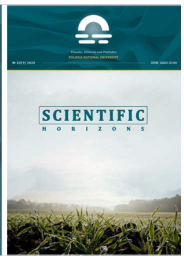
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(7), 48-61

UDC 631.17:330.341.1:338.43 DOI: 10.48077/scihor7.2025.48



Innovative technologies in crop production as a factor in improving the economic efficiency of agricultural production in Ukraine

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Article's History:
Received: 10.01.2025
Revised: 01.06.2025
Accepted: 25.06.2025

Abstract. The aim of the study was to determine the effectiveness of replacing chemical plant protection products, fertilisers, and growth stimulants with biological alternatives in terms of productivity, costs, profitability, and the agro-ecological state of soils. The research, conducted in 2020-2024, covered winter wheat varieties "Podolyanka", "Duma Odeska", "Favorytka", "Bohuslavka", "MIP Lada", and "Stolychna", barley varieties "Vakula", "Helios", and "Concerto", as well as maize hybrids "DKC 5143", "DKC 4014", "Pioneer 9892", "Khortytsia", and "Dniprovskyi 185 SV". The empirical base included statistical data, soil analysis results, case observations from farms in different regions, and economic modelling. It was established that the yield increase from applying biopreparations averaged 4.3-7.1 centners/ha for wheat and maize, and up to 4.8 centners/ha for barley, while costs decreased by up to 16%. The humus content in soils increased to 3.3%, and the number of microorganisms – to 3.8×10^6

Suggested Citation:
Farzaliyeva S., Safarova, V., Huseynova, L., & Opanasenko, A. (2025). Innovative technologies in crop production as a factor in improving the economic efficiency of agricultural production in Ukraine. *Scientific Horizons*, 28(5), 48-61. doi: 10.48077/scihor5.2025.48.

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colony-forming units per gram. An increase in the root system length of the "Stolychna" wheat variety up to 48 cm was observed, as well as a 40% reduction in barley fungal infections. Price analysis revealed that organic wheat was 48% more expensive than conventional wheat on the external market. The model forecast demonstrated the potential for cost savings for the agricultural sector of up to 15 billion UAH if 30% of farms transitioned to the biological model. The results obtained could be used to adapt agricultural technologies, develop support programmes for ecological farming, and enhance the export of organic products

Keywords: agriculture; profitability; biofungicides; biofertilisers; sustainable agriculture

INTRODUCTION

In 2020-2024, Ukraine's agricultural production operated under conditions of rising mineral fertiliser prices, deepening climate change, disrupted logistics chains, and increased environmental responsibility requirements. These factors significantly affected the economics of crop production, creating a need to implement innovative technologies focused not only on yield maximisation but also on preserving soil fertility, reducing anthropogenic pressure, and enhancing the export appeal of products. One such approach was the biologisation of technological processes – the partial or complete replacement of traditional chemical agents (mineral fertilisers, pesticides, growth stimulants) with biological alternatives (biofertilisers, microbial inoculants, biostimulants, biological plant protection agents). Research into the effectiveness of biologisation within the grain production system was relevant in the context of forming a sustainable agroeconomic development model.

Scientific publications demonstrated increasing interest in innovation within agricultural production, particularly in the context of technological process modernisation, profitability improvement, and ensuring ecological sustainability (Yaheliuk *et al.*, 2024). In the study by V. Mamchur and G. Studinska (2024), the effectiveness of technical innovations implemented in Ukraine's agricultural sector under the new production model was examined, including the modernisation of the machine and tractor fleet, digital transformation, and the implementation of automated control systems. The work of N. Kovalenko *et al.* (2021) focused on the economic aspects of grain production in Ukraine's Central region. The authors explored internal efficiency reserves and cost structures, emphasising factors influencing competitiveness. In turn, the publication by T. Shmatkovska *et al.* (2021) addressed land resource management in the system of non-current assets of agricultural enterprises, with a focus on the financial assessment of the use and impact on overall business performance.

Foreign authors concentrated on practices of "green" transformation in agricultural production, the introduction of biotechnologies, and the use of digital tools (Pavlenko *et al.*, 2025). In the study by S. Chen and J. Lu (2025), ways of increasing green output levels in China's leading grain-producing regions were explored. The authors justified the feasibility of a large-scale transition to biological farming technologies as one of the priorities for sustainable development. Y. Xing *et al.* (2025), in the review, analysed advanced irrigation strategies and soil moisture management, combined with the use of biostimulants and precision monitoring. The research by N. Ahmed *et al.* (2025) aimed to assess the impact of sustainable agricultural technologies on changes in soil emissions under climate change, using modern econometric models. In the publication by Y. Xie *et al.* (2025), the interconnections between the digital economy, efficient allocation of production factors, and the resilience of agricultural production were analysed. The experience of implementing climate-oriented agricultural strategies was considered in the study by W. Kabato *et al.* (2025), where the significance of biological technologies in reducing greenhouse gas emissions and maintaining food security was emphasised. The study by W. Geng *et al.* (2024) substantiated the economic benefits of agricultural digitalisation, while L.S. Fu *et al.* (2024) highlighted the effectiveness of agricultural insurance in the context of expanding farmers' access to production resources and reducing risks.

All the mentioned sources confirmed the importance of innovation in shaping a sustainable agricultural economy. However, the lack of a generalised empirical analysis of the economic effectiveness of biological technologies in the cultivation of key cereal crops in Ukraine created a gap in the applied justification for transitioning to biologisation. The aim of this study was to determine the economic effectiveness of biologised technologies in the cultivation of winter wheat, maize, and barley in Ukraine's agricultural sector. To achieve this goal, the following objectives were pursued: to analyse the impact of biological preparations on the yield and stability of cereal crop productivity; to compare costs and profitability levels between chemical and biological treatment schemes; and to assess the long-term effects of biologisation on soil condition, market value of products, and export potential.

