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PRODUCTIVITY AND ECONOMIC EFFICIENCY OF BUCKWHEAT CULTIVATION DEPENDING ON FERTILIZATION SYSTEMS IN THE CONDITIONS OF THE NORTHERN STEPPE

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Buckwheat plays a key role in Ukraine's agricultural sector, contributing to food security due to its rich composition of nutrients – proteins, microelements, and antioxidants. The relevance of the topic is driven by global trends: the demand for gluten-free and organic products, as well as the need to diversify crop rotations in the steppe zone to preserve soil fertility. Unresolved issues include the optimization of fertilization for maximizing productivity (yield, yield structure) and economic efficiency, especially in the arid climate of the Northern Steppe. Traditional mineral fertilization systems ($N_{30–60}P_{30–60}K_{30}$) increase yields by 20-30 %, but they risk nitrate pollution and plant lodging. Organic and combined fertilization systems (mineral + organic + biopreparation) promise sustainable productivity, but their regional adaptation is insufficiently studied, threatening the competitiveness of buckwheat. The purpose of the study was to determine the impact of mineral, organic, biological, and combined fertilization systems on the productivity and economics of buckwheat in the Northern Steppe, with an emphasis on sustainability and local adaptation. The research was conducted on experimental plots of Institute of Agriculture of the Steppe of the NAAS, where variants were established: control, mineral system ($N_{30}P_{30}K_{30}$), organic system (post-harvest residues of the previous crop), biologized fertilizer system, and their combinations. The highest yield indicators, 1.62 t/ha (+83.2 % compared to the control), were obtained using the organo-mineral biologized fertilization system; without the biological component, this system allowed forming a yield of 1.50 t/ha, +70.2 % compared to the control. Higher productivity of buckwheat was also ensured by the combined biologized fertilization

system – 2.43 t/ha (+82.7 %) grain units, 3.05 t/ha (+82.6 %) feed units, and 0.24 t/ha (+84.6 %) digestible protein units. With the increase in nutrient elements, the intensity of productivity growth decreased to 7.5 %, 7.3%, 9.09 %, respectively. The highest economic efficiency of buckwheat cultivation was achieved using the organo-mineral biologized fertilization system (conditional net profit 13890 UAH/ha, +310.2 % with a profitability of 69.0 %), with costs of 20130 UAH/ha, covered by the interaction of all nutrient elements. Thus, innovative approaches, including organic and biological components of the fertilization system, can be key to sustainable buckwheat cultivation under climate change conditions.

Key words: *buckwheat, fertilization systems, buckwheat productivity, biologization, economic efficiency of buckwheat cultivation.*

Мащенко Ю.В., Соколовська І.М. Продуктивність та економічна ефективність вирощування гречки залежно від систем удобрення в умовах Північного Степу

