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# Spring barley grain yield when grown in the conditions of southern Ukraine with elements of biologization and preservation of soil fertility

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## ABSTRACT

The study aimed to assess the effects of varietal characteristics, nutrition optimization, and pre-sowing seed treatment on the productivity of spring barley under conditions of climatic variability in the Southern Steppe of Ukraine, based on the implementation of biologized elements of cultivation technology. The research was conducted from 2021 to 2024 in a three-factor field experiment on southern chernozem soil, using a randomized block design with four replications. The effects of two spring barley cultivars (Avatar and Hermes), three nutrition backgrounds (no fertilization, $N_{30}P_{30}K_{30}$; and $N_{30}P_{30}K_{30}$ combined with winter wheat straw, white mustard as a green manure crop, the residue biodecomposer Ecostern, and additional nitrogen $N_{10}$), and two variants of pre-sowing seed treatment (water and the biopreparation BTU-R) were studied. The results were evaluated using analysis of variance (ANOVA). The highest grain yield of spring barley was obtained under the biologized fertilization system. Compared with the control, yield increases amounted to 1.32 t/ha (41.9%) for the cultivar Avatar and 1.36 t/ha (40.7%) for the cultivar Hermes. Pre-sowing seed treatment with BTU-R increased yield by 0.42 t/ha (12.4%) on the unfertilized background and by up to 5.9% under mineral fertilization. The average grain yield over four years was 4.25 t/ha for Avatar and 4.13 t/ha for Hermes. The results were obtained under the soil and climatic conditions of the Southern Steppe of Ukraine, and the effectiveness of the technological elements largely depended on annual moisture conditions. The proposed fertilization system can be applied in agricultural practice to increase crop yields and maintain soil fertility in arid regions. The study provides a comprehensive justification for the combined use of organo-biological and mineral nutrition elements as an effective adaptive strategy for spring barley cultivation under current climate change conditions.

**Keywords:** spring barley varieties, technological elements, seed treatment with biopreparations, stubble biodecomposer, grain yield, straw, green manure (cover crop), soil fertility.

## INTRODUCTION

The current economic and environmental conditions of the global agricultural sector, combined with the progressive degradation of soil fertility and increasing climate variability, pose significant challenges to achieving stable crop yields and high product quality. According to international assessments, soil degradation and declining organic matter content are among the key limiting factors for sustainable crop production in both developed and developing countries, particularly in regions characterized by water scarcity and high temperature stress (FAO, 2021; IPCC, 2022). Under such conditions, there is a growing demand for effective, resource-efficient, and environmentally safe technological approaches to crop cultivation (Kovalenko, 2021).

Numerous studies indicate that optimal and balanced soil nutrient supply is a prerequisite for realizing the genetic yield potential of agricultural crops. Fertilizer application alone may contribute up to 50–75% of yield increases, depending on soil type, crop species, and climatic conditions (Hamaiunova, 2014). The role of soil fertility and fertilization becomes even more critical under climate change, as their effectiveness largely depends on the soil's capacity to supply nutrients and retain moisture throughout the entire growing season (Balyuk et al., 2018). Similar conclusions have been reported in long-term field experiments conducted in Germany, France, and the United States, where soil organic matter content was identified as a key driver of nutrient-use efficiency and yield stability (Powlson et al., 2018; Lal, 2020).

Climatic variability, particularly precipitation patterns, strongly affects yield formation in cereal crops. In years with sufficient rainfall, significantly higher yields can be achieved, highlighting the dominant role of water availability in yield fluctuations (Panfilova et al., 2020). This relationship has enabled the development of yield prediction models for spring barley in different agro-climatic zones, including Eastern Europe and Northern China (Zhang et al., 2019).

Spring barley (*Hordeum vulgare* L.) is characterized by a relatively weak and shallow root system and a high sensitivity to both nutrient availability and soil moisture, especially during early growth stages. Insufficient soil moisture during tillering often prevents the formation of a well-developed secondary root system, which irreversibly limits productivity even if favorable conditions occur later in the season. Under such circumstances, precise regulation of nitrogen nutrition becomes particularly important (Hanhur et al., 2021). Comparable physiological constraints of spring barley have been reported in Canada, Scandinavia, and Australia, where early-season stress has been shown to determine final yield outcomes (Jensen et al., 2021; Kirkegaard et al., 2020).

Despite the recognized importance of fertilization, recent decades have been marked by a substantial reduction in the application of both mineral and, especially, organic fertilizers in many agricultural systems. This trend has been documented in Eastern Europe and parts of Central Asia and has resulted in a gradual depletion of soils in available nutrients and organic matter (Hamaiunova, 2014; Veremeyenko and Semenko, 2019). In the absence of regular organic inputs, soils tend to compact and lose their capacity to absorb and retain moisture; as a result, even intensive rainfall events may fail to benefit crops due to rapid evaporation or runoff. International research conducted in Spain, Italy, and Brazil confirms that soils with low organic matter content are significantly more vulnerable to drought stress and nutrient losses (Alori et al., 2017; Mendes et al., 2019).