MATERIALS AND METHODS

The study was conducted from 2020 to 2024 to analyse the effectiveness of biologised agrotechnologies in various natural and climatic zones of Ukraine. To achieve the research objectives, a range of scientifically grounded sources were used: statistical data from the State Statistics Service of Ukraine (n.d.), reports from the Food and Agriculture Organization (n.d.) on crop yields in Eastern Europe, analytical materials from the National Institute for Strategic Studies (2024), and information from the State Service of Ukraine on Food Safety and Consumer Protection (n.d.). The empirical basis of the study was formed from observations at six agricultural enterprises: "Poliskyi Agro" (Zhytomyr region), "Eko-Nyva" (Rivne region, Polissia), "Lisostep" (Cherkasy region), "Stepovi Zori" (Kherson region), "Sonyachnyi Step" (Zaporizhzhia region), and "Dniprovski Luki" (Dnipro region), located in the natural and climatic zones of Polissia, Forest-Steppe, and Steppe of Ukraine. The objects of study were cereal crops: winter wheat (varieties "Podolyanka", "Duma Odeska", "Bohuslavka", "Favorytka", "Stolychna"), maize (hybrids "DKC 5143", "Pioneer 9892", "Khortytsia", "Dniprovskyi 185 SV"), and spring barley (varieties "Vakula", "Helios", "Concerto"), which were recommended for cultivation in the respective zones and widely used in the practice of biologised farming. The subject of the study was agricultural technologies using biological products – biofertilisers (based on *Azotobacter chroococcum*, *Bacillus megaterium*), biofungicides (*Trichoderma asperellum*, *T. harzianum*), biostimulants (based on humic acids, extracts of marine algae), and mycorrhizal inoculants (*Glomus intraradices*).

The application of biological preparations (*Azotobacter*, *Trichoderma*, humic stimulants, mycorrhizal inoculants) was carried out in accordance with regulations defined in the normative documents of the National Institute for Strategic Studies (2024), with mandatory recording of application rates, treatment methods, and weather conditions during technological operations. Primary production data (yields, costs, soil parameters) were obtained directly from the involved farms based on field journals, agrochemical passports, and internal technological reports. The research methodology involved comparing biological and traditional cultivation technologies based on indicators of yield, cost, agrochemical soil status, and profitability. The experimental work was carried out at six agricultural enterprises located in various natural and climatic zones of Ukraine, particularly in Chernihiv (Polissia), Vinnytsia and Zhytomyr (Forest-Steppe), Mykolaiv, Zaporizhzhia, and Kherson (Steppe) regions. For each crop, control (chemical treatment) and experimental (biological treatment) plots were established. Observations were conducted throughout the entire growing season. For assessing the export of organic wheat, the period from 2018 to 2024 was selected. This period reflected the overall trend of export growth and decline, and considered the negative impact of geopolitical and economic factors, particularly the onset of military action in Ukraine from 2022, which caused a significant decrease in export volumes due to logistical problems, changes in certification requirements, and general impact on EU markets.

Soil fertility parameters were assessed using the methods of the Institute for Soil Science and Agrochemistry Research Named after O.N. Sokolovsky (n.d.). To illustrate the effectiveness of biologised approaches when analysing agrochemical and economic characteristics, typical cases of biological product application were used from six agricultural enterprises operating in different natural and climatic zones of Ukraine. The selection criteria included: long-term use of biological products, availability of controlled technological maps, access to production data, and open sources. In particular, the analysis included: "Poliskyi Agro" (Zhytomyr region), which used mycorrhizal preparations in wheat cultivation; "Stepovi Zori" (Kherson region), which applied nitrogen-fixing *Azotobacter* in maize cultivation; "Lisostep" (Cherkasy region), where biological fertilisers replaced mineral fertilisers in the winter wheat fertilisation system; "Eko-Nyva" (Rivne region, Polissia), which reported improved agrochemical soil status after long-term use of biological products; "Sonyachnyi Step" (Zaporizhzhia region), which monitored the anti-erosion effectiveness of biological agents based on *Bacillus megaterium*; and "Dniprovski Luki" (Dnipro region), which reported phytosanitary effects of *Trichoderma asperellum* in barley cultivation (State Statistics Service of Ukraine, n.d.; National Institute for Strategic Studies, 2024). Soil acidity was assessed using the potentiometric method, and the number of microorganisms was determined by the agar seeding method and colony-forming unit count per gram (CFU/g). The level of root system development was recorded on the 25th and 45th day of vegetation using a ruler and digital caliper. To calculate profitability, the standard formula (1) was used:

$$\text{Profitability}, \% = \frac{\text{Profit}}{\text{Cost of production}} \times 100, \qquad (1)$$

where Profit = gross income − cost per hectare; cost of production = total expenses on products, labour, machinery, and associated costs.

Yield fluctuations were assessed using the coefficient of variation formula (2):

$$\text{CV} = \frac{\sigma}{\text{x}} \times 100, \qquad (2)$$

where σ = standard deviation; x = mean yield for the period.

Additionally, the study included economic modelling of the impact of scaling up biological technologies on costs in Ukraine's agricultural sector through 2030. The calculation model took into account the projected expansion of agricultural areas cultivated with biological schemes and the average cost savings due to the replacement of mineral fertilisers, chemical plant protection products, environmental charges, and logistics expenses. Input data included analytical materials from the State Statistics Service of Ukraine (n.d.), National Institute for Strategic Studies (2024), and the authors' own calculations based on production case studies. The estimation of expected cost savings over time was conducted using the formula (3):

$$E_t = (P_t \times C) \times R, \quad (3)$$

where E_t is the cost saving in year t; P_t is the area cultivated using biological technology in year t; C is the average cost of treatment per hectare using traditional technology; R is the average percentage reduction in costs (15% to 20%).

