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Economic assessment and innovation management for microbial-hormonal treatments in organic soyabean under climate variability

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Abstract. The article examines the economic feasibility of using microbial and phytohormonal biopreparations in organic soyabean production in Ukraine under the conditions of climatic instability and market fluctuations. The aim of the study was to conduct a comprehensive economic assessment of the profitability of biotechnological cultivation schemes for the Khorol soyabean variety using biopreparations of different origins - Profix, Mycofriend and Violar - implemented over three years (2022–2024), taking into account the level of costs, organic product prices, and hydrothermal conditions. The study also sought to develop an adaptive model for choosing the optimal strategy for organic soyabean producers. The methodology is based on a combination of cost analysis, profitability sensitivity to price scenarios €475–661 per tonne, yield variation coefficients, as well as strategic grouping of schemes according to the "income-risk" criteria. The developed heat map and strategic matrices enabled the formulation of flexible recommendations based on financial capacities and market price expectations. It was found that the combined schemes (in particular, Mycofriend + Profix + Violar) demonstrate not only the maximum yield (3.23 t ha^{-1}) and the highest profitability (369%), but also the lowest level of yield fluctuation (CV=9.7%), which indicates their adaptability to hydrothermal stress. At the same time, some monocomponent options (Profix, Control) had unstable yields with a low level of profitability. Based on multi–criteria analysis, a Decision Matrix Model was proposed that combines producer goals, climatic expectations, and market prices of products.
Key words: biopreparations, economic efficiency, climate risks, decision matrix model, profitability.

Introduction

Soyabean (*Glycine max* (L.) Merrill) is one of the most versatile and in-demand crops on the global agri-food market due to its broad range of applications, from the food industry to the biodiesel, plastics, paints production and textiles (Huang *et al.,* 2024; Lin *et al.,* 2021; Nair *et al.*, 2023). In terms of production volume, soyabean ranks sixth among agricultural crops, and it holds fourth place in terms of economic significance and cultivated area (Bosanquet, 2023). The global soyabean market was estimated to be worth $198.1 billion in 2024. By 2029, it is projected to grow to $277.88 billion at a compound annual growth rate (CAGR) of 7.2% (Soybean Market Size & Share Analysis, 2024). Global soyabean production is expected to reach a record 421 million tonnes in the 2024/25 season, up 7% from the previous year. This growth is driven by increased demand from the feed, food and industrial processing sectors, where consumption is projected to reach 405 million tonnes (IGS: Global soyabean production, 2024). Ukraine achieved a record soyabean harvest in 2024 – 6.0 million tonnes compared with 5.2 million tonnes in 2023, despite a reduction in the sown area caused by intensified hostilities. At the same time, soyabean yields in Central and South-Eastern Europe declined significantly due to pod abortion, drought, and temperature stress. In this context, Ukraine emerged as a key driver of soyabean production in Europe, remaining among the top ten global producers (USDA: IPAD, 2025). Since the European Union is a key importer of Ukrainian soyabeans (accounting for 47% of total exports) (Rotundo *et al.,* 2024), it is critically important for Ukrainian producers to

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comply with the requirements of the European Green Deal. In particular, this concerns organic farming, which prohibits the use of pesticides and GMOs, promotes agroecological approaches to managing soil fertility and phytosanitary conditions, and contributes to the preservation of agrobiodiversity (Chaika, 2013). Prospects of organic farming depend on its competitiveness relative to conventional farming. A meta-analysis of global studies by Crowder and Reganold (2015), covering 55 crops grown across five continents, shows that despite lower yields, organic farming is significantly more profitable than conventional farming and has potential for global expansion. However, switching to organic production requires a significant initial investment.

The global organic soyabean market was valued at $1.5 billion in 2022, and it is projected to reach $3.4 billion by 2030, with a CAGR of 12.6%. The European organic soyabean market ranks second in volume among the world regions, with the United Kingdom and Germany driving the demand for this segment (Nandi, 2017).

According to the European Commission report, Ukraine is among the five largest suppliers of organic agricultural products to the EU, ranking second in organic soyabean exports (39.1 thousand tonnes, valued at $31 million), which accounts for 24.7% of the EU's demand. Despite an overall 20.7% decline in organic exports in 2023 due to the war, organic soyabean shipments increased by 27.5%, reaching 39.1 thousand tonnes worth $31.0 million ($793 per tonne) (OrganicInfo.ua, 2023).

Influenced by the growing awareness among the populations of Europe and North America about the risks associated with consuming trans fats, the demand for organic soy products remains high (Nandi, 2017). This has created favourable conditions for Ukraine, which achieved a record export of organic soy in 2024 – 52.9 thousand tonnes, representing a 67.1% increase compared with 2023 (Donau Soja, 2024).

The present study was conducted in the Poltava region, which accounts for 8.2–12.8% of national soyabean production and occupies an important position in the organic sector. Among the 19 certified producers, four specialise in organic soyabean cultivation, and two operate their own processing facilities for oil production (Organic Standard, 2025). The availability of these processing capacities creates favourable conditions for increasing added value in the region. The high concentration of production in Zhytomyr and Poltava regions, which together account for 63.2% of specialised farms, indicates the formation of a sustainable cluster model for industry development.

However, despite favourable market trends and infrastructure development, organic soyabean production remains vulnerable to global climate change, which is increasingly affecting yields, especially in agriculturally oriented regions.

Studies on the impact of climate change on soyabean productivity show considerable variability in results depending on the region and cultivation models used. According to a model comparison conducted by Kothari *et al.* (2022), for a temperature increase of +3 °C in Argentina's coldest region, some models predict a yield decrease of 24%, while others forecast an increase of 29%. At the same time, in the warmest location in Brazil, climate change models predict yield changes ranging from a 38% decrease to no effect at all for the same temperature rise. A simulation experiment by Elli *et al.* (2022) conducted in ten soyabean-producing regions of the United States, using the Agricultural Production Systems Simulator (APSIM) model, and future climate projections from five global circulation models, indicated that climate change between 2020 and 2080 will increase nitrogen mineralisation by 24% and N_2O emissions by 19%, but reduce nitrogen fixation by 32%, seed nitrogen content by 20%, and soyabean yield by 19%. Based on these results, it can be concluded that the considerable uncertainty in model responses limits their reliability in predicting climate change impacts on agri-food systems.

Fess and Benedito (2018) report that organic crop production is currently established in nearly every country in the world, and consumer demand is at all-time high with no decline expected. However, for its economic attractiveness for producers and accessibility for consumers under the challenges posed by global climate change, it is necessary to find an optimal biofertiliser application models for specific soil and climatic conditions to maximise yield and crop quality.

According to the long-term researches by Zhao *et al.* (2024), the biofertilisers application becomes an unavoidable prospect for replacing chemical fertilisers in sustainable agriculture. Evidence from ROI Biologicals (2024) demonstrates that biofertilisers have a significant impact on the yield increase, which enhances profitability through improved plant growth and development. Furthermore, studies (Burbano-Cuasapud *et al.*, 2023) indicate that widespread adoption of biofertilisers can substantially reduce environmental burdens and decrease dependence on mineral fertilisers.

At the same time, climatic stresses, primarily drought, increasingly constrain the potential of agricultural production. Wang *et al.* (2022) highlight the significant influence of weather factors on soyabean production, particularly organic soyabeans. Research by Bogati and Walczak (2022) demonstrates that global climate change is altering the soil environment and adversely affecting soil biota, including microorganisms and plants, thereby complicating crop cultivation. According to Poudel *et al.* (2023), global climate change may cause potential yield losses of up to 50% for many crops and up to 100% for soyabeans. Consequently, biological stress management tools are receiving growing attention as a means to enhance plant resilience to climatic events. In particular, Azarbad (2022) reports that applying soil-associated and symbiotic microorganisms can significantly enhance crop resistance to adverse environmental conditions. Strour *et al.* (2020) emphasise the importance of integrating microbiome-based technologies into modern agricultural systems as a critical step towards reducing anthropogenic environmental pressure without compromising productivity.

To increase crop production under organic farming conditions without extensive land-use changes or agricultural expansion, a biological approach can be used to ensure higher productivity, especially in rapidly changing climates. Considering our previous research, it should be noted that the use of biological preparations only at the pre-sowing seed treatment can ensure a yield increase of agricultural crops under organic farming conditions by up to 31% compared with conventional technology, as demonstrated for emmer wheat (Korotkova *et al.,* 2023). In soyabean production, several categories of commercial biopreparations have been widely adopted globally. Rhizobial inoculants, containing strains such as *Bradyrhizobium japonicum* and *B. elkanii*, enhance biological nitrogen fixation and are among the most established tools in sustainable soyabean cultivation (Hungria, Nogueira & Araujo, 2013). Arbuscular mycorrhizal fungi (AMF), particularly species from the genera *Glomus*, *Rhizophagus*, and *Funneliformis*, improve phosphorus uptake and drought tolerance (Smith & Read, 2008). Phytohormonal biopreparations based on auxins, cytokinins, and brassinosteroids are increasingly used to stimulate root development and enhance stress resilience (Aremu *et al.*, 2015). Studies have examined the combined application of microbial inoculants in soyabean systems: for example, co-inoculation of rhizobia with *Bradyrhizobium spp.* and *Azospirillum brasilense* in Brazil has been reported to result in yield increases of 10 to 15% (Hungria, Nogueira & Araujo, 2013). Similarly, dual inoculation of soyabean with rhizobia and AMF has been tested in South Africa and India, demonstrating improved nodulation, nutrient acquisition, and resilience to water stress (Igiehon & Babalola, 2020; Kumar & Choudhary, 2020). However, the integrated use of AMF, rhizobia, and phytohormonal stimulants in a single technological scheme remains largely unexplored in scientific literature. To the best of our knowledge, no previous studies have systematically evaluated the agronomic and economic performance of this triple-component biotechnological approach in organic soyabean production, which underscores the novelty and practical relevance of the present research.

