Butenko, A., Datsko, O., Shumkova, O., Bahorka, M., Musiienko, V., Yurchenko, N., Nechyporenko, V., Zavhorodnia, S., Mikulina, M. (2025). Sustainable buckwheat growing: agrotechnical and economic assessment of the mineral fertilizers' role, Agriculture and Forestry, 71 (1). 49-59. https://doi:10.17707/AgricultForest.71.1.04

DOI: 10.17707/AgricultForest.71.1.04

Andrii BUTENKO[1*], Oksana DATSKO[1], Olena SHUMKOVA[1], Mariia BAHORKA[2], Viktoriia MUSIIENKO[1], Nataliia YURCHENKO[2], Valentyna NECHYPORENKO[1], Svitlana ZAVHORODNIA[3], Maryna MIKULINA[1]

SUSTAINABLE BUCKWHEAT GROWING: AGROTECHNICAL AND ECONOMIC ASSESSMENT OF THE MINERAL FERTILIZERS' ROLE

SUMMARY

The sustainable cultivation of agricultural crops has become increasingly important, with innovations focused on increasing yields without harming the environment. In Ukraine, the use of biofertilizers and biopesticides is gaining popularity, though results vary due to specific application conditions. Organic fertilizers have shown clear benefits for many crops, but manure is not recommended for buckwheat. However, fertilizers containing effective microorganisms are promising, though they can be affected by adverse abiotic factors. This study aims to evaluate the impact of mineral fertilizers on buckwheat yield and to assess the economic viability of their use. Field experiments were conducted from 2021 to 2023 at Sumy National Agrarian University educational and research center, involving two buckwheat varieties, Slobozhanka and Yaroslavna, under different fertilization regimes. The study analyzed crop yield and economic efficiency under varying doses of NPK fertilizers ($N_{22}P_{22}K_{22}$, $N_{45}P_{45}K_{45}$, $N_{30}P_{45}K_{45}$ + N_{15}, $N_{50}P_{30}K_{70}$), as well as control (without fertilization). Results indicate that fertilizer use significantly improved yield compared to control, with the Slobozhanka variety showing higher responsiveness. The best economic outcomes were associated with moderate fertilizer use, balancing yield increase and input costs. Economic analysis shows that, while higher fertilization increased yields, it did not always result in higher profitability due to increased input costs, particularly for $N_{45}P_{45}K_{45}$. Excessive fertilizer use can also lead to long–term soil degradation, making balanced

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[1]Andrii Butenko* (Corresponding author: andb201727@ukr.net), Oksana Datsko, Olena Shumkova, Viktoriia Musiienko, Valentyna Nechyporenko, Maryna Mikulina, Sumy National Agrarian University, 160 H. Kondratieva St., 40021, Sumy, UKRAINE;

[2]Mariia Bahorka, Nataliia Yurchenko, Dnipro State Agrarian and Economic University, Sergei Yefremov, Str., 25, 49000, Dnipro, UKRAINE;

[3]Svitlana Zavhorodnia, National University of Life and Environmental Sciences of Ukraine, Heroyiv Oborony Str., 15, 03041, Kyiv, UKRAINE.

Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.

Recieved:07/11/2024 *Accepted:15/01/2025*

application crucial for sustainable production. Therefore, a strategic approach to fertilizer use is needed to optimize both yield and soil health, ensuring long–term agricultural sustainability.

Keywords: sustainability, yield, economic evaluation, soil health, fertilization strategies, profit.

INTRODUCTION

The issue of growing agricultural crops in a sustainable way is extremely relevant today (Datsko *et al.*, 2024; Mishchenko *et al.*, 2024; Trotsenko *et al.*, 2023). Under the term of sustainability, scientists mostly understand the ability to meet present needs without compromising the ability of future generations to meet their own needs. Increasingly, innovative approaches in agriculture are focused on boosting crop yields through means that do not harm the environment (Kovalenko *et al.*, 2024a; Kolisnyk *et al.*, 2024; Voitovyk *et al.*, 2024a). So, this could be called sustainable way of crop production. In Ukraine, the use of biofertilizers and biopesticides for pest and disease control is becoming more common (Radchenko *et al.*, 2024). However, the use of such products does not always lead to the desired effect due to specific conditions that must be met during their application. When it comes to organic fertilizers, the effect is usually clear and effective (Bhunia *et al.*, 2021; Tykhonova *et al.*, 2021). However, manure application for buckwheat is not recommended (Tao *et al.*, 2023; Radchenko *et al.*, 2023). At the same time, the use of fertilizers containing effective microorganisms is appropriate and effective. Yet, this type of fertilization does not always yield the desired results due to unfavorable abiotic factors that negatively affect microorganisms (Witkowicz *et al.*, 2020; Voitovyk *et al.*, 2024b). That is why a lot of agricultural producers are still using mineral fertilizers.

