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THE INFLUENCE OF BIOPREPARATIONS ON SOIL NUTRIENT REGIME AND PEA YIELD IN THE CONDITIONS OF SOUTHERN UKRAINE

S u m m a r y

Background. Modern farming systems require environmentally safe technologies that enhance crop productivity without the excessive use of mineral fertilizers. This is particularly important for legumes such as peas, which play a crucial role in restoring soil fertility and supporting food security. The aim of this study was to investigate the effects of biopreparations based on nitrogen-fixing bacteria and organic substances on pea productivity in the Southern Steppe of Ukraine and to evaluate their agronomic effectiveness. The research was conducted between 2024 and 2025 on the "Kruiz" and "Bilyi anhel" ("White Angel") pea cultivars. The study examined the effects of seed pre-sowing treatments with "Azotofit" (based on *Azotobacter chroococcum*) and "Humifrend" (containing humic substances and microorganisms), as well as foliar feeding with "Organic-balance".

Results and conclusions. The results showed that the highest yield increase was achieved with the combined treatment of "Azotofit" seed treatment and "Organic-balance" foliar application: 0.58 ÷ 0.63 t/ha (28.9 ÷ 32.5 % above control) for "Kruiz" and 0.47 ÷ 0.66 t/ha (18.9 ÷ 26.2 %) for "Bilyi anhel". The combination of "Humifrend" + "Organic-balance" also improved yields, giving 0.44 ÷ 0.45 t/ha for "Kruiz" and 0.55 t/ha for "Bilyi anhel." Individual seed treatments consistently increased productivity: "Azotofit" by 0.27 ÷ 0.37 t/ha and "Humifrend" by 0.24 ÷ 0.33 t/ha. Biopreparations also improved soil agrochemical properties, increasing easily hydrolysable nitrogen by 12 ÷ 15 % and slightly lowering pH by 0.2 ÷ 0.3 units. These findings confirm that using biopreparations in pea cultivation is an effective component of modern agricultural technology, enabling higher yields, enhanced soil quality and more environmentally sustainable farming.

Key words: Pisum sativum, nitrogen fixing bacteria, crops, pre-sowing treatment, cultivar, foliar application

Introduction

Under contemporary agricultural conditions, ensuring food security for a growing global population is increasingly challenged by soil degradation, rising energy costs

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and climate change. In this context, leguminous crops play a central role in sustainable farming systems because of their capacity for symbiotic nitrogen fixation, which makes them an important component of crop rotations aimed at maintaining soil fertility and reducing dependence on mineral fertilizers. Therefore, improving biological nitrogen fixation in pea cultivation is not only a local agronomic task, but also an important component of sustainable agriculture, as it can support crop productivity, while reducing reliance on mineral nitrogen fertilizers. As noted by Vasconcelos et al. [49], leguminous crops have a unique agronomic, economic and social impact, extending far beyond simple protein production, as they improve the soil environment for subsequent crops. However, as emphasized in the work of Kebede [23], the real potential of biological nitrogen fixation in agricultural systems often remains unrealized due to a range of abiotic and biotic stressors that limit the efficiency of symbiosis. For example, drought, soil salinity, heat stress and nutrient imbalance are abiotic stressors, whereas pathogen pressure, pest damage and competition with ineffective soil microorganisms are biotic factors that can disrupt nodulation and nitrogenase activity [23, 42, 43].

This problem is particularly acute in arid regions, especially in the conditions of southern Ukraine, where southern chernozems are widespread, prone to a moisture deficit, salinization and significant mineralization of organic matter. Low humus content, alkaline soil solution reaction and the imbalance of nutrients create unfavorable conditions for plant development and soil microorganisms [32, 50]. Under such conditions, traditional agricultural technologies often prove insufficiently effective, necessitating the search for innovative, resource- and energy-efficient approaches. One promising approach is the application of microbial biopreparations and humic-based products, which can significantly improve the efficiency with which plants use available resources [28, 29].

Research conducted in various climatic zones confirms the efficacy of biopreparations for increasing the productivity of agricultural crops. Panfilova et al. [37] demonstrated that biological preparations can enhance winter wheat productivity under irrigated conditions. Their subsequent study further indicated that the effectiveness of these preparations is strongly mediated by moisture availability [36]. Petrychenko et al. [38] investigated the influence of different pre-sowing treatment methods on soybean seed quality. The study showed that the application of biopreparations and microelements substantially improved germination energy and laboratory seed germination. However, as noted by Drobitko et al. [8], the potential of leguminous crops for the sustainable development of the agricultural sector is insufficiently realized, requiring a deeper study precisely of their response to the action of biological preparations. The importance of legumes for increasing soil fertility was emphasized by Rajput et al. [39] and Yuvaraj et al. [53], who pointed to their role in improving the physical, chemical and biological properties of soil through nitrogen fixation, green manuring and erosion

prevention. However, the response regarding soil fertility can differ significantly depending on the legume species, as demonstrated in the study by Romanyà and Casals [41]. Furthermore, Singh et al. [45] proved that organic fertilizers (to which humic preparations can also be attributed) play a crucial role in improving soil fertility by enhancing their structure, water-holding capacity and nutrient supply.

Despite previous studies on the effects of biopreparations, microbial inoculants, and organic fertilizers on crop productivity and soil fertility, the combined influence of nitrogen-fixing and humic preparations on pea productivity and the nutrient regime of southern chernozem under the conditions of southern Ukraine has not been sufficiently investigated. This gap is particularly important because a moisture deficit and low organic matter content are the main limiting factors in this region.

