable agriculture development, which is essential for a prosperous future, is achieved through innovation and new technologies, which provide national producers with a competitive advantage in the foreign market. According to them, Canadian agriculture is a vital sector, which, thanks to its competitiveness and sustainability, generated more than 7% of GDP and employs about 2.3 million workers.

The study by M. Yeung & W.A. Kerr (2021), which focused on the study of the opportunities of Canadian agri-food exports, also argued for Canada's competitiveness and its reliability as a supplier at the international level thanks to efficient supply chains, even despite the challenges caused by the COVID-19 pandemic. The authors emphasised that the country was the fifth largest exporter and major world producer supplying more than half of agricultural products to foreign markets. The competitiveness of the Canadian model was confirmed in the current study since with a stable and high return on budget support ($RTBSE = 11.66$, $\alpha_1 = 0.23$), with a 1% increase in budget spending, the value of agricultural products increased by 1.75%, second only to New Zealand. In addition to Canada, M. Yeung & W.A. Kerr (2021) also noted the United States as a competitive exporter of agricultural products to the world market. Moreover, A. Sulaiman *et al*. (2020) ranked the USA among the top three countries with the best competitiveness in the world, the main driver of which is the level of mastery of innovations. In addition, the Department of Agriculture, Fisheries and Forestry of the Australian Government (2021) characterised the impact of the USA agricultural sector on international markets as significant, and, being a large producer and exporter, changes in its production and agricultural policies cause transformations in the farming sectors of many countries around the world. According to their materials, about 76% of the state support structure was provided for domestic food aid programs, which was the largest expenditure direction. Although the results of the study determined a slightly lower share of funding aimed at supporting consumers (on average 47.44% in 2017-2022 and over 55% in 2022), their state support model was characterised by a significant level of imbalance ($D = 4.34$) precisely due to the absolute dominance of consumer support and the gradual curtailment of support for agricultural knowledge and innovations in federal funding in 2010-2022. Demonstrating similar estimates of the effectiveness of total budgetary support to the EU ($E_{y/TBSE} = 0.24\%$), Ukraine should not take the American model of state support in general as a basis, the return of which tended to decrease in 2017-2022 compared to 2011-2016.

According to the Ministry of Agriculture and Food Sovereignty of France (2025), useful conclusions can be drawn from the agricultural policy of New Zealand, which practically stopped state intervention in agriculture and reduced direct support for producers almost 30 years ago, which made the country's experience valuable in the context of studying the consequences of eliminating state distortions and subjecting the sector development to the influence of exclusively market forces. K. Bayne & A. Renwick (2021) also called New Zealand's model of state support an example for pursuing because, despite the abolition of agricultural subsidies, the country's farming sector is competitive globally. Above all, the role of the government is to invest in scientific research and development and create an environment where innovation can flourish. In such a model, the agricultural sector is in a system of light or low intervention, providing only general state support functions and with no direct intervention in the structure of farmers' incomes (Knook *et al.*, 2022).

The study results are fully correlated with the above statements because, according to the criterion of balance, the conceptual model of New Zealand was not only the closest to the balanced point of Euclidean space ($D = 1.13$) but prioritising support of general services for the agricultural sector, it also demonstrated the greatest return on budget support ($RTBSE = 44.43$), and efficiency, since with an increase in volumes by 1%, the value of agricultural products increased by 5.47%. While C. Saunders (2019), analysing recent trends in agriculture in New Zealand and the United Kingdom, concluded that knowledge capital is particularly significant for ensuring sustainable agricultural development, increasing the sector's contribution to sustainable well-being, J. Foley (2022) still considered investment in research and development by both government and commercial organisations to been low, even though the share for agricultural knowledge and innovation was over 34% in the structure of state support in 2017-2022.

A comparison of the conceptual models of state support in the EU and New Zealand indicated the greater effectiveness of the latter: while with an average share of *PSE* in the GFR structure in 2010-2022 at the level of 0.66%, there was an active increase in the value of agricultural products in New Zealand, on the contrary, in the EU the growth was gradual, although the gross income of farmers was provided by state support by as much as 18.10%. The conclusions obtained are similar to the statement of B. Finney (2021), according to which, unlike the EU, the agricultural sector of New Zealand achieves significant results even with small amounts of state support, which does not prevent the country from being one of the world leaders in agriculture, exporting approximately 95% of agricultural products. In addition, the author suggested that the USA could use New Zealand's successful measures as a template for implementing the policy of reducing destructive amounts of financing within the framework of agricultural sector reform. Given that New Zealand is at the forefront of technological advances that allow for resource optimisation and increased production in both the livestock and horticultural sectors (Vannier *et al.*, 2022) as evidenced by the $E_{y/TBSE}$ values in 2017-2022 compared to 2011-2016, which for New Zealand were higher than in the USA (5.47% > 0.24%), the USA may indeed attempt to adapt those measures of the New Zealand model that are more efficient. W. Yang *et al.* (2020) noted that New Zealand's agriculture and dairy industries have been competitive internationally due to efficient production systems.

The state support model of Ukraine was not balanced ($D = 3.17$) since, in various turbulent periods, both producer support and consumer support were dominant for Ukraine, and there was an increase in the volume of financing for agricultural knowledge and innovations, inspections, and control, and other general types of support in 2017-2022. The study by N. Vdovenko *et al.* (2024) determined that the application of state, market, and metrological supervision is critically important for maintaining food safety and, therefore, may explain the observed increase in the specific weight of x_9 in 2017-2022. Such dynamics of the state support structure were also a likely consequence of the need to bring the quality of agricultural products closer to international standards, especially in the context of European integration. I.S. Konovalchuk & V.G. Kovalov (2023) shared the same opinion since, given Ukraine's course towards further integration into the EU, ensuring the proper quality level and safety of agricultural products and aligning the production system with European requirements is a fundamental direction for the state.

On the one hand, such a model is likely to have a positive impact on the productivity and competitiveness of the agricultural sector of Ukraine since the livestock industry of New Zealand, which is the basis of its economy, depends on the achievement of a high level of productivity to ensure international competitiveness, compliance with regulatory requirements, development and implementation of new technologies, as well as ensuring an adequate and targeted level of investment in research and development (Caradus, 2024). On the other hand, compensating for the negative impact of market risks in conditions of war, natural and climatic circumstances, and any other instability is entrusted to producers with limited financial capabilities since the Ukrainian government will only provide financing for the general development of the agricultural sector.

However, the most characteristic conceptual feature of the hybrid Ukrainian model of state support was an increase in the total budgetary support by 1%, which was accompanied by a decrease in the value of produced products by 0.10%, which cast doubt on the effectiveness of support in its current format. In the article by O.M. Ilchuk (2019), which assessed the level of state support for agricultural producers, the need to increase its volume was argued by the fact that the implementation of state programs enabled the increase of production in the industry by 64.9% in 2017 compared to 2000. The study results refuted this statement by the author since without changing the model structure or conditions, an increase in the volume of state support will not give the desired result. In addition, the estimated increase in production volumes by almost 65% due to state support alone raised certain doubts, as agriculture development is influenced by many other factors (resource, natural and climatic conditions, and market conditions in foreign demands). Given the lack of statistically confirmed relationships in the study based on econometric models that could separate the impact of state support on agricultural production volumes from other factors and quantify it, the conclusion that the volume of state support by 2017 was the driving force of agricultural production is unlikely.

Based on an identical finding about the ineffectiveness of the state support model in Ukraine in 2010-2022, the current study did not hold completely the position of I. Dinis (2023) on the need to increase state support, especially if its measures (financial assistance to farmers, preferential lending and subsidies) will remain in the existing format. Since the results indicated a negative elasticity of the value of agricultural products comparatively to the total budgetary support (*TBSE*) in Ukraine, the change in funding did not have a positive effect on the dependent variable, which called into question the effectiveness of the mechanisms as a whole. Instead, before increasing the support volume, it is more appropriate to improve its structure with a focus on innovative and market-oriented measures, which have been tested in countries with a highly developed agricultural sector and the most effective conceptual models. In addition, subsidies and grants to producers, which, according to I. Dinis (2023), increase competitiveness in Ukrainian and foreign markets and ensure the growth of production volumes, remain the subject of scientific discussions regarding the effectiveness and impact on the long-term development of the agricultural sector. D. Amaglobeli *et al.* (2024), who studied the shortcomings of producer subsidy programs, believed that subsidies for agricultural production are often financially costly and unfavourable compared to alternative uses of government funds. Their article indicated that the efficiency and competitiveness of agricultural exports was the critical goal of countries relying on subsidy mechanisms. However, given $E_{y/TBSE}$ = 0.13%, which was calculated for the EU and turned out to be less than the corresponding indicators for New Zealand, Canada, and the USA, the stated goal was only partially confirmed in the Canadian case. A similar conclusion was also present in the study by L. Petliuk & N. Miedviedkova (2021), who were analysed the state and key forms of financial support for the agricultural sector, considered the inefficiency of subsidies to be one of its problems. In their opinion, a set of shortcomings of the current system of state support should be eliminated, and only based on the results of the updated model the agricultural sector of Ukraine can develop.

N. Shyian & V. Kolosha (2020), comparing the development of the agricultural sector of Ukraine and New Zealand, concluded that although they are both large farming countries with export-oriented production, New Zealand demonstrated much more stable development. For these reasons, the article assumed that Ukraine lacks a similar economic mechanism, one of the most crucial elements of which was the policy of state support. This interpretation correlates with the statement of the current study about the chaotic and forced transformation of Ukraine's agricultural policy, which was close to the EU and Canadian model with a predominance of producer support (5.48%) in 2010-2013 but already in 2017-2022 the share of direct payments in the structure of agricultural producers' revenues was less than 1% due to Russian aggression and the redistribution of resources in favour of the national security and defence sector.

However, the lack of state support cannot be considered one of the central factors hindering the development of the Ukrainian agricultural sector, especially when compared with the New Zealand model, in which minimising state intervention, on the contrary, is a competitive advantage, not a negative feature. It was deregulation and the abolition of subsidies in the mid-1980s that stimulated increased mechanisation, investment in research and development, as well as innovation in the primary sector, which led to increased productivity (Eckhold, 2024), which should be the focus of Ukraine's agricultural sector development policy in the long term.

Nevertheless, despite the long-term benefits and the successful example of New Zealand encouraging production without subsidies, it took more than a decade for agricultural producers, who recognised that economic problems required reduced state intervention (Hall, 2021), to learn to function effectively without state support. In addition, in the case of a sharp adaptation of the New Zealand model, high competition may simultaneously eliminate Ukrainian producers with low productivity from the game, causing an economic shock. Based on the recommendations of H. Lysenko (2024) on the need to partially maintain direct producer support and restore state funding for livestock, since the full-scale invasion worsened the already critical situation, the application of the Canadian model of state support is appropriate in the short-term perspective of post-war recovery. An additional argument in favour of the feasibility of adapting the state support model is that in Canada, compared to other key industries, leading agricultural sectors occupy high positions in terms of contribution to GDP and jobs (Windfeld & Lhermie, 2022), which is quite similar to Ukraine.

However, when implementing the Canadian model of state support, it is essential to hold its inherent focus on general sector services, which are key factors in increasing the value of agricultural products, as it was confirmed by the results of the correlation analysis in Table 3. In addition, technological innovations, infrastructure, knowledge, and innovation are fundamental since they are components of the Global Competitiveness Index, which is determined by the World Economic Forum and serves as a kind of assessment of the economic security level for countries that do not calculate it (Ivanov *et al.*, 2023). In this context, the role of the government in stimulating innovation and information and communication technologies in the agri-food sector is crucial because, according to L.F. Gutiérrez Cano *et al.* (2023), it leads to increased efficiency of agricultural tools and sustainable land use.

Thus, the results of the study showed that none of the analysed countries has a fully balanced model of state support for agriculture, which indicates the global complexity of building an effective agricultural policy. Ukraine, being in a wartime and post-war economy, demonstrates a hybrid approach to state support that requires targeted optimisation. Based on the structural and dynamic analysis and comparison with the models of countries with developed agricultural sectors, the article substantiates the feasibility of applying the Canadian model as an effective short-term solution, with a gradual transition to the New Zealand approach in the long term. Such a transformation will allow Ukraine to ensure stability, innovation and competitiveness of agriculture by adapting successful international practices to the national context.

CONCLUSIONS

The study demonstrated the lack of a balanced approach and significant differences in the conceptual models of state support for agriculture in the EU, Canada, New Zealand, the USA, and Ukraine, which are formed depending on the economic conditions and priorities of each country. While the EU had the highest overall level of imbalance due to the absolute dominance of direct payments to producers, in the USA, support in the form of consumer subsidies played a dominant role with a relatively low level of financing for agricultural infrastructure and innovations. Canada had a similar model of state support to the EU with a priority for producers, but on a smaller scale, paying more attention to the development of the agricultural sector as a whole compared to the EU and the USA, which led to a high and positive value of the elasticity of the value of products depending on the level of aggregate support. New Zealand used a fundamentally different approach, focusing on ensuring the competitiveness of the agricultural sector and the highest level of self-sufficiency and autonomy of producers, minimising their dependence on state support due to the predominant financing of the agricultural knowledge system, innovations, inspections, and quality control of products. At the same time, this model demonstrated the greatest efficiency because even small amounts of financing directed to innovations, infrastructure, and quality control provided the maximum economic effect for the value of agricultural products.

According to the results of the correlation analysis, since the prevalence of support for general services to the agricultural sector and investments in the agricultural knowledge system and innovations were key factors in increasing the value of agricultural products, countries that seek to increase the competitiveness of agriculture should shift the emphasis of state support from direct support for producers or consumers towards long-term investments in infrastructure, research, and technological development. Based on the fact that, according to the results of economic and statistical analysis, Ukraine did not have a stable and balanced policy, demonstrating the inefficiency of the current hybrid model of state support, the optimal solution is the Canadian approach with moderate support for producers and an emphasis on agricultural knowledge, innovation, verification, and control or the New Zealand approach with support for general services for the farming sector.

However, it is worth considering that a complete rejection of *PSE* in the short term is risky, and, therefore, the strategy of Ukraine's agricultural policy should, for the present, combine both state intervention with the preservation of moderate direct support in order to urgently stabilise the situation in regressive areas of agricultural production, and stimulate the growth of competitiveness, in particular through investments in technological renewal, infrastructure, knowledge, and innovation, which was characteristic of the Canadian model. In turn, in the long-term post-war perspective, the use of the New Zealand conceptual model is more appropriate for Ukraine, as it demonstrated the possibilities of reducing the dependence of the agricultural sector on direct state support without a critical decrease in the value of agricultural products, which was steadily growing due to market competition. A promising direction for further scientific research is to identify not only the prevailing directions and state support types for each of the conceptual models but also those measures that have a reliable and statistically confirmed impact on the value of agricultural products based on linear multiple regression models or production functions. It will contribute to a deeper understanding of the impact of individual state support types in the EU, Canada, New Zealand, and the USA and to Ukraine's adaptation of not only proven measures but also effective measures.