Given the limited availability of livestock manure in modern farming systems, the incorporation of crop residues, post-harvest biomass, and green manure crops has become a widely recommended alternative for replenishing soil organic matter. These practices enhance soil structure, stimulate microbial activity, and contribute to long-term fertility restoration (Patyka et al., 1993; Blanco-Canqui et al., 2022). Crop rotation, particularly with the inclusion of legumes, remains one of the most effective and economically viable approaches to maintaining soil fertility. Leguminous crops enrich soils with biologically fixed nitrogen and valuable organic residues, improving both nutrient availability and water-physical properties of soils (Didur and Mostovenko, 2019; Tkachuk and Vradii, 2022). Similar benefits of diversified rotations have been reported in France, Germany, and Australia (Hatfield and Dold, 2019; Hansen et al., 2020).

Systematic replenishment of soils with fresh organic biomass is of critical importance for sustaining soil microbial communities, which play a central role in nutrient cycling. Through the decomposition of organic matter, soil microorganisms release macro- and micronutrients in plant-available forms, thereby reducing dependence on mineral fertilizers and improving crop nutrition. Moreover, increased soil organic carbon and microbial activity contribute to lower greenhouse gas emissions and support climate change mitigation efforts (Skrylnyk et al., 2018; Gamayunova et al., 2025). These findings are consistent with international assessments emphasizing soil carbon sequestration as a key component of climate-smart agriculture (Lal, 2020; FAO, 2021).

In recent years, the application of residue biodecomposers has been increasingly recognized as an effective tool for accelerating organic matter mineralization and enhancing soil biological activity. Numerous studies conducted under diverse soil and climatic conditions have demonstrated their positive effects on soil fertility and crop productivity (Panfilova et al., 2019; Sydiakina, 2021; Dudchenko et al., 2021). Our previous research also confirmed the effectiveness of incorporating straw and green manure crops in combination with biodecomposers and mineral fertilizers in spring barley cultivation (Gamayunova et al., 2025). The integrated use of organic matter, biodecomposers, and mineral fertilizers has been shown to significantly increase yields of spring barley, a crop particularly responsive to improved nutrient availability (Sydiakina and Gamayunova, 2020).

Beyond fertilization strategies, the selection and introduction of high-yielding, regionally adapted cultivars represent a critical component of sustainable crop production systems. Modern varieties often exhibit enhanced nutrient-use efficiency and improved tolerance to climatic stress, resulting in more stable yields under comparable growing conditions (Panfilova et al., 2020; Panfilova and Hamaiunova, 2018; Kahiluoto et al., 2020). This advantage is particularly relevant for spring barley cultivation in the Southern Steppe of Ukraine, where the efficient utilization of limited soil moisture and nutrients is crucial (Panfilova and Gamayunova, 2018).

At the same time, an analysis of recent domestic and international studies indicates that, despite a substantial body of research on the role of organic matter, fertilization, and the biologicalization of agriculture, the complex interactions between resource-saving nutrient management systems, soil microbiota activity, and spring barley productivity under conditions of climate aridization remain insufficiently investigated. In particular, data on the combined effects of crop residue biodecomposers, alternative sources of organic biomass, and mineral fertilization on soil agrophysical properties, nutrient dynamics, and the realization of crop yield potential under the conditions of the Southern Steppe of Ukraine are limited.

The objective of this study is to identify the patterns governing the effects of the combined application of organic residues, biodecomposers, and mineral fertilizers on soil fertility indicators, yield structure components, and spring barley productivity under conditions of climate change. The study aims to expand the scientific understanding of the mechanisms underlying yield formation in spring barley for resource-saving farming systems and to clarify the role of biological factors in stabilizing production processes.

The research hypothesis is that integrating organic biomass with biodecomposers and optimizing rates of mineral fertilization produces a synergistic effect, manifested in improved agrophysical and nutrient properties of the soil, enhanced microbiological activity, and increased stability of spring barley productivity under water-stress conditions.

## RESEARCH METHODOLOGY

The research was conducted from 2021 to 2024 at the Educational, Scientific, and Practical Center of Mykolaiv National Agrarian University (Southern Steppe, Ukraine) on Southern Chernozem soil. Prior to establishing the experiment, soil samples were collected from the 0–30 cm layer and analyzed using standard agrochemical methods. The humus content ranged from 2.9 to 3.1%, available nitrogen content was 20–25 mg/kg of soil, available phosphorus ($P_2O_5$) was 40–45 mg/kg, and exchangeable potassium ($K_2O$) ranged from 370 to 520 mg/kg of soil. The experiment was established as a three-factor field trial arranged in a randomized block design with four replications. The total plot area was 80 m², and the accounting (harvested) area was 30 m². The selection of experimental factors was driven by the need to assess genotypic variability, fertilization systems, and biological seed treatments under conditions of increasing climatic aridity.