This research aimed to evaluate the effects of seed treatment and foliar application of nitrogen-fixing and humic biopreparations on the yield of two pea cultivars and selected agrochemical indicators of southern chernozem in southern Ukraine. To achieve the aim, the following objectives were set: to determine the dynamics of pea yield depending on the cultivar and scheme of biopreparations application; to assess changes in the content of easily hydrolysable nitrogen, mobile forms of phosphorus and potassium, humus and soil solution pH after the application of the preparations; to establish the most effective combinations of biopreparations for achieving maximum crop productivity.

Materials and methods

The research was conducted between 2024 and 2025 in the fields of the Educational-Scientific-Practical Center of the Mykolaiv National Agrarian University, located in the village of Senchyne, the Mykolaiv region (southern Ukraine). An agrochemical analysis of baseline soil samples, taken before establishing the experiment on heavy loamy southern chernozem formed on loess deposits with the signs of residual weak solonetzicity, revealed fertility limitations characteristic of the region. The soil solution reaction was slightly alkaline (pH – 7.8 ÷ 8.9), creating suboptimal conditions for microelement availability and microorganism activity. The humus content varied from low to very low levels (1.9 ÷ 3.8 % by horizons), and the supply of easily hydrolysable nitrogen was critically low (54.8 ÷ 88.9 mg/kg). Mobile phosphorus compounds had an uneven distribution across the profile: elevated content in the 0 ÷ 30 cm layer (109.2 ÷ 115.1 mg/kg) sharply changed to very low (1.9 mg/kg) in the 30 ÷ 60 cm layer. Potassium supply was characterized as very high in the arable horizon (226.2 ÷ 234.9 mg/kg) and medium in the 30 ÷ 60 cm sublayer (51.1 mg/kg).

Climatic conditions during the study reflected the continental climate typical of the Southern Steppe of Ukraine. The mean annual air temperature was +10.5°C, with mean January and July temperatures of -3.5°C and +23.2 °C, respectively. The annual

precipitation amounted to 425 mm, with approximately 70 % occurring during the warm period of the year. In 2024, a minor deviation from the long-term averages was observed, with a temperature increase of 1.2°C and a 15 % reduction in precipitation, whereas 2025 was marked by a more pronounced drought – the precipitation deficit reached 28 % of the norm with average temperature values. These conditions necessitated the application of resource-saving technologies aimed at the efficient utilization of limited moisture resources.

The study focused on pea stands of Pisum sativum L., represented by the mid-season cultivar "Kruiz" and the early-season cultivar "Bilyi anhel", as well as the soil of the experimental plot. These cultivars were selected because they differ in their maturity periods and productivity potential, which made it possible to compare the response of an early-season and a mid-season pea cultivar to biological treatments under the same soil and climatic conditions. The seeds were provided by the Educational-Scientific-Practical Center of the Mykolaiv National Agrarian University and complied with the requirements for cultivars according to DSTU 4138-2002. Seeds of agricultural crops. Methods for determining quality [10].

The experimental design included the following variants: Factor A – cultivar: 1. Kruiz 2. Bilyi anhel. Factor B – pre-sowing seed treatment: 1. Control (water treatment). 2. Humifriend. 3. Azotofit. Factor C – foliar application: 1. Water treatment. 2. Organic-balance. Each experimental variant was arranged in four replications. The total number of experimental plots was 40 (2 cultivars × 5 treatment variants × 4 replications). The size of the accounting plot was 25 m², with the preceding crop being winter wheat.

For pre-sowing seed treatment, the following biopreparations were applied: Azotofit (composition: cells of the bacterium *Azotobacter chroococcum* in the quantity of not less than 1.0×10^9 CFU/cm³; micro- and macroelements, biologically active substances; bacterial metabolites: enzymes, amino acids, vitamins, phytohormones, fungicidal substances) – according to the norm of 35 cm^3/0.5 dm^3 of water; and Humifriend (potassium salts of humic and fulvic acids, 120 g/ dm^3, a microbial complex of five strains of the genus Bacillus, microelements, BAS (biologically active substances) (amino acids, peptides, polysaccharides, succinic acid)) – according to the norm of 1.0 l/t of seeds. For foliar application, the biopreparation Organic-balance (*Bacillus velezensis* (*Bacillus subtilis*), Agrobacterium pusense (*Azotobacter chroococcum*), Paenibacillus polymyxa, Enterococcus hirae (*Enterococcus faecium*), Lactobacillus delbrueckii sp. bulgaricus, titre 1×10^9 CFU/cm³) was used at a rate of 0.5 dm^3/ha with a working solution application rate of 300 dm^3/ha, applied by spraying. Pea cultivation agronomy was conventional for the Southern Steppe zone. Field investigations were conducted in accordance with generally accepted methodologies.

Soil sampling was carried out in accordance with the requirements of DSTU 4287:2004. Soil quality. Sampling [11]. Sampling was performed using the "envelope" method from two depth horizons: 0 ÷ 30 cm and 30 ÷ 60 cm. Sampling was conducted twice: before establishing the field experiment to characterize the initial soil state and after the harvest to assess the dynamics of agrochemical indicators. For each treatment variant, soil subsamples from the four replicated plots were combined into one composite sample; therefore, soil agrochemical indicators were analyzed at the treatment-variant level rather than as separate replicate-level measurements.