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Концептуальні моделі державної підтримки сільського господарства: від безпосередньої допомоги виробникам до фінансування загальних аграрних послуг

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Анотація. Оскільки концепція державної підтримки сільського господарства України не є довершеною і вимагає вдосконалення, зважаючи на обмежені фінансові можливості країни під час повномасштабного вторгнення та повоєнного відновлення, метою статті був пошук оптимальної моделі державної підтримки, що спирається на досвід країн з високорозвиненим сільськогосподарським сектором. Особливості концептуальних моделей державної підтримки розглядались через низку показників структурно-динамічного аналізу та оцінок ефективності бюджетної підтримки в ЄС, Канаді, Новій Зеландії, США та Україні. Передумовою дослідження став аналіз загального рівня дисбалансу напрямків державної підтримки сільського господарства, за результатами розрахунку якого жодна з країн не мала збалансованого підходу до регулювання агросектору. Встановлено, що причиною найбільших рівнів дисбалансу в ЄС було беззаперечне домінування прямої підтримки виробників, а в США – підтримки споживачів одночасно з низькою пріоритетністю розвитку сільськогосподарських знань та інновацій в обох країнах. Для України характерною виявилась гібридна модель державної підтримки, оскільки у різні періоди турбулентності переважали різні її напрямки. З огляду на оцінку ефективності концептуальних моделей Україні у короткостроковій перспективі необхідно використовувати канадську модель, що, хоч і подібна до ЄС, але у значно менших масштабах підтримує фермерів, і має відносно більший фокус на загальних послугах для агросектору, зокрема перевірках та контролю і аграрних знаннях та інноваціях. Встановлено, що у довгостроковій перспективі пріоритетною є адаптація новозеландського підходу з абсолютним домінуванням інвестицій в інфраструктуру, науково-дослідницьку діяльність та технологічний розвиток, що забезпечує максимальний економічний ефект та конкурентоспроможність галузі. Отримані результати дослідження можуть бути використані органами державної влади України, зокрема Міністерством аграрної політики та продовольства, для вдосконалення програм державної підтримки сільського господарства шляхом адаптації ефективних моделей фінансування, що базуються на міжнародному досвіді та враховують економічні й ресурсні реалії країни

Ключові слова: агросектор; Україна; рівень дисбалансу державної підтримки; ефективність; вартість сільськогосподарської продукції; аграрні знання та інновації; Нова Зеландія

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Response of maize hybrids to irrigation methods and primary tillage in the Ukrainian Steppe

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Abstract. The aim of the study was to determine the response of maize hybrids to drip irrigation compared to traditional sprinkler irrigation under conventional plowing (30-32 cm) and deep tillage (35-37 cm) as the primary soil cultivation methods. The article presents the results of evaluating the effectiveness of drip irrigation and sprinkler irrigation, as well as the impact of deep non-inversion tillage versus classical plowing on maize yield across different FAO maturity groups in the Ukrainian Steppe. The research was conducted in an irrigated crop rotation on southern solonetsic chernozem soils with a humus content of 2.9-3.2% and a pH of 6.2. The preceding crop was sunflower. The total water application rate during the growing season was 4,000 m^3/ha. The study included 11 hybrids with FAO numbers ranging from 210 to 370. A low yield variation (CV = 12.7-13.4%) indicates a uniform response of the studied hybrids to changes in growing conditions. Maize yield significantly increased under drip irrigation by +0.75 to +2.13 t/ha (+7.5 to +18.3%). Deep tillage provided a notable yield increase of +0.46 t/ha under sprinkler irrigation and +0.70 t/ha under drip irrigation. The hybrids VN 63 (FAO 280) showed a strong positive response to deep tillage (+1.0 to +1.35 t/ha), as did Gran 6 (FAO 300) with +0.87 to +1.23 t/ha, Tesla (FAO 350) with +0.66 to +0.99 t/ha, and Gran 1 (FAO 370) with +0.89 to +1.12 t/ha under both irrigation methods. The study established that hybrids with FAO less than 280 are not suitable for cultivation in the Southern Steppe due to lower grain yield. Among the FAO 200-300 group, VN 63 and Gran 6 achieved significant yield increases of +0.5 to +2.5 t/ha, with yields of 10.93 and 11.99 t/ha, respectively. In the FAO 320-400 group, Tesla and Gran 1 demonstrated substantial yield gains of +0.61 to +2.08 t/ha, with average yields of 14.06 and 13.92 t/ha, respectively. The highest grain yields of 15.57 and 15.49 t/ha were achieved by the Tesla (FAO 350) and Gran 1 (FAO 370) hybrids under deep tillage combined with drip irrigation, significantly ($>CI_{0.99}$) outperforming the standard. The analysis indicates the high effectiveness of drip irrigation and deep tillage in enhancing maize yields in the Southern Ukrainian Steppet

Keywords: yield; drip irrigation; sprinkler irrigation; plowing; soil loosening

INTRODUCTION

Agricultural production in the arid conditions of the Steppe requires the use of advanced technologies for soil tillage, sowing, crop protection against diseases and pests, and the introduction of new high-yielding varieties and hybrids with a complex of economically valuable traits. Maize is one of the oldest crops and plays a significant role in Ukraine's economy. It provides livestock with concentrated feed, silage, and green mass. Maize grain contains carbohydrates (about 70%), oil (up to 8%), protein (9-12%), and amino acids. In terms of feed value, it equals 1.34 feed units and is an important ingredient in the food and processing industries as well

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as in livestock fattening (Polishchuk & Khavhun, 2023). Given its value in feed and food chains and its positive economic effect, maize is one of the essential crops in irrigated crop rotations. However, the expansion of Ukrainian maize hybrids to larger areas across diverse soil and climatic conditions is limited by a lack of information regarding their response to different primary tillage methods and the potential of various irrigation types. This issue has not received adequate attention in recent publications.

The effectiveness of irrigation has been studied by both Ukrainian and foreign researchers. Noteworthy contributions have been made by scientists from the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine (IIA NAAS) and Kherson State Agrarian University (KhSAU). Their studies focused on the cultivation efficiency of maize hybrids under drip and sprinkler irrigation with various plant protection regimes, and they examined the influence of irrigation methods and plant density on the seed productivity of maize parental lines. Research in Ukraine's Steppe zone has shown that drip irrigation is more efficient than traditional sprinkler irrigation, especially for medium-late hybrids, where yield increases of 1.02-2.35 t/ha were recorded (Ivaniv & Repilevsky, 2021). As noted by A.P. Shatkovskyi *et al*. (2021), irrigation methods are a key factor in intensifying grain production and implementing environmentally safe, energy- and resource-saving technologies. Classical drip irrigation can ensure maize yields of up to 20.69 t/ha. Studies from around the world confirm the advantages of drip irrigation compared to other methods of supplying water to crops (Shatkovskyi *et al.*, 2020). In Israel, maize yield increased by 72% under drip irrigation (up to 25 t/ha), and in Ukraine, by 60% (up to 16 t/ha). In the USA, 2023 harvest data showed a new world record maize yield of 39.14 t/ha, although on a limited area (~4.9 ha) under no-till and drip irrigation technology (Gusarova, 2023).

Cost reduction in cultivation technology is also possible through energy-saving soil tillage methods (Yeshchenko *et al.*, 2014). Modern tillage systems such as Mini-till, Strip-till, and No-till, as well as mulching, help reduce moisture evaporation from the soil surface and decrease energy costs. Combining new technologies with irrigation, balanced fertilisation, and plant protection enables full realisation of the genetic potential of new hybrids (A new world record…, 2024). Research by R. Vozhegova *et al*. (2022) demonstrated that shallow surface tillage does not provide economically viable high maize yields, particularly in dry Steppe regions. Deep non-inversion tillage offers advantages, reducing energy consumption by 20-22% and increasing maize yields in Ukraine's Steppe (Tomashuk, 2019). Yields of up to 11-12 t/ha were recorded with non-inversion tillage. According to M. Marenych & K. Koba (2024), maize parental line yields are influenced primarily by genetic factors (54%) and tillage methods (41%). Thus, improving maize cultivation technologies is a crucial factor in ensuring global food security.

Therefore, the study of the response of maize hybrids of various genetic origins under drip irrigation in the arid conditions of the Southern Steppe, combined with different primary tillage methods, is highly relevant for optimising cultivation technologies and realising the genetic potential of hybrids of different maturity groups. The aim of this study was to determine the specific yield response of Ukrainian-bred maize hybrids of various maturity groups under drip and sprinkler irrigation with different soil tillage methods. The objective was to assess the impact of irrigation method and primary tillage type on the grain yield of maize hybrids.

MATERIALS AND METHODS

Experimental conditions. The experiment was conducted in southern Ukraine at the farm "Matros" (Private Farm Enterprise) in Novotroitske District, Kherson Region, under irrigated conditions during 2019-2020. The soil type was southern solonetsic chernozem of heavy texture, with a humus content of 2.9-3.2% and pH of 6.2. Drip irrigation was applied using tape with emitters spaced 20 cm apart and row spacing of 140 cm. A total of 14 irrigation events were performed under the drip method, and 7 events using sprinkler irrigation with a "Fregat" system. In both cases, the total irrigation water applied during the growing season was 4,000 m^3/ha. Precipitation during the maize growing season (April 1 to August 31) was 134.6 mm in 2019 and 195.8 mm in 2020 (Meteopost, 2025). According to literature, maize total water consumption depends on the irrigation regime and ranges from 3,250 to 4,762 m^3/ha. Under ideal conditions (optimal soil moisture), the maximum consumption reaches 4,762-5,525 m^3/ha (Shatkovskyi *et al.*, 2021). These values justified the irrigation rate, considering long-term average rainfall in the region (Meteopost, 2025). Fertilisation included pre-plant application of 100 kg/ha ammonium sulfate and 150 kg/ha nitroammophoska. In January-February, urea was applied at a rate of 250 kg/ha during the winter fertilisation window for winter crops (under minimal snow cover). The total nutrient input per hectare in active ingredient terms was $N_{160}P_{24}K_{24}S_{24}$ and was kept consistent across all years and treatments. Weed control was performed using the post-emergence herbicide MaisTer (0.15 kg/ha) with Biopower (1.5 L/ha) at the 5-leaf stage. Foliar feeding was applied at the 6-leaf and 8-leaf stages using nitrogen in the form of urea (N5 + N5), insecticide, zinc, magnesium, and potassium humate – applied uniformly across all experimental treatments.

Experimental design and research objects. The study evaluated maize hybrids with FAO maturity indices ranging from 210 to 370. The following hybrids were studied: Gran 220 (FAO 210), Gran 310 (FAO 250), VN 63 (FAO 280), Gran 6 (FAO 300), VN 6763 (FAO 320), Amarok 290 (FAO 320), Amarok 300 (FAO 320), Tesla (FAO 350), and Gran 1 (FAO 370). For the FAO 200-300 group, the standard control hybrid was DKC 3795 (FAO 250); for the FAO 320-400 group, it was KWS 381 (FAO 350). Seeding rates were 90,000 seeds/ha for hybrids in the FAO 200-300 group and 80,000 seeds/ha for those in the FAO 320-370 group. Seeding rates were based on prior experimental data from the region under irrigation. The preceding crop was sunflower. Each plot area was 0.224 ha. The experiment included three replications, and plots were arranged in a randomized complete block design. The sowing pattern for hybrids remained identical across years, tillage types, and irrigation methods. Two types of primary tillage were tested: conventional moldboard plowing to a depth of 30-32 cm and deep chiseling with a disk-chisel harrow to a depth of 35-37 cm. Sowing was performed in the first ten days of April, when soil temperatures exceeded +11°C. Harvesting was carried out using a Claas Tucano 470 combine equipped with a maize header. Yield was determined using the weigh method and adjusted to 14% grain moisture. Statistical analysis was performed using two-factor analysis of variance (ANOVA) according to V.O. Ushkarenko *et al.* (2013). Factor A included irrigation methods and primary tillage type, while Factor B represented the maize hybrids of various maturity groups.

RESULTS AND DISCUSSION

The results of the study revealed the response of maize hybrids of various maturity groups to different irrigation methods and primary tillage practices. Two-factor ANOVA was conducted for each year and for each combination of irrigation method and tillage type. Additional analyses were performed by isolating irrigation method as factor A and tillage method as factor A, with maize hybrids as factor B in each case. The calculated data were consistent across the different statistical approaches. The statistical results of the two-factor experiment are presented in Table 1. According to the results, there was only slight variation in grain yield across the years and treatments among the studied maize hybrids (CV = 12.7-13.4%). This indicates a uniform response of the hybrids to changes in growing conditions and highlights the strong direct influence of the studied factors – irrigation method and tillage system on grain yield.

Hybrids Gran 220 (FAO 210) and Gran 310 (FAO 250) consistently produced significantly lower grain yields ($<CI_{0.99}$) than the standard hybrid DKC 3795 (FAO 250) for the FAO 200-300 maturity group across all treatments in both years. The difference ranged from −0.20 to −1.38 t/ha, or −8% to −14%. Similar trends were observed in the FAO 320-400 group, where Amarok 290 (FAO 320) and Amarok 300 (FAO 320) mostly showed significantly lower yields ($<CI_{0.95}$) than the standard hybrid KWS 381 (FAO 350), regardless of irrigation method or tillage type. In absolute values, this difference ranged from −0.22 to −0.86 t/ha, or −2% to −7% compared to the standard. Therefore, the cultivation of Gran 220, Gran 310, and Amarok 290 hybrids under irrigation in southern Ukraine is not advisable, as they do not provide yield advantages over the standard hybrids and are not economically viable under these soil and climatic conditions.

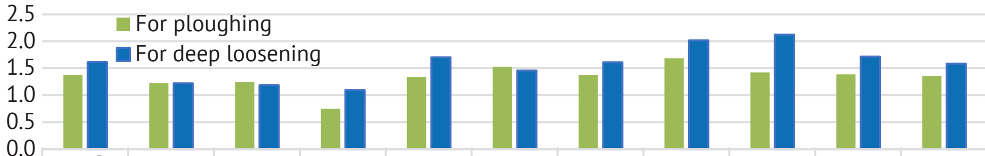
An exception was observed for Amarok 300 (FAO 320) under drip irrigation combined with deep tillage, where a significant yield increase ($>CI_{0.99}$) was recorded: +0.56 t/ha (+4.0%) in 2019 and +0.49 t/ha (+3.6%) in 2020 compared to the standard. Thus, Amarok 300 can be considered suitable for cultivation in the Steppe zone under drip irrigation with deep soil loosening as the primary tillage method. Other combinations involving Amarok 300 were not effective in increasing yield and are not recommended for production. All other tested hybrids consistently outperformed the standard hybrids of their respective maturity groups across all treatments over the two-year period. Therefore, hybrids VN 63, Gran 6, VN 6763, Tesla, and Gran 1 demonstrated significantly higher grain yields compared to the standards and are well-suited for cultivation under irrigation in the Steppe zone of southern Ukraine. Detailed results by irrigation method and tillage system are presented in Table 1 and illustrated graphically in Figures 1 and 2.

In 2019, under deep moldboard plowing, drip irrigation resulted in an increase in maize hybrid yields compared to sprinkler irrigation by +1.18 to +2.03 t/ha, which represented a yield gain of +11.9% to +18.0%. In 2020, the yield increase ranged from +0.32 to +1.53 t/ha (+3.2% to +13.4%). Under deep chiseling, the yield increase in 2019 due to drip irrigation was even greater-ranging from +1.32 to +2.46 t/ha (+14.5% to +21.7%). In 2020, the increase was between +0.66 and +1.91 t/ha (+5.9% to +16.5%). These results indicate a clear and positive response of the studied maize hybrids to the method of irrigation and demonstrate the significantly higher efficiency of drip irrigation compared to sprinkler irrigation using the "Fregat" system. The average yield increase over the two-year period (2019-2020) is presented graphically in Figure 1.