Гречка відіграє ключову роль в аграрному секторі України, сприяючи харчовій безпеці завдяки багатому складу поживних речовин – білкам, мікроелементам та антиоксидантам. Актуальність теми зумовлена глобальними тенденціями: попитом на безглютенові та органічні продукти, потребою в диверсифікації сівозмін степової зони для збереження ґрунтової родючості. Невирішені проблеми включають оптимізацію удобрення для максимізації продуктивності (урожайність, структура врожаю) та економічної ефективності, особливо в умовах Північного Степу з посушливим кліматом. Традиційні мінеральні системи удобрення ($N_{30\text{-}60}P_{30\text{-}60}K_{30}$) підвищують урожай на 20–30 %, але ризикують забрудненням нітратами та вилуговуванням рослин. Органічні та комбіновані системи удобрення (мінеральні + органічні + біопрепарати) прогнозують сталу продуктивність, але їх регіональна адаптація недостатньо вивчена, що загрожує конкурентоспроможності гречки. Метою роботи було визначення впливу мінеральної, органічної, біологізованої та комбінованих систем удобрення на продуктивність і економіку гречки в Північному Степу, з акцентом на сталість та локальну адаптацію. Дослідження проводили на дослідних ділянках Інституту сільського господарства Степу НААН, де закладали варіанти: контроль, мінеральні ($N_{30}P_{30}K_{30}$), органічні (пожнивні рештки попередньої культури), біопрепарат та їх комбінації. Вищі показники врожайності, 1,62 т/га (+83,2 % до контролю) отримали при використанні органо-мінеральної біологізованої системи удобрення, без біологічного компоненту ця система дозволяла сформувати врожайність на рівні 1,50 т/га, +70,2 % до контролю. Вищу продуктивність гречки забезпечувала також комбінована біологізована система удобрення – 2,43 т/га, (+82,7 %) зернових одиниць, 3,05 т/га (+82,6 %) кормових одиниць та 0,24 т/га (+84,6 %) одиниць перетравного протеїну. Із збільшенням елементів живлення інтенсивність приросту продуктивності зменшувалася до 7,5 %, 7,3 %, 9,09 % відповідно. Найвищу економічну ефективність вирощування гречки отримали при використанні органо-мінеральної біологізованої системи удобрення (умовно чистий прибуток 13890 грн/га, +310,2 % за рентабельності 69,0 %), з витратами 20130 грн/га, які покривалися взаємодією всіх елементів живлення. Таким чином, інноваційні підходи, включаючи органічні та біологічні компоненти системи удобрення можуть бути ключовими для сталого вирощування гречки в умовах кліматичних змін.

Ключові слова: *гречка, системи удобрення, продуктивність гречки, біологізація, економічна ефективність вирощування гречки.*

Formulation of the problem.

Buckwheat is an important crop in Ukraine's agricultural sector, ensuring food security due to its high content of nutrients, including proteins, microelements, and antioxidants. According to the State Statistics Service of Ukraine, the sown areas under buckwheat in 2024 amount to about 70 thousand hectares, with an average yield of 1.0-1.5 t/ha, which is significantly below the potential (up to 2.5 t/ha). The relevance of the problem presented in the article is driven by global challenges: the growing demand for gluten-free products and organic grains, as well as the need to diversify crop rotations in the steppe zone to preserve soil fertility. Unresolved issues remain regarding the optimization of fertilization systems to maximize productivity (yield, yield structure) and economic efficiency. The lack of regionally adapted recommendations leads to inefficient

resource use, reduced competitiveness of buckwheat on the market (exports to the EU and Asia), and threats to food security.

Analysis of recent research and publications.

Fertilization systems play a key role in forming the buckwheat yield, which is sensitive to excessive nitrogen nutrition due to the risk of lodging and reduced grain quality. Traditional mineral fertilizers ($N_{30–60}P_{30–60}K_{30–60}$ kg a.i./ha) provide a yield increase of 20-30 %, but often lead to nitrate soil pollution and reduced biodiversity. Alternatives, such as organic (manure 20–30 t/ha) or combined systems (mineral + organic + biopreparations), promise sustainable productivity, but their efficiency in the Northern Steppe is insufficiently studied. Research by Ukrainian scientists indicates the potential of organic systems to increase yields to 2.0 t/ha, but data on economic profitability is lacking, especially under climate change conditions (droughts, extreme temperatures +25-35°C in summer) [7, 11, 10, 14].

The productivity and economic efficiency of buckwheat cultivation are actively studied in scientific articles and reports, particularly in the context of the Ukrainian Northern Steppe. The application of mineral fertilizers contributes to an increase in buckwheat yield by approximately 33.8 %, while complex systems including biopreparations improve yield by 37.7 % compared to the control without fertilizers. Combined fertilization systems (organo-mineral with biopreparations) ensure a yield increase of 49.1%, positively affecting the photosynthetic potential and reducing weed infestation in crops. Such a system is also the most economically efficient [1, 5, 8, 9, 12, 13].