The determination of main agrochemical indicators was performed under laboratory conditions using standard methods. The measurement of acidity (pH) in a water extract was carried out by the potentiometric method using a Hanna Instruments laboratory pH-meter (Romania) in accordance with DSTU ISO 10390:2022. Soil, treated biowaste and sediment. Determination of pH [14]. Humus content was determined by the oxidation of organic matter with potassium dichromate solution (Tyurin method) with subsequent photocolorimetric measurement of color intensity on a Specord 40 spectrophotometer (Germany) according to DSTU 7855:2015. Soil quality. Determination of the group composition of humus by the Tyurin method in the modification of Kononova and Belchykova [12]. The determination of readily hydrolyzable nitrogen by the Kornfield method was performed by hydrolyzing the soil with an alkali solution, followed by ammonia distillation and its fixation in a boric acid solution according to DSTU 7863:2015. Soil quality. Determination of readily hydrolyzable nitrogen by the Kornfield method [13]. The determination of mobile forms of phosphorus and potassium was carried out by the Chirikov method in the modification of the Central Scientific Research Institute of Agrochemical Service (TsINAO) by extracting compounds with an ammonium carbonate solution in accordance with DSTU 4115-2002. Soils. Determination of mobile phosphorus and potassium compounds by the modified Chirykov method [9]. The phosphorus content in the extract was determined by the photocolorimetric method on a "FKP-2" photocolorimeter (Ukraine). The potassium content was determined by the flame photometric method using a "PFP7" flame photometer manufactured by Jenway (UK).

A yield assessment was carried out by the method of direct combine harvesting of each accounting plot. After harvesting, grain from each plot was weighed, and grain moisture was determined using analytical balances and a "SUF-110" drying oven (Ukraine) to adjust the yield to standard moisture content (14 %). Final yield data are presented in tons per hectare (t/ha).

Yield data were analyzed using three-way ANOVA, with cultivar, pre-sowing seed treatment, and foliar application as fixed factors; the main effects and their two- and three-factor interactions were tested in the Statistica 10.0 software environment (USA). To assess the significance of differences between the mean values of the vari-

ants, Student's t-test was used at a significance level of $p \leq 0.05$. All results are presented as the arithmetic mean value ± standard error of the mean.

Results

The results of the two-year study confirmed that biopreparations had a significant effect on the yield of the "Kruiz" pea cultivar. It was established that the use of different variants of biological seed treatment and foliar application provided significant differences in productivity levels compared to control plots (Figure 1).

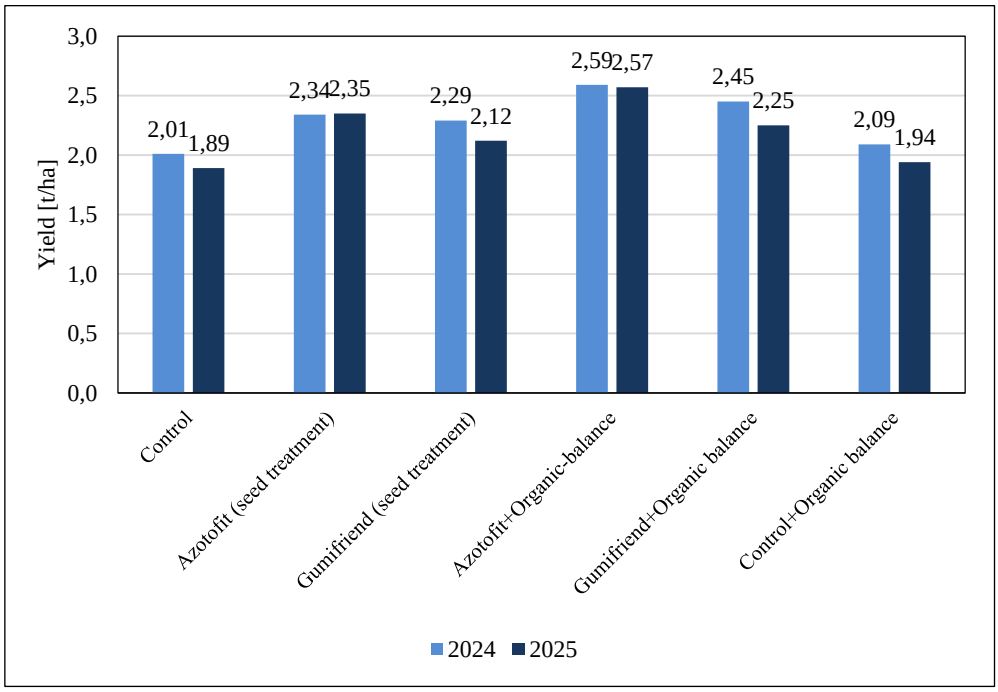


Figure 1. Yield of the "Kruiz" cultivar under the influence of biopreparations
Explanatory notes: source: compiled by the authors.