Table 1. *Results of the analysis of variance (ANOVA) for grain yield of maize hybrids of different maturity groups under drip and sprinkler irrigation with various primary tillage methods, 2019-2020*

Irrigation method (Factor A)	Hybrid, experimental variant (Factor B)	Hybrid maturity group (FAO)	2019 p. ploughing: Average for hybrid (variant), x̄, t/ha	2019 p. ploughing: Variance by factor A	2019 p. ploughing: Variance by factor B	2019 p. loosening: Average for hybrid (variant), x̄, t/ha	2019 p. loosening: Variance by factor A	2019 p. loosening: Variance by factor B	2020 p. ploughing: Average for hybrid (variant), x̄, t/ha	2020 p. ploughing: Variance by factor A	2020 p. ploughing: Variance by factor B	2020 p. loosening: Average for hybrid (variant), x̄, t/ha A	2020 p. loosening: Variance by factor	2020 p. loosening: Variance by factor B
Sprinkler machine type "Fregat"	DKC 3795 (st.)	250	9.63			9.33			9.68			9.96		
	Gran 220	210	9.16		-0.47	9.13		-0.20	8.58		-1.11	9.09		-0.87
	Gran 310	250	8.34		-1.29	8.55		-0.78	8.74		-0.95	9.31		-0.65
	VN 63	280	9.88		0.25	10.75		1.42	10.05		0.66	11.20		1.23
	Gran 6	300	11.03		1.40	11.86		2.53	10.55		1.17	11.45		1.49
	KWS 381 (st.)	350	11.74			11.36			11.59			12.16		
	VN 6763	320	11.92		0.18	11.73		0.37	11.43		-0.16	12.51		0.35
	Amarok 290	320	11.13		-0.61	10.90		-0.46	10.87		-0.72	11.48		-0.68
	Amarok 300	320	11.27		-0.47	11.65		0.29	11.37		-0.22	11.58		-0.58
	Tesla	350	12.80		1.06	13.50		2.14	13.10		1.52	13.73		1.57
	Gran 1	370	12.81		1.07	13.75		2.39	12.67		1.08	13.50		1.34
Drip irrigation	DKC 3795 (st.)	250	11.09	1.46		11.37	2.04		10.98	1.29		11.16	1.19	
	Gran 220	210	10.62	1.46	-0.48	10.46	1.32	-0.91	9.57	0.99	-1.28	10.21	1.12	-0.95
	Gran 310	250	9.71	1.37	-1.38	10.22	1.67	-1.15	9.85	1.11	-0.75	10.01	0.70	-1.14
	VN 63	280	11.06	1.18	-0.03	12.29	1.54	0.92	10.37	0.32	0.06	11.85	0.66	0.70
	Gran 6	300	12.29	1.26	1.20	13.51	1.65	2.14	11.96	1.42	1.65	13.21	1.76	2.06
	KWS 381 (st.)	350	13.34	1.60		13.43	2.07		13.05	1.46		13.01	0.85	
	VN 6763	320	13.14	1.22	-0.19	13.92	2.19	0.49	12.97	1.53	0.08	13.54	1.03	0.53
	Amarok 290	320	13.08	1.95	-0.25	13.36	2.46	-0.07	12.30	1.42	-0.76	13.06	1.58	0.06
	Amarok 300	320	13.30	2.03	-0.04	13.99	2.34	0.56	12.19	0.82	-0.86	13.49	1.91	0.49
	Tesla	350	14.65	1.84	1.31	15.57	2.08	2.14	14.03	0.93	1.39	15.09	1.36	2.08
	Gran 1	370	14.53	1.72	1.19	15.49	1.75	2.06	13.66	0.99	1.19	14.93	1.43	1.92
$CI_{0.95}$ by factors				**0.36**	**0.43**		**0.15**	**0.18**		**0.21**	**0.25**		**0.25**	**0.30**
$CI_{0.99}$ by factors				**0.84**	**0.61**		**0.35**	**0.26**		**0.48**	**0.35**		**0.57**	**0.42**
$CI_{0.95}$ search				**0.55**			**0.23**			**0.24**			**0.26**	
$CI_{0.99}$ search				**0.73**			**0.31**			**0.32**			**0.48**	
CV,%				**13.34**			**13.41**			**12.71**			**13.39**	
T, %				**98.36**			**99.31**			**99.26**			**98.91**	

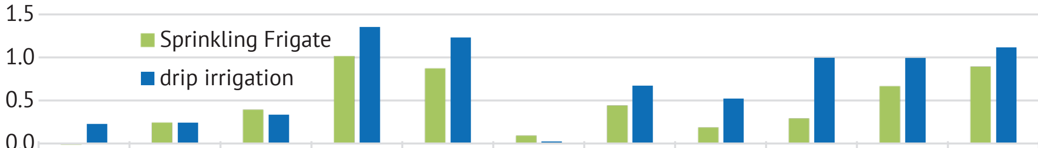
Source: *compiled by the author*



DKS 3795 (st.)	Gran 220	Gran 310	VN 63	Gran 6	KWS 381 (st.)	VN 6763	Amarok 290	Amarok 300	Tesla	Gran 1
1.38	1.22	1.24	0.75	1.34	1.53	1.38	1.69	1.42	1.39	1.36
1.62	1.22	1.19	1.10	1.70	1.46	1.61	2.02	2.13	1.72	1.59

Figure 1. *Two-year average grain yield increase of maize under drip irrigation compared to sprinkler irrigation by hybrid and primary tillage method, t/ha, 2019-2020*

Source: *compiled by the author*



DKS 3795 (st.)	Gran 220	Gran 310	VN 63	Gran 6	KWS 381 (st.)	VN 6763	Amarok 290	Amarok 300	Tesla	Gran 1
-0.01	0.24	0.39	1.01	0.87	0.09	0.44	0.19	0.29	0.66	0.89
0.23	0.24	0.34	1.35	1.23	0.02	0.67	0.52	1.00	0.99	1.12

Figure 2. *Two-year average grain yield increase of maize under deep non-inversion tillage compared to conventional plowing by hybrid and irrigation method, t/ha, 2019-2020*

Source: *compiled by the author*

Yield increases in absolute terms were generally higher in 2019 compared to the following year, which can be attributed to extreme temperature conditions during the 2020 growing season. Among the FAO 200-300 maturity group, the highest two-year average yield increases under drip irrigation were recorded for the hybrids Gran 6 and DKC 3795 (st.), regardless of the type of primary tillage – both exceeding +1.3 t/ha (+11.1%). Other hybrids in this group also showed average yield increases above +1.0 t/ha under drip irrigation. Early-maturing hybrids Gran 220 and Gran 310 responded positively to drip irrigation, with yield increases above +1.2 t/ha. However, these were the lowest among all studied hybrids, due to their generally lower yield potential compared to the standard and other maturity groups.

The average two-year yield increase under drip irrigation with conventional plowing exceeded +0.75 t/ha across all hybrids, while with deep loosening it was more than +1.1 t/ha. Under plowing, the most effective response to drip irrigation was observed in Amarok 290 ($\bar{x}$ = +1.69 t/ha), Tesla ($\bar{x}$ = +1.39 t/ha), and the standard hybrid KWS 381 ($\bar{x}$ = +1.53 t/ha). Under deep non-inversion tillage, a yield increase greater than +1.50 t/ha under drip irrigation was recorded for the hybrids DKC 3795 (st.), Gran 6, VN 6763, Amarok 290, Amarok 300, Tesla, and Gran 1. The overall average yield increase of maize grain under drip irrigation (regardless of hybrid) compared to sprinkler irrigation was +1.34 t/ha under plowing and +1.58 t/ha under deep loosening.

Thus, the results of the experiment confirm findings from the literature regarding the superior effectiveness of drip irrigation over conventional sprinkler irrigation for grain maize production (Marchenko *et al.*, 2023), regardless of hybrid maturity group or primary tillage method. While the response of the studied maize hybrids to different tillage types was differentiated, a general trend of significantly higher grain yields under deep non-inversion tillage compared to conventional plowing was observed across all irrigation methods. This trend is illustrated in Figure 2.

The hybrids DKC 3795 (st.) and KWS 381 (st.), used as standards for their respective FAO maturity groups, showed no significant response to deep non-inversion tillage compared to conventional plowing, regardless of the irrigation method. This conclusion is supported by the results of the variance analysis (Table 1, Fig. 2). Short-season hybrids Gran 220 and Gran 310 demonstrated a consistent and significant ($\geq CI_{0.95}$) increase in grain yield under deep loosening across both irrigation methods, with yield gains of +0.24 t/ha (2.7%) and +0.39 t/ha (4.6%), respectively. A highly significant increase in grain yield ($>CI_{0.99}=0.60$) under deep non-inversion tillage was observed in VN 63 (+1.01 t/ha, 10.1%), Gran 6 (+0.87 t/ha, 8.1%), Tesla (+0.66 t/ha, 5.1%), and Gran 1 (+0.89 t/ha, 7.0%) under sprinkler irrigation. Under drip irrigation, the respective increases were +1.35 t/ha (12.6%), +1.23 t/ha (10.0%), +0.99 t/ha (6.9%), and +0.30 t/ha (7.9%) ($CI_{0.99}$ = 0.46). The most pronounced positive response to deep non-inversion tillage – exceeding +1.0 t/ha compared to plowing – was recorded under drip irrigation for hybrids VN 63, Gran 6, Amarok 300, Tesla, and Gran 1.

The average grain yield increase across all hybrids due to deep loosening, regardless of genotype, was statistically significant ($CI_{0.99}$ = 0.45): +0.46 t/ha under sprinkler irrigation and +0.70 t/ha under drip irrigation. These findings confirm the effectiveness of deep non-inversion tillage compared to conventional plowing, as also reported by other researchers such as Yu.M. Pashchenko (2009), O. Tomashuk (2019) and R.A. Vozhegova *et al*. (2022). Grain maize cultivation requires significant energy and economic inputs, especially in the Steppe zone, where additional investments in irrigation are essential. In this study, the highest average grain yields over two years were achieved by hybrids Gran 1 (15.21 t/ha) and Tesla (15.33 t/ha) under drip irrigation combined with deep non-inversion tillage. These results align with the findings of O. Averchev *et al*. (2020), who reported that Ukrainian-bred maize hybrids can produce yields of up to 14-15 t/ha under irrigation in southern Ukraine, although their response to irrigation technologies has not been sufficiently studied. Hybrids Gran 1 and Tesla consistently and significantly ($>CI_{0.99}$) outperformed the standard hybrid of their FAO group (320-370) in terms of grain yield, regardless of irrigation method or tillage system.

The full realisation of maize yield potential is possible through the integration of optimal technologies and growing conditions, including soil tillage methods, mineral nutrition, sowing time and technique, pest and disease control systems, and consistent moisture availability throughout the growing season (Marchenko *et al.*, 2020). In light of changing climatic and weather conditions over the past 12-15 years, the main limiting factor for grain maize cultivation in Ukraine has become the unfavorable soil water regime, as emphasised by M. Tkachenko & N. Borys (2018). Due to its large vegetative biomass, maize has a significantly higher total water demand than small grain cereals, although it utilizes available soil moisture more efficiently than most crops. The dry Steppe zone of Ukraine is characterised by high temperatures during the growing season and the accumulation of high sums of active temperatures (above 3,000°C), which allows for the successful cultivation of high-FAO hybrids with greater yield potential. However, limited rainfall (100-200 mm) and its uneven distribution – particularly during critical phases such as flowering and grain filling – present substantial challenges. Economically viable maize cultivation in such regions is only possible with artificial irrigation. In areas with insufficient and unstable moisture availability, irrigation enables sowing at optimal soil temperature conditions, regardless of natural topsoil moisture, which positively affects seedling emergence and crop uniformity. One of the major advantages of artificial irrigation is the possibility of applying pre-sowing moisture-charging irrigations when needed, ensuring consistently high yields of the main product.

Given that soil moisture is the primary limiting factor for crop development, and precipitation during the growing season is highly unpredictable, while irrigation is a controllable agronomic input, the conditions in the Steppe zone favor high-yield maize production primarily on artificially irrigated lands. Sprinkler irrigation is the traditional method used in southern Ukraine. It enables regulation of moisture in the topsoil from spring pre-sowing preparation to the crop's physiological maturity stage (Krutyakova *et al.*, 2021). However, the cost of production significantly increases due to the additional expenses associated with irrigation – specifically, the price and transport of water to the field. In cultivating any agricultural crop, including grain maize, it is essential to consider factors influencing production efficiency – particularly yield level and technological costs. S.M. Dolya (2024) emphasises that the intensification of mechanised tillage is one of the drivers of increased fossil energy use, enhanced soil erosion, loss of organic carbon, and broader climate change.

Additional water losses must also be considered: evaporation during water transport through open canals, evaporation during sprinkler irrigation, and further evaporation from inter-row spaces -all of which negatively impact the economic efficiency of grain yield. This issue can be addressed through the use of drip irrigation, a resource-efficient method of water delivery, as supported by the studies of N.M. Galchenko *et al*. (2022). Grain maize production remains one of the key directions in Ukraine's agricultural sector. The trends in maize production at both national and global levels demonstrate the relevance of further research into cultivation methods aimed at increasing grain yield. For example, Ukraine's total maize grain production increased from 21.03 million tons in 2012/13 to 41.79 million tons in the 2021/22 marketing years, with the crop accounting for up to 16.1% of the total sown area (Polishchuk & Khavhun, 2023).

Breeding efforts by research institutions are currently focused on developing new heat-and drought-tolerant parental lines and hybrids to ensure stable grain maize production. According to literature sources, maize yields in various regions of the world are as follows: approximately 12.1 t/ha in Chile, 11.73 t/ha in New Zealand and Spain, 10.68 t/ha in Greece, 10.53 t/ha in the United States, 10.42 t/ha in Austria, and 9.99 t/ha in Italy (Kernasiuk, 2021). In Ukraine, the average yield of maize varies from 5.5 to 7.8 t/ha, depending on annual weather conditions (State Statistic Service of Ukraine, 2022). Currently, various irrigation technologies are in use, including sprinkler machines, drip irrigation, subsoil irrigation, furrow irrigation, and basin (check) irrigation. According to the Israeli company Netafim (Corn on drip irrigation…, 2022), maize grown under drip irrigation emits 53% less carbon compared to flood irrigation and 39% less compared to sprinkler irrigation. This highlights a major environmental advantage of drip irrigation. The novelty of the present study lies in the investigation of the yield response of Ukrainian-bred maize hybrids of various maturity groups to different irrigation methods combined with contrasting primary soil tillage systems under the arid conditions of the Ukrainian Steppe.

CONCLUSIONS

The experiment confirmed the high effectiveness and clear advantage of controlled drip irrigation over traditional sprinkler irrigation for all FAO maturity groups of the studied maize hybrids. Drip irrigation provided a statistically significant ($\geqslant CI_{0.95}$) grain yield increase ranging from 0.75 to 2.13 t/ha, equivalent to 7.5-18.3% compared to sprinkler irrigation. The use of deep non-inversion tillage as the primary soil cultivation method resulted in a significant grain yield increase compared to conventional plowing: an average of +0.46 t/ha under sprinkler irrigation and +0.70 t/ha under drip irrigation across the studied hybrids.

The highest grain yields in the experiment were achieved by the hybrids Gran 1 (FAO 370) and Tesla (FAO 350), with yields of 15.21 t/ha and 15.33 t/ha, respectively, under drip irrigation combined with deep loosening. These hybrids consistently and significantly ($>CI_{0.99}$) outperformed the standard across all treatment combinations. It is not advisable to cultivate maize hybrids with FAO values below 280 under irrigation in the Steppe region due to their insufficient yield potential compared to later-maturing hybrids. Based on yield performance under the given soil and climate conditions in southern Ukraine, the most suitable hybrids for irrigated crop rotations were Tesla (FAO 350) and Gran 1 (FAO 370), both exceeding 15 t/ha, as well as KWS 381 (FAO 350), which yielded more than 13 t/ha under drip irrigation.

The findings confirm the technical and economic feasibility of using drip irrigation and deep tillage as key elements of an efficient maize cultivation technology. A logical next step in optimising the system would be to investigate the effect of different seasonal irrigation rates on yield and economic efficiency. It is also recommended to expand research to include maize hybrids with FAO more than 400 under similar conditions.