Factor A (variety) included the spring barley varieties Avatar and Hermes, which differ in adaptive traits and yield potential.

Factor B (fertilization background) involved a comparison between a conventional mineral fertilization system and an integrated resource-saving system combining crop residues, green manure, and biological decomposition of organic matter.

Factor C (seed treatment) was aimed at evaluating the role of microbial inoculation in early plant development and nutrient uptake.

A three-factor field experiment was laid out with the following factors and treatments:

1. Factor A (varieties): Avatar, Hermes
2. Factor B (fertilization background):
   - control (no fertilizers);
   - $N_{30}P_{30}K_{30}$ (recommended dose for the region);
   - $N_{30}P_{30}K_{30}$ + winter wheat straw (from the preceding crop) + green manure + Ekostern (stubble biodecomposer) + $N_{10}$ (urea).
3. Factor C (pre-sowing seed treatment):
   - seed treatment with water;
   - seed treatment with BTU-R preparation (1 L/t).

The field experiment was established according to a unified stepwise scheme. After harvesting winter wheat, straw and post-harvest residues were evenly chopped and incorporated into the soil to a depth of 5–6 cm. White mustard (*Sinapis alba* L.) was sown as a green manure crop, and its green biomass was incorporated into the soil at the flowering stage at a depth of 20–22 cm.

Before autumn ploughing, the plant residue decomposer Ekostern was applied at a rate of 2 L/ha in combination with 10 kg/ha of nitrogen (active ingredient) in the form of urea, using a working solution volume of 300 L/ha.

Spring soil tillage included harrowing and pre-sowing cultivation to a depth of 5–6 cm. Seed treatment was carried out immediately before sowing in accordance with the treatments of Factor C. After sowing, the soil surface was compacted using ring-spike rollers (3KK-6). During the growing season, observations of plant growth and development were conducted, and phenological stages were recorded. Yield structure components and grain yield were also determined for each experimental treatment. The accounting, sampling, and yield determination were carried out in accordance with current national and international methodologies (Ushkarenko et al., 2014, Rozhkov et al., 2016a, Rozhkov et al., 2016в). The obtained experimental data were analyzed using analysis of variance (ANOVA) to evaluate the main effects and interactions of the studied factors.

Statistical analysis was conducted to assess the impact of genotype, fertilization background, seed treatment, and interannual climatic variability on spring barley grain yield. The experimental data obtained over a four-year period (2021–2024) were analyzed using a mixed-effects analysis of variance (ANOVA). Variety (A), fertilization background (B), and seed treatment (C) were treated as fixed factors, while the factor "Year" was considered a random effect to account for interannual variation in weather conditions. The model included main effects and their interactions (A × B, A × C, B × C), as well as interactions between fixed factors and year (A × Year, B × Year, C × Year). This approach allowed separation of treatment effects from climatic variability and ensured a statistically valid assessment of effect stability across years. Mean comparisons were performed using the least significant difference (LSD) test at a significance level of $P \leq 0.05$. Prior to analysis, data were checked for normality and homogeneity of variances. To evaluate the influence of moisture conditions on yield formation, correlation analysis was conducted between seasonal precipitation and grain yield. Additionally, regression analysis was applied to describe the relationship between yield response and fertilization background under contrasting annual moisture regimes. All statistical analyses were performed using standard statistical software.

## RESEARCH RESULTS

Based on the results of the conducted research, it was established that the technological elements studied in spring barley cultivation significantly increased grain yield (Table 1). In particular, applying the regionally recommended mineral fertilizer dose ($N_{30}P_{30}K_{30}$) substantially enhanced the grain productivity of this crop.

The implementation of a biologically-oriented fertilization system - comprising, in addition to the mentioned mineral fertilizer dose, the retention of winter wheat straw from the previous crop on the field, as well as the cultivation and incorporation of green manure biomass into the soil in combination with the stubble biodecomposer Ekostern and an additional dose of $N_{10}$ (urea) - resulted in a markedly higher increase in grain yield levels for both studied spring barley varieties.

Higher grain productivity was also achieved through pre-sowing seed treatment with the BTU-R biocomplex, as evidenced by the results in Table 1 and Figure 1. These findings demonstrate the importance of both nutrient supply for spring barley plants and seed treatment in influencing grain yield levels of both studied varieties.

The statistical analysis of the experimental data from 2021–2024 was carried out using a four-factor analysis of variance (ANOVA), in which spring barley grain yield (Y) was modeled as a function of the main effects of variety (A), fertilization background (B), seed treatment (C), and year (Y), as well as their interactions (Table 2).