Optimization of mineral fertilizer application rates and the use of growth regulators and microbial preparations also positively affects the formation of aboveground mass, photosynthetic activity, and yield, increasing it to 1.8-2.1 t/ha. Data indicate that fertilization systems with biopreparations enhance plant resilience to stress factors in the Steppe conditions (low humidity, nutrient deficiency), improve soil structure, and thus ensure more stable economic profitability in buckwheat production. The economic efficiency of such systems exceeds traditional ones by 15-30 %, due to reduced pesticide costs and increased yields [2, 3, 4, 6].

Thus, modern research confirms that innovative fertilization systems, which include organic components and biopreparations, are key to enhancing productivity and profitability of buckwheat cultivation in the conditions of the Northern Steppe of Ukraine.

Research aim. The aim of the study was to determine the impact of various fertilization systems (mineral, organic, biologized, and combined) on the productivity and economics of buckwheat cultivation in the Northern Steppe, with an emphasis on sustainability and adaptation to local conditions.

Materials and methods of research. he research was conducted by establishing experimental plots on agricultural land located in the administrative units of the Kropyvnytskyi district, Kirovohrad region, which is under the management of the Institute of Agriculture of the Steppe of the National Academy of Agrarian Sciences of Ukraine.

The main method of conducting the research is field and laboratory-field experiments. For the scientific substantiation of the purpose and implementation of the set tasks, as well as the generalization of the results of experimental work, the hypothesis method is used – selecting the direction of research, determining the relevance of the work, developing experimental schemes; the dialectical method – observing the development of crops and processes of yield formation; the synthesis method – generalizing research results and forming conclusions; the analysis method – determining the adaptability of the studied objects to cultivation conditions; the induction method – drawing conclusions based on identifying the best variants; the mathematical statistics

method – determining the significance of factors, accuracy of experiments, and correlative relationships.

Buckwheat of the Yaroslavna variety was grown in a stationary short-rotation grain-row crop rotation, which had the following crop sequence: soybeans, winter wheat, soybeans, corn for grain, buckwheat.

The buckwheat cultivation technology was generally accepted for the Steppe zone, except for the practices under study.

Buckwheat was sown using the wide-row sowing method in the first decade of May with a seeding rate of 2.25 million plants/ha, against the background of six fertilization systems:

1. Without fertilizers (control);
2. Biologized fertilization system (seed treatment with biopreparation before sowing);
3. Mineral fertilization system ($N_{20}P_{20}K_{20}$);
4. Mineral biologized fertilization system ($N_{20}P_{20}K_{20}$ + seed treatment with biopreparation before sowing);
5. Organo-mineral (N $N_{20}P_{20}K_{20}$ + by-product of the predecessor);
6. Organo-mineral biologized ($N_{20}P_{20}K_{20}$ + by-product of the predecessor + seed treatment with biopreparation before sowing).

Pesticides were not used in the experiment; weed control in buckwheat crops was carried out mechanically. In the biologized fertilization system, buckwheat seeds were treated with the Mikofriend biopreparation (1.0 l/t) before sowing.

The establishment and conduct of the experiments were carried out in accordance with the methodology of field experiments.

The weather conditions during the research period in 2024 and 2025 were unfavorable in the critical water-consuming periods of buckwheat plants. Maturation and completion of vegetation occurred with good heat supply but limited soil moisture reserves in the absence of precipitation.

The weather conditions during the vegetation period of 2021 were insufficiently favorable for obtaining high productivity indicators of buckwheat.

The weather conditions of the vegetation periods in 2022 and 2023 for buckwheat were favorable, with moderate air temperature increases and sufficient soil moisture reserves in the spring and summer periods.

Results and discussion.