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CONFLICT OF INTEREST

None.

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Реакція гібридів кукурудзи на способи зрошення та основного обробітку ґрунту в Степу України

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Анотація. Метою досліду було встановити реакцію гібридів на краплинне зрошення порівняно з традиційним поливом методом дощування на фоні оранки (30-32 см) та глибокого розпушування (35-37 см), як основного обробітку ґрунту. У статті наведено результати вивчення ефективності краплинного зрошення та поливу дощуванням і вплив глибокого безвідвального розпушування ґрунту поряд з класичною оранкою на урожайність кукурудзи різних груп ФАО в Степу України. Дослідження проведено в зрошуваній сівозміні на чорноземах південних солонцюватих з вмістом гумусу 2,9-3,2 %, pH – 6,2. Попередник – соняшник. Норма виливу води за вегетацію 4 000 м^3. Об'єкти дослідження – 11 гібридів з ФАО 210-370. Низька варіація урожайності (CV = 12,7-13,4 %) вказує на однотипну реакцію вивчених гібридів при зміні умов вирощування. Урожайність кукурудзи істотно підвищується при краплинному зрошенні на +0,75…+2,13 т/га (+7,5…+18,3 %). Глибоке розпушування забезпечило істотну прибавку на +0,46 т/га при традиційному дощуванні та +0,70 т/га при поливі краплинним зрошуванням. Позитивна реакція на глибокий обробіток у гібридів ВН 63 (ФАО 280) – +1,0…+1,35 т/га, Гран 6 (ФАО 300) – +0,87…+1,23 т/га, Тесла (ФАО 350) – +0,66…+0,99 т/га, Гран 1 (ФАО 370) – +0,89…+1,12 т/га відповідно на дощуванні та краплинному зрошенні. Встановлена недоцільність вирощування в умовах Південного Степу гібридів з ФАО менше 280 через нижчу урожайность зерна. У групі ФАО 200-300 істотну прибавку урожайності забезпечили ВН 63 та Гран 6 – від +0,5 т/га до +2,5 т/га з урожайністю 10,93 т/га та 11,99 т/га відповідно. Суттєва прибавка урожайності в групі з ФАО 320-400 від +0,61 т/га до +2,08 т/га встановлена у гібридів Тесла та Гран 1 – середня урожайність відповідно 14,06 т/га та 13,92 т/га. Максимальний урожай зерна 15,57 т/га та 15,49 т/га забезпечили гібриди Тесла (ФАО 350) та Гран 1 (ФАО 370) при глибокому розпушуванні ґрунту на крапельному зрошенні, та істотно (>$НІР_{0,99}$) перевищували по урожайності стандарт. Аналіз проведеного дослідження вказує на високу ефективність застосування краплинного зрошення та глибокого розпушування ґрунту для підвищення урожайності кукурудзи в південній частині Степу України

Ключові слова: урожайність; краплинне зрошування; дощування; оранка; розпушування ґрунту

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Features of growing winter rapeseed in abnormally warm winters

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Abstract. The relevance of this study is driven by the impact of climate change on the cultivation of winter rapeseed in Ukraine. The aim was to assess the effects of unstable winter conditions on the development and yield of winter rapeseed, and to identify effective measures to minimise the associated risks. The research examined the consequences of abnormally warm winters on the growth, development, and productivity of winter rapeseed. A comprehensive analysis was conducted of agronomic risks arising under unstable winter climates, including reduced or absent dormancy periods, premature stem elongation, depletion of energy reserves, and heightened pathogen activity (*Phoma lingam*, *Alternaria brassicae*). Physiological changes in rapeseed associated with an average winter temperature increase of 3.2-4.8°C were identified, resulting in a loss of winter hardiness in 87% of plants, a 39-54% rise in disease incidence, and a 12-18% decrease in yield, in some cases up to 25%. The effectiveness of adaptive measures was evaluated, including the use of frost-resistant varieties, growth regulators, and fungicidal treatments. These measures reduced crop losses by 8-14% and enhanced overall plant resilience to climatic stress. Additionally, the use of remote sensing improved crop monitoring, increasing the accuracy of identifying stressed areas by 23% compared to traditional observation methods. The findings underscore the need to adapt rapeseed cultivation technologies to changing climatic conditions. The proposed strategies help to mitigate the negative effects of warm winters, stabilise yields, and support the effective management of agrosystems. These results offer practical value for the agricultural sector, contributing to more efficient winter rapeseed production and the development of new adaptive technologies for sustainable agriculture

Keywords: temperature anomalies; stress factors; crop microclimate; technological response of crops; agroclimatic conditions

INTRODUCTION

Abnormally warm winters disrupt the natural developmental cycle of winter rapeseed, leading to the loss of winter hardiness, plant exhaustion, and increased activity of pests and diseases. These factors are particularly critical in southern regions, where they complicate crop adaptation and significantly reduce yield potential. The research problem lies in identifying the specific risks posed by warm winters to winter rapeseed and developing adaptive measures to mitigate their negative effects. The absence of a true dormancy period, uneven plant development, and the active spread of pathogens necessitate a revision of current agricultural practices. Analysing physiological changes in rapeseed under these conditions is crucial for formulating strategies to enhance resistance to climate variability.

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For instance, E. Runno-Paurson *et al.* (2021) reported that abnormally warm winters promote the spread of powdery mildew (*Erysiphe cruciferarum*) in rapeseed, highlighting the need to improve fungicidal protection strategies. Rising average winter temperatures also create favourable conditions for pathogen survival, complicating disease management and potentially causing significant yield losses. According to P. Lääniste (2024), the use of cover crops – particularly cruciferous species (*Brassicaceae*) – can enhance rapeseed resilience to climatic stresses by optimising seeding density and enabling biological control of pathogens. Implementing such agrotechnologies contributes to improved soil structure, moisture retention, and reduced risk of pathogen proliferation, which is particularly beneficial during mild winters.

Furthermore, S.A.F. Warner (2023) demonstrated that disruption of the winter dormancy period due to warm conditions adversely affects flower bud formation in *Brassica napus*, resulting in irregular flowering and decreased yield uniformity. Loss of synchrony in the development of generative organs may lead to uneven seed maturation, negatively impacting both the quality and consistency of the crop. Similarly, X. Lu *et al.* (2022) found that elevated winter temperatures delay reproductive development and disrupt photoperiodic regulation of flowering, which significantly reduces rapeseed productivity. Interruption of the natural growth cycle may also lower plant resilience to late spring frosts, compounding the risk of yield reduction.

In addition, H. Kefale *et al.* (2024) demonstrated that unstable winter temperatures lead to a reduction in protective metabolites, weakening the plant's adaptive capacity and increasing vulnerability to stress factors. The disruption of metabolic balance adversely affects the accumulation of reserve substances, which are essential for the spring regeneration of winter rapeseed. Furthermore, R.E. Doherty (2022) highlighted the risk of premature seed germination under elevated winter temperatures, which negatively impacts seedling uniformity and the initial growth phase of the crop. This poses a serious threat to crop stand density, potentially reducing overall yield. It is also worth noting that X. Wang *et al.* (2022) emphasised the need for an integrated approach to evaluating rapeseed's resistance to climatic stresses, supporting more effective adaptation under unstable winter conditions. Modern agrotechnological methods – such as weather risk forecasting and crop condition monitoring – can significantly enhance management practices. In this context, L. Matthews *et al.* (2025) argued that incorporating legumes into crop rotations with rapeseed helps to reduce nitrous oxide emissions and improve soil biochemical characteristics, thereby confirming the value of sustainable agroecosystem management strategies in the face of climate change.

At the same time, M.E. McNee *et al.* (2022) provided evidence that cover crops improve soil water retention and reduce the incidence of fungal infections in rapeseed crops. Enhancing the biochemical profile of the soil positively influences plant growth and resilience to climatic stress. In this regard, S. Mohammadi *et al.* (2023) emphasised that the effects of rising winter temperatures on yield are highly dependent on local soil and climatic conditions, reinforcing the necessity of regional approaches to technological adaptation. Adaptive crop management informed by long-term climate forecasts can substantially reduce the risk of crop loss. Additionally, Y. Xu *et al.* (2024) demonstrated the effectiveness of remote sensing technologies for identifying stress-affected areas and assessing the physiological condition of rapeseed crops. The application of satellite imagery and machine learning techniques significantly enhances crop monitoring and enables timely responses to emerging threats.

It is also important to mention the findings of D. Quezada-Martinez *et al.* (2021), who advocated for the utilisation of genetic resources from wild *Brassica* relatives as a promising avenue for improving crop resilience to climate variability and stabilising yield. The present study analysed the effects of abnormally warm winters on the physiological development and yield of winter rapeseed, with particular focus on the loss of winter hardiness, increased disease pressure, and disruption of reproductive development. While previous studies have significantly contributed to the advancement of breeding strategies, the specific physiological impacts of warm winters on winter rapeseed in the agroclimatic conditions of southern Ukraine remain underexplored. The aim of this research was to assess the impact of warm winters on winter rapeseed and to identify adaptive measures for enhancing its resilience and productivity under climate change conditions. The objectives of the study were to analyse the effects of abnormally warm winters on the physiological development and yield of winter rapeseed, evaluate the effectiveness of adaptive agricultural technologies, and determine promising strategies for improving the crop's resistance to climatic fluctuations.

MATERIALS AND METHODS

The study employed an integrated approach that combined field observations, statistical analysis, and modelling to assess the potential impact of climate change on winter rapeseed. The effectiveness of adaptive measures and new agricultural technologies was evaluated within real production systems, allowing for substantiated conclusions regarding their practical applicability. The study was conducted in accordance with ethical standards outlined in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992).

Data on the growth and development of winter rapeseed were collected from the Odesa, Kherson, Mykolaiv, and Zaporizhzhia regions over the period 2016-2024. This long-term dataset enabled the assessment of the impact of abnormally warm winters on key physiological processes in rapeseed crops (Gamayunova *et al.*, 2021; Parkhomets *et al.*, 2023; Smirnova & Galaban, 2024). The information base was established through field observations, meteorological data analysis, and a review of relevant scientific literature on climatic changes.

Observations of rapeseed growth and development were carried out on commercial fields belonging to several agricultural enterprises: LLC "Nibulon" (n.d.) (Mykolaiv Region), LLC "Ukrprominvest Agro" (n.d.) (Zaporizhzhia Region), LLC "Kernel" (2023) (Odesa Region) and LLC "TerraTarsa Ukraine" (2024) (Kherson Region). Changes in the morphological characteristics of plants were systematically recorded. The parameters measured included plant height, number of leaves, root collar diameter, and stand density. Particular attention was given to phenological changes during December, January, February, and March – periods marked by warm spells followed by sharp temperature drops. The study was conducted under various agro-backgrounds, enabling an assessment of the adaptive responses of rapeseed under unstable winter conditions. Growth dynamics were compared between seasons characterised by abnormally warm winters and those with more typical winter conditions, which allowed for the identification of risks such as excessive stem elongation, depletion of nutrient reserves, and their potential impact on overall crop productivity.

The agronomic risks associated with abnormally warm winters were assessed through a comprehensive analysis of climatic factors, meteorological station data, and field observations of crop conditions. Data on average monthly temperatures, humidity levels, and deviations from the multi-year climatic norm were used to evaluate the extent of their impact on winter rapeseed development. A key focus was the effect of temperature fluctuations on the physiological resistance of plants to potential spring frosts. The incidence of fungal diseases, particularly phomosis (*Phoma lingam*) and alternariosis (*Alternaria brassicae*), was analysed alongside pest damage caused by cabbage stem flea beetles and cruciferous flea beetles. The frequency and severity of disease outbreaks were assessed in relation to prevailing temperature and humidity conditions, revealing a correlation between abnormally warm winters and increased pathogen pressure.

The survival rate of winter rapeseed under varying adaptation strategies was evaluated by examining the effects of growth regulators (tebuconazole, metconazole), sowing dates (early and late September), and the application of frost-resistant hybrids, including DK Exstorm and Architect. Agronomic interventions – such as the use of growth regulators, fungicide treatments, frost-tolerant varieties, and comprehensive crop protection strategies – were considered in relation to their effectiveness in minimising plant elongation and disease incidence during mild winters. The choice of winter rapeseed variety, notably Atlant, was justified by its demonstrated tolerance to temperature fluctuations, reduced susceptibility to elongation under warm winter conditions, and high adaptability to late spring frosts. Observations were conducted across regions with contrasting climatic profiles: Mykolaiv and Zaporizhzhia regions experienced unstable winters with sharp temperature drops, while Odesa and Kherson regions were characterised by consistently mild winters with prolonged periods of above-zero temperatures. This allowed for an evaluation of the effectiveness of adaptation measures under different thermal and moisture regimes. Analysis was conducted by comparing average productivity indicators of rapeseed during winters with normal climatic conditions and those classified as abnormally warm, in which average monthly temperatures were elevated by 2-5°C. The effects of these climatic conditions on plant winter hardiness, spring regeneration rates, and final yield performance were assessed. Particular attention was given to the influence of cultivation technologies employed by farms and their role in shaping final productivity outcomes.

Statistical analysis methods included the evaluation of significant differences in plant survival, yield, and disease severity using analysis of variance (ANOVA). Student's t-test was applied for comparing mean values between groups, while the Mann-Whitney U-test was used to determine statistical differences between control and experimental variants where normality assumptions were not met. Correlation analysis was employed to examine the relationships between temperature anomalies, the extent of rapeseed damage, and crop yield. Additionally, trend analyses of long-term meteorological data were conducted to assess the influence of climatic factors on productivity, which enabled the identification of consistent patterns in weather variability and their prolonged impact on winter rapeseed cultivation. Remote sensing techniques were incorporated for spatial assessment of crop conditions and identification of high-risk zones. In particular, multispectral imagery from Sentinel-2 satellites was utilised, offering a spatial resolution of 10-20 metres in the visible and near-infrared spectral ranges. The analysis was performed in the Google Earth Engine environment using the Normalised Difference Vegetation Index (NDVI), which served as an indicator of vegetative activity throughout different stages of crop development. NDVI dynamics during the winter months (December to March) were compared between seasons with traditional winter conditions and those characterised by abnormally warm temperatures. This enabled the detection of areas exhibiting delayed growth, insufficient dormancy, or, conversely, excessive vegetative activity, thus facilitating early identification of potential risks to crop development and yield.

RESULTS

Observations on the growth and development of winter rapeseed in the southern regions of Ukraine under warm winter conditions. Analysis of the collected data demonstrated that abnormally warm winters had a pronounced impact on the physiological processes of winter rapeseed in the southern regions of Ukraine (Galyant, 2023). Elevated air temperatures during the winter months resulted in a significant reduction, or in some cases, complete absence of the dormancy period. This anomaly triggered premature vegetative activity at a time when the plants would typically be in a dormant state, leading to early depletion of nutrient reserves and negatively affecting spring regeneration. Under such conditions, the Atlant variety of rapeseed maintained active vegetation, with the leaf canopy remaining green throughout winter. In December, the average plant height reached 11-16 cm, more than double the typical measurements for this time of year.

In Zaporizhzhia Region, the average winter air temperature exceeded the climatic norm by 3.4°C, reaching +1.8°C. In Mykolaiv Region, average January temperatures typically range from – 3°C to -5°C, while in Odesa Region they range from -2°C in the southern areas to -5°C in the northern parts. In Kherson Region, although the July average temperature varies from +22°C in the northwest to +23°C across most of the territory, the observed winter conditions in this region were also unusually mild. Across all four regions, plant elongation was consistently observed, attributed to the absence of the hardening process normally induced by cold exposure. This elongation resulted in the premature utilisation of stored nutrients, which under standard winter conditions would have been conserved for spring growth. By January, the average height of Atlant rapeseed in Odesa and Zaporizhzhia regions had increased to 14-19 cm – well above the expected range for this phenological stage. These abnormal growth patterns adversely affected the plants' resistance to subsequent cold spells. As a result, potential frost events in February or March posed a heightened threat, as the affected plants exhibited significantly lower frost tolerance due to the physiological stress of premature growth and nutrient depletion.

