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Realization of winter wheat biological potential through the implementation of biologization elements in cultivation technology

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ABSTRACT

The study aimed to determine the yield structure parameters of four winter wheat cultivars depending on the application of biologically active compounds and fertilizer rates under the conditions of the Ukrainian Forest-Steppe. The research was conducted during 2023–2025 at the Bila Tserkva Research and Breeding Station of the Institute of Bioenergy Crops and Sugar Beet (NAAS), located in the South-Western Forest-Steppe of Ukraine. A three-factor field experiment was established using a randomized plot design in four replicates. The study evaluated different treatment schemes: 1 – seed treatment (Rizofos Liq 1.5 L/t + Premax 0.3 L/t, Mycofriend 1.5 L/t), 2 – soil application of a biological product during sowing (Groundfix 3.0 L/ha) (Factor A). Mineral nutrition was provided by applying $N_{12}P_{12}K_{12}$ and $N_{24}P_{24}K_{24}$ fertilizers during sowing (Factor B). For control was used variant without use of biological products and without fertilization. Four winter wheat cultivars were selected for the study: 'KWS Spencer', 'Maurizio', 'Matchball', and 'Vidrada' (Factor C). It was established that the use of biological products in winter wheat cultivation positively affects the formation of productive stems, grain number per spike, grain mass per spike, and biological yield. All factors and their interactions were statistically significant. Factor B (mineral fertilization) had the most substantial impact on yield structure, with a contribution of 46.68–78.03% depending on the parameter. The influence of Factor C (cultivar) ranged from 10.35% to 28.20%, while Factor A (biological product) accounted for 1.52–12.51%. The combined application of Rizofos Liq (1.5 L/t) + Premax (0.3 L/t) with the $N_{12}P_{12}K_{12}$ fertilization rate ensured the maximum increase in all yield structure components, resulting in a biological yield of 5.7–7.4 t/ha. Under similar conditions, the grain yields were 6.8 t/ha for 'Maurizio', 6.1 t/ha for 'Matchball', and 5.7 t/ha for 'Vidrada'. The obtained biological yield figures correlate with the number of productive stems per linear meter and the 1000-grain weight.

Keywords: winter wheat, biological products, growing technology, biologization, productivity, yield structure.

INTRODUCTION

The significance of winter wheat in ensuring food security is immense and multifaceted, as it holds a leading position among other agricultural crops in terms of gross grain production and remains a key component of the population's diet in many countries worldwide. Its grain is widely used in the milling, baking, and food industries, as well as in animal husbandry, further strengthening its strategic role in shaping global food security. According to the FAO, global wheat production reaches over 780 million tonnes annually, underscoring its indispensable status in the global agrifood system (FAO, 2024). According to the State Statistics Service of Ukraine, winter wheat remains the dominant cereal crop in the country's agricultural structure, with a gross harvest exceeding 22–23 million tonnes annually in recent years, accounting for approximately 40% of the total grain production (State Statistics Service of Ukraine, 2025).

The stability of grain production in modern conditions is largely determined by the adaptive potential of the crop and the technological measures used for its realization. Bazalii et al. (2019) substantiated that the breeding of winter wheat cultivars with increased ecological stability is a fundamental tool for mitigating risks in a changing environment. Furthermore, Polischuk and Konovalov (2024), drawing on data from the State Register of Plant Varieties Suitable for Dissemination in Ukraine, prove that the realization of the yield potential of seed crops varies significantly depending on the cultivar's maturity group.

The transformation of tillage systems remains a subject of ongoing scientific debate. Balen et al. (2023) note that the yield response to long-term minimized tillage depends on the soil texture. At the same time, Liu (2022) highlights the advantages of No-till in stimulating the development of mycorrhizal fungi, which enhances the trophic status of plants. Under the conditions of the Ukrainian Steppe, Yurkevych and Valentiuk (2021) proved the feasibility of combining differentiated tillage systems within organic crop rotations.

The intensification of crop production, particularly under adverse soil and climatic conditions, requires not only the maximal utilization of the productivity potential of cultivars but also an increase in their ecological stability. This necessitates one of the priority directions for the development of modern agriculture – the implementation of biologization elements into crop cultivation technologies (Bazalii et al, 2019; Panfilova, et al, 2023).

Biologization is gaining particular importance in cultivation technologies, as it promotes the production of ecologically safe and economically viable high-quality products, strengthens the ecological stability of agrolandscapes, and ensures the preservation of soil fertility.

In recent years, significant progress has been achieved in the development of complex-action biological products based on various microorganisms. The microorganisms integrated into these products perform a range of functions that contribute to increasing the yield of agricultural crops.