The general linear model applied was:

$$\begin{gathered} Y_{ijklm} = \mu + \alpha_i + \beta_j + \gamma_k + \delta_l + \\ + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\alpha\delta)_{il} + (\beta\gamma)_{jk} + \\ + (\beta\delta)_{jl} + (\gamma\delta)_{kl} + (\alpha\beta\gamma)_{ijk} + (\alpha\beta\delta)_{ijl} + \\ + (\alpha\gamma\delta)_{ikl} + (\beta\gamma\delta)_{jkl} + (\alpha\beta\gamma\delta)_{ijkl} + \varepsilon_{ijklm} \end{gathered} \tag{1}$$

where: $Y$ – grain yield, $\mu$ – overall mean, $\alpha_i$ – effect of factor $A$ (variety, $i$ = 1…2), $\beta_j$ – effect of factor $B$ (fertilization background, $j$ = 1…3), $\gamma_k$ – effect of factor $C$ (seed treatment, $k$ = 1…2), $\delta_l$ – effect of factor $Y$ (year, $l$ = 2021–2024) interaction terms – effects of combinations of factors, $\varepsilon_{ijklm}$ – random error, $\varepsilon \sim N(0, \sigma^2)$.

**Table 1.** Grain yield of spring barley varieties depending on the studied factors over the years of cultivation, t/ha

| Fertilization background (factor B) | Seed treatment (Factor C) | Years of research | | | | |
|---|---|---|---|---|---|---|
| | | 2021 | 2022 | 2023 | 2024 | 2021–2024 |
| Avatar variety (factor A) | | | | | | |
| Control (without fertilizers) | 1 | 3.72 | 3.47 | 3.31 | 3.14 | 3.41 |
| | 2 | 4.17 | 3.94 | 3.73 | 5.32 | 3.84 |
| $N_{30}P_{30}K_{30}$ | 1 | 4.67 | 4.32 | 4.12 | 3.78 | 4.25 |
| | 2 | 4.98 | 4.78 | 4.63 | 4.14 | 4.63 |
| $N_{30}P_{30}K_{30}$ + Straw + Green Manure + Ekostern + $N_{10}$ (urea) | 1 | 4.96 | 4.70 | 4.47 | 4.13 | 4.57 |
| | 2 | 5.17 | 4.95 | 4.73 | 4.52 | 4.84 |
| Hermes variety (factor A) | | | | | | |
| Control (without fertilizers) | 1 | 3.58 | 3.36 | 3.28 | 3.12 | 3.34 |
| | 2 | 4.02 | 3.86 | 3.66 | 3.46 | 3.75 |
| $N_{30}P_{30}K_{30}$ | 1 | 4.38 | 4.30 | 3.92 | 3.77 | 4.12 |
| | 2 | 4.73 | 4.70 | 4.49 | 3.98 | 4.48 |
| $N_{30}P_{30}K_{30}$ + Straw + Green Manure + Ekostern + $N_{10}$ (urea) | 1 | 4.83 | 4.56 | 4.28 | 4.10 | 4.44 |
| | 2 | 5.02 | 4.79 | 4.58 | 4.39 | 4.70 |
| $LSD_{05}$ by factor | A | 0.04 | 0.04 | 0.03 | 0.05 | |
| | B | 0.14 | 0.12 | 0.13 | 0.11 | |
| | C | 0.12 | 0.10 | 0.11 | 0.10 | |
| | AB | 0.13 | 0.12 | 0.12 | 0.11 | |
| | AC | 0.10 | 0.09 | 0.10 | 0.10 | |
| | BC | 0.09 | 0.11 | 0.10 | 0.08 | |
| | ABC | 0.15 | 0.13 | 0.13 | 0.12 | |

The results of the four-factor ANOVA demonstrated that the grain yield of spring barley was significantly affected by each of the individual experimental factors–variety (A), fertilization background (B), seed treatment (C), and year (Y)–as well as by a number of their two-way interactions. Among the main factors, fertilization background (B) explained the greatest proportion of variation in grain yield ($p < 0.001$), indicating that nutrient supply had a dominant role in determining crop productivity under the soil and climatic conditions of the Southern Steppe of Ukraine. Seed treatment with the microbial inoculant BTU-R (factor C) also had a statistically significant positive influence on yield performance ($p < 0.001$), suggesting enhanced nutrient uptake and root system development in the early growth phases. The effect of the variety factor (A) was found to be statistically significant ($p < 0.001$), although with a markedly smaller contribution to the total model variation, which confirms the relatively similar adaptive capacity and