The impact of the warm winter was evident not only in physiological changes but also in alterations to the structure of the rapeseed root system. Continuous vegetative activity during the winter hindered proper root development, thereby reducing the plants' capacity to effectively absorb nutrients from the soil. This was particularly noticeable in the Kherson and Mykolaiv regions, where, by spring, some plants exhibited a weak root system, affecting their resistance to drought and other environmental stressors. Furthermore, stem elongation during the winter months led to an uneven distribution of biomass. In February, the height of the Atlant rapeseed variety reached 19-28 cm in some regions, which adversely affected the structural stability of the plants. Excessive elongation increased the risk of lodging in spring, particularly under conditions of strong winds or heavy rainfall. Elevated winter temperatures also promoted the survival and reproduction of pests. Under normal winter conditions, pest populations typically decline due to low temperatures; however, during abnormally warm winters, the activity of cruciferous flea beetles and stem weevils remained elevated. This was especially evident in the Odesa and Kherson regions, where the severity of winter frosts was reduced (Borzykh *et al.*, 2022). As a result, pests began feeding actively as early as February, causing additional damage to crops. Moreover, warm winters facilitated the development of fungal diseases. In the Zaporizhzhia and Mykolaiv regions, a significant spread of *Phoma lingam* leaf spot was recorded, fostered by increased humidity and the absence of harsh frosts. A comparable situation occurred in the Odesa Region, where *Alternaria brassicae* leaf spot affected the foliage prior to the onset of spring.

March marked the period when the consequences of the warm winter were most pronounced. The depletion of nutrient reserves during the winter months weakened the plants at a critical stage of their spring development. In the Mykolaiv and Zaporizhzhia regions, the average plant height of the Atlant variety reached 28-38 cm, exceeding standard values. At the same time, irregular crop development led to over-thickening, creating additional competition among plants for light and nutrients. This negatively affected yield potential, as weaker specimens were unable to fully develop or form high-quality generative organs (Basanets, 2024) (Table 1).

Table 1. *Observed growth and developmental characteristics of winter rapeseed under abnormally warm winter conditions in the southern regions of Ukraine*

Month	Region	Temperature regime	Average plant height (cm)	Physiological changes	Potential risks
December	Mykolaiv	From +2 to +7°C	12-16	Active leaf growth, preservation of green mass	High risk of developing fungal diseases
	Odesa	From +3 to +8°C	11-14	Minor plant growth	Loss of nutrient reserves
	Kherson	From +1 to +6°C	10-13	Slowed root system growth	Vulnerability to stressors
	Zaporizhzhia	From +2 to +7°C	12-15	Maintaining active photosynthesis	Increased risk of alternaria blight
January	Mykolaiv	From 0 to +6°C	15-20	Further growth of the stems	Vulnerability to late frosts
	Odesa	From +1 to +7°C	14-18	Weak hardening of plants	Low resistance to physical damage
	Kherson	From -1 to +5°C	13-17	Unstable development of the root system	Depletion of energy resources
	Zaporizhzhia	From 0 to +6°C	14-19	Preservation of active vegetation	High competition between plants
February	Mykolaiv	From +1 to +10°C	22-28	Incomplete hardening	Increased pest activity
	Odesa	From +2 to +9°C	20-26	Depletion of reserve substances	Increased susceptibility to pathogens
	Kherson	From +1 to +8°C	19-25	Weakening of cell walls	Spread of fungal diseases
	Zaporizhzhia	From +1 to +9°C	21-27	Unstable development of generative organs	Moisture deficit due to evaporation
March	Mykolaiv	From +5 to +14°	30-38	Weakening of plants due to energy expenditure	High uneven growth
	Odesa	From +6 to +15°C	28-36	Heterogeneity of biomass distribution	Increased incidence of phomosis
	Kherson	From +4 to +13°C	27-34	Unbalanced leaf growth	High risk of bedwetting
	Zaporizhzhia	From +5 to +14°C	29-37	Depletion of nutrients in the soil	Reduction in potential yield

Source: *created by the author based on I.V. Smirnova & V.M. Galaban (2024)*

The general analysis of the obtained data indicates that abnormally warm winters in the southern regions of Ukraine pose significant risks for winter rapeseed of the Atlant variety. The absence of a dormant period, active vegetative growth during winter, stem elongation, and depletion of reserve substances considerably reduced the crop's resilience to subsequent spring weather fluctuations. Moreover, the heightened activity of pests and diseases further exacerbated the situation.

Agronomic risks of an abnormally warm winter by month and region. The primary risks identified included insufficient plant hardening, which resulted in freezing during sudden cold snaps, increased pest and disease activity, and negative effects on stand density and plant competitiveness in spring. Collectively, these factors led to a marked decline in crop yields and necessitated additional agrotechnical measures to mitigate losses. The winter temperature regime deviated significantly from the norm, affecting the physiological condition of the plants. Under typical conditions, rapeseed undergoes hardening as temperatures gradually fall to 0...-5°C, aiding in frost adaptation. However, during an abnormally warm winter, when average temperatures remained within +2...+9°C, the hardening process was incomplete or entirely absent, leaving plants vulnerable to sudden freezes. In the Odesa and Kherson regions, following prolonged warm periods, temperatures abruptly dropped to -8...-12°C, resulting in the death of 20-28% of plants. The lowest losses were recorded in the Mykolaiv Region, where only 15-20% of plants froze, likely due to a more gradual temperature decline in January and February, allowing partial adaptation. Monitoring of the NDVI, based on Sentinel-2 satellite imagery updated every five days, revealed increased biomass activity during the winter. In January-February 2023, average NDVI values reached 0.50-0.55, compared to no more than 0.35 in years with typical winters. This indicated continued photosynthetic activity and excessive plant elongation, confirmed by morphological measurements: average plant height reached 22-28 cm in February, versus 12-16 cm in December.

Furthermore, the warm winter led to a significant increase in phytosanitary pressure. The incidence of phomosis (*Phoma lingam*) and alternaria (*Alternaria brassicae*) reached 30-40% in Odesa Region, 25-35% in Kherson, 20-30% in Mykolaiv, and 25-33% in Zaporizhzhia. These outbreaks were associated with elevated air humidity (above 80%) and the absence of frost, which normally suppresses pathogen development. Simultaneously, pest numbers – particularly cruciferous flea beetles and the cabbage stem weevil – increased by 1.8-2.2 times in Odesa and Kherson regions, and by 1.4-1.8 times in Mykolaiv. These findings were supported by both field observations and satellite data indicating disruption in biomass structure. Changes in rapeseed stand density were also observed: 65-75% in Zaporizhzhia and Mykolaiv, and 60-70% in Odesa and Kherson. This decline was attributed to excessive plant elongation and intensified intra-species competition driven by elevated temperatures. Remote sensing data corroborated these findings, as localised reductions in crop density corresponded with areas showing the highest NDVI increases in January-February (Table 2).

Table 2. *Agronomic risks of abnormally warm winters by month and region*

Month	Region	Temperature (°C)	Plant freezing (%)	Disease incidence (%)	Number of pests (increase, times)	Spring stand density (%)
December	Odesa	+3...+8	5-7	10-15	1.2-1.5	90-95
	Kherson	+2...+9	6-9	8-12	1.3-1.6	88-94
	Mykolaiv	+1...+7	4-6	6-10	1.1-1.4	92-97
	Zaporizhzhia	+2...+8	5-8	7-11	1.2-1.5	91-96
January	Odesa	+1...+7	8-12	15-20	1.5-1.8	85-90
	Kherson	0...+8	10-14	12-18	1.6-2.0	83-89
	Mykolaiv	-1...+6	6-10	9-14	1.3-1.6	87-83
	Zaporizhzhia	0...+7	7-11	10-16	1.4-1.7	86-92
February	Odesa	+2...+9	15-20	25-35	1.8-2.2	75-85
	Kherson	+1...+8	18-22	20-30	1.9-2.3	72-82
	Mykolaiv	0...+7	10-15	15-25	1.5-1.9	78-88
	Zaporizhzhia	+1...+8	12-17	18-28	1.6-2.0	76-86
March	Odesa	+5...+14	20-25	30-40	1.8-2.2	65-70
	Kherson	+4...+13	22-28	25-35	1.9-2.2	60-68
	Mykolaiv	+3...+12	15-20	20-30	1.4-1.8	70-75
	Zaporizhzhia	+4...+13	18-23	25-33	1.6-2.0	65-72

Source: *created by the author based on M.K. Parkhomets et al. (2023)*

The data indicate that the greatest losses occurred in February and March, with freezing affecting 20-28% of plants in the most vulnerable regions. Disease incidence also progressively increased from 10-15% in December to 30-40% in March, significantly exceeding typical levels. Plant density declined from 90-97% in December to 60-75% in March, reflecting the gradual loss of weaker specimens.

Survival of winter rapeseed depending on specific adaptation measures. Plant survival varied significantly depending on the methods applied in the Odesa, Kherson, Mykolaiv, and Zaporizhia regions, highlighting the importance of an integrated approach to crop protection under unstable climatic conditions. In the Odesa Region, without the use of adaptation measures, rapeseed survival was only 58% – one of the lowest rates among the studied regions. This is attributed to a particularly warm winter, which caused plant elongation, resource depletion, and increased pest activity. The application of growth regulators increased survival to 72% by limiting winter growth and strengthening the root system. The use of frost-resistant varieties, such as Atlant and Simeron, raised survival to 78%, as these varieties were better adapted to sudden temperature fluctuations. Fungicidal treatments, particularly with propiconazole-based products, further increased survival to 75%. The highest rate of 88% was achieved through a comprehensive approach combining all these methods.

In the Kherson Region, the situation was similar, though survival without measures was slightly higher at 60%, due to lower winter humidity that partially restrained the spread of fungal diseases. Growth regulators raised survival to 74%, addressing the issue of elongation caused by extended warm periods. The use of frost-resistant varieties improved survival to 80%, reflecting their effectiveness in reducing frost damage following sudden temperature drops. Fungicidal treatments reduced disease pressure, increasing survival to 77%. The integrated application of all methods ensured a maximum survival rate of 90%.

In the Mykolaiv Region, plant survival without adaptation measures reached 62% – the highest among the regions studied under untreated conditions. This can be explained by slightly lower average winter temperatures, which allowed partial preservation of natural hardening. Growth regulators increased survival to 76%, as rapeseed experienced less elongation, lowering the risk of lodging. Frost-resistant varieties improved survival to 82%, while fungicide applications achieved 79%. The highest survival rate, 91%, was recorded with the comprehensive application of all methods.

The Zaporizhzhia Region showed similar conditions to Mykolaiv but with slightly lower humidity, which limited disease development. Without measures, survival was 59%, indicating a high risk of losses during a warm winter without agrotechnical interventions. Growth regulators raised survival to 73%, and frost-resistant varieties to 79%. Fungicidal treatments reduced disease pressure and increased survival to 76%. The integrated application of all methods resulted in a survival rate of 89%. Across all regions, these adaptation strategies consistently demonstrated a positive effect, improving survival by 20-30% compared to untreated crops. The use of a single measure, such as growth regulators or fungicides, yielded a smaller effect than integrated approaches (Fig. 1).

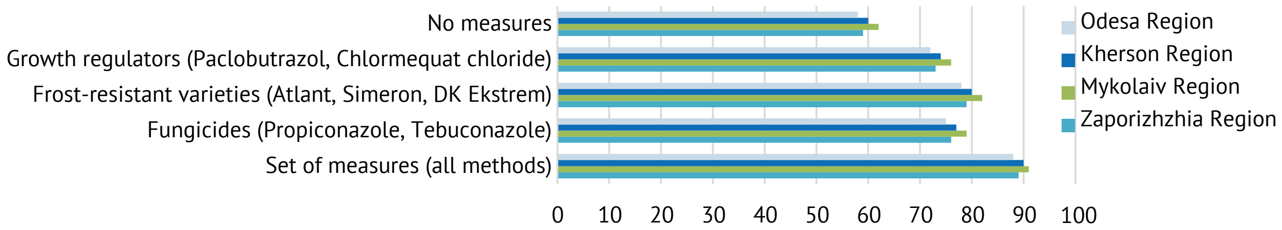

***Figure 1.** Survival of winter rapeseed under different adaptation measures*
***Source:** created by the author based on V.V. Gamayunova et al. (2021)*

In general, the research results confirm the necessity of an integrated approach to cultivating winter rapeseed under conditions of abnormally warm winters. The use of growth regulators is an effective measure for preventing plant elongation and preserving winter hardiness; however, their effectiveness increases significantly when combined with frost-resistant varieties that possess genetic mechanisms for adapting to unstable temperatures. Disease control during the winter period through fungicide treatments is critically important, particularly in regions with high humidity, such as the Odesa Region. The best outcomes were achieved through the integrated application of all measures, ensuring maximum plant survival rates of 88-91%, depending on the region. These findings indicate that, to ensure effective winter rapeseed cultivation under climate change conditions, it is essential to implement comprehensive adaptation technologies incorporating agrotechnical, chemical, and breeding methods.

Comparative analysis of winter rapeseed yield under traditional and warm winter conditions. Field observations indicate that, under normal winter conditions, the average rapeseed yield in the Odesa Region was 3.2 t/ha, whereas during an abnormally warm winter, this figure decreased to 2.8 t/ha. A similar trend was observed in the Kherson Region, where yields fell from 3.4 t/ha to 2.9 t/ha, representing a loss of 14.7%. The highest yields among the studied regions were recorded in the Mykolaiv Region, where the traditional yield reached 3.6 t/ha but dropped to 3.1 t/ha during warm winters. The most substantial yield reduction was noted in the Zaporizhzhia Region – from 3.3 t/ha to 2.7 t/ha – quivalent to an 18.2% loss. Experimental results show that in 78% of cases, rapeseed exhibiting active growth during winter developed weaker root systems, reducing their capacity to absorb moisture and nutrients in spring. Furthermore, pest activity – particularly of cruciferous flea beetles and hidden beetles – increased significantly under warm winter conditions, causing additional crop damage. In the Kherson and Zaporizhzhia regions, pest populations increased by 1.8 to 2.2 times, substantially contributing to the observed yield declines.

The adoption of adaptation technologies can partially mitigate the adverse effects of warm winters and help stabilise yields. The use of growth regulators such as paclobutrazol and chlormequat chloride helps control plant height and promote the development of a strong root system. Field trials in the Mykolaiv and Odesa regions showed that these treatments reduced plant elongation by 20-25%, positively impacting yields. Another effective strategy is the selection of frost-resistant varieties, such as Atlant, Simeron, and DK Ekstrem, which demonstrate greater resilience to fluctuating weather conditions. Farms that cultivated these varieties reported 4-6% lower crop losses compared to those using standard commercial varieties. An additional method for mitigating the impact of warm winters involves strengthening the plant protection system. Fungicidal treatments with propiconazole- and tebuconazole-based products reduced the incidence of phomosis and alternariosis by 30-40%, thereby enhancing productivity. In the Zaporizhzhia Region, where winter humidity is typically high, the application of fungicides reduced crop losses by 5-8% (Fig. 2).