In 2025, less favorable weather conditions were observed, as confirmed by a decrease in the yield of control plots to 1.89 t/ha. Despite this, the general trend of the positive influence of biopreparations remained consistent. Pre-sowing seed treatment with the preparation Azotofit in 2025 provided a yield of 2.35 t/ha, constituting an increase of 0.46 t/ha or 24.3 % compared to the control (1.89 t/ha). With the application of Humifriend, the yield was 2.12 t/ha, corresponding to a gain of 0.23 t/ha or 12.2 % relative to the control. The application of combined schemes proved more effective: seeds treated with Humifriend followed by the foliar application of Organic-

balance provided a yield of 2.25 t/ha, exceeding the control by 0.36 t/ha (19.1 %). The highest indicators were obtained with the combined use of Azotofit and Organic-balance – 2.57 t/ha, which is 0.68 t/ha (36.0 %) more compared to the control.

A summary of the two-year results indicates that the application of biopreparations during the cultivation of "Kruiz" provided a stable yield increase of 0.25 ÷ 0.63 t/ha, depending on the year and treatment variant. The most effective was the combination of pre-sowing seed treatment with Azotofit and subsequent foliar application of Organic-balance, confirming the advisability of an integrated approach to the biologization of cultivation technologies for the "Kruiz" pea cultivar. It is also important that even under unfavorable climatic conditions, the biopreparations retained their ability to increase yield, indicating their potential in mitigating the negative impact of stress factors.

The "Bilyi anhel" pea variety was characterized by a higher yield potential compared to the "Kruiz" variety, which was confirmed by data from both years of the study. On average, the productivity indicators in all studied variants for this variety exceeded the corresponding results of the "Kruiz" variety; however, the relative effect of biopreparation application remained stable (Figure 2). This suggests that biopreparations can both increase a yield and enhance the expression of the genetic potential of the crop.

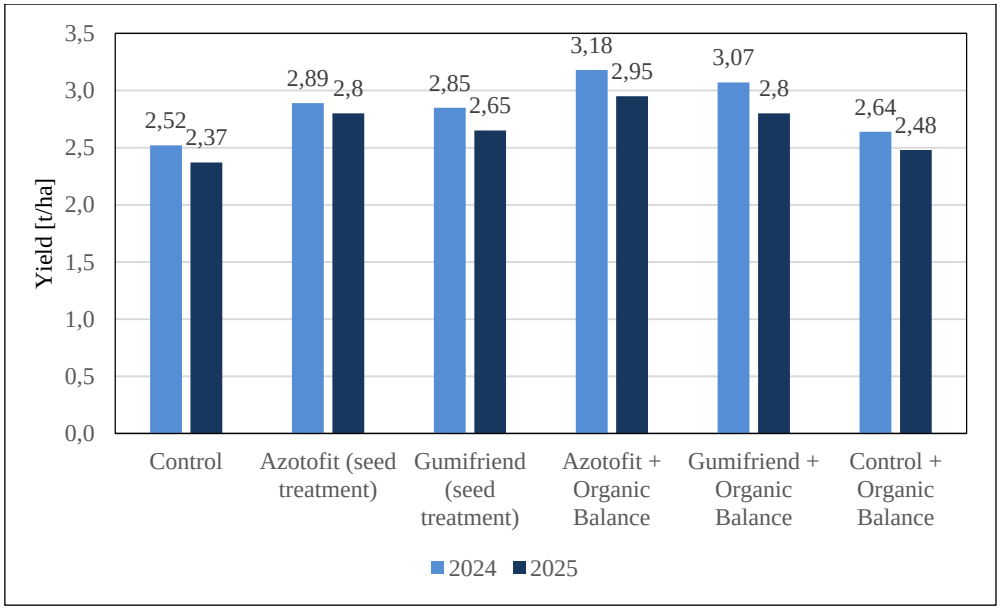


Figure 2. Yield of the "Bilyi anhel" variety under the influence of biopreparations
Explanatory notes: source: compiled by the authors.

In 2024, the yield of the control plots of the "Bilyi anhel" variety was 2.52 t/ha, which was 0.51 t/ha higher than the corresponding indicator for the "Kruiz" variety. Pre-sowing seed inoculation with Azotophyt provided a yield of 2.89 t/ha, with an increase of 0.37 t/ha or 14.7 % relative to the control. Similar results were observed in the variant using Humifriend (2.85 t/ha), where the yield increase was 0.33 t/ha (13.1 %). However, the most significant effect was achieved by combining seed inoculation with Azotophyt and foliar feeding with Organic-balance: the yield in this variant reached 3.18 t/ha, exceeding the control by 0.66 t/ha (26.2 %). A slightly lower, but still significant result was observed with the combination of Humifriend and Organic-balance (3.07 t/ha), which was 0.55 t/ha (21.8 %) higher than the control level. Thus, 2024 demonstrated a high level of the realization of the "Bilyi anhel" variety potential under the conditions of combined biopreparation application.

In 2025, a general decrease in yield was observed across all variants, which is associated with less favorable weather conditions. This is confirmed by the reduction in yield of the control plots of the "Bilyi anhel" variety to 2.37 t/ha, which is lower than in the previous year. Despite this, the relative effectiveness of biopreparations remained high. Thus, the use of Azotophyt for seed treatment provided a yield of 2.80 t/ha, exceeding the control by 0.32 t/ha (12.9 %). When applying Humifriend, the yield increased to 2.65 t/ha (an increase of 0.17 t/ha or 6.9 %), and a combination with Organic-balance allowed for a yield of 2.80 t/ha (an increase of 0.32 t/ha, 12.9 %). The maximum yield indicators, similarly to the previous year, were obtained with the combined use of "Azotophyt + Organic-balance", where the yield reached 2.95 t/ha, exceeding the control by 0.47 t/ha (18.9 %).