Despite the active promotion of microbial and phytohormonal biopreparations in organic farming systems, several recent studies focus on potential limitations and barriers to their widespread adoption. In particular, agroecological conditions, including agricultural practices, soil conditions, climate variability, and water availability, directly or indirectly affects the agricultural productivity and natural ecosystems, complicating the sustainably apply of biological inoculants in regions with contrasting or variable climatic dynamics (Kavadia *et al.,* 2020). Climatic conditions, especially temperature, precipitation and groundwater availability are powerful regulators of the soil microbial composition, reducing the efficiency of their interaction in a consortium with plants (Landa, Navas-Cortés & Jiménez-Díaz, 2004; Wang *et al.,* 2022; Xu *et al.,* 2024). This underscores the high sensitivity of these microbes to abiotic stresses. An additional challenge is the limited shelf life of some drugs, the necessity of maintaining appropriate transport and storage conditions (temperature regime, protection from UV-radiation), as well as the need for specialised equipment for high-quality application of biological products to seeds or plants (Adesemoye, Torbert & Kloepper, 2009; Bellows, Morris & Mitchell, 2020). Significant barriers to the adoption of biotechnology are also observed in the context of small and medium-sized farms. Small-scale agriculture faces several challenges such as lower incomes, lack of technology, poor access to information, market and certification barriers, and labour shortages (Dhillon & Moncur, 2023). Therefore, demonstrating biological efficacy alone does not guarantee the economic viability of the technology, highlighting the need for a systematic profitability analysis under stressful climatic and market conditions.

Thus, it can be concluded that under the conditions of global climate change and growing demand for organic products, biotechnological solutions are acquiring strategic importance for ensuring the economic efficiency of organic soyabean production. Despite extensive research on the impact of climatic factors on soyabean productivity and the prospects of organic farming, there remains a need for comprehensive economic evaluation of innovative microbial and hormonal technologies in organic soyabean cultivation amid climate variability. Particularly relevant is the development of scientifically grounded recommendations for selecting optimal biotechnological schemes tailored to specific agro-climatic conditions and the economic objectives of producers. This will enable maximising production profitability while minimising environmental risks.

This study aimed to conduct a comprehensive economic assessment of the profitability of organic soyabean cultivation technologies employing microbial and phytohormonal biopreparations and to develop a scientifically grounded adaptive model for selecting the optimal technological scheme, taking into account predicted climatic conditions, possible cost fluctuations, and expected market prices. This research integrates economic analysis, agronomic data, and climate-related risks into a unified decision-making model for organic soyabean production.

Materials and Methods

The study was based on the results of a field experiment aimed at evaluating the impact of microbial and phytohormonal biopreparations on the physiological and biochemical adaptation mechanisms of organic soyabean. The experiment has been described in detail in a previous publication by Chaika *et al.* (2025b).

Eight technological schemes, differing in biopreparation composition and application method, were selected for economic analysis:

Schemes 1: **Control** – seed and plant treatment with water.

Schemes 2: **Profix®** (Certis Belchim, Belgium) – nitrogen-fixing bacteria, including strains of *Bradyrhizobium* (*japonicum* strain USDA442 (532 C) and *diazoefficiens* strains SEIMA 5079 and SEIMA 5080); dry seed inoculation before sowing.

Schemes 3: **Violar®** (LLC "Innovative Company Bioinvest-Agro", Ukraine) – phytohormonal biopreparation comprising phytohormones from various classes (auxins, cytokinins, and gibberellins), along with free amino acids, lipids, sterols, and abscisic acid; seed treatment + foliar spraying in the stage of BBCH 61.

Schemes 4: **Mycofriend®** (liquid form, BTU-Center, Ukraine) – complex of mycorrhiza-forming fungi (*Glomus* sp., *Trichoderma harzianum*) and rhizospheric bacteria (*Pseudomonas fluorescens*, *Streptomyces* sp., *Bacillus subtilis*, *B. megaterium* var. *phosphaticum*, *B. muciloginosus*, *Enterobacter* sp.); seed inoculation before sowing.

Schemes 5: **Profix + Violar** – combined application: seed inoculation + foliar spraying.

Schemes 6: **Mycofriend**® (solid form, BTU-Center, Ukraine) **+ Profix:** seed inoculation before sowing.

Schemes 7: **Mycofriend (**solid form) **+ Violar** – combined scheme: seed inoculation + foliar spraying.

Schemes 8: **Mycofriend (**solid form) **+ Profix + Violar** – full combined scheme.

The study was conducted over a three-year period (2022–2024) under organic farming conditions in the Left Bank Forest-Steppe of Ukraine, which made it possible to analyse the economic efficiency of technological schemes in the context of interannual climate variability (Chaika *et al.,* 2025a). All prices for inputs (biopreparations, fuel, mechanised operations) were updated with the market conditions of 2025. Soil cultivation intensity served as a baseline parameter corresponding to standard organic soyabean production practices (four harrowings), as comprehensively described in Chaika *et al.* (2025b). For scenario analysis purposes, two additional cultivation intensity levels were modelled: intensive (five harrowings) and highly intensive (six harrowings), representing increased weed management efforts.

The economic assessment was carried out by calculating the full cost of production, gross income (as the product of yield and selling price), profit (the difference between income and expenses) and the level of profitability (the ratio of profit to expenses as a percentage). As part of the sensitivity analysis, the change in the profitability of each scheme was assessed depending on the variation in the selling price of organic soyabeans in the range of €475–661 per tonne, which made it possible to determine the influence of market conditions on the feasibility of using various biopreparations.

Extension of Economic and Mathematical Methods

In order to quantitatively assess the dependence of economic efficiency on changes in market conditions, the price elasticity coefficient of profitability (E) was applied. It can be determined as given in equation (1).

$$E = \frac{\Delta R/R}{\Delta P/P}, \tag{1}$$

where: $\Delta R/R$ = the relative change in profitability;
$\Delta P/P$ = the relative change in the selling price of the product.

In addition to elasticity analysis, a multifactor sensitivity analysis was conducted. It included variation in production costs (due to changes in the number of mechanical operations) and the influence of climatic conditions.

Yield stability over the years was assessed using the coefficient of variation (CV) as given in Equation (2).

$$CV = \left(\frac{\sigma_y}{\mu_y}\right) \times 100\%, \tag{2}$$

where: σ_y = the standard yield deviation;
μ_y = the average yield.

Multi-Criteria Decision Analysis Based on Profitability and Risk

The integrated evaluation of technological solutions was performed using a strategic positioning matrix of profitability–risk, in which the average profitability and its standard deviation were compared for each experimental scheme using a coordinate-based approach. The standard deviation of profitability (σ_r) was calculated as given in equation (3).

$$\sigma_r = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(R_i - \bar{R})^2}\,, \qquad (3)$$

where: R_i = profitability value in the i-th scenario;
$\bar{R}$ = mean profitability; n = number of scenarios;
σ_r = standard deviation of profitability.

This approach made it possible to identify strategic clusters of biotechnological options according to their investment attractiveness and risk levels. The identification of these clusters enables producers to select the most appropriate technological schemes based on their financial capacity and individual risk tolerance profile.

Analysis of the Effectiveness of Additional Investments

The economic feasibility of investing in biopreparations was evaluated using the return on investment (ROI) indicator as given in equation (4).

$$\mathrm{ROI} = \frac{\Delta R}{\Delta C}\,, \qquad (4)$$

where: ΔR = the increase in profitability compared with the control;
ΔC = the additional cost associated with the respective biotechnological scheme.

This indicator made it possible to identify the most effective strategies under resource-constrained conditions and to assess the attractiveness of each scheme for potential investors with varying levels of available capital.

Integrated Climate-Economic Analysis

The study accounted for interannual weather variability, which has a significant impact on the outcomes of organic production. To account for this factor, yield stability over the three-year study period (2022–2024) was analysed using the coefficient of variation (CV). The years were conditionally classified according to weather conditions as follows: 2023 – favourable, 2022 – moderate, and 2024 – stressful (Figure 1). This approach allowed for incorporating climate instability into the system for evaluating the effectiveness of innovative technologies and creating a basis for adaptive management in agricultural production.

Development of Recommendation Models

A three-level decision-making model has been developed to form strategic choices. This model takes into account the manufacturer's financial capabilities, risk tolerance profile, and market expectations. At the first level, the model considers the allowable expenditure per hectare, enabling the preliminary exclusion of unsuitable strategies. The second level involves selection based on risk attitude, ranging from a conservative approach to an aggressive profit-maximisation strategy. The third level incorporates price scenarios – pessimistic, baseline, and optimistic – and determines the boundaries of the economic feasibility of implementing each scheme. Such a structure allows for the formalisation of the choice of agricultural innovations, taking into account financial and market realities.

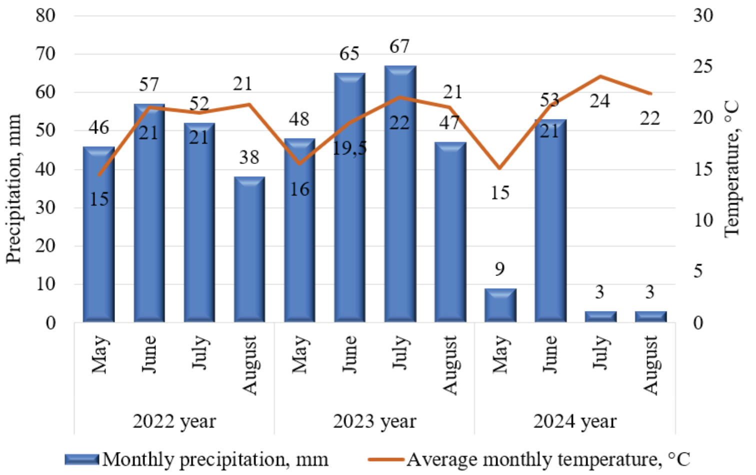


Figure 1. Monthly precipitation and average monthly temperature during the soyabean growing season.

Source: Research findings.

Model Validation

Model reliability was assessed by analysing variability in key performance indicators and simulating alternative scenarios. Coefficients of variation and standard deviation were calculated to evaluate the stability and risk level of different schemes. The robustness of the conclusions was tested by changing the initial parameters, such as cost level, number of harrowing, sales prices. The obtained results demonstrated the stability of key trends, which indicates the internal consistency and analytical reliability of the constructed model.