The economic evaluation of a technology or its individual components is a crucial criterion that helps farmers determine the impact of a particular practice on the crops they grow (Farooq *et al.*, 2016; Silver *et al.*, 2021; Kovalzhy *et al.*, 2024). The rising costs of fuel and agricultural production inputs have a significant impact on the industry’s economy (Dhakal *et al.*, 2015; Kovalenko *et al.*, 2024b). It is also important to understand the feasibility of their use and to consider the effect of a particular practice on economic efficiency and the environment. With limited budgets and significant environmental impacts, farmers must efficiently grow crops, especially buckwheat.

Government officials strive to support agricultural producers (Hryhoriv *et al.*, 2021; Vykliuk *et al.*, 2022; Williams *et al.*, 2022), but given the rising costs of fertilizers and fuel, farmers need to be particularly cautious when choosing optimal growing technologies. They should carefully assess the economic efficiency of each method to find the best balance between cultivation profitability, high yield, and environmental impact. Agricultural producers are encouraged to actively seek and implement innovative cultivation methods to reduce their dependence on fertilizer costs due to changes in the economic environment (Masoero *et al.*, 2021; Hryhoriv *et al.*, 2024). Moreover, when choosing fertilization and soil management methods, it is crucial to consider the ecological factor.

Therefore, the aim of this study was to examine the impact of mineral fertilization on buckwheat yield as well as to conduct an economic and environmental assessment of fertilizer use feasibility.

MATERIAL AND METHODS

Field studies were conducted at the Sumy National Agrarian University educational and research center from 2021 to 2023. A two–factor experiment was established, which included the following factors: varieties (Slobozhanka, Yaroslavna) and fertilization levels. The buckwheat (*Fagopyrum esculentum* Moench) cultivation technology involved several key stages, including plowing to a depth of 25–27 cm, harrowing to level the soil surface, and pre–sowing cultivation.

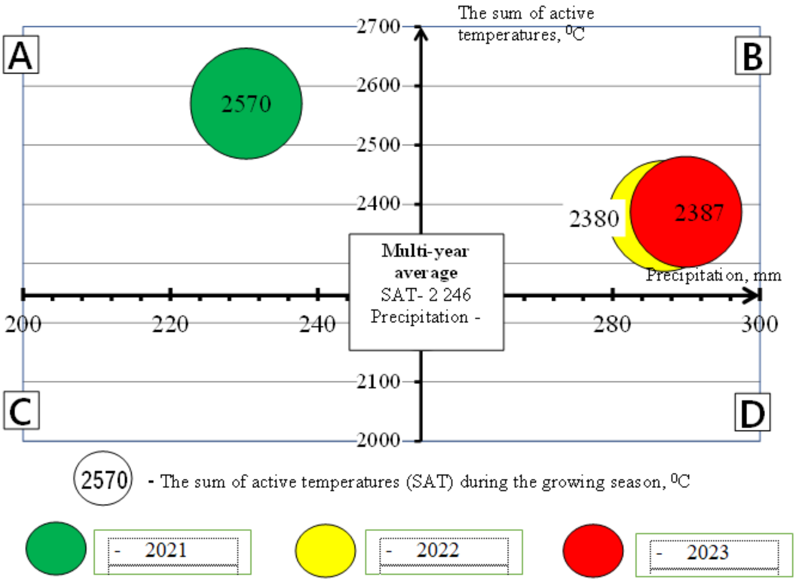

Figure 1. The sum of active temperatures (>10 °C) and the amount of precipitation during buckwheat growing season (May–August) compared to the average long–term values (meteorological station in the village of Sad Sumy region, Sumy district. GPS coordinates: 50.88095 Northern latitude, 34.71525 East longitude, 2021–2023). Conditions: A – warmer and drier; B – warmer and more humid; C – cool and dry; D – cool and wet.

Fertilization was carried out according to several schemes, including a control option without fertilizers and various fertilizer doses: $N_{22}P_{22}K_{22}$, $N_{45}P_{45}K_{45}$, $N_{30}P_{45}K_{45}$ + N_{15} and $N_{50}P_{30}K_{70}$. Harvesting was performed after most of the seeds had fully matured to prevent losses due to shattering. After harvesting, yield, grain quality, and the economic efficiency of the technology were evaluated.