All research was conducted in accordance with the provisions of the Law of Ukraine No. 3116-XII (1993). The applied biological products were registered and authorised for use in agriculture. Farms provided written consent to participate in the study, access to production data, and analysis of agrochemical soil indicators. Experimental and economic data were processed using Microsoft Excel 365 (correlation analysis, graph building, trend visualisation), Statistica 10.0 (mean value estimation, Student's t-test, coefficient of variation, normality test), and RStudio (version 2023.06) for mathematical modelling and scenario building of savings from the scaling up of biologisation. Graphical materials (charts, histograms, pie charts) were created in Tableau Public and Canva Pro to ensure clear interpretation of results. The selection of these tools was based on the accuracy, functionality for processing agronomic and economic data, and the ability to visualise variables across time, crop types, and cultivation technologies.

RESULTS

The impact of biological products on the yield of grain crops. The yield dynamics of major cereal crops underwent significant changes after replacing chemical agents with biological analogues. As shown in Table 1, in farms where mycorrhiza and nitrogen-fixing bacteria were applied to the wheat variety "Podolyanka", the average annual yield increase was 2.1-3.4 c/ha, whereas under chemical treatment this figure did not exceed 1.5 c/ha. For the maize hybrid "DKC 5143", the maximum annual increase (4.8 c/ha) was recorded on a farm that had fully transitioned to biofertilisers.

***Table 1**. Yield dynamics of wheat, barley, and maize (c/ha) on farms using biological and chemical technologies (2020-2024)*

Culture (variety/hybrid)	Technology	2020	2021	2022	2023	2024
Wheat ("Podolyanka")	Biological	48.2	50.3	52.7	54.1	55.6
Wheat ("Podolyanka")	Chemical	49.1	49.8	50.2	50.9	51.3
Corn ("DKC 5143")	Biological	72.4	75.1	77.3	79	80.5
Corn ("DKC 5143")	Chemical	70.8	71.5	72.1	72.9	73.4
Barley ("Vakula")	Biological	42.5	43.8	45.2	46.7	47.9
Barley ("Vakula")	Chemical	41.9	42.1	42.5	42.8	43.1

***Source:** developed by the authors based on data from the State Statistics Service of Ukraine (n.d.)*

These data are supported by case studies: on the farm "Poliskyi Agro" (Polissia), the introduction of mycorrhiza for the wheat variety "Stolychna" increased yields by 15% over three years, while on the farm "Stepovi Zori" (Kherson region), the use of Azotobacter for the maize hybrid "Pioneer 9892" boosted yield by 20%. Figure 1 presents a comparison of the average yields of crops in 2024. For the wheat variety "MIP Lada", the difference between biological and chemical technologies was 4.3 c/ha; for the maize hybrid "Khortytsia" – 7.1 c/ha; and for the barley variety "Helios" – 4.8 c/ha. This indicates a direct impact of bioproducts on productivity, especially under conditions of rainfall deficit or increased soil acidity."

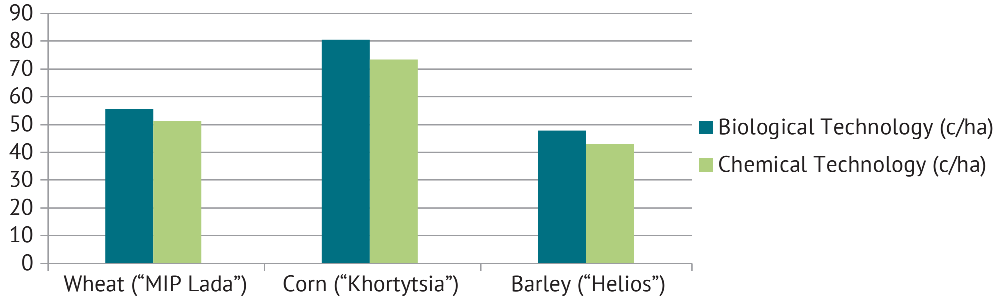

***Figure 1**. Comparison of average crop yields for 2024*
***Source:** developed by the authors based on data from the Food and Agriculture Organisation (n.d.)*

A critical aspect is yield stability. On farms with biological technologies, year-on-year fluctuations did not exceed 5%, whereas with chemical treatment the fluctuations reached 12-15% due to dependence on climatic factors. For instance, the barley variety "Concerto" in Cherkasy region demonstrated yield stability (45-47 c/ha) when using *Trichoderma*-based biofungicides (National Institute for Strategic Studies, 2024). The obtained results highlight the potential of biologised technologies as a means of improving cereal crop productivity without harming the environment. Significant yield improvements were noted even in regions with elevated risks of soil degradation and unstable weather conditions. Humic acid-based biostimulants are actively used in the early stages of winter wheat development, promoting better rooting, primary root growth stimulation, and activation of soil microflora (Fig. 2).