Analytical Tools and Visualization of Results

Calculations of profitability, return on investment (ROI), and price elasticity were performed using Microsoft Excel software (Microsoft Corporation, USA), using adapted process maps, calculation formulas, and macros for scenario analysis. Graphical interpretation of the study results played a key role in ensuring the clarity and accessibility of analytical conclusions. Heat maps demonstrating the change in profitability depending on the sales prices level and the mechanical processing intensity were constructed in the RStudio® environment (R Software, R Development Core Team, Austria; version 4.4.3, release date: 28-02-2025).

An interactive Decision Matrix Model, developed using HTML, CSS, and JavaScript (Netscape Communications, USA), was implemented to formalise the decision-making process and to build a recommendation framework. This model allows taking into account and combine agronomic, economic and behavioural factors in the process of choosing biotechnological schemes. The integration of computational and visualisation tools has enabled the combination of high-precision analytics with result accessibility for a wide range of practitioners, analysts, and decision-makers in the agricultural sector.

Results

Yield is a key indicator of the effectiveness of biological products used in organic farming, as it reflects the combined influence of multiple factors, including weather and soil conditions, crop variety, cultivation practices, and the level of agrotechnical support. To assess the sensitivity of biotechnological schemes to climate fluctuations, soyabean yields were analysed separately for each year of the study. The year 2022 was conventionally classified as favourable, 2023 as the most favourable in terms of hydrothermal conditions, and 2024 as stressful, characterised by signs of hydrothermal deficiency. The annual yield dynamics is shown in Figure 2.

As shown by the data, the difference between the control treatment (2.46 t ha^{-1}) and the most effective Scheme 8 was 1.11 t ha^{-1} in the favourable year of 2023, representing an increase of more than 45.1%. The use of the fully combined scheme provided a yield of 2.96 t ha^{-1} in the stressful year of 2024, which is 1.10 t ha^{-1} higher than the control, despite hydrothermal instability, indicating that the advantage was preserved even under adverse weather conditions. Throughout the study period, the lowest indicators were recorded in the control (2.24; 2.46; 1.86 t ha^{-1}, respectively), while the highest were with the combined use of mycorrhizal, bacterial and phytohormonal preparations.

Assessment of the Economic Efficiency of Biological Product Application Schemes

Table 1 summarises the economic performance of each treatment scheme, including average yield, total production costs per hectare, gross income, profit, and profitability. This serves as a basis for evaluating the effectiveness of innovations and for developing practical recommendations for organic producers operating under fluctuating market prices and climate conditions.

The profitability of all treatment schemes significantly exceeded that the control (Scheme 1)

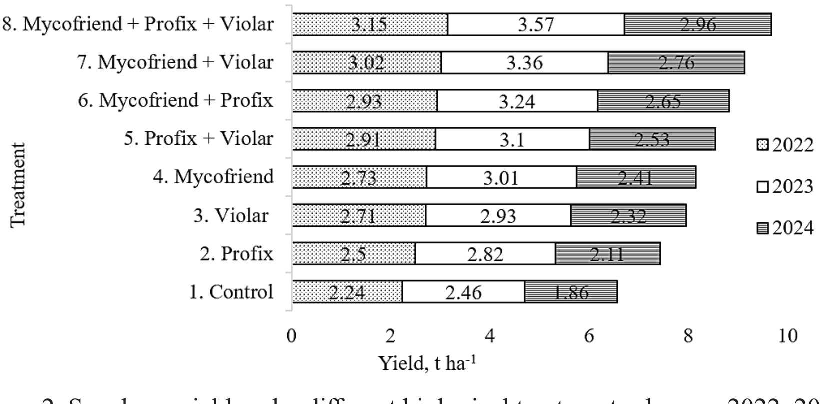


Figure 2. Soyabean yield under different biological treatment schemes, 2022–2024.

Source: Research findings.

Table 1

Economic performance of biological treatment schemes in organic soyabean production

Treatment schemes	Costs[1], € ha^{-1}	Yield, t ha^{-1}	Gross income, € ha^{-1}	Profit[2], € ha^{-1}	Profitability, %
1. Control	402	2.19	1357	955	237.5
2. Profix	409	2.47	1530	1121	273.7
3. Violar	415	2,63	1629	1215	292.8
4. Mycofriend	405	2.72	1685	1280	315.8
5. Profix + Violar	422	2.83	1753	1331	315.5
6. Mycofriend + Profix	414	2.94	1822	1407	339.8
7. Mycofriend + Violar	419	3.05	1890	1471	350.8
8. Mycofriend + Profix + Violar	427	3.23	2001	1575	369.0

Source: Research findings.

Note: Cost calculations were based on an adapted technological map according to the approach described by Chaika and Ponomarenko (2016), with a 20% contingency allowance, and did not include the costs of certification in accordance with organic standards, which were estimated at €1,500–2,000 per plot (up to 1,000 ha). The gross income for organic soyabeans was calculated based on an estimated price of approximately €620 t^{1}, derived from the current non-GMO soyabeans market prices (€403–415 per tonne) plus a 50–70% organic premium, and supported by USDA estimates (~$822 t^{1}) (U.S. Department of Agriculture, Agricultural Marketing Service, 2024).

confirming the high economic feasibility of using biological products in organic farming. Among all treatments, Scheme 8 demonstrated the highest profitability (369.0%) at baseline market prices €620 t^{-1} due to the optimal ratio of input costs and yield gains. Schemes 4 and 2 were identified as the most cost-effective options with low costs (€405 and €409 ha^{-1}, respectively), offering moderate profitability with minimal investment. This makes them attractive for small-scale organic farms or producers with a low risk tolerance.

Scheme 1 (without biopreparations) demonstrated the lowest economic performance, with a profit of €955 ha^{-1} and a profitability of 237.5%, highlighting the justification for biological intensification even within the constraints of organic farming. Overall, the super-profitability of organic soyabean cultivation was driven by an optimised cost structure – excluding synthetic pesticides and fertilisers and the premium market price for organic produce.

Profitability Sensitivity Analysis

To assess the impact of market fluctuations on the economic feasibility of implementing biotechnological schemes for organic soyabean production, a sensitivity analysis was performed using five selling price scenarios: €475, €516, €558, €620 and €661 per tonne. Additionally, the analysis considered a potential increase in the number of harrowing operations to enhance weed control efficiency – from four passes (baseline) to five and six mechanical treatments. The results are presented as a heat map (Figure 3), which visualises changes in profitability levels depending on fluctuations in market prices and the costs of technological support.

Figure 3 shows that all biological treatment schemes remain profitable across the entire range of price scenarios considered. However, the level of profitability and the relative performance of the schemes vary depending on market price fluctuations. In both the lower (€475–558 t^{-1}) and upper (€620–661 t^{-1}) price ranges, Scheme 8 demonstrates the highest profitability. It provides the maximum average yield (3.23 t ha^{-1}) and consistently maintains a strong economic advantage (259.6–400.3%) despite high total production costs. The most cost-efficient among all biological treatment schemes is Scheme 4 (Table 1), which maintains stable profitability within the range of 218.8–343.6%, making it suitable for implementation on farms with limited budgets. Scheme 1 (without biopreparations) consistently demonstrates the lowest profitability levels (158.8–260.0%), indicating economic inefficiency in an organic production system even when biopreparations are completely excluded.

Increasing the number of harrowings to five reduces the overall profitability of all schemes, however, economic efficiency remains positive (Figure 3). Scheme 8 maintains its leading position across all price ranges, with a profitability index of 230.8–360.2%, demonstrating the highest resilience to cost increases. Scheme 4 remains the optimal choice for low-budget conditions, sustaining profitability between 192.0% and 306.3%, even under pessimistic scenarios. Scheme 1 continues to exhibit profitability levels above 136.9%, indicating potential economic

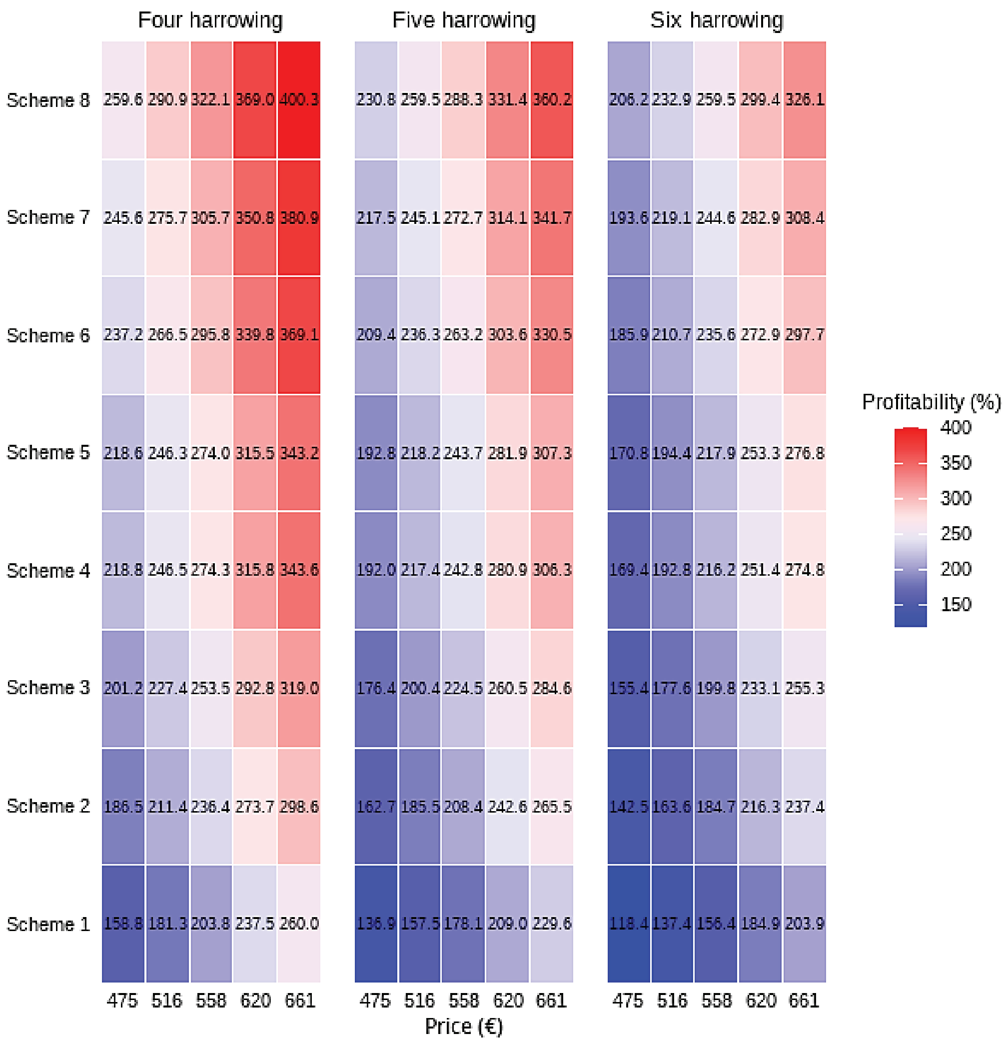


Figure 3. Heat map of profitability sensitivity in organic soyabean cultivation using biocides under different price scenarios and a number of harrowings.