**Table 2.** Four-factor ANOVA of the effects of variety, fertilization background, seed treatment and year on spring barley grain yield (average 2021–2024)

| Fertilization background (factor B) | Under seed treatment with water (factor C) | | Under seed treatment with biopreparation (factor C) | | Compared to the absolute control (seed treatment with water) | |
|---|---|---|---|---|---|---|
| | t/ha | % | t/ha | % | t/ha | % |
| Avatar variety | | | | | | |
| $N_{30}P_{30}K_{30}$ | 0.84 | 24.6 | 0.79 | 20.6 | 1.22 | 35.8 |
| $N_{30}P_{30}K_{30}$ + Straw + Green Manure + Ekostern + $N_{10}$ (urea) | 1.16 | 34.0 | 1.00 | 26.0 | 1.32 | 41.9 |
| Hermes variety | | | | | | |
| $N_{30}P_{30}K_{30}$ | 0.78 | 23.4 | 0.73 | 19.5 | 1.14 | 34.1 |
| $N_{30}P_{30}K_{30}$ + Straw + Green Manure + Ekostern + $N_{10}$ (urea) | 1.10 | 32.9 | 0.95 | 25.3 | 1.36 | 40.7 |

yield responses of both tested varieties, Avatar and Hermes, under the given production conditions. The year factor (Y) was also highly significant ($p < 0.001$), reflecting variable hydrothermal conditions across seasons and highlighting the sensitivity of spring barley to climatic variability.

A number of two-way interactions were significant, including A × B, A × C, B × C, and B × Y ($p < 0.05$), suggesting that the magnitude of the yield response to fertilization and seed treatment depended on genotype and was modulated by differences in seasonal conditions. By contrast, none of the three-way or four-way interactions reached statistical significance ($p > 0.05$), implying the absence of synergistic effects among all investigated technological components simultaneously. This pattern indicates that the implementation of complex resource-saving management practices does not lead to overcompensation or antagonistic interference among factors at higher interaction levels.

Taken together, these results provide strong statistical support for the adoption of biologized fertilization systems, which combine mineral fertilizers, crop residue management, green manure biomass incorporation, biodecomposer application, and microbial seed inoculation, as a viable strategy to enhance the productivity and yield stability of spring barley under climatic aridization. The statistically verified performance advantage of integrated nutrient management over mineral fertilization alone highlights its relevance for sustainable agricultural intensification and soil fertility preservation in drought-prone agroecosystems.

Notably, several two-way interactions–including A × B, A × C, B × C, and B × Y–were statistically significant ($p \leq 0.05$). These effects underline that the grain yield response of spring barley depends not only on individual technological inputs but also on their combinations. The A×B interaction reflects genotype-dependent nutrient utilisation, with both varieties responding to fertilization at different magnitudes. A × C demonstrates that the efficiency of microbial seed treatment is partially genotype-specific, likely linked to varietal differences in early vigor and rhizosphere-microbiome compatibility. The B × C interaction indicates complementary benefits of inoculation and fertilization; inoculation provides greater relative advantage under low-input conditions, whereas its incremental effect diminishes when mineral nutrients are readily available. Finally, the B × Y interaction confirms that the efficiency of fertilization varies across seasons, driven by rainfall and temperature regimes. In contrast, higher-level interactions (A × B × C, A × B × C × Y) were not significant, suggesting that cumulative management interventions do not yield non-linear synergistic outcomes. Together, these findings underscore the need for integrative fertilization strategies and demonstrate that tailored nutrient management is more crucial for yield stability than cultivar choice alone in arid climates.

The observed positive effect of the studied technological elements was consistent across all years of the research (Figure 2). The data clearly