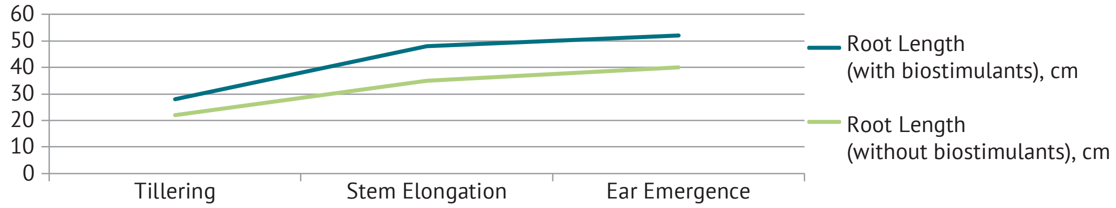

***Figure 2**. The effect of humic acid-based biostimulants on the development of the root system of "Stolychna" wheat (root length, cm)*
***Source:** developed by the authors*

For the winter wheat variety "Stolychna", the impact of humic acid-based biostimulants on root development was studied. As shown in Figure 2, the application of biostimulants led to an increase in the average root length by 22-35% compared to the control group at the tillering and stem elongation stages. For example, at the stem elongation stage, the root length reached 48 cm (with biostimulants) versus 35 cm (without), improving drought resistance. For the maize hybrid "DKC 5143", the effectiveness of microbial inoculants *Azotobacter chroococcum* was analysed across different climatic zones of Ukraine (Table 2). The highest yield increase (6.7 c/ha) was recorded in the Forest-Steppe zone (Cherkasy region), where sufficient soil moisture promoted nitrogen fixation. In the Steppe (Kherson region), effectiveness was lower (3.2 c/ha) due to rainfall deficit, which limited microbial activity.

***Table 2**. Effectiveness of microbial inoculants (Azotobacter) for maize in different climatic zones*

Climatic zone	Yield (with inoculants), c/ha	Yield (without inoculants), c/ha	Increase, c/ha
Polissya (Zhytomyr region)	78.5	72.1	6.4
Forest-steppe (Cherkasy)	82.3	75.6	6.7
Steppe (Kherson)	68.9	65.7	3.2
Steppe (Zaporizhzhya)	70.2	67	3.2
Forest-steppe (Vinnytsia)	74.5	71	3.5
Step (Dnipro)	69.8	66.2	3.6

***Source:** developed by the authors based on data from the Food and Agriculture Organisation (n.d.)*

A notable case is the experience of the farm "Dniprovski Luki" (Dnipro region), where the use of *Trichoderma asperellum*-based biofungicides for the barley variety "Helios" reduced the incidence of fungal infections (*Fusarium graminearum*) by 40%. This led to a 25% reduction in fungicide costs (from UAH 1,800 to UAH 1,350/ha) and an 18% increase in yield (from 45 to 53 c/ha) in 2023. Overall, the study results confirm the effectiveness of targeted selection of bioproducts for specific crops, taking into account the agroecological environment, enabling optimisation of agrotechnologies, cost reduction, and increased yields in a naturally balanced manner.

Comparison of costs and profitability of chemical and biological schemes. As part of the study, a comparison was made of the costs of growing winter wheat of the "Duma Odeska" variety using two treatment schemes – chemical and biological. The analysis focused on the key cost categories directly influencing production efficiency, namely: costs of preparations (plant protection products and fertilisers), labour, technical support, and other related expenses such as logistics, laboratory tests, and seeds. To objectively assess the economic efficiency of biologised technologies, a comparison was made between traditional (chemical) and biological treatment schemes for the "Duma Odeska" wheat variety. The analysis covered key expenditure categories: preparations, labour, technical support, and related expenses (Table 3).

Table 3. *Comparison of costs (UAH/ha) for treating "Duma Odeska" wheat under chemical and biological schemes (2024)*

Expense category	Chemical scheme	Biological scheme
Preparations (plant protection products, fertilisers)	8,200	5,900
Labour	1,100	1,200
Equipment (fuel, depreciation)	2,000	2,200
Other (logistics, laboratory tests, seeds)	1,700	1,600
Total	13,000	10,900

Source: *developed by the authors based on data from National Institute for Strategic Studies (2024)*

As seen in Table 3, implementing the biological scheme made it possible to reduce the treatment costs per hectare of wheat by an average of UAH 2,100 (≈16.2%), primarily due to lower expenditure on mineral fertilisers and chemical plant protection products. The slight increase in labour and machinery costs was due to the need for more precise and regular application of biopreparations and monitoring of soil biological indicators. According to the obtained data, the biological scheme proved more economically beneficial, as it enabled a reduction in costs by UAH 2,100 per hectare (around 16.2%). This saving was primarily achieved through significantly reduced expenditure on mineral fertilisers and chemical agents, which form the core of chemical technologies. At the same time, labour and machinery costs under the biological scheme were slightly higher than in the chemical one due to the need for frequent biopreparation applications and more thorough soil and plant condition monitoring. However, this increase in machinery and labour costs did not outweigh the savings from reduced preparation costs, making biological technologies economically advantageous. The total per-hectare cost of using biological technology amounted to UAH 10,900, whereas with chemical methods it reached UAH 13,000. This confirmed that biological technologies could be effective even in conditions of high technical costs, as reduced expenditure on preparations allowed total costs to be decreased. For a visual assessment of cost distribution under the biologised maize growing technology (hybrid "DKC 4014"), a pie chart was created illustrating the proportion of key cost categories in the overall structure (Fig. 3).

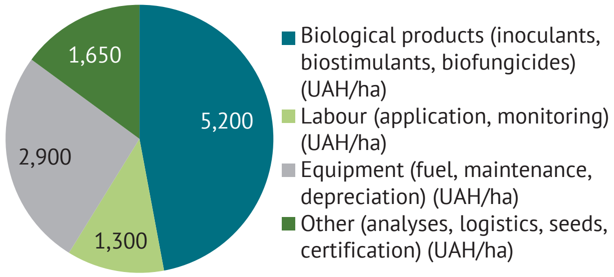

Figure 3*. Cost structure under biological treatment of maize (hybrid "DKC 4014"), 2024*

Source: *developed by the authors based on data from the Food and Agriculture Organization (n.d.)*