Source: Research findings.

returns at minimal costs without the use of biological products.

Figure 3 also illustrates the scenario simulating the most costly conditions, characterised by an increased weed load and the maximum number of harrowings in soyabean crops. The overall profitability decreases by an average of 40.4–74.2% compared with the baseline cost option, and by 18.5–34.1% relative to the intermediate cost scenario. Scheme 8 maintains the highest profitability across all price ranges, with values ranging from 206.2% to 326.1%. Scheme 4 continues to demonstrate economic feasibility, maintaining profitability levels of 169.4–274.8%, and outperforming the more expensive Schemes 2 and 3. Scheme 1 (control) approaches the threshold of economic feasibility, particularly at a selling price of €475 t^{-1} (profitability of 118.4%), confirming the inefficiency of soyabean cultivation without biological stimulation under high-risk conditions.

Thus, the heat maps support the key conclusion of the study: the choice of an optimal technological scheme largely depends on the pricing environment and cost level, and should be based on an adaptive scenario-based approach. This approach is implemented in the recommendation matrix and decision-making model developed below, which take into account not only economic, but also climatic and managerial factors.

Matrix of Strategic Positioning: Stability–Profitability

Innovative management in organic production requires a comprehensive approach to assessing technological decisions, integrating profitability and risk criteria. The construction of a two-dimensional matrix based on average profitability and its volatility

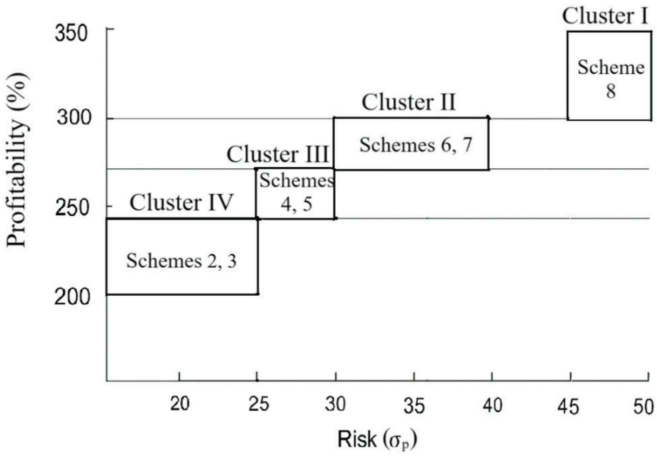


Figure 4. Strategic positioning matrix of biotechnological schemes based on the profitability–risk criteria.
Source: Research findings.

(standard deviation, σ_p) made it possible to identify four strategic clusters of biotechnological schemes (Figure 4).

The clustering of technological decisions made it possible to distinguish the following strategic groups:

Cluster I: High Return – High Risk

This cluster includes Scheme 8, which demonstrates the highest average profitability (331.5%) alongside significant volatility (σ_p = 47.2 p.p.). It is considered appropriate for agricultural producers with a high level of investment readiness.

Cluster II: Balanced Approach (Moderate Return – Moderate Risk)

This group comprises Schemes 6 and 7, which ensure profitability levels of 280–290% with moderate risk (σ_p = 35–38 p.p.). These are the most suitable options for medium-sized farms.

Cluster III: Conservative Approach (Lower Return – Lower Risk)

This cluster includes Schemes 4 and 5, characterised by lower, but stable profitability (250–260%, σ_p = 28–32 p.p.). These schemes are recommended for small-scale farmers or beginners.

Cluster IV: Minimal Risk (Low Return – Low Risk)

This cluster includes Schemes 2 and 3, which demonstrate the lowest profitability levels (210–230%) with minimal risk (σ_p = 22–25 p.p.). These schemes are suitable for use under conditions of limited financial resources.

Thus, the graphical positioning of strategic biotechnological schemes based on profitability–risk criteria enables agricultural producers to tailor their choice of technological decisions according to their risk tolerance, financial stability, and expected profitability. This serves as a crucial tool in innovation management within agricultural production systems.

Analysis of Capital Investment Efficiency

A critical aspect of innovation management is the evaluation of the marginal efficiency of additional investments. Calculating the indicator “incremental profitability per €1 of additional expenditure” relative to the control variant reveals the investment attractiveness of various technological decisions (Table 2).

Scheme 4 demonstrates the highest efficiency of additional investments (ROI = 26.1% return per €1 of expenditure), making it an optimal solution for resource-constrained enterprises. Combined schemes 6–8, despite their lower marginal ROI (5.3–8.5% per €1), deliver the highest absolute increase in profitability, aligning with the needs of capital–intensive agroholdings.

Elasticity of Economic Efficiency under Price Fluctuations

The analysis of profitability elasticity revealed significant differentiation in how the biotechnological schemes responded to changes in market selling prices and production cost levels. An increase in the selling price of organic soyabeans from €475 to €661 per tonne (39.1% growth) results in changes in elasticity coefficients, as shown in Figure 5.

The calculation of profitability elasticity coefficients for eight experimental biological treatment schemes revealed consistent differences in the sensitivity of economic indicators to changes in market product prices. Scheme 1 exhibits the highest elasticity coefficient (1.63), indicating the greatest dependence of profitability on price fluctuations. This implies that a 1% increase in price results in a 1.63% increase in profitability for the control treatment, creating both high profit potential under favourable conditions and significant risk of decline under adverse conditions. The schemes with mono-treatment biopreparations exhibit

Table 2

Efficiency of additional investments in organic soybean treatment schemes at baseline costs

Treatment Schemes	Additional costs, € ha^{-1}	Profitability growth, %	ROI of additional investments, % per €1
2. Profix	7	36.2	5.2
3. Violar	13	55.3	4.3
4. Mycofriend	3	78.3	26.1
5. Profix + Violar	20	78.0	3.9
6. Mycofriend + Profix	12	102.3	8.5
7. Mycofriend + Violar	17	113.3	6.7
8. Mycofriend + Profix + Violar	25	131.5	5.3

Source: Research findings.

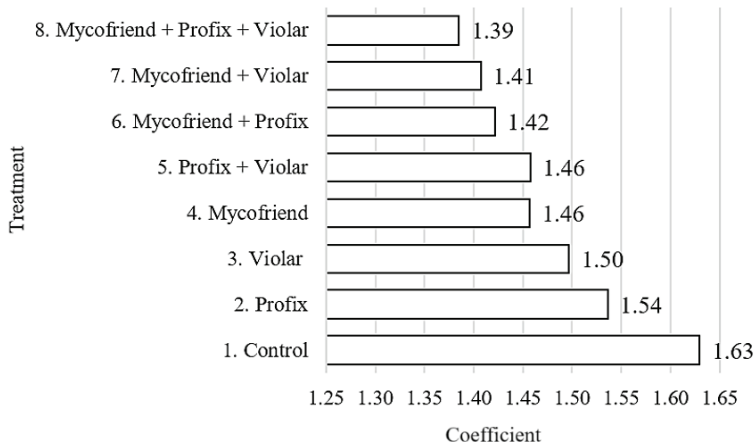


Figure 5. Price elasticity coefficients of profitability for organic soyabean treatment schemes at baseline costs.

Source: Research findings.

moderately high elasticity values: Scheme 2 – 1.54; Scheme 3 – 1.50; Scheme 4 – 1.46. A gradual decline in elasticity is observed along this sequence, which is associated with differing biological mechanisms of the preparations affecting yield stability.

Binary combinations of biopreparations show a notable decrease in elasticity compared with single-component treatments: Scheme 5 – 1.46; Scheme 6 – 1.42; Scheme 7 – 1.41. This indicates a stabilising effect resulting from the combination of biopreparations with different action mechanisms. The lowest elasticity coefficient was recorded for the three-component Scheme 8 (1.39), which supports the hypothesis that comprehensive application of biopreparations enhances the stability of economic indicators.

The obtained results make it possible to rank the schemes according to their exposure to price risk – from the high-risk control scheme to the more stable three-component system. The difference of 0.24 points between the extreme values (1.63 vs 1.39) is economically significant and highlights the potential for effective risk management through the selection of an appropriate biological treatment scheme.

To investigate in detail the impact of production cost variation on profitability stability, three representative schemes were selected, reflecting different production strategies: Scheme 1 (control), Scheme 4 – the least costly among the biological treatments, and Scheme 8 – the most economically efficient. The analysis was carried out for three soil cultivation intensity scenarios: baseline (four cultivations), intensive (five cultivations with a 9.1% increase in costs), and highly intensive (six cultivations with an 18.2% increase in costs), under conditions of simultaneous market price fluctuations.

The results revealed that Scheme 1 demonstrates the highest sensitivity to market changes, with a progressive increase in elasticity coefficients: from 1.63 under baseline costs to 1.73 (+6.1%) under five cultivations, and 1.84 (+12.9%) under six cultivations. This dynamic indicates an exponential rise in risk associated with the intensification of cultivation without biological treatment.

Scheme 4 is characterised by a moderate increase in elasticity: 1.46 → 1.52 (+4.1%) → 1.59 (+8.9%), confirming its balanced position between economic efficiency and indicator stability. Scheme 8 maintains the lowest elasticity values across all scenarios: 1.39 → 1.43 (+2.9%) → 1.48 (+6.5%), demonstrating the least sensitivity to rising production costs and the highest resilience to market fluctuations.