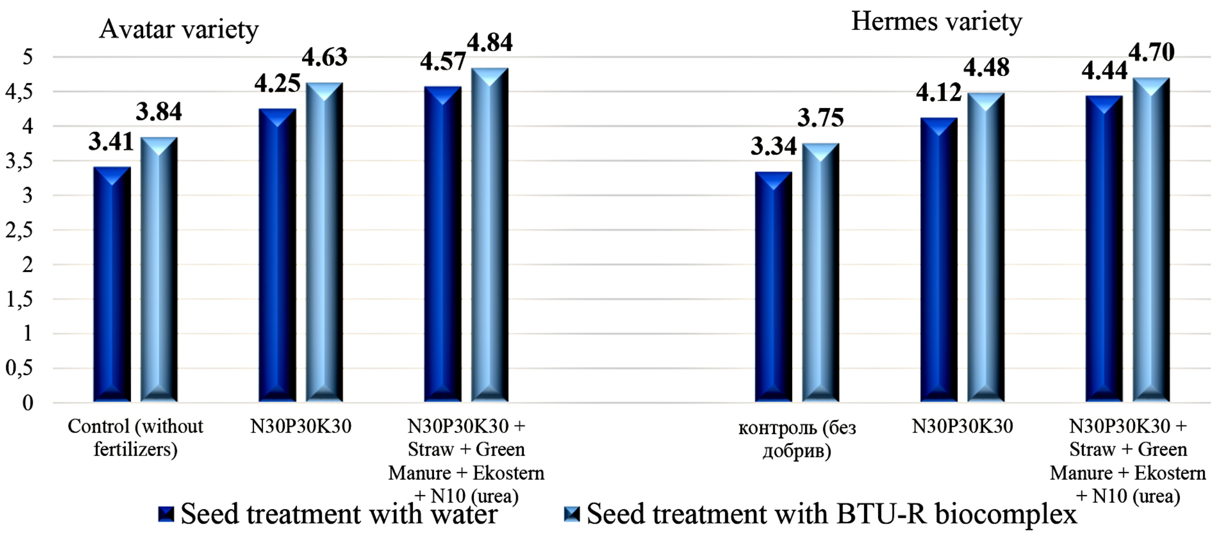


**Figure 1.** Grain yield formation of spring barley varieties under nutrient optimization and pre-sowing seed treatment (average for 2021–2024), t/ha

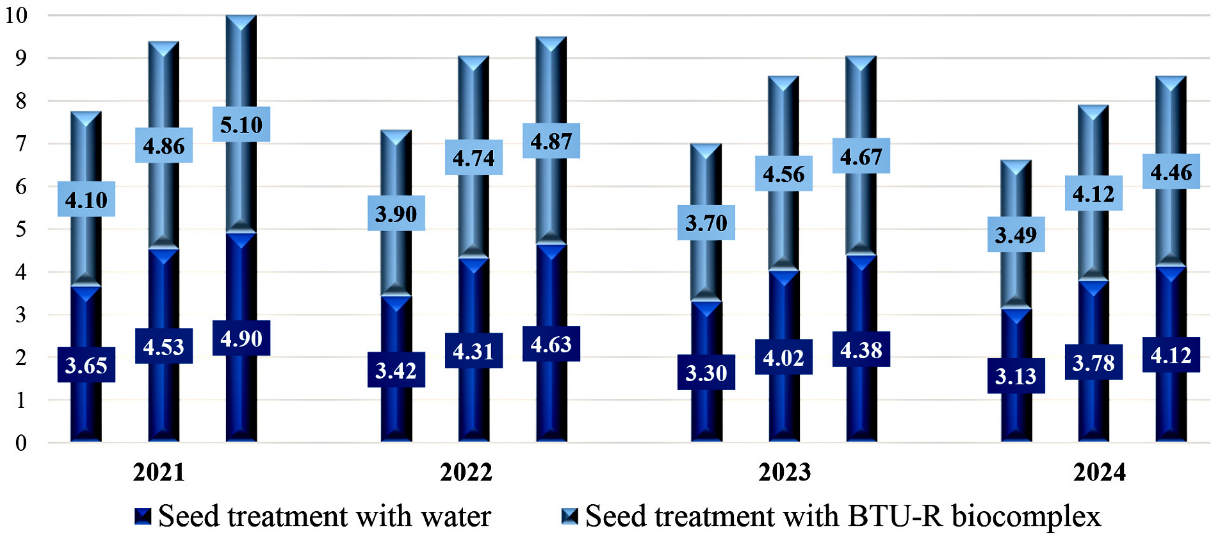


**Figure 2.** Effect of studied technological elements on spring barley grain yield by year of cultivation (average across varieties), t/ha

illustrate the advantages of optimizing spring barley plant nutrition and using pre-sowing seed treatment with the BTU-R biocomplex compared to the control.

It can also be concluded that grain yield levels varied across the years of cultivation. The highest yields were recorded in 2021, which was favorable in terms of moisture availability, whereas the lowest yields occurred in 2024, the driest year of the study period.

This trend was observed for both spring barley varieties grown in the experiment, as illustrated in Figure 3. According to the data, the Avatar variety demonstrated slightly higher productivity, while the Hermes variety yielded somewhat lower values. On average over the four years of cultivation, the grain yield amounted to 4.25 t/ha for Avatar and 4.13 t/ha for Hermes. These levels of varietal grain productivity (calculated as weighted average yields) indicate that both varieties are well adapted to the region's growing conditions and respond similarly to the implemented technological elements.

In most cases, the differences in productivity between the varieties across treatments fell within the experimental error range.