Effective fertilization systems play a key role in increasing yield and grain quality. Advanced agrotechnologies include the combined use of mineral fertilizers, organic substances, and biopreparations, which promote better nutrient uptake and plant adaptation to stress conditions. Analysis of research shows that the proper choice of fertilization systems significantly affects the yield level. It is important to consider a comprehensive approach to buckwheat nutrition to maximize productivity and economic efficiency. Such an approach ensures production stability in challenging natural conditions.

The average buckwheat yield for 2021-2025 ranged from 0.42-2.19 t/ha, reflecting the influence of climatic factors, especially in 2024, and variation in indicators depending on the crop cultivation conditions. However, field research data demonstrate a clear gradation in buckwheat fruit yield depending on fertilization systems, where the transition from the control without fertilizers to integrated approaches ensured a yield increase of 83.2 % (LSD_{05} = 0.16 t/ha). These differences are explained not only by the content of nutrient elements but also by synergy with biological stimulants that enhance plant adaptation to steppe conditions (Table 1).

The variant without fertilizers (control) provided an average yield of 0.88 t/ha – a typical indicator for unfertilized sowings in the Steppe, where nitrogen and phosphorus deficiency hinders root system growth and reproductive organ formation, leading to losses due to drought and weed competition.

Table 1

Buckwheat yield by research years, 2021-2025

Fertilization systems	Years					Average for 2021-2025	Difference	
	2021	2022	2023	2024	2025		t/ha	%
Without fertilizers (control)	1.06	1.02	1.10	0.42	0.81	0.88	–	–
Biologized	1.13	1.34	1.53	0.43	0.96	1.08	0.20	22.3
Mineral	1.33	1.48	1.70	0.46	1.05	1.21	0.32	36.8
Mineral biologized	1.39	1.79	1.85	0.62	1.19	1.37	0.49	55.4
Organo-mineral	1.43	1.98	1.98	0.77	1.35	1.50	0.62	70.2
Organo-mineral biologized	1.49	2.09	2.19	0.82	1.49	1.62	0.73	83.2
Average	1.31	1.62	1.72	0.59	1.14	1.28	–	–
LSD_{05}. t/ha	0.03	0.12	0.08	0.02	0.02	0.16	–	–

The transition to a biologized system contributed to increasing the yield to 1.08 t/ha (+0.20 t/ha, or 22.3 %), as biopreparations stimulate phosphorus mobilization and nitrogen fixation, improving soil water retention – an effect that exceeds LSD_{05} and confirms an alternative to chemical fertilizers.

The use of a mineral fertilization system contributed to a significant increase in yield to 1.21 t/ha (+0.32 t/ha, 36.8 %), which can be explained by the activation of vegetative growth and photosynthesis due to additional nitrogen in the soil, and flowering – under the influence of phosphorus, compensating for the natural deficiency of steppe soils. The difference is statistically significant ($p<0.05$ by LSD_{05}), but excessive nitrogen sometimes provoked lodging, which is relevant for the windy conditions of the Steppe. The combination of mineral fertilizers with element of biologization (mineral biologized fertilization system) ensured an increase in yield indicators to 1.37 t/ha (+0.49 t/ha, 55.4 %), where microorganisms contributed to the optimization of fertilizer uptake, reducing losses due to evaporation – a key factor for the region with low moisture supply.

The highest results in our study were obtained with the organo-mineral fertilization system, yielding 1.50 t/ha (+0.62 t/ha, 70.2 %), where organic residues from the previous crop positively influenced soil structure and moisture retention, which is critical for the Steppe. The difference from the control exceeds LSD_{05} by twofold, emphasizing the role of the organic component. The organo-mineral biologized system maximized the crop's potential, with yields reaching 1.62 t/ha (+0.73 t/ha, 83.2 %). The integration of biopreparations enhanced microbial activity in the rhizosphere, stimulating symbiosis and nitrogen fixation, which allowed buckwheat to withstand droughts and achieve a potential of 2.19 t/ha in 2023, close to the optimal under Steppe conditions in Ukraine.