The weather conditions during the vegetation periods of buckwheat plants (May–August) in the 2021–2023 research years showed significant differences compared to both the long–term average values and between each other (Figure 1).

To determine the economic efficiency of intensive cultivation of two buckwheat varieties, both value and natural indicators were used. Descriptive statistics were made at Microsoft Excel. The least significant difference (LSD) for buckwheat yield between varieties and fertilization treatments was calculated using the standard statistical approach based on the ANOVA model. LSD was determined at the 0.05 probability level to evaluate significant differences in yield across experimental treatments.

RESULTS AND DISCUSSION

Research results from 2021–2023 showed that buckwheat yield significantly depends on the level of fertilization and variety (Table 1). The Yaroslavna variety demonstrated an average yield of 1.47 t ha^{-1} without fertilizers, while increasing doses of mineral fertilizers led to higher yields. Specifically, with the recommended dose of $N_{45}P_{45}K_{45}$, the yield reached 1.78 t ha^{-1}, and with additional nitrogen feeding, the yield increased to 1.96 t ha^{-1}. However, at the calculated dose of $N_{50}P_{30}K_{70}$, the yield slightly decreased to 1.83 t ha^{-1}.

Table 1. Yield of different buckwheat morphotypes depending on fertilization level, 2021–2023

Varieties	Fertilization	Grain yield, t ha^{-1}			
		2021	2022	2023	Average
Yaroslavna	Control	2.17	1.30	0.95	1.47
	$N_{22}P_{22}K_{22}$	2.64	1.40	0.97	1.67
	$N_{45}P_{45}K_{45}$ – recommended	2.87	1.48	0.98	1.78
	$N_{30}P_{45}K_{45}$ + N_{15}	2.91	1.88	1.09	1.96
	$N_{50}P_{30}K_{70}$ calculated	2.93	1.54	1.02	1.83
Slobozhanka	Control	2.68	1.25	0.86	1.60
	$N_{22}P_{22}K_{22}$	2.68	1.41	0.88	1.66
	$N_{45}P_{45}K_{45}$ – recommended	3.21	1.46	0.89	1.85
	$N_{30}P_{45}K_{45}$ + N_{15}	3.29	1.62	0.92	1.94
	$N_{50}P_{30}K_{70}$ calculated	3.52	1.91	0.90	2.11
LSD_{05} for varieties, t ha^{-1}		0.33	0.36	0.05	0.24
LSD_{05} for fertilizes, t ha^{-1}		0.19	0.20	0.03	0.14

Compared to Yaroslavna, the Slobozhanka variety showed a higher average yield. Without fertilizers, this variety produced a yield of 1.60 t ha^{-1}, and with the use of both recommended and calculated doses of fertilizers, the figures significantly increased. The maximum yield was achieved with the calculated dose of $N_{50}P_{30}K_{70}$, reaching 2.11 t ha^{-1}, indicating a more effective response of this variety to fertilization.

The statistical analysis demonstrates the effectiveness of different fertilization treatments and buckwheat varieties on grain yield over three years (2021–2023). The inclusion of LSD values at the 0.05 probability level provides a reliable means to discern statistically significant differences between treatments and varieties. Specifically, the LSD for varieties (0.33 t ha^{-1}) and fertilization treatments (0.19–0.22 t ha^{-1}) highlights the sensitivity of the analysis in identifying meaningful yield variations, ensuring the robustness and validity of the experimental conclusions.

The total costs for cultivating the varieties using row planting without fertilizers amounted to € 258.62 ha^{-1} for the Yaroslavna variety and € 170.22 ha^{-1} for the Slobozhanka variety. These figures also included additional costs associated with the use of fertilizers. As a result, the cost differences between the options became even more pronounced.

Table 2 provides important data on the costs and revenues from cultivating the Yaroslavna variety depending on different fertilization options. Total costs increase with the use of various fertilizer regimes. The highest costs are observed in the options with the $N_{22}P_{22}K_{22}$ and $N_{45}P_{45}K_{45}$ fertilizer regimes, due to the high cost of the fertilizers.

Yield depends on the quantity and type of fertilizers applied, which affect both the quality and quantity of the harvest. Based on this, revenue from grain sales was calculated.