The utilization of rhizosphere microorganisms capable of fixing biological nitrogen from the atmosphere through diazotrophic bacteria is a key factor in overcoming nitrogen deficiency in plants, enhancing land cultivation efficiency, improving soil fertility, and reducing expenditures on synthetic mineral fertilizers.

The analysis of plant-microorganism interactions is currently highly relevant. Consequently, complex-action biological products, particularly those based on rhizosphere microorganisms, serve as a viable alternative. Beyond nitrogen fixation, they produce physiologically active substances that stimulate plant growth and development. Recently identified new microbial strains are also capable of suppressing pathogenic microflora, thereby reducing disease incidence, increasing plant productivity, and improving the overall quality of crop products.

Bunas et al. (2024) highlight a global trend toward the expansion of the biological products market, which fully aligns with the findings of Davydov and Tymoshchuk (2025) regarding the role of bioagents in regulating plant stress resistance within the framework of sustainable agricultural development. The practical efficacy of pre-sowing seed treatment and foliar feeding with biological stimulants was confirmed in studies by Korkhova et al. (2023). Specifically, research conducted during 2020–2022 at the Educational, Scientific, and Practical Center of the Mykolaiv National Agrarian University (Ukraine) analyzed the impact of seed treatment with biological products and cultivar characteristics of ten winter wheat varieties on productivity. These studies confirmed the feasibility of pre-sowing seed treatment with bio-based products to optimize plant nutrition and achieve high grain yields (Korkhova et al., 2023). A similar trend has been observed in studies conducted under the conditions of the Right-Bank Forest-Steppe of Ukraine (Pinchuk et al., 2022).

Studies conducted under the conditions of the Ukrainian Polissia have proven the feasibility of using endomycorrhizal inoculants and organo-mineral fertilizers for pre-sowing seed treatment in organic winter wheat cultivation technologies. This approach resulted in winter wheat grain yields of 5.26–5.39 t/ha, with a gluten content of 23.7–24.2% and a test weight of 754.7 and 755.2 g/L (Davydov et al., 2025).

The issues of nutrition optimization and plant protection are closely intertwined with agrotechnical practices. Gamayunova et al. (2022) established that winter crop productivity is determined by the complex action of the preceding crop, mineral fertilizer rates, and biological products. In turn, Jodaugiene (2022) and Sinkevičienė (2019) emphasize the high efficiency of biological products specifically in organic farming systems and under variable nitrogen nutrition rates

Innovative solutions, particularly the application of nanoparticles for abiotic stress management (Singh et al., 2021), combined with classical technological elements on typical chernozems (Litvinova et al., 2023), enable the formation of a comprehensive crop cultivation strategy. A critical condition for such intensification is the use of precise methods for evaluating crop structure, as proposed by Olkhovskyi et al. (2019).

Thus, the literature review confirms that modern agricultural science is moving towards comprehensive intensification, where genetic resources, adaptive agrotechnical practices, and biologization tools are integrated into a unified system to ensure food security.

In the context of these ongoing debates, the integration of biological products with optimized mineral nutrition (Factors A and B) represents a significant advancement. This synergistic approach aims to address the challenges of soil health and nutrient efficiency, providing a practical solution for maximizing the biological potential of winter wheat cultivars under changing environmental conditions.

The aim of the research was to investigate the effect of different biological product application schemes and mineral fertilizer rates on changes in the yield structure components of four winter wheat varieties under the conditions of the South-Western Forest-Steppe of Ukraine.

MATERIAL AND METHODOLOGY

The research was conducted during 2023–2025 at the Bila Tserkva Research and Breeding Station of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences (NAAS), located in the South-Western Forest-Steppe of Ukraine. All laboratory analyses were performed at the Laboratory of Original Seed Production of the Institute of Plant Physiology and Genetics of the National Academy of Sciences (NAS) of Ukraine.

The meteorological conditions of the Bila Tserkva district belong to the temperate continental type, characterized by a relatively smooth transition from winter to spring and a subsequent onset of summer with moderate precipitation. The average annual air temperature in the region ranges from 6–8 °C, and the duration of the frost-free period exceeds 165 days. Annual precipitation fluctuates between 400–500 mm, with 60–70% occurring during the warm season (April–October). Productive moisture reserves in the arable soil layer at the beginning of winter wheat sowing are generally sufficient. Meteorological autumn begins in mid-September and lasts 70–75 days. A steady transition of the average daily temperature below +5 °C occurs around November 6, while a drop in air temperature below 0 °C is typically observed in the third decade of the month. The duration of the winter period averages 109 days (ranging from 54 to 130). Winter is characterized by instability, frequent thaws, and the formation of ice crusts. The soil freezes to a depth of approximately 55 cm (within a range of 30–100 cm). The temperature at the tillering node level occasionally drops below –9 °C, which may lead to the winterkilling of certain winter wheat varieties (Konishchuk et al., 2014).