The study results confirm the general pattern: the intensification of mechanical tillage (by increasing the number of harrowings) leads to an increase in the sensitivity of profitability to price fluctuations for all experimental schemes. This creates additional challenges for the financial planning of agricultural enterprises, especially in conditions of high agricultural markets volatility. However, the degree of this sensitivity varies significantly depending on the type of biological treatment scheme. For Scheme 1, an increase in costs by 18.2% is accompanied by an increase in elasticity by 12.9%, and for Scheme 8 this value is only 6.5%, which indicates its significantly higher adaptability to changes in operating costs.

Profitability elasticity coefficients serve as an effective risk management tool in agricultural production, enabling not only the assessment of potential losses due to adverse market fluctuations, but also the justification of optimal production strategy selection. The research results demonstrate that investments in complex biologics yield a dual benefit: increasing absolute profitability while reducing relative risks, which is particularly important for long-term strategic planning under conditions of market uncertainty.

Analysis of Threshold Profitability Levels of Biotechnological Treatment Schemes

The identification of critical thresholds of economic feasibility is a fundamental component of the risk management system for innovative projects in the field of organic farming. The analysis of threshold values based on Figure 3 made it possible to identify the following key efficiency boundaries:

1. A profitability threshold of 200% is considered the minimum acceptable for organic production, taking into account the specific risks associated with certification, price volatility, and logistical challenges. At baseline costs, all biotech schemes, except Scheme 2, consistently exceeded this threshold, even under the pessimistic scenario of product selling price (€475 t^{-1}). Increasing the number of harrowings to five (a 9.1% increase in costs) led to a decrease in profitability below 200% for Scheme 2 at prices of €475–516 per tonne, and for Schemes 3, 4 and 5 at a price of €475 t^{-1}. In the six-harrowing model (an 18.2% increase in costs), profitability falls below 200% for Schemes 2 and 3 at prices of €475–558 per tonne, for Scheme 4 at €475–516 per tonne, and for Schemes 6 and 7 at the minimum price of €475 t^{-1}. Scheme 1, across all cost models, shows significant vulnerability, especially with an 18.1% cost increase, approaching or falling below the critical threshold throughout the price range of €475 to €620 per tonne (118.4–184.9%).
2. A profitability threshold of 300% is defined as the target level necessary to ensure stable innovation-driven development, funding of research and development (R&D) activities, as well as maintaining the adaptability of production to climate-related risks. At baseline costs, Schemes 7 and 8 reach this threshold at a selling price of €558 t^{-1}, Schemes 4, 5 and 6 starting from €620 t^{-1}, Scheme 3 only at €661 t^{-1}, while Scheme 2 approaches the specified threshold. A cost increase due to five harrowings shifts the target boundary: Schemes 6, 7 and 8 achieve 300% profitability only at a price of €620 t^{-1}, Schemes 4 and 5 at €661 t^{-1}, whereas options 1, 2 and 3 remain below this threshold. In the maximum cost scenario (six harrowings), only Schemes 7 and 8 reach the target profitability threshold at a selling price no lower than €661 t^{-1}. Scheme 1 fails to achieve this level under any of the considered scenarios.

Thus, the profitability threshold levels analysis made it possible to identify the boundary conditions of economic feasibility for the implementation of innovative biotechnological schemes in organic soyabean production. The threshold values of 200% (the minimum acceptable level) and 300% (the target level for innovative development) provide benchmarks for managerial decisions under conditions of price volatility and technological adaptation to climatic challenges. The obtained results indicate that under adverse market or production conditions, a significant portion of the schemes maintain economic efficiency; however, their potential varies considerably depending on the cost level. This confirms the necessity of considering an adaptive scenario-based approach when selecting technological strategies in organic farming.

Integrated Climate-Economic Analysis

Yield stability is a crucial criterion for making management decisions in organic farming, especially in the context of climate uncertainty and restrictions on the use of chemical crop protection

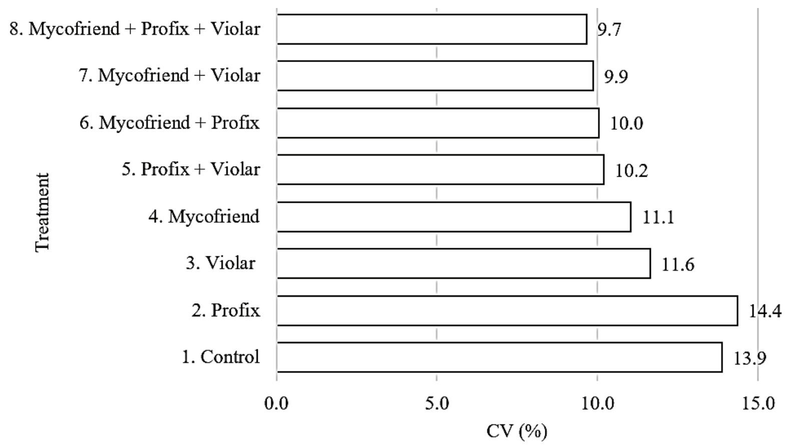


Figure 6. Yield stability (CV, %) under biotechnological schemes of organic soyabean cultivation.
Source: Research findings.

agents. To assess the stability of yield outcomes over the three-year research cycle (2022–2024), coefficients of variation (CV) were calculated for eight biotechnological Schemes of organic soyabean cultivation (Figure 6).

The highest stability (CV<10%) is demonstrated by combined Schemes 8 (CV=9.7%) and 7 (CV=9.9%) (Figure 6). These technologies provide not only the maximum average yields of 3.23 and 3.05 t ha^{-1}, respectively, but also the lowest sensitivity to hydrothermal fluctuations. Schemes 3, 4, 5 and 6 exhibit a moderate level of stability (CV within 10–12%), indicating an acceptable degree of adaptability. In contrast, Scheme 2 (CV=14.4%) and the control variant (CV=13.9%) are the most unstable, indicating their vulnerability to adverse weather conditions. The analysis of the relationship between yield level and the coefficient of variation confirmed an inverse correlation ($r = -0.73$, $p<0.05$) as yield increases, the variability of results decreases. This trend highlights the economic and managerial value of an integrated approach to plant biostimulation.

The use of the coefficient of variation as an integral indicator for assessing risks and the feasibility of implementing biotechnologies is innovative in this context. The constructed profitability–risk matrix (Figure 3) enabled the segmentation of technological schemes into strategic clusters based on the expected income level and fluctuations in profitability. This, in turn, provides a sound basis for practical decision-making regarding the selection of optimal agricultural production strategies in accordance with the resource potential of farms and their risk tolerance levels.

Thus, the yield stability indicator should be regarded as one of the key components in the system of economic justification for the implementation of innovations in agriculture. Its application contributes to the formation of an adaptive, evidence-based strategy for advancing the organic agricultural sector amid climate change and growing market risks.

Algorithm for Strategic Selection of Innovative Decisions

Based on a multidimensional analysis, a three-level algorithm for selecting the optimal biotechnological strategy was developed (Figure 7). The algorithm incorporates six biotechnological schemes (3, 4, 5, 6, 7 and 8) that demonstrated economically justified performance across varying conditions. Two schemes were excluded: Scheme 1 (control without biopreparations) consistently showed the lowest profitability levels (237.5% at baseline, declining to 118.4% under high-cost scenarios) and exhibited the highest price elasticity (1.63), indicating extreme vulnerability to market fluctuations; Scheme 2 demonstrated the highest yield instability (CV=14.4%) and failed to reach the minimum acceptable profitability threshold of 200% under pessimistic price scenarios combined with intensive cultivation (five or six harrowings).

This algorithm enables a differentiated selection of biotechnological strategies for organic soyabean production, taking into account financial capacity, risk tolerance profile, and market price expectations.

Financial capacity, as the selection criterion at the first level, implies that financial feasibility serves as a fundamental constraint at the initial stage, allowing for the preliminary filtering of technological schemes based on total production costs per hectare. Under limited budgets (< €413 ha^{-1}), Scheme 4 is the only economically viable option due to its low cost intensity and stable profitability under low-expenditure conditions. An average budget (€413–423 ha^{-1}) enables the implementation of Schemes 3, 6 and 7, which involve more complex combinations of microbial and hormonal treatments, with moderately higher costs and greater yield potential. Sufficient financial capacity (over approximately €423 ha^{-1}) allows investment in Schemes 5 and 8, the latter being the most comprehensive and resource-intensive, but also characterised by the highest profitability under favourable climatic conditions.

A key factor at the second stage of managerial decision-making is the level of risk perception by the agricultural producer. For farms adopting a conservative financial strategy, Schemes 4 or 5 are advisable, as they are characterised by stable profitability with minimal fluctuations in economic efficiency. In cases of moderate risk tolerance, technological decisions 6 and 7 represent the most balanced options, combining adequate yields with an acceptable level of economic volatility. For producers who wish to pursue a more aggressive investment policy, Scheme 8 is advisable – being the most profitable on average, yet potentially vulnerable to market fluctuations and requiring higher capital investments.

At the third level, a strategic selection is made according to soyabean market scenarios, ranking the schemes by the maximum allowable expenditure. Under the pessimistic price forecast (< €558 ha^{-1}), Schemes 8, 7, 6, 5 and 4 are the most effective, as they maintain profitability even under constrained market conditions. The baseline scenario (€558–620 ha^{-1}) also favours Schemes 8, 7, 6, 5 and 4, confirming their stability and adaptability to moderate market conditions. Under the optimistic scenario (> €620 ha^{-1}), Scheme 8 becomes the preferred choice due to its higher yield potential, followed by Schemes 7 and 6, which remain profitable and scalable.

The proposed decision-making algorithm provides a structured and adaptive tool for strategic management in organic farming. By integrating financial constraints, behavioural risk profiles, and price expectations, the algorithm enables producers to select the most appropriate biotechnological strategy for their specific operational context. This approach combines agronomic innovation with economic feasibility, offering practical recommendations for differentiated decision-making under conditions of climate and market uncertainty. Such multilevel modelling enhances the applicability of innovation management principles in sustainable agriculture and can serve as a basis for targeted policy recommendations and risk–oriented investment planning.