Based on field research data, where $LSD_{05} = 0.16$ t/ha determines a statistically significant difference ($p<0.05$), the yield increase due to the biopreparation can be assessed compared to corresponding backgrounds without treatment. The increment varies from 5.0 % to 12.2 %, with predominant significance for the mineral fertilization system and

control backgrounds, confirming the synergistic effect of the biopreparation with nutrient elements, but lower efficiency for the organic system.

On the background without fertilizers (control, 0.88 t/ha), seed treatment with the biopreparation increased yield to 1.08 t/ha (+0.20 t/ha, or 22.3 % compared to the control). The increment of 0.20 t/ha is significant (equal to LSD_{05}), as microorganisms compensate for the natural deficiency of nitrogen and phosphorus in Steppe chernozems, stimulating nitrogen fixation and root expansion, which is critical under low moisture conditions.

On the mineral nutrition background (1.21 t/ha), seed treatment before sowing with the biopreparation (mineral biologized system) ensured harvesting 1.37 t/ha of fruits (+0.16 t/ha, or 13.2 % compared to the mineral background). The difference exactly equals LSD_{05}, making the increase statistically significant.

For the organo-mineral fertilization system, buckwheat yield was 1.50 t/ha; the use of the biopreparation contributed to increasing yield to 1.62 t/ha (+0.12 t/ha, or 8.0 % compared to organo-mineral). The increment is less than LSD_{05} (0.16 t/ha), so it is not statistically significant: the organic base (humus + residues) already provides high microbial activity, and the biopreparation adds only a marginal effect due to rhizosphere saturation, although it improves moisture retention.

In summary, the yield increase in buckwheat from the biopreparation is significant on the background without fertilizers and under the mineral fertilization system (+20-13 %, $>LSD_{05}$), but insignificant on the rich organo-mineral (+8 %, $<LSD_{05}$), where synergy is limited. The average yield increase in buckwheat by 11-12 % makes seed treatment with the biopreparation advisable for the Steppe.

The results of our research demonstrate how fertilization systems transform buckwheat productivity into sustainable high-yield production. In the Northern Steppe, where climatic challenges are intensifying, priority is given to integrated approaches that not only increase yields by 30-40 % but also ensure environmental safety by reducing nitrate pollution. Further research should focus on adapting these systems to climate change to enhance the region's food resilience.

Research on buckwheat productivity emphasizes fertilization systems as a key factor in optimizing grain yield, fodder mass, and digestible protein output, which determines its value for animal husbandry and the food industry. Based on field research data, we observed a clear gradation in indicators: from the control without fertilizers (1.33 t/ha grain units, 1.67 t/ha feed units, 0.13 t/ha protein units) to integrated organo-mineral systems with biologization, where the increase reaches 1.10 t/ha grain units, 1.39 t/ha feed units, and 0.11 t/ha protein units. These differences are due to the synergy of mineral nutrient elements (NPK), organic residues, and biopreparations, which enhance nutrient uptake, improve soil aggregation, and increase plant resistance to abiotic stresses such as drought (Fig. 1).

In the control variant without fertilizers, buckwheat productivity was the lowest: grain units yield – 1.33 t/ha, feed units yield – 1.67 t/ha, digestible protein units yield – 0.13 t/ha. These indicators reflect typical limitations of steppe conditions, where the deficiency of available nitrogen and phosphorus hinders vegetative development, photosynthesis, and biomass accumulation, leading to reduced grain quality and fodder value. Biologized fertilization systems provided a significant increase in these indicators compared to traditional crop rotations: +7.5-21.8 % grain and feed units, +9.1-23.1 % digestible protein units. The mechanism of the effect is associated with the stimulation of nitrogen fixation and phosphorus mobilization in the rhizosphere, which compensates for the natural deficiency of elements and increases tolerance to moisture stress, making this approach environmentally safe.