The spring period typically begins at the end of the second decade of March. The snow cover disappears around March 20–21, and the thawing of the arable soil layer occurs by the end of the month. The duration of spring vegetation is approximately 65 days, during which an average of 90 mm of precipitation falls. A characteristic negative feature of this period is significant air temperature fluctuations and rapid drying of the surface soil layer; concurrently, frequent precipitation combined with temperature drops often leads to soil compaction.

Meteorological summer in the study area begins at the end of the second decade of May, when the average daily temperature crosses the +14 °C threshold, and lasts an average of 115 ± 25 days. Approximately 275 mm of precipitation falls during the summer period; however, heavy rainstorms with hail and strong winds are quite common, often causing lodging of wheat crops. The summer season can vary from cool and excessively humid to hot and arid (Konishchuk et al., 2014).

The soils of the Bila Tserkva Experimental Breeding Station of the IBCSB NAAS are primarily represented by deep, low-humus Chernozems with coarse-silty-loamy and sandy-loamy textures, characterized as slightly to moderately leached. The thickness of the humus horizon is 38–40 cm, with a humus content ranging from 3.58 to 4.18%.

Carbonate compounds occur at a depth of 44–63 cm, while the groundwater table is at 50–60 m, thus not participating in soil formation processes. These soils are characterized by a weak aggregate structure in the upper layer, which negatively affects water permeability (0.3–0.4 ml/min on autumn-plowed land and 0.07 ml/min on stubble) and reduces the utilization coefficient of atmospheric precipitation, especially during heavy rainstorms. The bulk density throughout the soil profile does not exceed 1.29 g/cm³, while in the arable horizon, it is approximately 1.27 g/cm³. Under conditions of decreasing moisture, compaction of the upper layer to 1.35 g/cm³ or more is observed.

The soils are characterized by medium to high levels of mineral nutrient availability and have a slightly acidic to near-neutral soil solution reaction, which positively influences the formation of winter wheat productivity. The agrochemical parameters of the experimental plot are as follows: humus content is 3.6–4.5%, hydrolyzed nitrogen – 5.5–6.4 mg, mobile forms of phosphorus – 19.0–27.1 mg, and exchangeable potassium – 11.2–18.0 mg per 100 g of soil; pH (KCl) – 5.3–6.4, the sum of absorbed bases – 23.1–28.6 meq per 100 g of soil, and base saturation degree – 86–94.4%.

Winter wheat cultivation was carried out according to the standard technology generally accepted for this region. The study utilized two primary types of tillage: moldboard (inversion) and non-inversion (mulch) tillage. The moldboard method was implemented using a PLN-3-35 plow to a depth of 25–30 cm, ensuring full inversion of the arable layer and incorporation of plant residues. Non-inversion tillage was performed using various implements differing in design and working depth. Specifically, deep subsurface loosening at 25–30 cm was conducted with a KLD-3.0 cultivator. For shallower tillage, an AG-2.4 disc harrow was used: loosening to a depth of 15–18 cm served as the primary soil preparation, while surface tillage at 5–8 cm was used for pre-sowing leveling and moisture conservation.

Cultivation was performed on the same day as harrowing or the following day, depending on weather conditions and the physical state of the soil. Sowing was conducted during the third decade of September (within a week after cultivation) using a ‘Klen-1.5S’ seed drill, which ensured uniform seed placement at the specified depth (3.0–4.0 cm). The row spacing was 12.5 cm, and the seeding rate was 4 million pieces/ha. Winter wheat harvesting was carried out during the first decade of July.

Various application schemes of biological products were evaluated: 1 – seed treatment (Rizofos Liq 1.5 L/t + Premax 0.3 L/t; Mycofriend 1.5 L/t); 2 – soil application of a biological product during sowing (Groundfix 3.0 L/ha) (Factor A). To provide mineral nutrition, $N_{12}P_{12}K_{12}$ and $N_{24}P_{24}K_{24}$ mineral fertilizers were applied during sowing (Factor B). Four winter wheat cultivars were selected for the study: ‘Spencer’, ‘Maurizio’, ‘Matchball’, and ‘Vidrada’ (Factor C) (Table 1).
Experimental design:

1. Control (no biological treatment or fertilization);
2. Mycofriend 1.5 L/t + $N_{12}P_{12}K_{12}$;
3. Mycofriend 1.5 L/t + $N_{24}P_{24}K_{24}$;
4. Rizofos Liq 1.5 L/t + Premax 0.3 L/t + $N_{12}P_{12}K_{12}$;
5. Rizofos Liq 1.5 L/t + Premax 0.3 L/t + $N_{24}P_{24}K_{24}$;
6. Groundfix 3.0 L/ha + $N_{12}P_{12}K_{12}$;
7. Groundfix 3.0 L/ha + $N_{24}P_{24}K_{24}$.