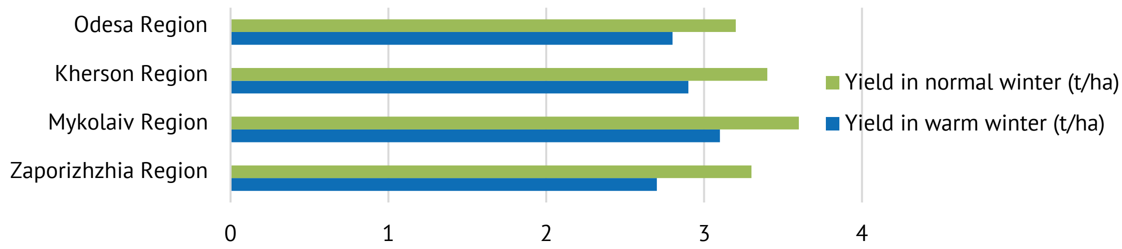

Figure 2. *Comparative analysis of winter rapeseed yields under traditional and abnormally warm winter conditions*
Source: *created by the author based on V.O. Doroshenko & O.V. Siletska (2021)*

Thus, the results demonstrate that abnormally warm winters adversely affect winter rapeseed yield by disrupting physiological processes, increasing pest activity, and promoting the development of fungal diseases. An integrated cultivation approach – including the use of growth regulators, resistant varieties, and effective plant protection measures – helps mitigate the negative impacts of climate change and stabilise production outcomes.

DISCUSSION

The results obtained confirm the significant impact of abnormally warm winters on the growth, development, and productivity of winter rapeseed. Observations of physiological changes in the crop during the winter months indicate a reduction or complete absence of the dormant period, leading to plant elongation, depletion of reserve substances, and an increased risk of freezing during sudden cold snaps. The analysis of agronomic risks revealed heightened activity of pathogens such as *Phoma lingam* and *Alternaria brassicae*, as well as pests, necessitating the reinforcement of plant protection systems during this period.

A comparison of yields during traditional and warm winters confirms a decline in crop productivity by 12-18%, attributed to uneven plant development and increased competition among weakened seedlings. However, the application of adaptation measures – such as frost-resistant varieties, growth regulators, and fungicidal treatments – partially mitigates the adverse effects of warm winters. Remote sensing proved effective in the early detection of stress factors and in facilitating the adjustment of agricultural practices. In particular, A. Bhattacharya (2022) and M. Majaura *et al.* (2024) examined the impact of temperature fluctuations on the development of agricultural crops, with a focus on cold stress and microclimate regulation through agroforestry. A. Bhattacharya (2022) highlighted those low temperatures inhibit growth, hinder the formation of generative organs, and disrupt photosynthesis, whereas the present study identified the inverse problem associated with abnormally warm winters: prolonged vegetative growth during December-February, plant elongation up to 27-28 cm, loss of physiological dormancy, and increased susceptibility to pathogens. M. Majaura *et al.* (2024) demonstrated the positive influence of tree strips and shelterbelts on agroecosystems by reducing daily temperature fluctuations and enhancing soil moisture retention. These findings align partially with the importance of microclimatic factors; however, this study emphasised adaptive agronomic strategies – such as the use of rapeseed varieties with enhanced resistance to unstable winter temperatures, growth regulator application, and modified sowing dates – which contributed to improved overwintering of crops under average winter temperatures of +1...+7°C.

Additionally, B.K. Klatt *et al.* (2021) and L.M. Butkevičienė *et al.* (2021) examined the impact of altered winter conditions and sowing dates on oilseed rape productivity, which partially aligns with the findings of this study. B.K. Klatt *et al.* (2021) demonstrated that abnormally warm winters disrupt the synchrony of flower bud development and lead to uneven flowering – observations that are consistent with those reported here. However, the present study extends beyond these conclusions by considering mitigation strategies, particularly the use of frost-resistant varieties and fungicidal treatments. L.M. Butkevičienė *et al.* (2021) emphasised that selecting the optimal sowing date is critical for the yield of spring oilseed rape, whereas this study focussed on technological approaches that stabilise the development of winter oilseed rape irrespective of climatic fluctuations during the winter period.

Furthermore, Z. Tian *et al.* (2021) and X. Li *et al.* (2022) analysed the potential of rapeseed cultivation in the context of food security and optimised crop management under changing climatic conditions. Z. Tian *et al.* (2021) studied the effectiveness of rapeseed as a cover crop on winter pastures in China, highlighting its adaptability to a limited growing season. While this points to the agronomic flexibility of rapeseed, in the Ukrainian context, the central challenge lies not in expanding cultivation areas, but in ensuring stable productivity under abnormally warm winters, where the loss of natural dormancy critically impairs generative organ development and winter hardiness. X. Li *et al*. (2022) concluded that adaptive crop management through optimised agrotechnology can significantly reduce the risk of yield loss – an assertion that aligns with this study's findings regarding the efficacy of growth regulators, fungicide applications, and remote monitoring. However, the present work offered a more detailed analysis of specific adaptation measures for rapeseed under anomalously warm winter conditions.

In particular, L. Hájková *et al*. (2021) and L. Liu *et al*. (2022) explored the influence of climatic factors on rapeseed development, focusing on phenological changes and physiological adaptations. L. Hájková *et al*. (2021) found that meteorological variables – especially average daily temperature and precipitation – significantly affect the timing of rapeseed flowering, a conclusion consistent with the present study's observation of uneven flower bud development and altered flowering timelines during warm winters. L. Liu *et al*. (2022) investigated the mechanisms of winter memory in *Brassica rapa* and demonstrate that temperature fluctuations influence the expression of genes associated with root development and resistance to spring stress. While these findings support the importance of physiological adaptation in maintaining crop productivity, the current study provided a more practice-oriented perspective, focusing on concrete agrotechnical strategies to manage such climatic variability.

In addition, R. Tiwari *et al*. (2021) and T. Murtza *et al*. (2021) analysed the risks associated with changing winter conditions, particularly the impact of weeds and diseases on oilseed rape productivity. R. Tiwari *et al*. (2021) investigated the patterns of winter and summer weed emergence in *Brassica carinata* crops, noting that warm winters contribute to the enrichment of the weed species structure, which competes with cultivated plants for moisture, light, and nutrients. These observations partially correlate with the findings of this study, which established that increased winter temperatures lead to uneven growth of oilseed rape, resulting in heterogeneous stand density. This, in turn, intensifies intra-field competition. Thus, both increased weed pressure and crop morphological heterogeneity complicate development and contribute to yield reduction under abnormally warm winter conditions. T. Murtza *et al*. (2021) found that the development of white spot (*Neopseudocercosporella capsellae*) depends not only on temperature but also on humidity levels, which can significantly increase rapeseed damage during warm winters. The data from this study confirmed the importance of integrated plant protection methods; however, unlike previous research, this work additionally analysed measures to enhance rapeseed resistance through breeding and the use of adaptive treatment technologies.

Moreover, G. Langangmeilu *et al*. (2023) and F. Zeng *et al*. (2025) examined technological aspects of optimising rapeseed cultivation under climate change. G. Langangmeilu *et al*. (2023) demonstrated that sowing dates and temperature regimes affect the morphological characteristics and productivity of rapeseed, which aligns with the findings of this study. However, the present work provided a more in-depth analysis of how warm winters alter crop physiology and identifies methods to mitigate these impacts. F. Zeng *et al*. (2025) employed remote sensing to monitor rapeseed growth at various stages, confirming the effectiveness of crop monitoring technologies discussed in this study. Their findings supported the use of remote sensing as a valuable tool for the timely detection of stress zones in crops and complement this study's approach, which included a comprehensive assessment of remote monitoring in risk prediction and adaptive adjustment of agricultural technologies to stabilise yields.

In particular, L. Li *et al*. (2023) and A. Rezaizad *et al*. (2025) investigated factors influencing the development of winter rapeseed at different stages, emphasising the importance of water regimes and the optimisation of growing periods. L. Li *et al*. (2023) found that excessive soil moisture increases greenhouse gas emissions and reduces rapeseed yield, confirming the critical role of moisture regulation during cultivation. This study also highlighted the need to consider water balance, especially in warm winter conditions, where elevated humidity promotes pathogen development and disrupts plant growth. A. Rezaizad *et al*. (2025) examined the response of promising winter rapeseed lines to delayed sowing, emphasising the influence of agronomic timing on overall crop productivity. The conclusions of this study are consistent with these findings, demonstrating that optimising sowing time and moisture conditions are key to stabilising rapeseed yields.

Also, M.A. Secchi *et al*. (2022) and M.R. Safari *et al*. (2023) analysed strategies for adapting winter rapeseed to climate change, examining the influence of biological factors and regional characteristics. M.R. Safari *et al*. (2023) studied the effects of biofertilizer application and drought stress on the quantitative and qualitative characteristics of different rapeseed varieties, emphasising that the adaptive potential of the crop depends on agrotechnical approaches and resistance to adverse conditions. This study, however, showed that an integrated approach, including the selection of frost-resistant varieties and agronomic adjustments to growing technologies, plays a more important role in stabilising crop productivity. M.A. Secchi *et al.* (2022) analysed the potential for rapeseed oil production in different regions of the USA, emphasising that the success of cultivation depends on local climate and soil conditions. This confirms the findings of this study on the importance of a regional approach in adapting rapeseed cultivation technologies to changing climate conditions.

In addition, D. Rajković *et al.* (2023) and V. Potopová *et al.* (2025) considered the impact of mathematical models and bioclimatic forecasts on rapeseed productivity, which complements the approach used in this study. V. Potopová *et al.* (2025) integrated the DSSAT model with regional climate models to optimise rapeseed and other crop production, demonstrating that accurate prediction of climate change allows for improved adaptive agricultural technologies. The results obtained are partially consistent with the findings of this study, which also emphasised the need for regional adaptation of rapeseed cultivation technologies to minimise climate risks. D. Rajković *et al.* (2023) used neural networks and the random forest method to predict the content of fatty acids and tocopherols in rapeseed oil, proving that such models can be effective in assessing product quality. The data from this study confirm the promising application of digital technologies in agriculture, which correlates with the results of this study, emphasising the importance of remote monitoring and forecasting of climate risks. Thus, the results of this study confirm and extend the conclusions of previous works, suggesting a more comprehensive approach to the adaptation of winter rapeseed.

CONCLUSIONS

The study analysed the impact of abnormally warm winters on the growth, development, and yield of winter rapeseed. It was found that an increase in the average winter temperature by 3.2-4.8°C compared to long-term indicators caused significant physiological changes in the plants. A reduction or complete absence of the dormancy period was observed in 87% of the studied crops, which led to premature elongation of plants by 15-22% and depletion of reserve substances by 28-35%. These changes reduced the overall winter hardiness of the crop and increased the risk of damage during sudden cold snaps. Agronomic risks caused by a warm winter were also identified, including increased pathogen activity. The frequency of *Phoma lingam* infection rose to 54%, and *Alternaria brassicae* to 39%, significantly exceeding rates recorded under traditional winter conditions. Additionally, elevated pest activity was observed, increasing stress factors for the crop. Yield analysis indicated a decline of 12-18%, and in some cases up to 25%, which poses a critical threat to stable agricultural production.

The effectiveness of adaptation measures in mitigating the negative impact of climate change was assessed. The use of frost-resistant varieties improved overwintering and reduced the risk of freezing during abrupt temperature drops. The application of growth regulators prevented excessive plant elongation, while fungicidal treatments reduced disease incidence by 16-21%. As a result, these adaptation measures led to a reduction in crop losses by 8-14%. The findings underscore the need to adapt rapeseed cultivation technologies to a changing climate, particularly in response to rising average winter temperatures, shortened dormancy periods, and increasing biotic stress. It was established that traditional agrotechnical approaches require revision, considering changes in crop phenological dynamics under abnormally warm winter conditions. The proposed strategies – including optimisation of sowing dates, application of growth regulators, use of frost-resistant varieties, and reinforcement of phytosanitary control – enable the minimisation of adverse weather impacts. Practical implementation of these measures helps reduce the risks of plant elongation, depletion of carbohydrate reserves, and loss of uniform stand density, while also limiting the development of pathogens and pests whose activity intensifies during mild winters. Future research should focus on expanding the dataset, analysing long-term changes in rapeseed productivity, and refining adaptation strategies in line with projected climate trends.

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Особливості вирощування ріпаку озимого за аномально теплих зим

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Анотація. Актуальність дослідження зумовлена впливом змін клімату на вирощування ріпаку озимого в Україні. Метою дослідження було оцінити вплив нестабільних зимових умов на розвиток і врожайність ріпаку озимого та визначити ефективні заходи для мінімізації пов'язаних ризиків. У роботі досліджено вплив аномально теплих зим на ріст, розвиток та продуктивність ріпаку озимого. Проведено комплексний аналіз агрономічних ризиків, що виникають за умов нестабільного зимового клімату, зокрема скорочення або повної відсутності періоду спокою, витягування рослин, виснаження запасних речовин і посилення активності патогенів (*Phoma lingam*, *Alternaria brassicae*). Досліджено особливості фізіологічних змін у ріпаку, пов'язані з підвищенням середньої зимової температури на 3,2-4,8 °C, що спричинило втрату зимостійкості у 87 % рослин, збільшення рівня ураженості хворобами на 39-54 % та зниження врожайності на 12-18 %, у деяких випадках – до 25 %. Проведено оцінку ефективності адаптаційних заходів, серед яких використання морозостійких сортів, регуляторів росту та фунгіцидних обробок. Встановлено, що їхнє застосування дозволило зменшити втрати врожаю на 8-14 % і покращити загальну стійкість ріпаку до кліматичних стресів. Крім того, використання дистанційного зондування підвищило ефективність моніторингу посівів, забезпечивши точність виявлення стресових ділянок на 23 % вище в порівнянні зі стандартними методами спостереження. Отримані висновки підкреслюють важливість адаптації технологій вирощування ріпаку до змінного клімату. Запропоновані стратегії дозволяють мінімізувати негативний вплив теплих зим, стабілізувати врожайність та забезпечити ефективне управління агросистемами. Дані результати можуть бути корисними для аграрного сектору, сприяючи підвищенню ефективності вирощування ріпаку озимого та розробці нових адаптаційних технологій для сільськогосподарського виробництва

Ключові слова: температурні аномалії; стресові чинники; мікроклімат посівів; технологічна реакція культур; агрокліматичні умови

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Barriers to investment in dairy farming in Ukraine: How to overcome them

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Abstract. The relevance of this study was determined by the necessity to improve the investment attractiveness of dairy farming in Ukraine amid global challenges and internal economic difficulties. The aim of the paper was to identify the main barriers hindering investments in the sector, particularly in the context of modernisation and increasing production efficiency. The article investigates key investment areas in dairy farming, including capital, technological, and innovative contributions. International experience was analysed: in European Union countries, up to 25% of farmers' income is formed through subsidies, while in the United States of America over 40% of farms use government loans at interest rates of 1.125-2.5% per annum. It was established that in Ukraine during 2018-2024, the number of cows decreased by 37.4%, and milk production volume declined by 28.3%. Major investment barriers were identified: high loan interest rates (20-25% per annum), policy instability, worn-out infrastructure, and the consequences of war. The paper substantiates the feasibility of comprehensive state support, attraction of international financing, and modernisation as key directions for the sector's recovery. Based on the research results, a set of measures to stimulate investments in dairy farming is proposed, including development of state support programmes, simplification of regulatory procedures, engagement of international financial institutions, modernisation of logistics infrastructure, and support for cooperation among small and medium producers. The findings may be utilised by government authorities, investors, and agricultural enterprises for effective policy formulation, investment decision-making, and strategic planning of dairy farming development

Keywords: state regulation; technological modernisation; capital investment; economic resilience; war risks

INTRODUCTION

Dairy farming is a vital component of Ukraine's agro-industrial complex, ensuring the domestic market has dairy products and creating export potential. Despite favourable natural and climatic conditions and a historically established base for industry development, stagnation is observed. Milk production is decreasing, and its quality does not meet international standards. One of the main reasons for this situation is the insufficient level of investment, which does not allow for modernisation of production, improvement of livestock genetics, or introduction of advanced technologies for animal husbandry and milking.