As previously noted, the grain yield of spring barley significantly increased with improved fertilization background, particularly under the implementation of a biologically oriented approach to soil fertility preservation. Enriching soil with fresh organic matter positively affected

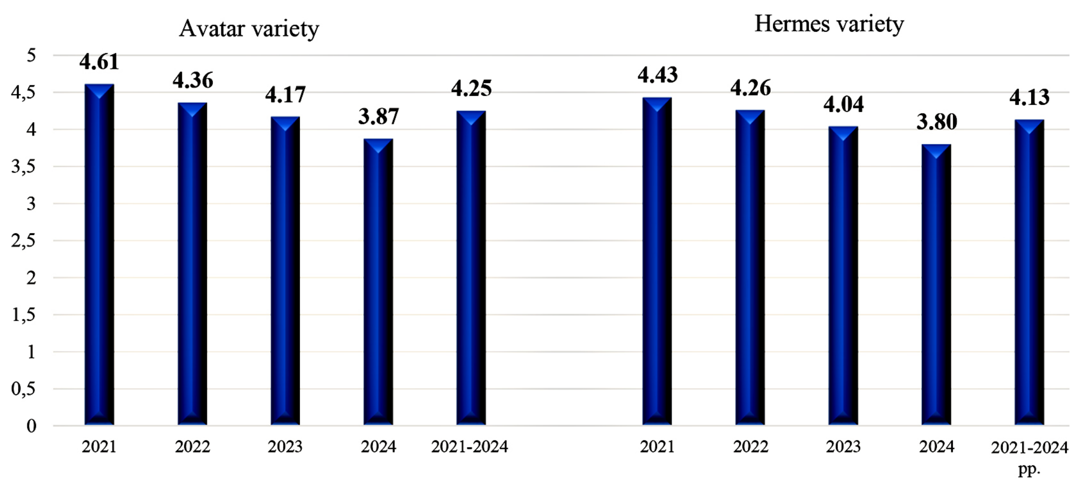


**Figure 3.** Average grain yield levels of spring barley varieties across all experimental treatments by year of cultivation, t/ha

its capacity to accumulate and retain moisture, which is considered the primary limiting factor for yield formation in the Southern Steppe of Ukraine. This is reflected in the grain yield increases presented in Table 2.

For instance, under seed treatment with water and mineral fertilization ($N_{30}P_{30}K_{30}$), the average yield increase over the study years for the Avatar variety was 24.6%, while for the Hermes variety, it was 23.4%. When seeds were treated with the BTU-R biocomplex, the yield increases reached 20.6% and 19.5%, respectively, indicating a slightly lower effect.

Much greater increases in grain yield were observed with the fertilization background that included, in addition to mineral fertilizers, the application of organic materials - wheat straw and green manure - combined with the stubble biodecomposer Ekostern and an additional dose of $N_{10}$ (urea) to accelerate organic matter decomposition. In this treatment, compared to the unfertilized control, the Avatar variety showed a 1.16 t/ha (34.0%) increase in grain yield under seed treatment with water. For the Hermes variety, the yield increase was 1.10 t/ha (32.9%).

Relative to the absolute control (no fertilizers and seed treatment with water), the biologized fertilization system provided even higher productivity gains: 1.32 t/ha (41.9%) for Avatar and 1.36 t/ha (40.7%) for Hermes.

The data presented in Table 1 highlight the significant role of pre-sowing seed treatment (Factor C) in spring barley cultivation. This factor was isolated, and its impact on the increase in grain yield was assessed (Table 3). A clear pattern was observed regarding the effect of this technological element. Using BTU-R biocomplex for seed treatment resulted in the most pronounced yield increases under unfertilized conditions: Avatar, +0.43 t/ha or +12.6%; Hermes, +0.41 t/ha or +12.3%. Under mineral fertilization ($N_{30}P_{30}K_{30}$), the yield increase was slightly lower: Avatar: +0.38 t/ha (+8.9%), Hermes: +0.36 t/ha (+8.7%). On the fertilization background that included $N_{30}P_{30}K_{30}$, organic matter, and stubble biodecomposer, the increases were even lower: Avatar: +0.27 t/ha (+5.9%), Hermes: +0.26 t/ha (+5.9%). Thus, the biologized fertilization system, combined with the recommended mineral fertilizer rate for the region, yielded the lowest relative increases in yield from seed treatment with BTU-R. These findings indicate that pre-sowing seed treatment with BTU-R biopreparation significantly affects grain productivity when spring barley is cultivated on nutrient-depleted soils, regardless of the variety.

To supplement yield-related findings, additional soil analyses were conducted in 2021, prior to establishing the experiment, and in autumn 2024, after the completion of the four-year study. Soil samples were collected from the 0–30 cm layer and analyzed according to standard national and international protocols. The results demonstrated measurable treatment effects on the temporal dynamics of soil fertility. Plots managed under the integrated biologized nutrient system ($N_{30}P_{30}K_{30}$ + straw incorporation + green manure + Ekostern + $N_{10}$) maintained or slightly increased soil humus content (+0.04–0.12%) and available phosphorus and potassium levels, whereas unfertilized control plots exhibited reductions in available nitrogen (−3–6 mg/kg) and phosphorus (−4–7 mg/kg) during the same period. Mineral fertilization