Table 2. Costs for cultivating the Yaroslavna variety using row planting depending on the fertilization regime

Indicator	Units of measurement	Control	$N_{22}P_{22}K_{22}$	$N_{45}P_{45}K_{45}$	$N_{30}P_{45}K_{45}$ +N_{15}	$N_{50}P_{30}K_{70}$
Cumulative costs	€ ha^{-1}	252.3	457.0	669.0	547.9	588.7
Nitroamofoska	€ ha^{-1}		204.6	416.7		
Ammonium nitrate	€ ha^{-1}				30.6	
Urea	€ ha^{-1}				34.3	56.6
Superphosphate	€ ha^{-1}				88.5	59.3
Potassium sulfate	€ ha^{-1}				142.1	220.5
Price of grain at sale	€ ha^{-1}	292.7				
Income	€ ha^{-1}	430.2	488.8	521.0	573.7	535.6
Profit	€ ha^{-1}	177.9	31.8	–148.0	25.8	53.1
Profitability	%	41.4	6.5	–28.4	4.5	9.9

The table on the costs of cultivating the Yaroslavna variety using row planting under different fertilization regimes indicates various profit levels per hectare for each option. Profit is calculated as the difference between income (the value of the harvested grain multiplied by yield) and the total cultivation costs. The highest profit is € 177.9 € ha^{-1}, achieved in the control fertilization option. This suggests that fertilizer costs were the lowest in this variant, leading to higher profits, even considering lower yields or other factors. Excluding the control option, the highest yield was obtained in the $N_{50}P_{30}K_{70}$ option.

The lowest profit was recorded with the $N_{45}P_{45}K_{45}$ fertilization regime, where profit amounted to – € 148 € ha^{-1}. This indicates that the total costs of fertilizers and other production expenses exceeded the income from grain sales, resulting in a loss.

Analyzing the data from the table on the costs of cultivating the Slobozhanka variety (Table 3) using row planting under different fertilization regimes, the highest total costs were observed in the $N_{45}P_{45}K_{45}$ and $N_{30}P_{45}K_{45}$ + N_{15} regimes, indicating high fertilizer costs in these combinations.

Table 3. Costs for cultivating the Slobozhanka variety using row planting depending on the fertilization regime

Indicator	Units of measurement	Control	$N_{22}P_{22}K_{22}$	$N_{45}P_{45}K_{45}$	$N_{30}P_{45}K_{45}$ +N_{15}	$N_{50}P_{30}K_{70}$
Cumulative costs	€ ha^{-1}	166.1	370.7	582.8	461.6	502.5
Nitroamofoska	€ ha^{-1}		204.6	416.7		
Ammonium nitrate	€ ha^{-1}				30.6	
Urea	€ ha^{-1}				34.3	56.6
Superphosphate	€ ha^{-1}				88.5	59.3
Potassium sulfate	€ ha^{-1}				142.1	220.5
Price of grain at sale	€ ha^{-1}	292.7				
Income	€ ha^{-1}	468.3	485.9	541.5	567.8	617.6
Profit	€ ha^{-1}	302.2	115.1	–41.3	106.2	115.1
Profitability	%	64.5	23.7	–7.6	18.7	18.6

The highest income is achieved in the option with $N_{50}P_{30}K_{70}$ fertilization background (€ 617.5 € ha^{-1}), which is related to the higher yield obtained using this fertilizer rate. The highest profitability level for fertilization backgrounds, excluding the control option, is also observed in the $N_{22}P_{22}K_{22}$ variant, confirming its financial effectiveness.

Regarding fertilizer costs, it is worth noting that certain types of fertilizers, such as superphosphate and potassium sulfate, have a significant impact on total costs and may vary depending on their prices and the quantities applied.

A comprehensive analysis of the costs of growing buckwheat varieties (Yaroslava and Slobozhanka) using row sowing methods, depending on different fertilization backgrounds, shows that the efficiency of cultivation significantly depends on the proper selection and application of fertilizers. The most profitable options are characterized by an optimal balance between total costs and revenue from the harvest.

However, it should be noted that the natural fertility of the soil plays an important role in achieving high profitability. Soils with a high level of natural fertility can provide the highest yields and. Accordingly, the greatest income without significant fertilizer costs. However, with intensive soil use without replenishing nutrients, depletion is possible.

Therefore although natural fertility is an important factor in buckwheat cultivation, the use of minimal fertilizers is still necessary to preserve soil fertility in the long term. Proper fertilizer use helps conserve soil resources, improve crop resilience to stress, and ensure consistently high yields year after year.