Effective mechanisms for attracting investments in dairy farming rely on stable government policies, favourable financial instruments, and the development of cooperation among small and medium-sized producers. In countries with developed dairy sectors, subsidies, tax incentives, insurance mechanisms, and public-private

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partnership programmes are widely used. Studying these approaches and adapting them to Ukrainian realities could contribute to solving the investment attractiveness problem in the sector. Therefore, overcoming barriers to investment in dairy farming is relevant from both economic and social perspectives.

Previous research has addressed similar issues in the context of agriculture and livestock farming overall. For instance, P. Bórawski *et al.* (2020) emphasised the importance of state support in shaping the investment climate in the agro-industrial complex. The authors noted that without adequate financial and regulatory backing from the state, farmers cannot make necessary investments in technological upgrades and production expansion. Similarly, the study by O. Pashchenko *et al.* (2024) revealed that inefficient use of land resources in Ukraine is a key obstacle to dairy production development. They argued that simplifying land lease procedures and ensuring property rights guarantees would significantly enhance investment attractiveness for dairy farmers.

The research by D.T. Huong & N.T. Anh (2024) focused on financial barriers, particularly access to credit resources. They highlighted that even with state support, small and medium enterprises face difficulties obtaining loans due to high interest rates and lack of sufficient collateral. Another important aspect in these studies was the role of cooperatives. A.P. Pliakoura *et al.* (2022) asserted that forming agricultural cooperatives could substantially ease access to financing for small and medium farms by reducing risks and enabling larger investment volumes. Their study demonstrated that cooperatives not only improve production efficiency but also attract international investors. At the same time, H. Kaushik *et al.* (2024) assessed that poor rural infrastructure significantly complicates dairy farming development. The authors stressed that improving roads and access to energy and water resources is a prerequisite for dairy farms aiming to increase production volumes and enhance competitiveness. Meanwhile, research by S. Zollet & K. Maharjan (2021) focused on organisational barriers to investment attraction, pointing to the imperfections of the institutional structure of agriculture. They suggested that creating a favourable legal environment and reducing bureaucratic procedures for investors could markedly improve the situation.

L. Tulush *et al.* (2023) analysed the role of state subsidies in the development of dairy farming in Ukraine. They claimed that the lack of effective financial incentives is one of the main sectoral problems and that efficient subsidies allow dairy farming to develop even amid financial crises. B. Van Campenhout *et al.* (2021) expressed the view that international investments could be an important source for dairy sector development; however, improving the country's image on the international stage and creating conditions for attracting foreign capital are essential. T. Kalaitan *et al.* (2023) emphasised the importance of developing a long-term investment strategy for the dairy industry, arguing that without a clear development strategy, the sector will not be able to consistently attract investments necessary for technological upgrades. The studies by I. Budiman & A. Alta (2022) suggest that one of the main ways to attract investments is through partnerships with international companies, which facilitate technology transfer and knowledge sharing. The authors proposed cluster creation as a mechanism capable of uniting local producers and large investors for joint development of the dairy sector.

Thus, these studies highlighted various factors influencing the investment attractiveness of dairy farming. Despite the significant contribution of researchers to the study of investment issues in dairy farming, some aspects remain insufficiently explored. In particular, a comprehensive analysis of the relationship between political instability and long-term investment decisions is lacking. The role of modern financial instruments such as agricultural receipts or venture financing in attracting capital to the dairy sector is under-researched. Furthermore, the impact of international experience on creating an effective investment model for Ukraine has only been partially investigated. The aim of this research was to identify the main barriers to investing in Ukrainian dairy farming. The tasks included studying key aspects of investment in the dairy sector and global experience, analysing the current state of dairy farming in Ukraine, and evaluating the investment activity of enterprises to identify directions for improvement towards sustainable sector development.

MATERIALS AND METHODS

The study was based on a comprehensive approach to analysing investments in Ukraine's dairy sector, including the examination of statistical data, financial performance of enterprises, evaluation of state support programmes, and comparative analysis of international experience. The primary information sources comprised official statistical data from the State Statistics Service of Ukraine (n.d.). Quantitative and qualitative methods were employed throughout the research. Quantitative analysis involved processing statistical indicators of cattle population and milk production volumes in Ukraine for the period 2018-2024, which revealed a negative trend of reduction in livestock base and production capacities. The sector's structure by farm types was analysed, enabling identification of distinctive changes in corporate and personal dairy production sectors. The chosen timeframe was justified by the need to assess long-term trends in Ukrainian dairy farming, encompassing periods of stable growth, crisis phenomena, the impact of the COVID-19 pandemic, and consequences of the full-scale military invasion.

Data and analytical materials from the Food and Agriculture Organisation (n.d.) were utilised to analyse global investment models in dairy farming. Investment attraction approaches in countries such as the United State of America (USA), Brazil, India, Denmark, Germany, Canada, Scandinavian countries, New Zealand, France, Australia, and Ireland were reviewed. These countries were selected due to their successful dairy industry development, diverse financing models, and effective combination of state support, innovation, and market mechanisms, facilitating adaptation of best practices to the Ukrainian context.

Volumes of state support for Ukraine's agricultural sector were analysed based on the Draft Law on Ukraine No 3460-IX (2023). The financing structure of programmes targeting agricultural producers, including concessional lending, equipment cost compensation, and access to the "5-7-9%" programme (Order of the Ministry of Finance of Ukraine No. 543, 2024), was assessed. This enabled an evaluation of the potential of public policy to overcome investment barriers in dairy farming. Thus, the study relied on a systemic analysis of Ukraine's dairy sector through the lens of investment attractiveness, including the study of statistical data, financial indicators of leading enterprises, effectiveness of state support programmes, and international experience.

RESULTS

Key aspects of investment in the dairy sector and global experience. In conditions of globalisation and fierce competition in international markets, dairy products must comply with high-quality standards, necessitating substantial capital investments in advanced technologies, livestock genetics, feed base, and product processing. Economically, investments in dairy farming are considered long-term allocations aimed at enhancing productivity, reducing production costs, and optimising business processes (Bravo-Ureta *et al.*, 2021). These investments are categorised into capital investments (farm construction and modernisation, equipment acquisition); technological investments (automation of production processes, herd management systems development); innovative investments (genetic improvement, biotechnology, digital solutions); and financial instruments (risk insurance, cooperative development, establishment of investment funds supporting farms) (Subić *et al.*, 2020).

The importance of investments in the dairy sector extends beyond producers themselves. They contribute to job creation in rural areas, which is crucial for regional economic development. Moreover, increased productivity of farms positively affects related industries – from feed production to transportation and dairy processing (Skevas & Oude Lansink, 2020). Hence, investment in dairy farming has a multiplicative effect on the economy, stimulating agro-industrial complex growth and improving living standards in rural communities. Investment attractiveness depends on a combination of economic, legal, technological, and financial factors. The sector requires significant long-term investments in livestock, farm infrastructure, equipment, and innovative technologies. Therefore, investors assess political stability, legal protection, and clarity of regulation, as these influence capital risk levels. Access to financing is a key aspect. High initial costs for equipment, genetic improvement, and infrastructure development require affordable, long-term loans. For example, over 40% of US dairy farms use government credit programmes (Farm Service Agency, n.d.). Insurance programmes and alternative financial instruments – such as agricultural bonds, state subsidies, and support via equity instruments – also play important roles (Qian & Olsen, 2021).

A major barrier to investment remains the low level of technological advancement. Farms lacking automated milking systems have significantly higher labour costs and lower productivity. Implementing advanced solutions reduces costs, improves product quality, and enhances competitiveness. Furthermore, insufficient modern infrastructure (electricity, transport, milk cooling and storage) increases logistical expenses and lowers profitability (St Aisyah Ra *et al.*, 2020). Public policy plays a decisive role in shaping the investment climate. In EU countries, up to 25% of agricultural enterprise income is formed by subsidies and grants (Common Agricultural Policy..., 2022). Effective support programmes – including subsidies for equipment, concessional loans, risk insurance, and investments in rural infrastructure – create a stable environment for investors. Tax incentives, support for market entrants, and development of internal demand increase private capital interest in dairy investments.

Demand for dairy products is a critical factor determining sector investment appeal. Stable demand domestically and internationally underpins investment attraction. Under globalisation, dairy products must meet international quality standards, requiring significant investments in technology improvements and production efficiency. Growing demand for organic or specialised dairy products opens new investment opportunities, as such products typically command higher market prices (Goli *et al.*, 2021). Human capital and workforce qualifications are crucial for production efficiency and competitiveness. Investors face challenges due to insufficient rural agricultural workforce qualifications, limiting technological progress and overall farm efficiency. Attracting investments necessitates not only qualified personnel but also conditions for rural community development – through infrastructure investments, improved living standards, and education access (Deming *et al.*, 2020).

One of the most widespread mechanisms for attracting dairy investments is state financing and subsidies. For instance, the European Union (EU) implements special support programmes under the Common Agricultural Policy (European Commission, n.d.). Farmers receive grants for equipment purchases, genetic improvement, and environmental technology implementation. In the US, state programs such as the Farm Service Agency (FSA) provide financial resources for dairy farmers. FSA offers direct loans for farmers unable to obtain commercial bank financing due to low creditworthiness. These loans target family farms, socially vulnerable farmers, and beginners, with interest rates ranging from 1.125% to 2.5% per annum. FSA also guarantees up to 95% of loan amounts, enabling high-risk farmers to access credit from other lenders.

Alternative financial mechanisms are used in many countries to attract dairy investments. Agricultural bills have become popular in Brazil and India, allowing producers to secure financing against future harvests or livestock output, reducing investor risks and increasing credit availability. Agricultural investment funds promote capital diversification and institutional investor involvement in dairy production (Mukherjee & Yadav, 2024). For example, in the Netherlands, cooperative financing models enable farmers to pool resources, lowering financial risks and ensuring farm stability (The cooperative approach..., 2016).

Modern technologies play a key role in enhancing dairy investment attractiveness. Denmark, Germany, and Canada actively implement automated milking systems, sensor technologies for animal health monitoring, and blockchain solutions for product quality tracking. Such technologies reduce production costs, increase productivity, and attract investors interested in high-tech agricultural projects. An additional factor is green economy development. In Sweden, government incentives promote eco-friendly dairy production through grants for energy-efficient technologies and renewable energy use. This attracts environmentally conscious investors and expands export opportunities (Groher *et al.*, 2020; Krizsan *et al.*, 2021).

Cooperation in the dairy sector is one of the most effective investment attraction models, as it allows small and medium producers to jointly finance infrastructure development, optimise production processes, and increase market access. For example, New Zealand has implemented a successful cooperative dairy business model, where Fonterra, a company owned by farmer cooperatives, controls a significant share of global dairy exports. This model enables producers to pool capital, reduce risks, and achieve higher profits. In France, cooperatives also play an important role in dairy production by allowing farmers to combine resources for shared use of equipment, storage, and product marketing. This facilitates attracting additional investments and creates a more stable business environment (Snikersproge, 2020).

Investors are interested in projects with sustainable product demand and international market access. Successful examples include countries focused on dairy product exports. For instance, Australia actively develops an export strategy targeting Asian markets, especially China, where demand for dairy products continues to grow (Australian dairy industry..., 2025; Department of Agriculture, Food and Marine, n.d.). Ireland operates a national export support programme that helps local producers obtain certification to enter international markets and attract investments into production capacity. As a result, in 2023, Ireland exported dairy products to over 140 countries totalling EUR 6.42 billion, making it one of the leading global dairy market participants.

Status of dairy farming in Ukraine. Dairy production in Ukraine is based on a combination of large agricultural enterprises, small farms, and private household plots. Figure 1 presents the number of cows and milk production volumes across all categories of farms.

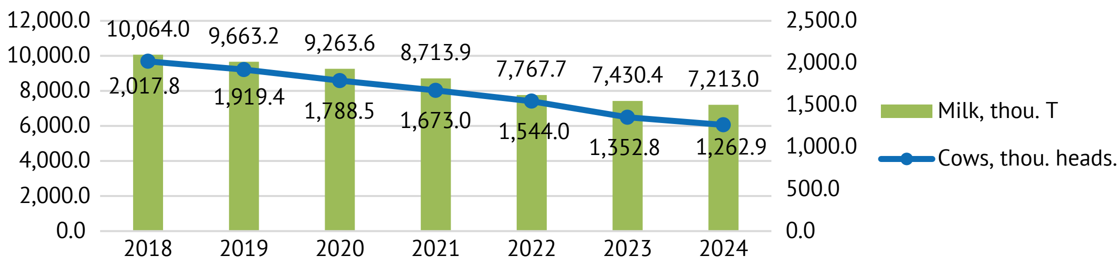

Figure 1. *The number of cows and milk production in Ukraine for 2018-2024*
Source: *developed by the author on the basis of data from the State Statistics Service of Ukraine (n.d.)*

The data presented in Figure 1 indicate a consistent downward trend in both the number of cows and the volume of milk production in Ukraine from 2018 to 2024. Over six years, the cattle population decreased by 37.4% (from 2,017.8 thousand to 1,262.9 thousand head), which directly contributed to a 28.3% decline in milk production (from 10,064 thousand tonnes in 2018 to 7,213 thousand tonnes in 2024). A particularly sharp drop occurred between 2022 and 2024, primarily due to the consequences of the war-farm destruction, logistical disruptions, and financial difficulties faced by farmers. If this trend continues, Ukraine may face a shortage of domestically produced milk and increased dependence on imports. Table 1 presents the number of cows per type of farm.

Table 1. *Number of cows by type of farm in Ukraine in 2018-2024, thousand heads*

Year	2018	2019	2020	2021	2022	2023	2024
Households of all categories	2,017.8	1,919.4	1,788.5	1,673	1,544	1,352.8	1,262.9
Enterprises	466.6	467.9	438.6	423.9	423.7	394.2	382.2
Households	1,551.2	1,451.5	1,349.9	1,249.1	1,120.3	958.6	880.7

Source: *developed by the author on the basis of data State Statistics Service of Ukraine (n.d.)*

The greatest reduction has been observed among household farms. While agricultural enterprises lost 18.1% of their herd (from 466.6 thousand to 382.2 thousand head), the decline in private peasant farms amounted to 43.2% (from 1,551.2 thousand to 880.7 thousand head). This indicates a gradual phasing out of small-scale dairy production due to financial difficulties, low profitability, and lack of support. In contrast, large enterprises show relative stability, although they are also experiencing a decline. This trend may lead to further concentration of dairy production in agroholdings and reduced accessibility of fresh milk for the population.

Various programmes operate in Ukraine to support agriculture, including dairy production, offering grants and other financial assistance. One such initiative is the partial compensation programme, which covers 25% of the cost of domestically produced agricultural machinery and equipment. In 2025, the Ministry of Economy of Ukraine made the first payment under this programme, amounting to UAH 126.6 million, demonstrating its active implementation and support for the agricultural sector (Nemtseva, 2025). The programme provides compensation for machinery and equipment comprising at least 60% Ukrainian materials and components, aiming to enhance agricultural production efficiency, reduce costs for new technologies, and support domestic machinery manufacturers. Strategy for the Development of Agriculture and Rural Areas in Ukraine for the Period Until 2030 (2024) aims to support agricultural producers, including dairy farmers, by providing funding for infrastructure development and social facilities in rural areas. Grants under this programme can be used for modernising dairy farms, constructing processing facilities, and even creating new jobs in rural communities. The strategy also provides funding for improving milk logistics and storage.