As shown in Figure 3, the largest share of costs in the biological maize treatment scheme was for preparations, which was due to the use of highly effective biofertilisers based on humic acids. Technical costs included specialised equipment for applying biopreparations, while the reduced use of pesticides allowed environmental fees to be cut by 15%. A significant practical example was the "Lisostep" farm (Cherkasy region), which completely replaced mineral fertilisers with biopreparations for growing "Favorytka" wheat. Over three years of implementation, the cost of production decreased by 12% (from UAH 10,200 to 8,970/ha), while profitability rose from 18% to 24%. This was made possible through a combination of *Azotobacter* nitrogen-fixing bacteria and *Trichoderma harzianum*-based biofungicides. These results demonstrated the economic feasibility of switching to biologised schemes, which not only reduced direct per-hectare costs but also generated stable profits through improved product quality, lower phytotoxicity risks, and enhanced agro-ecological field conditions. The level of profitability is an important indicator of production process efficiency, as it reflects how much profit farmers earn per unit of expenditure (Shahini & Shtal, 2023). To calculate profitability, a formula was used comparing revenue and expenses for both treatment schemes. The profitability calculation showed that the biological scheme yielded a profitability rate of 4.288%, which was significantly higher than the chemical scheme's 2.584% (Formula 1). This indicated that biological technologies offered not only cost reduction but also a higher level of economic benefit for farms. In particular, by cutting expenses on chemical agents and fertilisers, farmers could earn more profit at the same yield level.

Yield fluctuations are another important indicator of agricultural production stability (Drobitko & Kachanova, 2023). High yield stability reflects lower risks for producers, especially in the context of climate change and seasonal variability (Struminska *et al.*, 2014). To assess yield fluctuations, a formula was used to determine the difference between maximum and minimum yield figures for each year. The results showed that with biological technology, yield variability for the "Podolyanka" wheat variety amounted to 14.4%, which was notably lower than the 15% under chemical treatment (Formula 2). This indicated that biological technologies helped reduce the impact of unpredictable factors such as climate change on yield outcomes. At the same time, yield stability was one of the main advantages of biological technologies, as it allowed farmers to secure more stable profits in the long run. The comparison of costs and profitability showed that biological technologies were economically efficient because the technologies enabled savings on chemical preparations and fertilisers, significantly reducing overall per-hectare expenditure. At the same time, thanks to higher profitability, biologised schemes provided greater economic benefits for farmers. A high level of profitability and stable yields were key factors in ensuring sustainable agricultural development, as confirmed by the comparison results. Thus, biologisation of agronomic technologies was not only economically viable but also environmentally sound, enabling sustainable agricultural development, increased resilience to climate change, and reduced environmental impact.

Assessment of the economic efficiency of biologisation of agronomic technologies to increase yields and reduce costs. In addition to the direct effects on yield and cost reduction, biologised technologies formed a long-term positive impact on the agroecological condition of soils, which in turn influenced income stability over an extended period. In particular, improvements in soil fertility, increased activity of soil microflora, reduced acidity and erosion processes contributed to sustainable productivity growth without extensive pressure on natural resources. A study of soil indicators at the "Eko-Nyva" farm (Polissia) over 2020-2024 revealed a positive trend in humus content (Fig. 4). For example, on plots with biological treatment of the wheat variety "Bohuslavka", the humus content increased from 2.8% to 3.3%, while on control plots with chemical technologies this figure remained at 2.7-2.9%.

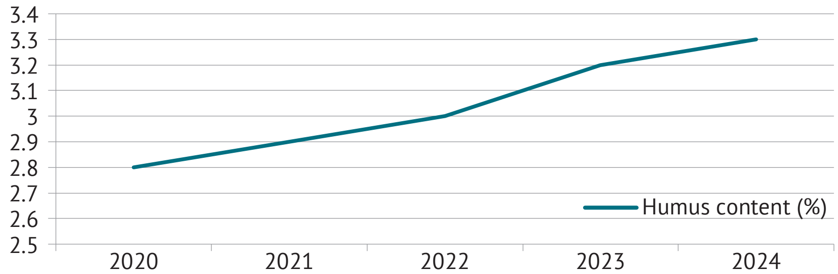

Figure 4*. Dynamics of humus content in soils (2020-2024), "Eko-Nyva" farm (Polissia)*

Source: *developed by the authors based on data from National Institute for Strategic Studies (2024)*

According to Table 4, after five years of biologisation, farms with different soil types showed improvements in key agrochemical indicators. For instance, on chernozems in the Sumy region, soil pH stabilised at 6.5-6.7, and the number of microorganisms increased from 1.2×10^6 to 3.8×10^6 CFU/g (colony-forming units). This indicated the activation of microbiological processes that ensured natural plant nutrition.

Table 4*. Soil fertility indicators after 5 years of biologisation (2020-2024)*

Indicator	Chernozems (Sumy region)	Serozems (Kherson region)	Sod-podzolic soils (Zhytomyr region)
pH	6.7	7.1	5.9
Humus (%)	4.1	1.8	2.5
Microorganisms (CFU/g)	3.8×10^6	2.1×10^6	1.9×10^6

Source: *developed by the authors*

A significant economic effect was the reduction in costs associated with the reclamation of degraded soils. At the farm "Sonyachnyi Step" (Zaporizhzhia region), the introduction of biofertilisers based on *Bacillus megaterium* bacteria reduced soil erosion by 30% over four years. This led to a reduction in anti-erosion costs from UAH 2,500 to UAH 1,750/ha and increased the yield of the maize hybrid "Dniprovskyi 185 SV" by 18%. Thus, biologisation ensured ecologically sound economic benefits by reducing anthropogenic pressure on the soil environment, increasing its self-regeneration potential, and preserving productivity in the medium and long term. The obtained indicators were particularly important for zones of risky agriculture (Polissia, Steppe), where soil degradation was a systemic issue.

