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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.

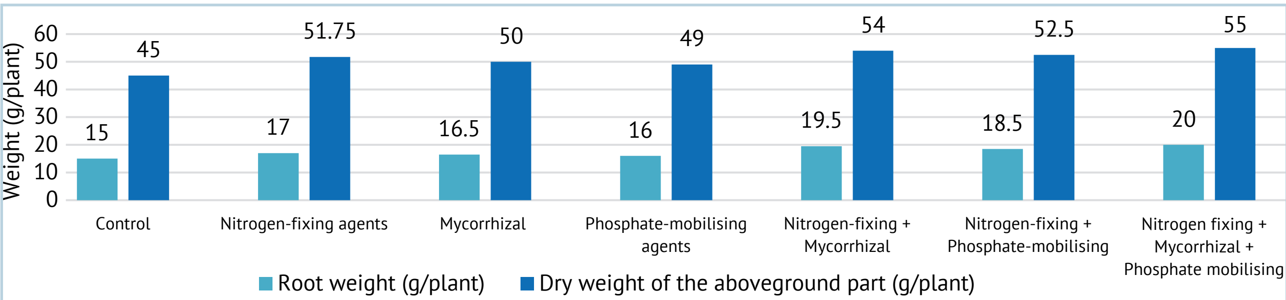

Figure 1. *Growth dynamics of the root system and ground parts of plants*
Source: *compiled by the authors*

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).

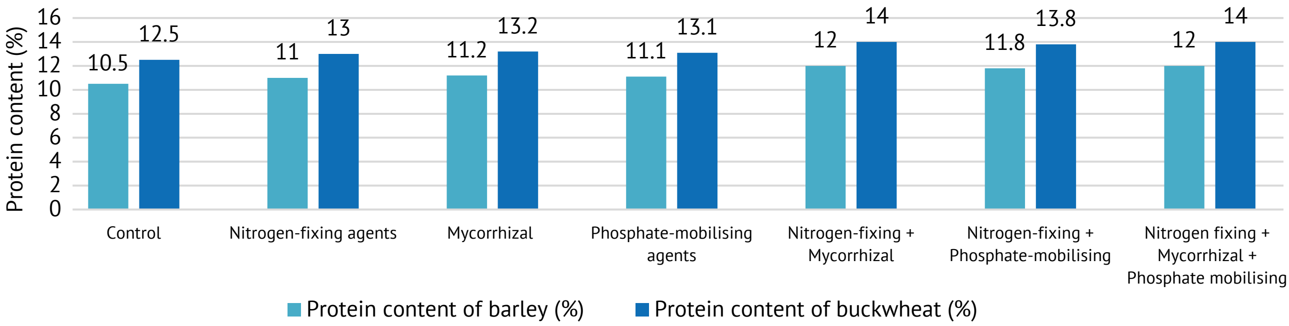

Figure 2. *The impact of biological products on grain quality*

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.

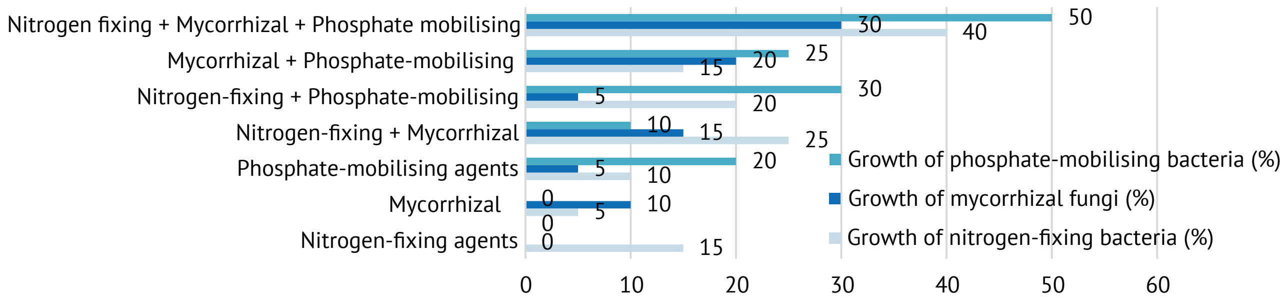

Figure 3. *Changes in the composition of soil microflora when using different biological products*
Source: *compiled by the authors*

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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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