Dairy farming in Ukraine has significant potential, but its development is hampered by a range of barriers that complicate investment. Political and economic instability is one of the main risk factors. Frequent changes in legislation, particularly in tax regulations and the state subsidy system, make investment unpredictable. For instance, the cancellation of milk subsidies in 2017 reduced the profitability of many farms (Kukuruza, 2018). Additionally, inflation and hryvnia devaluation diminish the purchasing power of businesses planning to acquire modern equipment. Financial difficulties and limited access to credit hinder farm modernisation. In Ukraine, agricultural loans carry high interest rates (20-25% annually), while in the EU, farmers can access preferential loans at 2-5%. Small and medium-sized farmers struggle to secure financing due to a lack of adequate collateral, which hampers the acquisition of modern equipment and production expansion.

Infrastructure issues and technological lag significantly reduce production efficiency. Farms use outdated equipment, resulting in low productivity – on average, 5,000-6,000 litres of milk per cow annually, compared to over 10,000 litres in Germany. Furthermore, the lack of modern cooling facilities and underdeveloped transport logistics lead to milk losses and a reduction in quality. Insufficient government support and uncontrolled imports create unequal conditions for domestic producers. While the USA and EU countries have robust subsidy and risk insurance programmes, support in Ukraine is selective. Meanwhile, large volumes of cheap imported dairy products, particularly palm oil-based substitutes, create pricing pressure on producers, forcing them to operate with minimal profit margins. Land legislation issues also deter investors. Despite the launch of the land market, the mechanisms for purchasing and leasing land remain complex and opaque. A shortage of qualified personnel exacerbates the sector's crisis. Young professionals see little future in working on farms due to low wages and poor working conditions. Whereas in the USA or the Netherlands, automated farms require minimal staff, the lack of technological modernisation in Ukraine increases reliance on manual labour, further reducing productivity.

The war in Ukraine has become one of the main barriers to investment in the dairy sector, causing physical destruction of farms, livestock losses, logistical problems, and market instability. The high risks associated with active hostilities make investment unpredictable and asset insurance nearly inaccessible. Furthermore, disruptions to supply chains and export restrictions reduce the profitability of production. To attract investors in the future, it is essential to restore production infrastructure, ensure war risk insurance, expand farmer support, and stabilise the economic environment. The level of state support for the sector in 2024 provides a basis for assessing the real potential for overcoming investment barriers, although the funding volume still falls short of the needs of the dairy industry. According to the Draft Law on Ukraine No 3460-IX (2023), the agricultural sector received UAH 4.2 billion in state support, of which UAH 881 million was allocated directly to programmes for agricultural producers. Part of these funds relate to areas that directly or indirectly support dairy farming. In particular, compensation for the cost of Ukrainian agricultural machinery is provided, which partially updates enterprises' technical base after war-related losses. There is also a concessional loan programme for small and medium-sized farms, which is a vital source of funding for the sector given the overall shortage of financial resources.

Additionally, the "Affordable Loans 5-7-9%" programme remains in place, under which the financing limit for agricultural producers in 2024 was increased to UAH 150 million (Order of the Ministry of Finance of Ukraine No. 543, 2024). This creates further opportunities for borrowing, even for large producers. However, it is worth noting that dairy farming is not identified as a separate priority in the budget support structure, which complicates the targeted allocation of resources for the sector's recovery. Despite the availability of financial instruments, the amount of funding does not compensate for the extensive losses in the regions most affected by destruction – such as Kharkiv, Mykolaiv, and Sumy regions. The absence of a clear state strategy for restoring livestock infrastructure and the lack of specialised insurance mechanisms for wartime risks are holding back investment activity. Thus, while certain budget programmes can partially ease the financial burden on farmers, their volume and dispersal limit their effectiveness in overcoming key barriers to investment in the dairy sector. Nevertheless, the existence of such mechanisms provides a potential foundation for a more targeted policy in the future.

Investment activity of dairy enterprises and ways to improve it. Investment activity directly affects the financial stability and competitiveness of dairy enterprises, especially under conditions of high instability. To create a favourable investment environment, it is necessary to implement comprehensive government support mechanisms, including financial incentives, institutional reforms, and technological modernisation. One of the key tools for attracting investment is state financing and subsidies for milk production. An important step is the expansion of subsidy programmes for producers breeding high-yield cattle breeds. The introduction of state grants for the purchase of pedigree livestock and farm modernisation would increase animal productivity and improve milk quality. Furthermore, the interest rate compensation programme for loans related to dairy development should be expanded. Given the country's difficult economic situation, loans for farmers are largely inaccessible due to high rates and short repayment terms. Providing state guarantees and subsidising interest rates would enable access to cheaper financial resources for the construction of modern dairy complexes, purchase of new equipment, and improvement of livestock conditions.

Given the considerable financial needs of the dairy sector, an important area of government policy should be attracting international investors and donor organisations. Ukraine already has experience cooperating with the World Bank, the European Bank for Reconstruction and Development, and the Food and Agriculture Organisation, but the potential of such cooperation remains largely untapped (Nozdrin, 2022). It would be appropriate to establish a national dairy farming support fund based on co-financing from the state and international partners. This initiative would help accumulate funds for long-term projects, including the establishment of large industrial dairy farms, modernisation of logistics, and the introduction of energy-efficient technologies in production. In addition, Ukraine should actively participate in European funding programmes for the agricultural sector, such as Horizon Europe (n.d.) and through the European Investment Bank. The introduction of government mechanisms to facilitate Ukrainian producers' access to grants and loans from international financial institutions would contribute to the sector's development.

Transparent and effective regulatory policy is a critical factor for attracting investment in the dairy farming sector. One of the key challenges is the complexity of obtaining permits for the construction of new dairy farms and passing environmental assessments, which delays the implementation of investment projects. Simplifying licensing procedures, digitalising permitting processes, and reducing the time required to review applications for state subsidies would accelerate the development of the sector. It is also essential to ensure the stability of land ownership rights, which is crucial for long-term investment. The introduction of state-backed investment insurance mechanisms in dairy farming could further reduce risks for potential investors. A significant deterrent for investors is the underdeveloped state of logistics infrastructure, which complicates the delivery of dairy products to processing facilities and export markets. The government should invest in the creation of modern dairy hubs that allow for the centralised processing and transportation of products. In addition, it is necessary to expand public-private partnership programmes for the development of refrigeration equipment, logistics centres, and transport corridors for the export of milk and dairy products to the EU and other countries.

One of the main areas of state support should be the promotion of technological modernisation in dairy production. It is advisable to establish state-run agricultural innovation centres that would provide producers with access to modern technologies in animal husbandry, veterinary control, and milk processing. The government could also stimulate the development of digital technologies, such as automated farm management systems, genetic improvement of livestock, and monitoring of animal health through artificial intelligence. The use of modern IT solutions would enhance production efficiency and reduce costs.

A comprehensive approach to reforming public policy and investment stimulation mechanisms in dairy farming will significantly improve the situation in the sector. The introduction of financial incentives, attraction of international investment, simplification of regulatory procedures, development of infrastructure, and technological modernisation will create the necessary conditions for increasing the competitiveness of Ukrainian dairy production. The implementation of these measures will not only foster the development of the domestic market but also strengthen Ukraine's position as a reliable exporter of dairy products.

DISCUSSION

One of the key findings of the study is the gradual decline in milk production due to a reduction in the dairy herd. This trend diminishes the sector's investment appeal, as production capacities are shrinking and economies of scale become unattainable. The reduction in herd size may stem not only from economic hardship but also from a lack of incentives for farmers to expand their operations. Potential investors assess the sector in terms of risk, and when basic production indicators are declining, capital investment becomes less viable. N. Khan (2020), who studied global milk production, concluded that a declining herd does not necessarily mean reduced output, as modern breeding and nutritional strategies can boost productivity. While this study confirmed a similar trend in herd reduction, it highlighted that in Ukraine it coincides with a decline in total milk output, indicating ineffective production methods. Thus, the conclusions of Khan partially align with the current findings, though his focus is more applicable to stable economies with access to modern technologies.

The study reveals a shift in the structure of dairy production: the number of small farms is decreasing, while large enterprises are gradually dominating the market. This trend can be considered positive in terms of the implementation of modern technologies and improved product quality. Larger producers have better access to investment resources, are more capable of adopting innovations, and operate in compliance with international standards. However, this trend also has negative implications. The disappearance of small farms leads to reduced competition, which may negatively affect prices and the availability of dairy products. J.M. McDonald *et al.* (2020) analysed the consolidation of dairy enterprises and concluded that, although it enhances efficiency, it contributes to the decline of smallholder farms. They viewed this process as inevitable and recommended that public policy support the creation of powerful agroholdings. While the present study confirms the trend toward production concentration, it stresses the dual effect: large enterprises attract more investment, but the decline of small farms may have adverse socio-economic consequences. Unlike the aforementioned authors, this study emphasised the importance of supporting small producers to maintain balance within the sector.

The research confirmed that technological upgrading is a key factor in making dairy farming more competitive. Automation of processes, implementation of modern quality control systems, and adoption of energy-efficient technologies can substantially reduce costs and increase productivity. Technological development, however, requires significant capital investment, which is inaccessible to all enterprises. Therefore, mechanisms of state stimulation play a crucial role – including tax relief for investors, grant programs, or reimbursements for modernisation expenses. M. Subhan Qureshi (2021) founded those investments in cutting-edge technologies, such as automated milking and energy-efficient systems, significantly lower production costs and improved enterprise profitability.

M. Yin (2023) also highlighted the importance of "smart farms", where digital technologies and health-monitoring sensors optimise decision-making and reduced productivity losses. The present findings corroborate this link, showed that companies investing in technological renewal achieve better financial results. However, unlike the referenced authors, this study points out that access to investment resources remains a major barrier, and without government support, technological advancement will remain limited.

Introducing energy-efficient equipment, using renewable energy sources, and optimising dairy transportation processes can reduce costs. However, these measures require substantial investment, raising the question of their feasibility without additional financial incentives. P. Shine *et al*. (2020) explored the impact of energy costs on dairy product prices, noting that biogas installations significantly reduce expenses and increase resilience during energy crises. The current study also confirmed that high energy costs are a critical issue for the sector. However, unlike international experience, the adoption of alternative energy in Ukraine remains low due to significant investment barriers.

Access to finance is another crucial factor for attracting investment. The study showed that obtaining credit resources remains difficult for dairy farms due to high interest rates and substantial collateral requirements. Small and medium-sized producers are often unable to use banking tools, which limits their development opportunities. Successful international practices demonstrated the importance of public support in this area. Credit guarantee programs, partial interest rate compensation, or the establishment of special investment funds can significantly improve the situation and encourage capital inflows. M. Guth *et al*. (2020), analysed farm credit mechanisms in the EU, found that state guarantees significantly increase investment levels. Similarly, P. Pazienza & C. De Lucia (2020) stressed that farmers with access to long-term, low-interest loans are more likely to invest in technology and expand production. The present study confirms the importance of accessible financing but also showed that such mechanisms in Ukraine are ineffective due to high interest rates and bureaucratic obstacles. Unlike the EU, Ukrainian farmers face limited opportunities to attract affordable investment.

Expanding export markets is a key direction for dairy sector development. Access to new trade platforms allows risk diversification related to domestic demand fluctuations and ensures stable foreign currency revenues. However, entering international markets requires compliance with strict quality standards, certified production, and robust logistics. These factors require substantial investment, making state support for export activities vital. C.A. Pírela *et al*. (2024) founded that successful export strategies depend on long-term partnerships and strict adherence to international standards. The current study also showed that export development is strategic but hampered in Ukraine by regulatory barriers and the need for further investment in certification.

One of the most influential aspects affecting the attractiveness of dairy farming for investors is government regulation. Clear, stable, and predictable policy encourages capital inflows. Key measures include tax incentives, streamlined permitting processes, infrastructure development, and support for scientific research in dairy farming. M. Kondaridze & J. Luckstead (2023) noted that strong government investment helps maintain sector stability during crises. Their findings showed that state compensation for feed and veterinary costs lowers production costs and boosts competitiveness. The present study confirmed the critical role of public support but also finds that in Ukraine such mechanisms are either ineffective or underfunded, limiting producers' ability to improve production. Dairy farming is a promising yet complex sector for investment. The studies referenced above demonstrate that investment, state support, technological modernisation, export capacity, and environmental challenges are key development factors for global dairy farming. However, these aspects have distinct characteristics in each national context.

CONCLUSIONS

The study of investment attractiveness in the dairy farming sector has made it possible to identify key challenges limiting the industry's development, as well as the main factors that could stimulate its growth. An analysis of statistical data for the period 2018-2024 revealed that the number of dairy cows in Ukraine declined from 2,017.8 thousand in 2018 to 1,262.9 thousand in 2024, while milk production fell from 10,064 thousand tonnes to 7,213 thousand tonnes. This trend indicates a systemic contraction of the livestock base, caused by insufficient investment, rising production costs, and difficult economic conditions. Alongside the general decline in production volumes, a structural transformation is taking place: the number of cows on agricultural enterprises has remained relatively stable (approximately 382.2 thousand in 2024), while household farms lost over 670 thousand cows during the analysed period. This indicates the crowding out of small-scale producers from the market and highlights the need for state support and the creation of cooperative associations to enhance the competitiveness of smallholder farms.

An analysis of government support programmes for dairy farming in Ukraine has revealed several major barriers to investment. In particular, the low level of funding, the limited availability of insurance schemes, and difficulties in accessing concessional loans restrict the industry's development potential. The war in Ukraine has further exacerbated the situation, causing widespread infrastructure destruction and a decrease in profitability. To overcome these barriers, it is necessary to increase state support, improve financial instruments, and ensure economic stability.

A limitation of this study lies in its reliance on existing statistical data and the financial indicators of a single enterprise, which do not cover the full range of factors influencing the investment attractiveness of the sector. Future research may include an in-depth analysis of the effectiveness of government support programmes, an assessment of war-related investment risks, and a comparative study with similar models in other countries.

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Бар'єри для інвестування у молочне тваринництво в Україні: як їх подолати

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Анотація. Актуальність дослідження зумовлена необхідністю покращення інвестиційної привабливості молочного тваринництва в Україні в умовах глобальних викликів та внутрішніх економічних проблем. Метою роботи стало виявлення основних бар'єрів, які стримують інвестування в галузь, зокрема в контексті модернізації та підвищення ефективності виробництва. У статті було досліджено ключові напрями інвестування в молочне тваринництво, зокрема капітальні, технологічні та інноваційні вкладення. Було проаналізовано міжнародний досвід: у країнах Європейського Союзу до 25 % доходів фермерів формується за рахунок дотацій, у Сполучених Штатах Америки понад 40 % ферм користуються державними кредитами під 1,125-2,5 % річних. Встановлено, що в Україні за 2018-2024 рр. поголів'я корів скоротилося на 37,4 %, а обсяг виробництва молока – на 28,3 %. Було виявлено основні бар'єри для інвестування: високі ставки кредитів (20-25 % річних), нестабільність політики, зношена інфраструктура та наслідки війни. У підсумку обґрунтовано доцільність комплексної державної підтримки, залучення міжнародного фінансування та модернізації як ключових напрямів відновлення галузі. У результаті дослідження запропоновано комплекс заходів для стимулювання інвестицій у молочне тваринництво, зокрема розвиток програм державної підтримки, спрощення регуляторних процедур, залучення міжнародних фінансових установ, модернізацію логістичної інфраструктури та підтримку кооперації малих і середніх виробників. Отримані результати можуть бути використані органами державної влади, інвесторами та аграрними підприємствами для формування ефективної політики підтримки, ухвалення інвестиційних рішень та стратегічного планування розвитку молочного тваринництва

Ключові слова: державне регулювання; технологічна модернізація; капіталовкладення; економічна стійкість; воєнні ризики

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