One of the key economic arguments in favour of implementing biologised technologies in crop production was the increase in market value of ecologically certified products and expanded access to international markets (Kulazhanov *et al.*, 2024). The organic grain production segment demonstrated stable demand for produce with low pesticide residue levels, grown according to the principles of sustainable agriculture. In 2024, the average price for organic grain on the domestic market of Ukraine exceeded that of conventional produce by 20-35%, and on external markets – by more than 40% (Table 5).

***Table 5**. Average grain prices in Ukraine (2024): organic vs traditional production*

Culture	Product type	Domestic market, UAH/t	External market (EU), $/t
Winter wheat	Traditional	6,800	230
	Organic	8,600	340
Spring barley	Traditional	6,100	210
	Organic	7,400	295
Corn	Traditional	6,300	225
	Organic	8,100	320

***Source:** developed by the authors based on data from the State Statistics Service of Ukraine (n.d.)*

As shown in Table 5, the largest difference in export value was observed for winter wheat, which is one of Ukraine's main export commodities. In 2024, the premium on the price of organic wheat amounted to $110/t, or about 48% more than produce grown with conventional technology. Despite the price premium, the export of organic wheat from Ukraine experienced significant fluctuations. The highest volume of deliveries to the EU over the last six years was recorded in 2018 – 75,971 t (Fig. 5). However, by 2022 this figure had dropped to 20,797 t, and in 2023 it fell to 11,000 t. This trend was associated with a decrease in the number of certified organic farms, increased international market competition, and geopolitical factors.

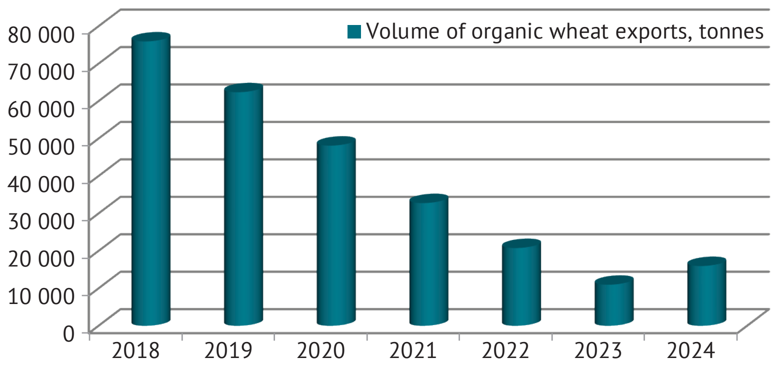

***Figure 5**. Export of organic wheat from Ukraine to the EU (2018-2024), thousand tonnes*

***Source:** compiled by the authors based on data from the State Service of Ukraine on Food Safety and Consumer Protection (n.d.)*

In addition to the decline in volumes, the geographical profile of exports also changed. While in 2018, 85% of organic wheat exports went to Germany and the Netherlands, by 2023 this share had dropped to 60%, with the rest redirected to markets in Poland and Romania. A successful example of diversification was the "Zolotyi Kolos" farm (Vinnytsia region), which in 2023 signed a contract with the German company "BioGetreide GmbH" to supply 5,000 t of organic maize of the hybrid "Dniprovskyi 185 SV" at a price of €310/t. This allowed the farm to offset losses from the decline in wheat exports. Thus, the introduction of innovative biological technologies in crop production contributed to the creation of economic added value through certification, ecological positioning, and entry into premium sales markets. This opened new opportunities for farmers, including small and medium-sized enterprises, provided the enterprises adhered to traceability requirements, phytosanitary safety, and environmental responsibility. The projected cost savings for Ukraine's agricultural sector by 2030 were based on an analysis of trends in the transition of farms to biological technologies. Provided such practices were scaled up, it was expected that by 2025 the annual savings would amount to UAH 4.68 billion, and by 2030 this figure would rise to UAH 15.21 billion (Formula 3). These calculations took into account the average cost of traditional cultivation of 1 hectare of cereal crops and the empirically confirmed level of cost reduction in farms that had already implemented biological methods. The dynamics of savings demonstrated an economy-of-scale effect: with an increase in cultivated area up to 6.5 million ha, the potential for reducing costs on fertilisers, pesticides, and environmental payments grew significantly. According to the forecast shown in Figure 6, the total annual cost savings with a full transition of 30% of farms to biological schemes could reach UAH 12-15 billion. This was due to reductions in the cost of mineral fertilisers (by 25-40%), pesticides (by 20-35%) and environmental fines (by 18-22%).

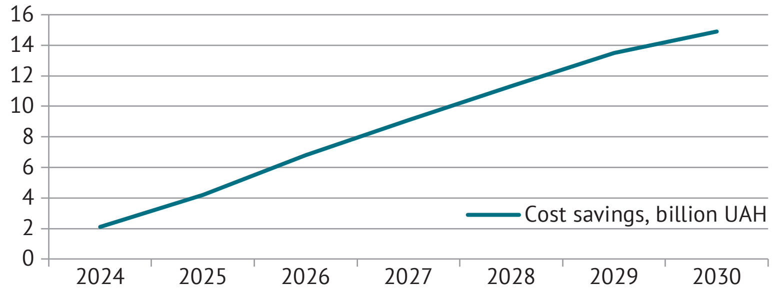

***Figure 6**. Projected cost savings of Ukraine's agricultural sector by 2030 with the scaling of biologisation (UAH billion)*
***Source:** developed by the authors based on data from the State Statistics Service of Ukraine (n.d.)*

To maximise the effect, it was necessary to consider the soil-climatic characteristics of the regions. As shown in Table 6, the optimal technologies for chernozems included mycorrhiza and biofertilisers based on humic acids, which increased yield by 15-20%. For serozems in the steppe zone, the use of nitrogen-fixing bacteria (*Azotobacter*) and seaweed-based biostimulants was critical, because of reducing the impact of drought. On sod-podzolic soils, effective measures included biopesticides based on *Trichoderma* and phosphorus-mobilising microorganisms, which increased phosphorus availability by 30-35%.