The comparison of the two-year results reveals several important patterns. Firstly, regardless of the yield level in the control plots (which varied under the influence of weather conditions), the increase from biopreparation application remained stable, ranging from 0.17 to 0.66 t/ha. Secondly, the most effective practices were the combined applications involving pre-sowing seed treatment followed by foliar feeding, indicating a stronger combined effect of different forms of biological preparation application. Thirdly, the "Bilyi anhel" variety demonstrated a higher level of the realization of its potential under the conditions of the biologization of cultivation technologies, as its maximum indicators exceeded the corresponding results of the "Kruiz" variety by an average of 0.55 ÷ 0.60 t/ha (Table 1).

A three-way ANOVA confirmed significant main effects of the cultivar, pre-sowing seed treatment and foliar application on the pea yield, as well as a significant seed treatment × foliar application interaction, indicating that the effect of combined application exceeded the effect of separate treatments. Thus, the data obtained suggest that the application of biopreparations is a promising direction for increasing pea productivity, particularly for high-yielding varieties. Biopreparations not only increase

yield in favorable years, but also allow for partial compensation of the negative impact of stress factors in the years with less favorable conditions, which is an important argument in favor of their practical use in commercial crops [15, 26].

Table 1. Pea yield [t/ha] depending on the variety, seed treatment and foliar feeding

Year	Variety	Pre-sowing seed treatment	Foliar feeding (water)	Foliar feeding (Organic-balance)
2024	Kruiz	Control (water)	2.01	2.09
		Humifriend	2.29	2.45
		Azotophyt	2.34	2.59
	Bilyi anhel	Control (water)	2.52	2.64
		Humifriend	2.85	3.07
		Azotophyt	2.89	3.18
2025	Kruiz	Control (water)	1.89	1.94
		Humifriend	2.12	2.25
		Azotophyt	2.35	2.57
	Bilyi anhel	Control (water)	2.37	2.48
		Humifriend	2.65	2.80
		Azotophyt	2.80	2.95

Explanatory notes: source: compiled by the authors.

The analysis of soil agrochemical properties after the completion of the vegetation period demonstrated certain changes that can be linked to the use of biopreparations in the pea cultivation technology. The most noticeable dynamics were observed in the content of easily hydrolysable nitrogen in the topsoil layer (0 ÷ 30 cm), while other indicators, including humus content, mobile forms of phosphorus and potassium, as well as soil solution acidity, changed less significantly.

In the variants where the Azotophyt biopreparation was applied, a significant increase in the concentration of easily hydrolysable nitrogen was noted, averaging 12 ÷ 15 % compared to the control. The highest values were observed in the variants with a combined effect – pre-sowing seed inoculation with Azotophyt followed by foliar feeding with Organic-balance. In these variants, the content of available nitrogen compounds in the soil was maximal, indicating the effective work of nitrogen-fixing bacteria *Azotobacter chroococcum*, which are part of the preparation. These microorganisms are capable of not only fixing atmospheric nitrogen, but also synthesizing biologically active substances that stimulate plant growth and development, thereby promoting a more active nitrogen uptake and its incorporation into the soil-plant cycle [33, 34, 35].

Changes in soil solution acidity were less pronounced, but still positive. The initial pH values averaged 7.8 ÷ 8.9, corresponding to a weakly alkaline reaction. After biopreparation application, a decrease in this indicator by 0.2 ÷ 0.5 units, i.e. to a level

of 7.3 ÷ 8.7, was noted. Although such a shift is not radical, it has agronomic significance as it moves the soil solution reaction closer to neutral. For leguminous crops, particularly peas, neutral or weakly alkaline conditions are optimal for the development of symbiotic nitrogen-fixing bacteria of the genus *Rhizobium*, which improves the formation and functioning of nodular structures [48]. Therefore, even slight acidification of the soil can be considered an additional positive effect of biopreparations.

Regarding the humus content, statistically significant changes were not recorded over the two years of the study. This is expected, as humus is the most inert part of soil organic matter and the formation of significant changes in its content requires long time and the systematic application of organic and biological technologies. At the same time, in the variants with biopreparation application, a trend towards a slight increase in this indicator (by 0.1 ÷ 0.2 % compared to initial data) was observed, although this trend should be interpreted cautiously, since a two-year observation period is insufficient to confirm stable changes in humus accumulation. A similar situation is characteristic of the mobile forms of phosphorus and potassium. Over the two years, their concentrations remained relatively stable, without significant fluctuations. At the same time, in the variants with biopreparations, a trend towards improved availability of these elements for plants was noted. This can be explained by the fact that microorganisms included in the studied preparations participate in the mobilization of nutrients, converting them into more available forms. In particular, part of the microbiota is capable of producing organic acids that dissolve poorly soluble phosphorus compounds, as well as enzymes that facilitate the mineralization of organic residues [18, 30]. Thus, although the overall nutrient balance in the soil did not change significantly, their biological availability to cultivated plants increased.