Analysis of the Technology Selection Model

Management decisions in organic agriculture require a multidimensional approach that integrates agronomic efficiency, economic feasibility, and risk-oriented forecasting. The proposed Decision Matrix Model is structured around a three-level classification system encompassing climatic conditions, market scenarios, and the farmer's strategic objectives (Figure 8).

The first evaluation block concerns climatic conditions, classified based on yield variation coefficients (CV). The schemes with CV>12% (Scheme 1 and 2) are identified as sensitive to hydrothermal stress; values of CV within 10-12% (Schemes 3-6) indicate moderate stability; CV values below 10% (Schemes 7 and 8) reflect high adaptability to climatic variability.

The second level involves modelling market conditions based on three scenarios: pessimistic (< €558 t^{-1}), baseline (€558–620 t^{-1}), and optimistic (> €620 t^{-1}). Accordingly, the feasibility of implementing each scheme was interpreted within the framework of allowable expenditures and expected profitability.

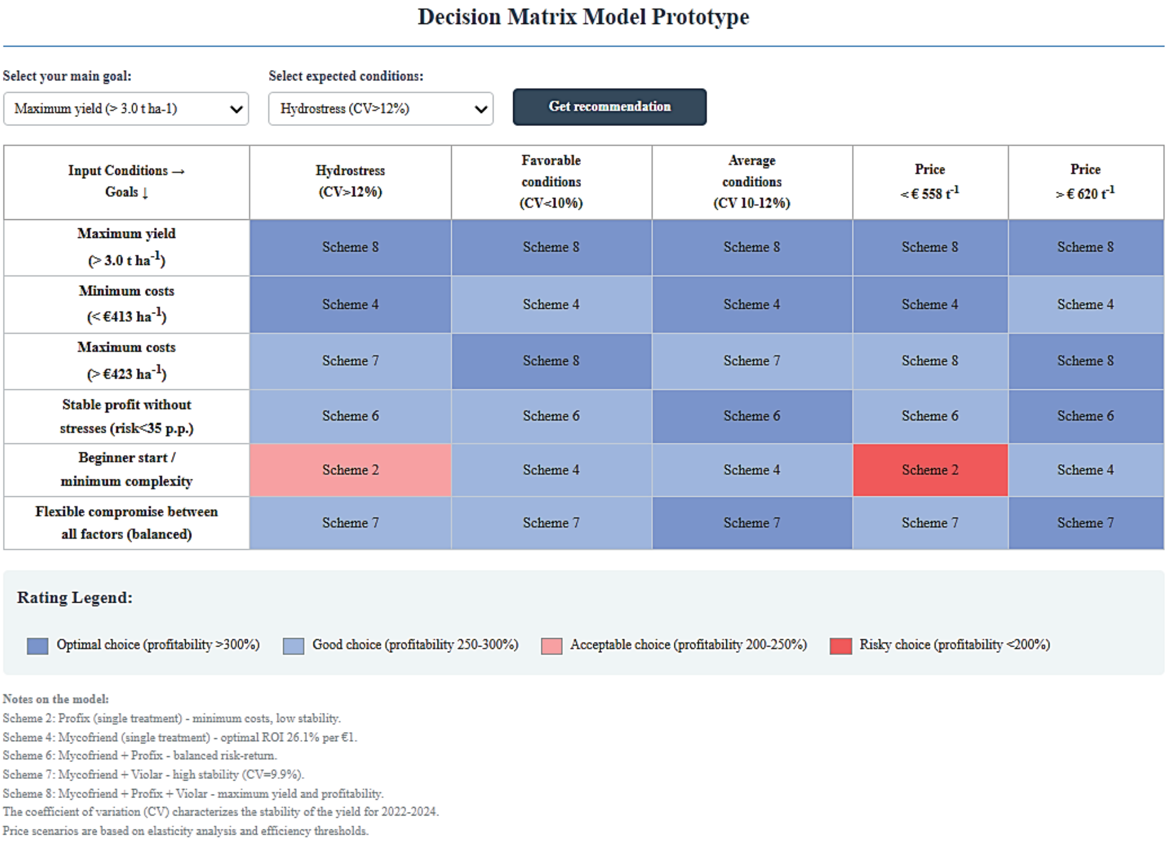
The third model level reflects the strategic objectives of the farm, including yield maximisation, cost optimisation, stable profit generation, entry-level decisions for beginner producers, and achieving a balanced compromise among these parameters.

The results of the modelling revealed the most rational biotechnological strategies for organic soyabean cultivation depending on projected agro-climatic conditions, available resources, and expected market prices.

The best performance was observed under Scheme 8, which consistently ensured a stable yield exceeding 3 t ha^{-1} throughout all study years, resulting in profitability above 200%, even under hydrothermal stress conditions. At the same time, this scheme showed the lowest variability in outcomes (CV = 9.67%), confirming its high level of adaptability.

For producers with limited working capital, Scheme 4 is the most suitable option. With lower input costs, it delivers a relatively high economic return − offering the highest return on investment (ROI), approximately 26.1% per €1. Scheme 6 is identified as the most balanced choice for farms with a medium level of investment, providing a yield of around 2.9 t ha^{-1} with moderate expenditures and an acceptable level of risk.

Scheme 7 stands out as a versatile option, characterised by good resilience to climatic factors, moderate costs, and a high level of financial return. In contrast, the outcomes for Schemes 3 and 5 were less promising. Scheme 3 demonstrated limited efficiency with expenditures exceeding €413 ha^{-1} and a yield of 2.63 t ha^{-1}. Scheme 5 performed even worse: despite similar costs, it showed the lowest return on investment among all the studied options (ROI ≈ 3.9% per €1). Therefore, the economic feasibility of these two strategies remains questionable.


Decision Matrix Model Prototype

Select your main goal: Maximum yield (> 3.0 t ha-1)

Select expected conditions: Hydrostress (CV>12%)

Get recommendation

Input Conditions → Goals ↓	Hydrostress (CV>12%)	Favorable conditions (CV<10%)	Average conditions (CV 10-12%)	Price < € 558 t^{-1}	Price > € 620 t^{-1}
Maximum yield (> 3.0 t ha^{-1})	Scheme 8	Scheme 8	Scheme 8	Scheme 8	Scheme 8
Minimum costs (< €413 ha^{-1})	Scheme 4	Scheme 4	Scheme 4	Scheme 4	Scheme 4
Maximum costs (> €423 ha^{-1})	Scheme 7	Scheme 8	Scheme 7	Scheme 8	Scheme 8
Stable profit without stresses (risk<35 p.p.)	Scheme 6	Scheme 6	Scheme 6	Scheme 6	Scheme 6
Beginner start / minimum complexity	Scheme 2	Scheme 4	Scheme 4	Scheme 2	Scheme 4
Flexible compromise between all factors (balanced)	Scheme 7	Scheme 7	Scheme 7	Scheme 7	Scheme 7

Rating Legend:

Optimal choice (profitability >300%) Good choice (profitability 250-300%) Acceptable choice (profitability 200-250%) Risky choice (profitability <200%)

Notes on the model:
Scheme 2: Profix (single treatment) - minimum costs, low stability.
Scheme 4: Mycofriend (single treatment) - optimal ROI 26.1% per €1.
Scheme 6: Mycofriend + Profix - balanced risk-return.
Scheme 7: Mycofriend + Violar - high stability (CV=9.9%).
Scheme 8: Mycofriend + Profix + Violar - maximum yield and profitability.
The coefficient of variation (CV) characterizes the stability of the yield for 2022-2024.
Price scenarios are based on elasticity analysis and efficiency thresholds.

Figure 8. Decision matrix model for selecting biotechnological strategies in organic soyabean cultivation.
Source: Research findings.

Conceptually, the Decision Matrix Model includes only those technological decisions that demonstrate dominance in specific evaluation categories (minimal costs, maximum ROI, optimal risk–return balance, highest stability, or maximum productivity). Schemes 3 and 5 do not rank as leaders in any of these categories, which justifies their exclusion from practical recommendations for agricultural producers. This approach ensures that managerial attention is focused on economically optimal technological solutions and helps to avoid suboptimal investment strategies in organic soyabean production.

A key element of the proposed model is its flexibility: for each target objective, regardless of environmental or market conditions, one or more of the most relevant technological strategies are identified. This allows management decisions to be adapted to the actual resource and climatic farm constraints.

Thus, the Decision Matrix Model serves as a practical tool for innovation management, grounded in a comprehensive agro-economic analysis, and contributes to enhancing the resilience and profitability of organic production under conditions of climatic and market uncertainty.

Discussion

The results of this study deepen the understanding of the role of biological products in enhancing the economic efficiency of organic farming, while also revealing new aspects of strategic innovation management under conditions of climatic and market uncertainty. These findings align with Rogers' (2003) innovation diffusion theory, which states that the successful adoption of biotechnological solutions depends not only on their agronomic effectiveness, but also on their economic accessibility and adaptability to local conditions. The highest ROI recorded for Scheme 4 (26.1% per €1) indicates its strong diffusion attractiveness and confirms the concept of relative advantage as a key factor in the adoption of innovations. The proposed Decision Matrix Model aligns with the principles of adaptive management (Holling, 1978), as it integrates a multi-criteria evaluation of effectiveness with consideration of climate variability. In light of current sustainable development challenges, where agroecosystems require high flexibility, this model enables the formulation of more resilient strategies (Folke *et al.*, 2010).

The correlation analysis revealed an inverse relationship between the technological scheme's productivity and the yield variability level (r= –0.73), indicating a stabilising effect resulting from the combined use of biological products with different action modes. This has important practical implications for reducing production risks in organic farming and aligns with the concept of ecological intensification (Bommarco, Kleijn & Potts, 2013), where biological decisions are viewed not only as alternatives to chemical preparations, but also as a factor of enhancing the functional resilience of agroecosystems.

In this context, the results obtained under Scheme 8 deserve special attention, which, under the stressful year conditions of 2024, provided a yield of 2.96 t ha^{-1} – 59.1% higher than the control scheme (1.86 t ha^{-1}). This confirms the high potential of integrated biotechnological approaches as a tool for adaptation to climate change, which, according to Lipper *et al.* (2014), aligns with the principles of climate-smart agriculture.