***Table 6**. Recommended technologies for different soil types*

Soil type	Priority biological technologies	Efficiency (yield increase, %)
Chernozems	*Mycorrhizae*, biofertilisers based on humic acids	15-20
Serozems	*Azotobacter*, biostimulants from seaweed	10-15
Sod-podzolic	*Trichoderma*, phosphate-mobilising bacteria	12-18

***Source:** developed by the authors*

Implementation of these recommendations required state support, including subsidies for the purchase of bioproducts and training of farmers. For instance, the experience of the "Stepovi Zori" farm (Kherson region) demonstrated that combining biofertilisers with drip irrigation enabled maize yields of 80-85 c/ha even under arid conditions. This highlighted the importance of integrating biological and technical solutions for stabilising agricultural production. Summarising the modelling results, it could be stated that scaling up biologisation had strategic significance for Ukraine's agricultural economy, as it allowed: reducing production costs without compromising yields; preserving and improving soil resources; creating an export advantage in the ecological products market; and integrating Ukraine's agro-industrial complex into global sustainable development trends. The effectiveness of biologised technologies in Ukraine's agricultural sector manifested both in the short and long term – through increased yields, reduced costs, improved soil quality, and expanded export opportunities. In view of this, it was advisable to develop a national strategy for incentivising biologisation as a key component of the country's agroecological policy.

DISCUSSION

The results obtained demonstrated the significant effectiveness of biologised technologies in improving yields, economic viability, and the agroecological condition of soils. Comparison with current scientific research indicated alignment with conclusions on the potential of bioproducts for achieving the goals of sustainable agriculture. Yield increases in wheat, maize, and barley due to the use of mycorrhizae, nitrogen-fixing bacteria, and biostimulants confirmed the findings of H. Lu *et al.* (2024), who identified agglomeration benefits in cereal production under conditions of optimised ecological efficiency in the agricultural environment. Similarly, in China, the application of biological treatments and digital tools led to increased agricultural productivity under conditions of water and soil scarcity. The observed reduction in yield fluctuations in farms using biological systems – at levels up to 5% – correlated with the findings of M.J. Usigbe *et al.* (2023), who proved that adaptive technologies, including microbial and digital monitoring systems, significantly enhanced the resilience of agricultural systems to climate risks. It was found that the use of artificial intelligence platforms combined with bioproducts enabled precise application and control of agri-inputs, thus improving production stability.

The study recorded a consistent increase in humus content and soil bioactivity following five years of bioproduct use, aligning with the analysis by Y. Pan *et al.* (2024), which emphasised the importance of innovations – particularly farmer-led initiatives introducing microbiological solutions – for long-term restoration of soil functions. The research highlighted that introducing biofungicides and humic substances had positive effects on pH, soil structure, and microbial biomass. The economic efficiency of biologised technologies, documented in the form of a 16.2% reduction in costs and increased profitability, corresponded with the analysis by C. Bernini and F. Galli (2024), who showed that agricultural entities with high ecological efficiency delivered better economic performance under spatially diversified policies. Similarly, S.K. Kuchimov (2021) emphasised the importance of transitioning to innovative farming models to lower production costs and optimise spending on crop protection and fertilisers. Cost structure analysis for biologised maize cultivation revealed a dominance of spending on bioproducts, explained by the high effectiveness under arid conditions. Similar conclusions were presented in the work of S. Alharbi *et al.* (2024), noting that in arid and semi-arid regions, the use of *Azotobacter* and phytostimulants improved water retention capacity in plants and resistance to stress. The study also mentioned reduced environmental fees, corresponding with the findings of L. Aldieri *et al.* (2021) regarding the link between technological modernisation and reduced environmental impact through knowledge-intensive innovations.

The forecasted cost savings from scaling biologisation to 30% of farms (up to UAH 15 billion annually) matched the macroeconomic estimates presented by J. He *et al.* (2025). The researchers showed that introducing digital and biological technologies could increase total factor productivity by 12-15% in the medium term. The work of Y. Hu *et al.* (2024) noted that the digital economy in agriculture delivered maximum effect when combined with biologised farming schemes. This alignment with the current study was evidenced by farms that implemented biological technologies alongside technical elements (e.g., precision application, regular lab monitoring, soil condition control), which recorded not only yield increases (up to 6.7 c/ha in maize) but also a reduction in annual yield variability to 5%. Additionally, improvements in agrochemical indicators were observed (humus content increased by 0.5-0.6%) and production costs decreased by 16.2%.

Premium organic product market results – particularly a price difference of up to 40% – were consistent with the findings of L. Ma *et al.* (2021) and K.K. Shah *et al.* (2021), who noted a stable rise in demand for organic agricultural products amid global consumer shifts towards sustainable food models. The recorded decline in organic wheat exports from Ukraine to the EU aligned with the observations of O. Adisa *et al.* (2024) regarding the need to strengthen certification, traceability, and smallholder support systems to maintain market positions. Performance indicators for *Azotobacter chroococcum* in various climate zones (up to 6.7 c/ha in Forest-Steppe regions) confirmed the findings of G. Papadopoulos *et al.* (2024), which noted that synergistically combining bioproducts with precision farming technologies produced maximum effect in moderately humid regions, while under drought conditions, supplementary irrigation or improved soil structure was needed. The outcomes from "Dniprovski Luki" and "Sonyachnyi Step" farms demonstrated that targeted use of biofungicides *Trichoderma asperellum* and *Bacillus megaterium* reduced yield losses from fungal infections and erosion. This supported the models proposed by D.M. Hemathilake and D.M. Gunathilake (2022), who recommended prioritised microbial protection in regions with high soil degradation risk and phytopathogen prevalence.