**Table 3.** Grain yield increases of spring barley compared to control under nutrient optimization (average for 2021–2024)

| Fertilization background (factor B) | Under seed treatment with water (factor C) | | Under seed treatment with biopreparation (factor C) | | Compared to the absolute control (seed treatment with water) | |
|---|---|---|---|---|---|---|
| | t/ha | % | t/ha | % | t/ha | % |
| Avatar variety | | | | | | |
| $N_{30}P_{30}K_{30}$ | 0.84 | 24.6 | 0.79 | 20.6 | 1.22 | 35.8 |
| $N_{30}P_{30}K_{30}$ + Straw + Green Manure + Ekostern + $N_{10}$ (urea) | 1.16 | 34.0 | 1.00 | 26.0 | 1.32 | 41.9 |
| Hermes variety | | | | | | |
| $N_{30}P_{30}K_{30}$ | 0.78 | 23.4 | 0.73 | 19.5 | 1.14 | 34.1 |
| $N_{30}P_{30}K_{30}$ + Straw + Green Manure + Ekostern + $N_{10}$ (urea) | 1.10 | 32.9 | 0.95 | 25.3 | 1.36 | 40.7 |

alone preserved nutrient levels but did not compensate for the depletion of organic matter. These changes suggest that biologized systems serve a dual role, supporting crop nutrition while also contributing to the maintenance of long-term soil fertility.

Given the strong interannual variability in precipitation and temperature across 2021–2024, correlation analysis was conducted to quantify the dependence of yield formation on hydrothermal conditions. Pearson correlation coefficients revealed a consistently strong positive relationship between grain yield and total rainfall during the period of stem elongation to grain filling (r = 0.73–0.82), while correlations between soil available nitrogen and grain yield were moderate to high (r = 0.55–0.69). These findings indicate that both nutrient availability and seasonal water supply exert statistically meaningful effects on yield, thereby supporting the conclusion that agronomic intensification must be integrated with strategies that ensure soil moisture retention, particularly under increasing climatic aridization.

To further validate factor effects and support predictive interpretation, multiple regression models were constructed using fertilizer input (expressed as N equivalent) and growing-season rainfall as explanatory variables. Significant regression equations ($p < 0.01$) were obtained for both cultivars tested:

$$\text{Avatar: } Y = 2.41 + 0.031F + 0.007R \quad (R^2 = 0.71) \tag{2}$$

$$\text{Hermes: } Y = 2.32 + 0.028F + 0.008R \quad (R^2 = 0.74) \tag{3}$$

where: $Y$ – yield, t/ha; $F$ – fertilizer $N$ equivalent (kg/ha); $R$ – growing-season rainfall (mm).

The coefficients indicate that fertilizer supply and water availability have synergistic rather than isolated effects, and yield enhancement is maximized when both resource inputs are at optimal levels. The models also reinforce the experimental findings, demonstrating the increasing marginal returns associated with biologized fertilization as precipitation decreases.

## CONCLUSIONS

For the first time under southern chernozem conditions, a biologically integrated fertilization system combining mineral nutrients with crop residues, green manure biomass, a residue biodecomposer, and supplementary nitrogen was demonstrated to outperform conventional mineral fertilization in terms of yield stability, soil-supporting capacity, and overall productivity. The biologized fertilization strategy increased grain yield by 41.9% in the Avatar cultivar and 40.7% in the Hermes cultivar relative to the unfertilized control, exceeding the effect of mineral fertilization alone and confirming improved nutrient-use efficiency and enhanced soil biological functioning.

The study further established a clear dependency of the yield response to microbial seed inoculation on the nutritional background. Seed treatment with the BTU-R microbial preparation had the strongest effect under nutrient-limited conditions, increasing grain yield by 12.4%, whereas its relative contribution decreased as soil fertility improved. This finding provides a basis for tailoring biological inputs in the context of resource-efficient production systems.

Collectively, the four-year soil fertility dynamics, rainfall–yield correlation patterns, and predictive regression models confirm that rational plant nutrition systems, which combine mineral fertilizers with crop residue recycling and microbial activation, generate cumulative agronomic advantages. These include (1) sustained increases in yield relative to the unfertilized control, (2) greater efficiency in nutrient utilization, and (3) mitigation of soil fertility decline and crop sensitivity to climate-induced water stress. The integrated nutrient management approach, therefore, fills a key knowledge gap regarding the ecological and physiological mechanisms underlying spring barley productivity under aridizing climatic conditions.

The obtained results show that biologized fertilization not only enhances current crop performance but also contributes to long-term soil resilience by maintaining organic matter turnover and stimulating microbial processes, thereby reducing dependence on synthetic nutrient inputs. The proposed nutrient management framework represents an effective adaptive strategy for cereal production in semi-arid regions. Its adoption may improve agroecosystem sustainability, strengthen soil fertility conservation, and buffer production risks associated with extreme rainfall variability, thus aligning spring barley cultivation with the core principles of climate-smart and environmentally responsible agriculture.

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