The obtained profitability indicators ranging from 273.5% to 369.0% are consistent with previous findings, particularly of Chaika and Ponomarenko (2016), who reported that the profitability of organic soyabean production in Ukraine ranges from 233.0% to 565.0%. This confirms the economic feasibility of this crop being integrated into the national organic farming system. At the same time, according to Kazakova and Kondratiuk (2015), the average profitability level of traditional soyabean production (15.8%), which is significantly different from the level of organic production, emphasise the advantages of the organic direction and confirm our hypothesis regarding the competitiveness of biotechnological decisions in the organic sector.

Our profitability findings align with recent global trends in organic agriculture economics. Seufert and Ramankutty (2017) reported that organic farming profitability in developed countries typically exceeds conventional systems by 22–35% despite 20% lower yields, primarily due to premium prices. A recent meta-analysis by Ponisio *et al*. (2023) confirmed that integrated biological approaches, including mycorrhizal inoculation combined with biostimulants, can reduce the yield gap to 8–12% while maintaining economic advantages. The superior performance of Scheme 8 in our study (profitability 369%, yield 3.23 t ha^{-1}) surpasses these benchmarks, suggesting that Ukrainian organic soyabean production has significant competitive potential in European markets. Furthermore, Mitter *et al*. (2021), in their review of innovative biofertiliser technologies, highlighted that multi-component microbial consortia (PGPR + AMF) deliver substantially higher economic returns than single-strain products due to synergistic nutrient mobilisation and stress tolerance effects, which aligns with our findings that combined schemes (Schemes 6, 7 and 8) outperformed monopreparations (Schemes 2, 3 and 4) in both profitability and yield stability. However, our study extends beyond agronomic efficiency by integrating climate-risk analysis with economic modelling – an approach rarely applied in organic farming research. The inverse correlation between the yield level and coefficient of variation (r= –0.73) demonstrates that diversified bioinoculant strategies enhance both productivity and resilience. This finding is supported by the recent review by Cruz *et al*. (2025), which emphasised that growth-promoting bacteria can significantly improve crop production while contributing to agricultural sustainability and food security – particularly relevant for organic systems facing climate variability.

Research by Chaika *et al.* (2025b) on the physiological and biochemical aspects of biological preparations in pre-sowing seed treatment supports our conclusions regarding the synergistic effect of their combined application. The authors also noted an improvement in biochemical markers of stress resistance, which explains the high and stable yield in our studies under different climatic conditions.

The proposed "stability–profitability" matrix is a methodological addition to modern approaches for managing innovative technologies in the agricultural sector. This concept combines the assessment of economic efficiency with risk analysis based on the variability indicators unlike predominantly productivity−centric models. The differentiation of four strategic clusters, based on the ratio of profitability to volatility, enables the development of targeted recommendations that take into account both the financial resources, and the risk tolerance level of agricultural producers. This approach is particularly relevant to organic production, where, along with the desire for profitability, environmental and social factors play a significant role.

The analysis of the price elasticity of profitability revealed an important trend: the use of complex biological technologies contributes not only to increased economic returns, but also to reduced sensitivity to price fluctuations. A comparison of elasticity coefficients shows that the control scheme responds more strongly to price changes (1.63) than Scheme 8 (1.39), indicating a stabilising effect of the biological products.

This observation has practical significance for agricultural enterprises planning long-term strategies under market instability. Investments in biotechnology not only increase the overall profitability, but also make production outcomes more predictable, which is essential for minimising financial risks.

Integrating climatic and economic parameters in the assessment of biotechnological solutions opens new approaches to agricultural production planning. The conducted analysis showed that technological schemes with higher yields simultaneously exhibit lower interannual variability, indicating better adaptability to weather fluctuations. Such stability in productivity gains particular importance amid increasing climatic variability characteristic of most regions in Ukraine. The obtained results confirm that the implementation of integrated biological schemes not only contributes to yield improvement, but also reduces production vulnerability to climatic risks, which is a key factor for long-term planning in the organic sector.

Conclusions

The conducted study enabled a comprehensive assessment of the economic efficiency, risk levels, and adaptability of eight biotechnological schemes for organic soyabean cultivation under conditions of unstable climate and price volatility. The methodological framework combined approaches of innovation management, scenario analysis, and decision-making in agricultural systems with an increased level of risk.

The highest overall efficiency was demonstrated by the combined technology Mycofriend + Profix + Violar (Scheme 8), which provided the highest yield (3.23 t ha^{-1}), profitability (369%), and result stability (CV=9.67%). Meanwhile, Scheme 4 (Mycofriend) proved to be the most efficient in terms of return on investment per euro spent (ROI=26.1% per €1), highlighting its suitability for producers with limited financial resources.

A heat map confirmed the high sensitivity of profitability levels to changes in prices and costs. Increasing the number of harrowings to five and six (which respectively raised total expenses by 9.1% and 18.2%) significantly reduced profitability in low-yielding Schemes 2, 3 and 4, whereas Scheme 8 maintained profitability above 200% even under the least favourable implementation scenario (€475 t^{-1}). Despite high total costs (>€423 ha^{-1}), Schemes 6, 7 and 8 provided the best return on investment, indicating the effectiveness of combined biological approaches. In contrast, Scheme 2 and Scheme 1 (control) were the least economically viable options.

Two profitability threshold levels were identified: 200% as the minimum acceptable level for the organic sector, considering additional costs and risks; and 300% as the target benchmark to ensure financial stability and support further innovative investments. Under the baseline scenario, only Schemes 6, 7 and 8 reached this level at prices not lower than €620 t^{-1}.

Analysis of yield variation coefficients revealed a relationship between result stability and technological productivity. Schemes 7 and 8 showed the lowest yield fluctuations (CV<10%), while Scheme 1 and 2 exhibited the highest (>13%). Based on the profitability-risk ratio, a two-coordinate strategic positioning matrix was developed, classifying all technologies according to investment behaviour type − from cautious to risky.

A key outcome of the study was the development of an adaptive Decision Matrix Model, which enables consideration of climatic conditions, expected prices, and financial resources for the informed selection of an optimal biotechnological strategy. This model can support decision-making in large, medium, and small agricultural enterprises. It is advisable to focus future research on multi-year validation of the obtained results across different agro-climatic zones in Ukraine, assessment of the long-term effects on soil fertility, and the development of digital tools to facilitate decision-making on biotechnological innovations in organic farming.

References

Adesemoye, A.O., Torbert, H.A., & Kloepper, J.W. (2009). Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial Ecology, 58(4), 921–929. DOI: 10.1007/s00248-009-9531-y.

Aremu, A.O., Masondo, N.A., Rengasamy, K.R.R., Amoo, S.O., Gruz, J., Bíba, O., Šubrtová, M., Pěnčík, A., Novák, O., Doležal, K., & Van Staden, J. (2015). Physiological role of phenolic biostimulants isolated from brown seaweed *Ecklonia maxima* on plant growth and development. *Planta,* 241(6), 1313–1324. DOI: 10.1007/s00425-015-2256-x.

Azarbad, H. (2022). Conventional vs. organic agriculture − Which one promotes better yields and microbial resilience in rapidly changing climates? Frontiers in Microbiology, 13, 903500. DOI: 10.3389/fmicb.2022.903500

Bellows, B., Morris, M., & Mitchell, C. (2020). *Microbial inoculants*. National Center for Appropriate Technology (NCAT). Retrieved June 21, 2025, from https://attradev.ncat.org/wp-content/uploads/2022/06/microbial-inoculants.pdf.

Bosanquet, J. (2023) TABLE Summary series: Soy. Retrieved June 17, 2025, from https://www.tabledebates.org/building-blocks/table-summary-series-soy.

Bogati, K., & Walczak, M. (2022). The impact of drought stress on soil microbial community, enzyme activities and plants. *Agronomy,* 12(1), 189. DOI: 10.3390/agronomy12010189.

Bommarco, R., Kleijn, D., & Potts, S.G. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution,* 28(4), 230–238. DOI: 10.1016/j.tree.2012.10.012.

Burbano-Cuasapud, J.M., Solarte-Toro, J.C., Restrepo-Serna, D.L., & Cardona Alzate, C.A. (2023). Process sustainability analysis of biorefineries to produce biofertilizers and bioenergy from biodegradable residues. *Fermentation,* 9(9), 788. DOI: 10.3390/fermentation9090788.

Chaika, T., Korotkova, I., Liashenko, V., Pospielova, H., & Onipko, V. (2025a). Abscisic acid and biopreparations as markers of organic soybean adaptation to hydrothermal stress. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine,* 21(3), 76–95. DOI: 10.31548/dopovidi/3.2025.76.

Chaika, T., Korotkova, I., Shevnikov, M., Liashenko, V., & Horbenko, O. (2025b). Physiological and biochemical aspects of pre-sowing treatment of soybean (*Glycine max* L. Merr.) seeds. *Scientific Reports of the National University of Life and Environmental Sciences of Ukraine,* 21(2), 106–119. DOI: 10.31548/dopovidi/2.2025.106.

Chaika, T.O. (2013). *Development of organic production in the agricultural sector of Ukrainian economy.* Donetsk: Knowledge. (in Ukraine)

Chaika, T.O., & Ponomarenko, S.V. (2016). Technology of organic forage soybean and winter wheat cultivation, their economic efficiency. Agronomist Magazine, 2(52), 106–111. (in Ukraine)

Cruz, A.L.A., García Montalvo, I.A., Matías Pérez, D., Pérez Santiago, A.D., & Sánchez Medina, M A. (2025). Use of microbial consortia in agriculture as an alternative for achieving sustainable agriculture. *Ciencia Latina Revista Científica Multidisciplinar*, 9(2), 872–887. DOI: 10.37811/cl_rcm.v9i2.16893.

Dhillon, R., & Moncur, Q. (2023). Small-scale farming: A review of challenges and potential opportunities offered by technological advancements. *Sustainability,* 15(21), 15478. DOI: 10.3390/su152115478.