The observed changes occurred independently of the research year and weather conditions, although the absolute values of some indicators exhibited certain fluctuations. This indicates that the application of biopreparations not only positively impacts yields, but also contributes to the stabilization of the soil agrochemical status [20]. In the long term, the systematic use of such preparations may create preconditions for a gradual improvement in fertility, particularly under the conditions of intensive agriculture, where the depletion of soil resources is observed. Consequently, the primary effect of biopreparation application in the experiments was an increase in the content of readily hydrolysable nitrogen and optimization of the soil solution acidity. Changes in the content of humus, mobile phosphorus and potassium were of a trending nature, without statistically significant deviations. This indicates that the action of biopreparations is primarily aimed at activating biological processes in the soil and mobilizing existing nutrient reserves, rather than their fundamental accumulation. These soil changes help explain the observed yield response: the increase in readily hydrolysable nitrogen improved nitrogen supply during active pea growth, while the shift of soil pH

towards neutral conditions favored nutrient availability and the activity of beneficial microorganisms. Therefore, the higher yields in the combined treatment variants can be interpreted not only as a direct plant-stimulating effect of the biopreparations, but also as a consequence of improved soil conditions for pea growth.

A statistical analysis of the results from the two-year studies allowed for an objective ranking of biopreparation application variants based on their effectiveness regarding pea productivity and optimization of soil agrochemical parameters. The highest indicators were recorded in the variant with the combined scheme of seed treatment with Azotofit + foliar feeding with Organik-balance. This combination provided a yield increase of 18 ÷ 22 % compared to the control, which proved stable for different cultivars and in both research years. This result is explained by the synergistic action of two biological agents: nitrogen-fixing bacteria *Azotobacter chroococcum* in Azotofit and a complex of humic acids and biologically active compounds in Organik-balans. Due to this, not only nitrogen availability increased, but also root nutrition stimulation, the improvement of soil water-holding capacity and the activation of metabolic processes in plants occurred.

The second most effective was the variant Humifrend+Organik-balans, which provided an average yield increase at the level of 14 ÷ 17 %. In this case, the key factor is the increased bioavailability of nutrients due to the action of humic substances and microbial metabolites, which promote the activation of rhizospheric processes. However, it should be emphasized that Azotofit demonstrated higher efficacy compared to Humifrend, as its effect is more directly linked to providing plants with nitrogen, whereas Humifrend primarily performs stimulatory and modifying functions. It is worth noting that even the separate application of biopreparations for pre-sowing seed treatment (without foliar feeding) had a consistently positive effect. Thus, seed inoculation with Azotofit increased the yield by an average of 9 ÷ 11 %, while the use of Humifrend provided an increase of 6 ÷ 8 % compared to the control. This indicates the important role of nitrogen-fixing bacteria in enhancing pea productivity, especially under the conditions of available nitrogen deficiency in the soil, which is a characteristic feature of southern Ukraine. The data obtained confirm that seed inoculation acts as a key element of the agricultural biologization system under these conditions.

Furthermore, the application of biopreparations had not only a direct effect in the form of yield growth, but also an indirect one – through the improvement of soil characteristics. It was established that the use of Azotofit contributed to an increase in the content of readily hydrolysable nitrogen and a partial decrease in pH, whereas Humifrend stimulated root system development and positively affected crop moisture supply. These properties provide the preparations with a long-term agronomic value, extending beyond short-term yield enhancement. Thus, the results of the comparative evaluation confirmed the agronomic expediency of applying biopreparations in pea

cultivation. What is the most promising is the combined use of biopreparations, which ensures not only the maximum effect, but also results in stability under different weather conditions and for different cultivars.

Discussion

The results demonstrated the considerable potential of biopreparations to increase pea productivity and improve selected soil fertility parameters under the conditions of southern Ukraine. The pronounced positive effect, particularly from the combined application of the inoculant Azotofit and the organic stimulant Organik-balans, is consistent with current global trends in agricultural biologization. As noted by Shebanin et al. [44] and Korkhova et al. [27], the use of biologization elements is key not only for obtaining high-quality products, but also for environmental conservation. The application of biopreparations contributed not only to a yield growth, but also to positive dynamics in the content of readily available nitrogen in the soil. The significant yield gain from seed inoculation with nitrogen-fixing bacteria (*Azotobacter chroococcum*) is important under the conditions of the southern region, where a critically low content of readily hydrolysable nitrogen in the soil is observed. Similar results were obtained by Borase et al. [7], who proved that the long-term use of leguminous crops and microbial inoculants significantly enhances soil microbial activity and biochemical properties. However, unlike the long-term soil-biological focus of Borase et al. [7], the present study demonstrates a short-term yield response under arid Southern Steppe conditions, where the initial nitrogen deficiency made the effect of Azotofit more pronounced. The synergistic effect from combining a microbial preparation with an organic stimulant (Azotofit+Organik-balans) can be explained by the fact that humic substances act as cofactors, stimulating bacterial metabolic activity and improving conditions for their symbiotic interaction with the plant. The present findings are comparable with Ye et al. [51] in confirming the advantage of combined biological and organic inputs; however, the mechanism in this study was primarily associated with nitrogen fixation and humic stimulation rather than with reduced chemical fertilization. In contrast to Barbosa et al. [2], who analyzed rhizobia–Trichoderma co-inoculation, the current experiment involved Azotobacter-based and humic preparations, which suggests that combined biological effects may be achieved through different microbial and organic pathways. The stability of biopreparation action in the years with differing weather conditions (2024 and 2025) confirms their ability to mitigate stresses caused by unfavorable environmental factors. This is especially relevant for the steppe zone of Ukraine, where droughts are a regular phenomenon. Research by Kachanova et al. [22] on chickpeas also showed that the productivity of leguminous crops largely depends on the weather conditions of a year, and measures aimed at increasing stress resistance are justified. Tereshchenko and Tarabrina [47] also indicated the effectiveness of resource-saving

technologies, including biological agents, for cultivating leguminous crops in the Southern Steppe of Ukraine.