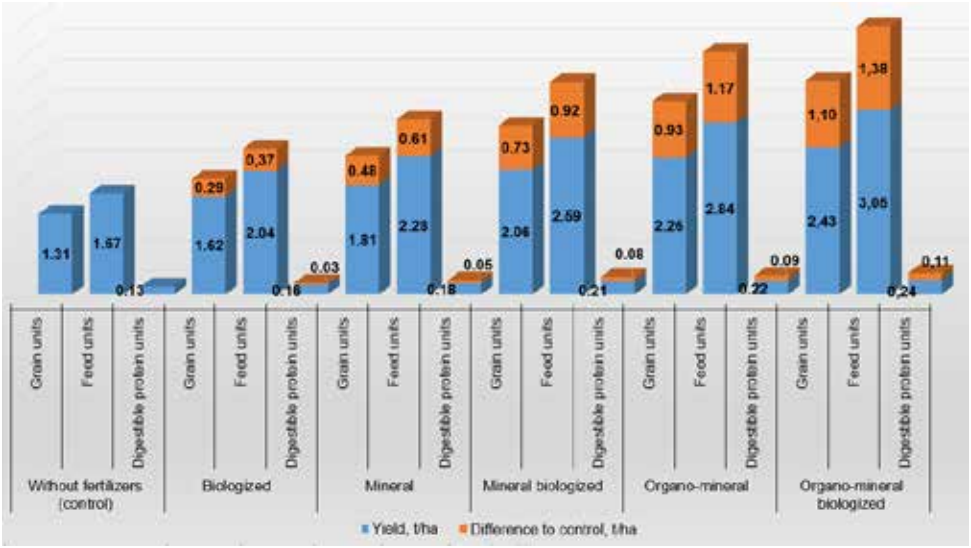

Fig. 1. Buckwheat (average for 2021-2025)

The mineral fertilization system increased buckwheat productivity compared to cultivation without fertilizers: 1.81 t/ha grain units (+0.49 t/ha), 2.28 t/ha feed units (+0.61 t/ha), and 0.18 t/ha protein units (+0.05 t/ha). Under these conditions, nitrogen contributed to the accumulation of vegetative mass, phosphorus to the formation of reproductive organs, and potassium to water balance, which is critical for the arid conditions of the Steppe. The mineral biologized fertilization system further enhanced these processes: 2.06 t/ha (+0.73 t/ha), 2.59 t/ha (+0.92 t/ha), and 0.21 t/ha (+0.07 t/ha) for grain, feed units, and digestible protein, respectively.

The highest levels of productivity were achieved with the organo-mineral fertilization unitssystem: 2.26 t/ha grain units (+0.93 t/ha), 2.84 t/ha feed units (+1.17 t/ha), and 0.22 t/ha protein units (+0.09 t/ha). The organo-mineral biologized system demonstrated the greatest potential in the study for forming buckwheat productivity: 2.43 t/ha grain units (+1.10 t/ha), 3.05 t/ha feed units (+1.39 t/ha), and 0.24 t/ha digestible protein units (+0.11 t/ha).

Summarizing the results confirms the advantage of integrated fertilization systems, which increased buckwheat productivity by 82.7 % for grain units yield, 82.6 % for feed units yield, and 84.6 % for protein units yield compared to the control, ensuring comprehensive efficiency in steppe conditions.

The calculations of economic efficiency were based on prices for agricultural and industrial products prevailing on the Ukrainian exchange market in the first decade of December 2025. The calculations took into account direct monetary-material costs, which included wages, seed costs, fertilizers, fuel and lubricants, as well as payments to social insurance funds, pension and others, deductions for depreciation and current repairs.

The economic component of buckwheat production depends on the chosen fertilization system, which affects the level of production costs, gross output, net profit, and profitability. Based on average indicators for 2021-2025, key trends can be identified.