Donau Soja. (2024). *Market report: Record soya output in Ukraine in 2024.* Retrieved June 18, 2025, from https://www.donausoja.org/market-report-record-soya-output-in-ukraine-in-2024/

Elli, E.F., Ciampitti, I.A., Castellano, M.J., Purcell, L.C., Naeve, S., Grassini, P., La Menza, N.C., Moro Rosso, L., de Borja Reis, A.F., Kovács, P., & Archontoulis, S.V. (2022). Climate change and management impacts on soybean N fixation, soil N mineralization, N_2O emissions, and seed yield. Frontiers in Plant Science, 13*,* 849896. DOI: 10.3389/fpls.2022.849896.

Fess, T.L., & Benedito, V.A. (2018). Organic versus conventional cropping sustainability: A comparative system analysis. *Sustainability,* 10(1), 272. DOI: 10.3390/su10010272.

Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society, 15(4), Article 20. Retrieved June 20, 2025, from https://www.ecologyandsociety.org/vol15/iss4/art20/

Huang, Y., Liu, L., Sun, B., Zhu, Y., Lv, M., Li, Y., & Zhu, X. (2024). A comprehensive review on harnessing soy proteins in the manufacture of healthy foods through extrusion. Foods, 13(14), 2215. DOI: 10.3390/foods13142215.

Hungria, M., Nogueira, M., & Araujo, R. (2015) Soybean seed co-inoculation with *Bradyrhizobium* spp. and *Azospirillum brasilense*: A new biotechnological tool to improve yield and sustainability. *American Journal of Plant Sciences*, 6, 811–817. DOI: 10.4236/ajps.2015.66087.

Holling, C.S. (1978). Adaptive environmental assessment and management (International Series on Applied Systems Analysis, 3). John Wiley & Sons.

Igiehon, O.N., & Babalola, O.O. (2021). Rhizobium and mycorrhizal fungal species improved soybean yield under drought stress conditions. *Current Microbiology*, 78(4), 1615–1627. DOI: 10.1007/s00284-021-02432-w.

IGS: Global soybean production in 2024/25 MY to break record. (2024). *Tridge*. Retrieved June 17, 2025, from https://www.tridge.com/news/igs-global-soybean-production-in-202425-my-t-ndaksl.

Kavadia, A., Omirou, M., Fasoula, D., & Ioannides, I.M. (2020). The importance of microbial inoculants in a climate-changing agriculture in Eastern Mediterranean region. *Atmosphere,* 11(10), 1136. DOI: 10.3390/atmos11101136

Kazakova, I.V., & Kondratiuk, N.V. (2015). Efficiency of soybean production and development of the soybean products market in Ukraine and the world. *Efektyvna Ekonomika, 5*. Retrieved July 7, 2025, from http://www.economy.nayka.com.ua/?op=1&z=4070 (in Ukraine)

Korotkova, I.V., Chaika, T.O., Romashko, T.P., Chetveryk, O.O., Rybalchenko, A.M., & Barabolia, O.V. (2023). Emmer wheat productivity formation as depending on pre-sowing seed treatment method in organic and traditional technology cultivation. Regulatory

Mechanisms in Biosystems, 14(1), 41–47. DOI: 10.15421/022307.

Kothari, K., Battisti, R., Boote, K.J., Archontoulis, S.V., Confalone, A., Constantin, J., Cuadra, S.V., Debaeke, P., Faye, B., Grant, B., Hoogenboom, G., Jing, Q., van der Laan, M., Macena da Silva, F.A., Marin, F.R., Nehbandani, A., Nendel, C., Purcell, L.C., Qian, B., Ruane, A.C., & Salmerón, M. (2022). Are soybean models ready for climate change food impact assessments? *European Journal of Agronomy,* 135, 126482. DOI: 10.1016/j.eja.2022.126482.

Kumar, S., & Choudhary, P. (2020). Dual inoculation with rhizobium and arbuscular mycorrhizal fungi enhances the nodulation, nutrient acquisition, and drought tolerance of soybean. *Microorganisms,* 8(12), 1932. DOI: 10.3390/microorganisms8121932.

Lin, C.-H., Chang, Y.-T., Lai, M.-C., Chiou, T.-Y., & Liao, C.-S. (2021). Continuous biodiesel production from waste soybean oil using a Nano-Fe_3O_4 microwave catalysis. Processes, 9(5), 756. DOI: 10.3390/pr9050756.

Landa, B.B., Navas-Cortés, J.A., & Jiménez-Díaz, R.M. (2004). Influence of temperature on plant–rhizobacteria interactions related to biocontrol potential for suppression of fusarium wilt of chickpea. *Plant Pathology,* 53, 341–352. DOI: 10.1111/j.0032-0862.2004.01008.x.

Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., Hottle, R., Jackson, L., Jarvis, A., Kossam, F., Mann, W., McCarthy, N., Meybeck, A., Neufeldt, H., Remington, T., Pham Thi Sen, Sessa, R., Shula, R., Tibu, A., & Torquebiau, E.F. (2014). Climate-smart agriculture for food security. *Nature Climate Change,* 4(12), 1068–1072. DOI: 10.1038/nclimate2437.

Mitter, E.K., Tosi, M., Obregón, D., Dunfield, K.E., & Germida, J.J. (2021). Rethinking crop nutrition in times of modern microbiology: Innovative biofertilizer technologies. *Frontiers in Sustainable Food Systems*, 5, 606815. DOI: 10.3389/fsufs.2021.606815.

Nair, R.M., Boddepalli, V.N., Yan, M.-R., Kumar, V., Gill, B., Pan, R.S., Wang, C., Hartman, G.L., Silva e Souza, R., & Somta, P. (2023). Global status of vegetable soybean. Plants, 12(3), 609. DOI: 10.3390/plants12030609.

Nandi, P. (2017). *Organic soybean market research report by application (crush, food use, feed use) and by region (North America, Europe, Asia-Pacific, and rest of the world) – market forecast till 2030* (89 p.). Market Research Future. Retrieved June 17, 2025, from https://www.marketresearchfuture.com/reports/organic-soybean-market-4208.

OrganicInfo.ua. (2023). *Export of Ukrainian organic products: Top 10 exported products (EU, 2023*). https://organicinfo.ua/en/infographics/top10-exported-products-eu-2023/

Organic Standard. (2025). *Catalogue of Ukrainian organic exporters 2025*. Retrieved June 27, 2025, from https://organicstandard.ua/content/docs/catalogs/catalogue_of_ukrainian_organic_exporters_en.pdf.

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., & Kremen, C. (2015). Diversification practices reduce organic to conventional yield gap. *Proceedings of the Royal Society B: Biological Sciences*, 282(1804), 20141396. DOI: 10.1098/rspb.2014.1396.

Poudel, S., Vennam, R.R., Shrestha, A., Reddy, K.R., Wijewardane, N.K., Reddy, K.N., & Bheemanahalli, R. (2023). Resilience of soybean cultivars to drought stress during flowering and early-seed setting stages. *Scientific Reports,* 13, Article 1277. DOI: 10.1038/s41598-023-28354-0.

Rotundo, J.L., Marshall, R., McCormick, R., Truong, S.K., Styles, D., Gerde, J.A., Gonzalez-Escobar, E., Carmo-Silva, E., Janes-Bassett, V., Logue, J., Annicchiarico, P., de Visser, C., Dind, A., Dodd, I. C., Dye, L., Long, S.P., Lopes, M. S., Pannecoucque, J., Reckling, M., Rushton, J., Schmid, N., Shield, I., Signor, M., Messina, C.D., & Rufino, M.C. (2024). European soybean to benefit people and the environment. *Scientific Reports,* 31(14): 7612. DOI: 10.1038/s41598-024-57522-z.

ROI Biologicals. (2024). *Economic benefits of switching to biofertilizers for farmers*. Retrieved June 19, 2025, from https://roibiologicals.com/blog/economic-benefits-switching-to-biofertilizers-farmers/

Rogers, E.M. (2003). Diffusion of innovations (5th ed.). Free Press.

Seufert, V., & Ramankutty, N. (2017). Many shades of gray – The context-dependent performance of organic agriculture. *Science Advances*, 3(3), e1602638. DOI: 10.1126/sciadv.1602638.

Smith, S.E., & Read, D.J. (2008). *Mycorrhizal symbiosis* (3rd ed.). Academic Press. DOI: 10.2136/sssaj2008.0015br.

Soybean Market Size & Share Analysis − Growth Trends & Forecasts (2024 - 2029). (2024). Mordor Intelligence. Retrieved June 17, 2025, from https://www.mordorintelligence.com/industry-reports/soybean-market

Srour, A.Y., Ammar, H.A., Subedi, A., Pimentel, M., Cook, R.L., Bond, J., & Fakhoury, A.M. (2020). Microbial communities associated with long-term tillage and fertility treatments in a corn–soybean cropping system. Frontiers in Microbiology, 11, 1363. DOI: 10.3389/fmicb.2020.01363.

USDA: Foreign Agricultural Service. IPAD [cited 2025 Feb 10]. Ukraine soybean area, yield and production.

U.S. Department of Agriculture, Agricultural Marketing Service. (2024). *Livestock, poultry and grain market news: Nonfat dry milk options futures report* [PDF]. Retrieved June 17, 2025, from https://www.ams.usda.gov/mnreports/lsbnof.pdf.

Wang, J., Wang, C., Zhang, J., Wu, X., Hou, Y., Zhao, G., & Sun, H. (2022). Decreased precipitation reduced the complexity and stability of bacterial co-occurrence patterns in a semiarid grassland. Frontiers in Microbiology, 13, 1031496. DOI: 10.3389/fmicb.2022.1031496.

Xu, Y., Liu, X., Ling, N., He, J.-S., Yuan, J., Shen, Q., & Xue, C. (2024). Long-term warming and decreased precipitation regulated microbial community structure and potential function through enhanced predator–prey relationships in the Tibetan Plateau. Science of the Total Environment, 174576. DOI: 10.1016/j.scitotenv.2024.174576.

Zhao, G., Zhu, X., Zheng, G., Meng, G., Dong, Z., Baek, J. H., Jeon, C.O., Yao, Y., Xuan, Y.H., Zhang, J., & Jia, B. (2024). Development of biofertilizers for sustainable agriculture over four decades (1980–2022). *Geography and Sustainability,* 5(1), 19–28. DOI: 10.1016/j.geosus.2023.09.006.