The improvement of soil agrochemical indicators, particularly the slight acidification of the soil solution and the trend towards increased content of readily hydrolysable nitrogen, is of great importance. Alkaline soils of the southern region create suboptimal conditions for micronutrient availability and the activity of beneficial microorganisms. Javed et al. [21] emphasized that biodiversity is one of the key factors of soil fertility. Therefore, the shift in pH towards neutrality, caused by the release of organic acids by microorganisms and the action of humic preparations, creates more favorable conditions for microbial diversity and nutrient availability. This partly explains why the variants with improved nitrogen availability and moderated alkalinity also produced higher pea yields, especially under the combined application of Azotofit and Organic-balance. This aligns with the conclusions of Fall et al. [16] regarding the role of arbuscular mycorrhizal fungi in improving soil physical, chemical and biological properties. At the same time, the present study differs from mycorrhiza-focused research because the observed soil changes were limited mainly to readily hydrolysable nitrogen and pH, whereas humus, phosphorus and potassium showed only weak trends without statistically confirmed changes. A statistically significant increase in humus content over two years was not recorded, which is expected, as humus formation processes are long-term. However, the slight trend towards increased humus content in treated variants should be regarded only as a preliminary indication, because stable changes in soil organic matter require longer-term monitoring and cannot be reliably confirmed within a two-year experiment. Bonanomi et al. [6] also established that repeated applications of organic substances promote the development of beneficial microbiota, improve soil fertility and increase crop yield. The effectiveness of biopreparations was higher for the Bilyi anhel cultivar, which has higher genetic potential. This indicates that the biologization of technology allows for the more complete realization of varietal capabilities. Similar data are presented by AbdElgawad et al. [1], who showed that actinomycetes improve nitrogen availability and legume metabolism, positively affecting seed quality and productivity.

In the context of sustainable agriculture, research on organic farming conducted by Soni et al. [46] indicates a connection between the application of biopreparations and the preservation of biodiversity, the improvement of soil structure and the reduction of environmental pollution. The authors' conclusions support the feasibility of using biopreparations in the current study as an alternative to traditional chemical fertilizers. Research on the impact of organic methods on soil health, conducted by Rani et al. [40], demonstrates a correlation between organic farming systems and increased content of micronutrients and antioxidants in plant products. The data obtained are consistent with the results regarding changes in the agrochemical properties of soil and

pea productivity under the influence of biopreparations. Farhangi-Abriz et al. [17], in a meta-analysis, confirmed the positive impact of biochar on the yield of leguminous crops, which further underscores the importance of the organic component. The results obtained regarding the positive influence of biopreparations on pea productivity are consistent with the conclusions of contemporary studies. Thus, Kocira et al. [25] emphasized that leguminous cover crops are a key element of strategic weed management and improvement of soil quality. It has been established that leguminous cover crops not only suppress weed development, but also significantly improve soil biological activity and microbial diversity, which is consistent with the dynamics of easily hydrolyzable nitrogen in the soil under the influence of biopreparations. In the study by Behera et al. [3], the prospects of using microbial consortia for maintaining the productivity of non-leguminous crops are considered. It is proven that complex microbial preparations are more effective than monocultures due to synergistic effects between different species of microorganisms [52]. This explains the high efficacy of combining nitrogen-fixing bacteria in the composition of "Azotofit" with organic stimulants and microorganisms of "Organic-balance". The authors also emphasize the need to adapt microbial preparations to soil and climatic conditions, which confirms the relevance of research in the southern region of Ukraine. An analysis of the agronomic effectiveness of organic fertilizers of animal origin is presented in the work of Bhunia et al. [5]. It is shown that such fertilizers supply nutrients, serve as a substrate for microbiota development, improve soil structure and enhance water-holding capacity. Despite the differences from the used plant-microbial preparations, the general principle of stimulating soil biological activity through organic amendments confirms the results obtained. In the work of Harefa [19], the influence of traditional agricultural practices on soil fertility in South Nias is shown. The use of local biological resources and organic materials is considered a key factor in preserving fertility. This provides grounds to consider modern biopreparations as a scientifically substantiated continuation of traditional knowledge. Research by Kebede [24] on grain legumes in smallholder farms in Ethiopia showed their significance for food security and farmers' income. The author emphasized the need to improve cultivation technologies through the use of high-quality seeds and biological inoculants, which corresponds to the direction of improving pea cultivation technology with the involvement of biopreparations. The review by Mangena [31] concerns the application of algae-based nanoparticles to enhance stress tolerance in leguminous crops. It is shown that such nanoparticles improve nutrient uptake, stimulate growth and increase resistance to abiotic factors. Although nanotechnologies were not used in this study, the data obtained indicate the prospects of combining biopreparations with nanomaterials. Bhardwaj et al. [4] investigated nitrogen mineralization and its availability at critical growth stages. A close relationship was established between soil biological activity, the content of available nitrogen and crop

productivity. This confirms that stimulation of microbial activity with biopreparations contributes to an increase in the level of easily hydrolyzable nitrogen and, consequently, pea yield. Overall, the research results indicate the high efficacy of biopreparations for intensifying pea production under stress conditions.