The application of humic acid-based biostimulants, which promoted 22-35% growth in wheat root systems, fully correlated with the research by M. Pisante *et al.* (2012), which confirmed that early root formation was a critical factor for stress resistance and high yield potential. Similar approaches were supported in the review by K. Takacs-Gyorgy (2012), which pointed to the economic feasibility of transitioning to precision farming with biological inputs. The importance of accounting for soil types in selecting biological technologies was supported by the research of S. Algarni *et al.* (2023), which stated that bioproduct effectiveness significantly depended on pH, organic content, and microbial activity. The research by R. Reddy (2022) emphasised that applying modern agricultural machinery – including precision seeding units, application systems, and digital field management platforms – significantly improved bioproduct usage efficiency. This approach aligned with findings showing that while technical costs in biologised schemes partly increased, ensuring better process control. Additionally, results from implementing adaptive crop varieties and hybrids in combination with biological technologies confirmed the assertion by A. Abdul-Rahaman *et al.* (2021) that bridging the technological gap in agriculture was only possible through aligned adoption of both genetic innovations and agrotechnological practices. Yield increases of 15-20% indicated the high effectiveness of combining breeding achievements with biological stimulation under regional conditions.

In conclusion, the study's results aligned with the international theoretical and empirical discourse on the benefits of biologised technologies in the context of sustainable development, economic efficiency, agro-ecological safety, and climate adaptation. The findings confirmed the rationale for developing a national policy to support biologisation in agriculture, taking into account regional specifics, certification needs, digitalisation, and expert support for farmers.

CONCLUSIONS

Within the study, it was established that the introduction of biological technologies in the cultivation of winter wheat, maize, and barley under Ukrainian conditions contributed to increased economic efficiency of production by reducing costs, increasing yields, and improving soil quality. A comparative analysis over 2020-

2024 showed that when bioproducts were applied, the average yield of the wheat variety "Podolyanka" increased from 48.2 to 55.6 c/ha, whereas under the chemical scheme it remained around 51.3 c/ha. For the maize hybrid "DKC 5143", the yield increase amounted to 8.1 c/ha, and for the barley variety "Vakula" – 4.8 c/ha. The overall reduction in per-hectare costs for the wheat variety "Duma Odeska" amounted to UAH 2,100 (16.2%), including reductions in input costs of up to UAH 2,300 per hectare. The profitability of cultivating the wheat variety "Favorytka" in the Cherkasy region increased from 18% to 24%.

Soil improvements were recorded over the five-year application of biofertilisers: humus content increased to 3.3% (0.5% higher than the control), acidity stabilised at 6.5-7.1 pH, and the number of microorganisms rose from 1.2×10^6 to 3.8×10^6 colony-forming units per gram of soil. A 30% reduction in soil erosion activity was also confirmed in farms in Zaporizhzhia region. For individual crops, it was established that the root length of the wheat variety "Stolychna" increased to 48 cm, and fungal infection in the barley variety "Helios" decreased by 40%. Price analysis showed that organic products were sold at a premium: on the foreign market, the price of organic wheat reached USD 340 per tonne – USD 110 per tonne more than conventional wheat. The forecast of economic modelling suggested that if the biologised model were scaled to 30% of farms by 2030, the annual savings for the agricultural sector could amount to UAH 14.9 billion. Prospective directions for further research included the development of local agrotechnological maps with consideration of soil types, the creation of digital solutions for monitoring biological processes in the field, and the long-term evaluation of the effectiveness of bioproducts.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Інноваційні технології у рослинництві як фактор підвищення економічної ефективності аграрного виробництва України

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Анотація. Метою роботи було встановити ефективність заміни хімічних засобів захисту рослин, добрив і стимуляторів росту на біологічні аналоги в контексті продуктивності, витрат, рентабельності та агроекологічного стану ґрунтів. Дослідження, проведене у 2020-2024 роках, охоплювало сорти озимої пшениці «Подолянка», «Дума одеська», «Фаворитка», «Богуславка», «МІП Лада» та «Столична», ячменю «Вакула», «Геліос» і «Концерто», а також гібриди кукурудзи «ДКС 5143», «ДКС 4014», «Піонер 9892», «Хортиця» та «Дніпровський 185 СВ». Емпірична база включала статистичні дані, результати ґрунтових аналізів, кейс-спостереження в господарствах різних регіонів та економічне моделювання. Було встановлено, що приріст врожайності при застосуванні біопрепаратів становив у середньому 4,3-7,1 ц/га для пшениці й кукурудзи та до 4,8 ц/га для ячменю, при цьому витрати знижувалися до 16 %. Вміст гумусу у ґрунтах зріс до 3,3 %, а кількість мікроорганізмів – до 3,8×106 колонієутворювальних одиниць на грам. Спостерігалося збільшення довжини кореневої системи пшениці сорту «Столична» до 48 см та зменшення ураження ячменю грибковими інфекціями на 40 %. Аналіз цін виявив, що органічна пшениця коштувала на 48 % дорожче за традиційну на зовнішньому ринку. Прогноз моделі засвідчив потенціал економії для аграрного сектору до 15 мільярдів гривень за умов переходу 30% господарств на біологічну модель. Отримані результати можуть бути використані для адаптації агротехнологій, формування програм підтримки екологічного землеробства та розвитку експорту органічної продукції

Ключові слова: сільське господарство; рентабельність; біофунгіциди; біодобрива; стале землеробство