Production costs vary widely depending on the fertilization system. In the control variant without fertilizers, they were the lowest – 15095 UAH/ha. The use of the biologized

system increased costs to 15776 UAH/ha, associated with additional expenses for biopreparations. Costs increased more significantly with the application of mineral fertilizers – 20029 UAH/ha, and in the mineral biologized system – 20704 UAH/ha due to the cost of fertilizers and services for applying biopreparations. Organo-mineral systems, thanks to the use of organic residues, had slightly lower costs (19462–20130 UAH/ha), which allowed for an effective balance of costs and profits (Table 2).

Table 2

Economic efficiency of buckwheat cultivation under different fertilization systems

Fertilization systems	Yield (average for 2021-2025)	Production costs, UAH/ha	Gross output value, UAH/ha	Conditional net profit, UAH/ha	Profitability, %
Без добрив (контроль)	0,88	15095	18480	3385	22,4
Without fertilizers (control)	1,08	15776	22680	6904	43,8
Biologized	1,21	20029	25410	5381	26,9
Mineral	1,37	20704	28770	8066	39,0
Mineral biologized	1,50	19462	31500	12038	61,9
Organo-mineral	1,62	20130	34020	13890	69,0

The conditional net profit is the lowest when growing buckwheat without fertilizer application – 3385 UAH/ha, reflecting low yield and minimal costs. The biologized system nearly doubled the profit (6904 UAH/ha), demonstrating high return on investment in biopreparations. Interestingly, the mineral system had higher costs and yield but lower profit (5381 UAH/ha) compared to the biologized one, due to higher fertilizer expenses. Under the mineral biologized system, the conditional net profit increased to 8066 UAH/ha, indicating the effect of the combined action of fertilizers and biopreparations.

The most profitable in our study were the organo-mineral systems – 12038 UAH/ha and 13890 UAH/ha for the traditional and biologized systems, respectively. These indicators demonstrate the best combination of higher yield and relatively balanced costs.

Analysis of profitability indicators shows a trend toward increasing production efficiency from 22.4 % in the control to 69.0 % under the organo-mineral system with biologization elements. The highest profitability values indicate the economic feasibility of a comprehensive fertilization approach that includes mineral fertilizers, organic components, and biological stimulants. The mineral system alone, due to high costs, has a profitability rate of only 26.9 %, making it the least efficient.

Overall, the analysis indicates that the most optimal from an economic perspective were the organo-mineral and organo-mineral biologized fertilization systems. They provided a balance between increasing yield, controlled costs, and maximum return on investment in buckwheat production under the conditions of the Northern Steppe of Ukraine.

Conclusions.

Higher yield indicators were ensured by the organo-mineral biologized fertilization system for buckwheat (yield 1.62 t/ha, +83.2 % compared to the control), involving the

incorporation of post-harvest residues + mineral fertilizers ($N_{20}P_{20}K_{20}$) + biopreparation. Under the organo-mineral system, yield indicators were slightly lower (1.50 t/ha, +70.2 %), but the yield increase was also high.

Under the organo-mineral biologized fertilization system, plant productivity was the highest: 2.43 t/ha (+82.7 %) grain units, 3.05 t/ha (+82.6 %) feed units, and 0.24 t/ha (+84.6 %) digestible protein units. The largest increases in productivity indicators were obtained without fertilizer application: +21.8 %, +22.1 %, and +23.7 % for grain, fodder units, and protein units, respectively. With the increase in nutrient elements, the intensity of productivity growth decreased to 7.5 %, 7.3 %, and 9.09 %, respectively.

The highest economic efficiency of buckwheat cultivation was achieved using the organo-mineral biologized fertilization system (conditional net profit 13890 UAH/ha, +310.2 % with profitability of 69.0%), with costs of 20130 UAH/ha, covered by the interaction of all nutrient elements. The organo-mineral system provided 12038 UAH/ha profit and 61.9 % profitability, balancing costs (19462 UAH/ha).

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