Conclusions

1. The two-year study conducted on southern chernozem under the conditions of southern Ukraine established a significant positive effect of biopreparations on a pea yield and selected agrochemical soil properties. The application of the biopreparations Azotofit and Humifriend ensured a stable and statistically significant increase in the pea yield for both studied varieties – "Kruiz" and "Bilyi anhel" – throughout the 2024 ÷ 2025 period. The highest efficacy was demonstrated by the combination of pre-sowing seed treatment with Azotofit followed by foliar feeding with Organic-balance. This experimental variant provided the highest and most stable yield increase across both cultivars and years, confirming the agronomic advantage of combining seed inoculation with foliar biological treatment.
2. Even the separate application of biopreparations for seed pre-sowing treatment without subsequent feeding showed a positive result. Azotofit demonstrated higher efficacy than Humifriend, which underscores the important role of nitrogen-fixing bacteria under the conditions of limited readily available nitrogen in the soils of southern Ukraine. The "Bilyi anhel" cultivar realized higher genetic yield potential than the "Kruiz" cultivar in all experimental variants. However, the relative effectiveness of the biopreparations (the magnitude of relative increase) was similar for both varieties, indicating the universality of their mechanism of action, independent of varietal characteristics.
3. Biopreparations demonstrated the ability to mitigate the negative impact of unfavorable weather conditions observed in 2025. Although absolute yield indicators in all variants of this year were lower, the relative increase from their application remained stable or even increased, confirming their adaptive and stress-mitigating role. The agrochemical soil analysis revealed positive dynamics of key indicators under the influence of biopreparations. The main soil-related effect was the improvement of nitrogen availability and a moderate shift of soil pH towards more favorable conditions for pea growth and nitrogen-fixing microbial activity.
4. The results obtained prove the agronomic and economic feasibility of integrating biopreparations into the pea cultivation technology under the conditions of southern Ukraine. The combined application of Azotofit and Organic-balance is the most promising technique for increasing yields and improving the soil nitrogen balance, which is the basis for the sustainable intensification of agriculture under the conditions of soil degradation and climate change. From a practical perspec-

tive, this combined scheme may be considered an element of resource-saving pea cultivation technology in arid regions, especially under the conditions of nitrogen deficiency and limited moisture availability. Further research should examine the influence of these biopreparations on other leguminous crops in crop rotation and assess their long-term impact on organic matter formation and soil microbiome.

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WPŁYW BIOPREPARATÓW NA ŻYWNOŚĆ GLEBY I PLONY GROCHU W WARUNKACH POŁUDNIOWEJ UKRAINY

S t r e s z c z e n i e

Wprowadzenie. Nowoczesne systemy rolnicze wymagają bezpiecznych dla środowiska technologii, które zwiększają produktywność upraw bez nadmiernego stosowania nawozów mineralnych. Jest to szczególnie ważne w przypadku roślin strączkowych, takich jak groch, które odgrywają kluczową rolę w przywracaniu żyzności gleby i wspieraniu bezpieczeństwa żywnościowego. Celem niniejszego badania było zbadanie wpływu biopreparatów na bazie bakterii wiążących azot i substancji organicznych na produktywność grochu na stepach południowych Ukrainy oraz ocena ich skuteczności agrotechnicznej. Badania przeprowadzono w latach 2024 ÷ 2025 na odmianach grochu „Kruiz" i „Biały Anhel" („Biały Anioł"). W badaniu zbadano wpływ przedsiewnego zaprawiania nasion preparatem „Azotofit" (na bazie Azotobacter chroococcum) i „Humifrend" (zawierającym substancje humusowe i mikroorganizmy), a także dokarmiania dolistnego preparatem „Organic-balance".

Wyniki i wnioski. Wyniki wykazały, że największy wzrost plonów uzyskano przy łącznym zastosowaniu zaprawy nasiennej „Azotofit" i dolistnego stosowania preparatu „Organic-balance": 0,58 ÷ 0,63 t/ha (28,9 ÷ 32,5 % powyżej grupy kontrolnej) dla odmiany „Kruiz" i 0,47 ÷ 0,66 t/ha (18,9 ÷ 26,2 %) dla odmiany „Bilyi anhel". Połączenie „Humifrend" i „Organic-balance" również poprawiło plony, osiągając 0,44 ÷ 0,45 t/ha dla odmiany „Kruiz" i 0,55 t/ha dla odmiany „Bilyi anhel". Indywidualne zaprawy nasienne konsekwentnie zwiększały wydajność: „Azotofit" o 0,27 ÷ 0,37 t/ha, a „Humifrend" o 0,24 ÷ 0,33 t/ha. Biopreparaty poprawiły również właściwości agrochemiczne gleby, zwiększając zawartość azotu łatwo hydrolizującego o 12 ÷ 15 % i nieznacznie obniżając pH o 0,2 ÷ 0,3 jednostki. Wyniki te potwierdzają, że stosowanie biopreparatów w uprawie grochu jest skutecznym elementem nowoczesnej techniki rolniczej, umożliwiającym wyższe plony, poprawę jakości gleby i bardziej zrównoważone ekologicznie rolnictwo.

Słowa kluczowe: groch, bakterie wiążące azot, plon, zaprawianie przedsiewne, odmiana, dokarmianie dolistne