An ecological–economic assessment of buckwheat cultivation from 2021 to 2023 showed the importance of optimal use of mineral fertilizers to increase yields. The Yaroslava variety, without fertilizers, provided an average yield of 1.47 t ha^{-1}, while with the recommended dose of $N_{45}P_{45}K_{45}$, the yield increased to 1.78 t ha^{-1}. Similar results were observed for the Slobozhanka variety, where yields increased from 1.60 t ha^{-1} without fertilizers to 2.11 t ha^{-1} with the calculated dose of $N_{50}P_{30}K_{70}$.

The economic evaluation indicates that the most profitable options were those with minimal or control levels of fertilization, where costs were lower. For the Yaroslava variety, the maximum profit (177.9 € ha^{-1}) was achieved in the control option, while other options with higher doses of fertilizers (e.g., $N_{45}P_{45}K_{45}$) showed a decline in profitability due to high costs. For the Slobozhanka variety, the highest income was achieved with $N_{50}P_{30}K_{70}$ fertilization (617.5 € ha^{-1}), demonstrating the greater efficiency of this variety under intensive fertilization.

Findings of this paper are supported by the work of Bonilla-Cedrez et al. (2021), who highlight that addressing the ‘ecological yield gap’ in agriculture, particularly in sub-Saharan Africa, requires not only technological advancements but also economic considerations. Their study emphasizes that while the ecological yield gap represents significant untapped potential, the economic yield gap—the difference between current yields and profit-maximizing yields—remains a critical limiting factor. They further suggest that complementary strategies, such as improving soil fertility, reducing fertilizer costs, and spatially optimizing fertilization practices, are necessary to enhance both productivity and profitability in agricultural systems. The findings of this study align with the review by Folina et al. (2021), which emphasizes the critical role of nitrogen management in promoting sustainability within diversified farming systems. Nitrogen over-application often leads to low nitrogen use efficiency (NUE), despite high crop yields. Folina et al. (2021) highlight the potential of nitrification and urease inhibitors in improving nitrogen uptake, storage, and yield components while reducing nitrogen losses in the form of NO_3^- leaching and NH_3 emissions. Their work underscores the importance of integrating such inhibitors into fertilization schedules to enhance nitrogen-related indices, such as NUE, Nitrogen Agronomic Efficiency (NAE), and Nitrogen Harvest Index (NHI). This approach not only supports sustainable nitrogen management but also contributes to the profitability of farming systems through improved nitrogen supply and crop performance. Meanwhile, findings of Khan et al. (2022), demonstrated that the combined application of synthetic phosphorus fertilizers and organic amendments can significantly improve crop productivity and profitability. Their research highlighted the superior performance of single super phosphate (SSP) combined with farmyard manure (FYM), which enhanced key yield parameters such as grains per spike, thousand-grain weight, biological yield, and grain yield. Under full irrigation, SSP + FYM provided the highest benefit–cost ratio (BCR), indicating its economic viability. Furthermore, the integration of organic supplements with inorganic phosphorus sources not only improved wheat yield under optimal irrigation but also provided a sustainable strategy for soil fertility management and resource use efficiency.

From an environmental perspective, excessive fertilizer use can lead to soil depletion and reduced fertility in the long term. Therefore, it is important to maintain a balance between yield and ecological sustainability by applying fertilizers moderately to preserve soil fertility and avoid its depletion. Efficient fertilizer use helps conserve natural resources, stabilize yields, and enhance crop resilience.

CONCLUSIONS

The findings of this study highlight the critical balance between fertilization levels. Yield, and economic efficiency in buckwheat cultivation. Both the Yaroslavna and Slobozhanka varieties responded positively to mineral fertilizers, with increased yields under optimal fertilization conditions. However, the study also revealed that the most economically viable cultivation methods did not necessarily involve the highest fertilizer doses. For the Yaroslavna variety, the most profitable option was the control (unfertilized) approach, where lower costs led to higher profits, despite slightly lower yields. In contrast, the Slobozhanka variety showed the highest income with intensive fertilization using the $N_{50}P_{30}K_{70}$ scheme, though profitability varied across different regimes. This study underscores the importance of optimizing fertilization to enhance both productivity and cost–effectiveness. Excessive fertilizer use, while boosting yields, may reduce profitability due to high input costs and can pose environmental risks by contributing to soil degradation over time. Therefore, an integrated approach that balances fertilizer use with environmental sustainability is essential.

Such practices will help maintain long–term soil fertility, ensure consistent yields, and promote sustainable buckwheat cultivation. Ultimately, the study demonstrates that effective fertilization strategies must consider both the economic and environmental impacts, guiding farmers toward practices that maximize both yield and profitability while preserving the natural resource base for future cultivation.

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