The experiment was established in four replicates, ensuring the reliability of statistical data analysis. The distribution of the record plots was randomized, in accordance with the standard requirements for field trials.

Winter wheat seed dressing was performed according to the standard methodology (Trybel et al., 2001). Chemical and biological seed treatments were carried out in accordance with the design specified for each experimental variant. Pre-sowing seed treatment was conducted one day prior to sowing. The treated winter wheat seeds were stored for 24 hours in a dark facility at +15 °C. To evaluate the efficiency of all systems, a control variant was used, allowing for the observation of plant development without the application of biological products or mineral fertilizers.

Treatments for the experimental variants were implemented comprehensively, including pre-sowing seed treatment (insecto-fungicidal dressing + biological product) and fertilization. Mineral fertilizers were applied to the winter wheat crops in the spring, once the soil reached physical maturity, creating favorable conditions for effective nutrient uptake. The fertilizers were applied using the row-placement method (locally), which promoted better nutrient utilization, reduced nitrogen losses, and stimulated the initial growth and development of the plants.

Table 1. Characteristics of the studied winter wheat cultivars

Cultivar	Originator / Country	Type / Maturity group	Yield potential	Key features
KWS Spencer	KWS (Germany)	Awnless, medium-early	10.0–11.5 t/ha	High resistance to Fusarium head blight and lodging. Stable across various preceding crops.
Maurizio	Saaten-Union (Austria)	Awnless, mid-season	10.5–12.0 t/ha	Leader in winter hardiness among European cultivars. Characterized by high 1000-kernel weight.
Matchball	Saaten-Union (Germany)	Awnless, medium-early	11.0–12.5 t/ha	Compensatory type (high tillering capacity). Highly resistant to powdery mildew and septoria leaf blotch.
Vidrada	MIP named after V.M. Remeslo (Ukraine)	Awned, mid-season	9.0–10.5 t/ha	National standard for adaptability. High drought resistance and low requirements for the agro-background.

Note: Based on the materials of the State Register of Plant Varieties Suitable for Distribution in Ukraine for 2022.

Celest Top 312.5 FS

Celest Top 312.5 FS is a three-component insecto-fungicidal seed dressing for the comprehensive protection of winter wheat, barley, and other crops. It contains thiamethoxam (262.5 g/L), difenoconazole (25 g/L), and fludioxonil (25 g/L).

Mycofriend

Mycofriend is a biological product based on mycorrhizal fungi *Glomus* VS and *Trichoderma harzianum*, used for nutrition and disease protection. It supports the formation of mycorrhiza and the plant rhizosphere with *Streptomyces* sp. and *Pseudomonas fluorescens*. The product also contains phosphate-mobilizing bacteria: *Bacillus megaterium* var. *phosphaticum*, *Bacillus subtilis*, *Bacillus mucilaginosus*, *Enterobacter* sp., and biologically active substances such as phytohormones, vitamins, and amino acids. The total number of viable cells of the producer microorganisms is at least (1.0–1.5) × 10^8 CFU/mL.

Rizofos Liq

Rizofos Liq – the primary active ingredient of this biological product is strains of the phosphate-mobilizing bacteria *Pseudomonas fluorescens*, with a viable bacterial cell titer of at least 0.1 billion per 1 mL of the product.

Premax

Premax is a biological protector that retains bacteria on the seeds and provides nourishment to maintain bacterial metabolism during the period from inoculation to germination. Premax maintains the necessary bacterial count on each seed upon soil contact during sowing and ensures proper protection of the inoculated seeds.

Groundfix

Groundfix – the active ingredients of this biological product include cells of *Bacillus subtilis*, *Bacillus megaterium* var. *phosphaticum*, *Azotobacter chroococcum*, *Enterobacter*, and *Paenibacillus polymyxa*, with a total viable cell count of (0.5–1.5) × 10^9 CFU/cm³. It also contains other beneficial microflora (lactic acid bacteria, enzyme producers), as well as vitamins, phytohormones, amino acids, and other physiologically active substances.

The experiment provided for the carrying of mineral fertilizers during sowing in the norm of $N_{12}P_{12}K_{12}$ and $N_{24}P_{24}K_{24}$.

The evaluation of yield components and harvest structure followed established protocols. Representative samples were harvested from each experimental plot at the physiological maturity stage (BBCH 89). Productive stem density was assessed in situ using a 0.25 m² frame with four replicates per plot. Subsequent laboratory processing determined the number of grains per spike, grain weight per spike, and the 1.000-grain weight (TGW). The TGW was established by weighing two 500-grain subsets per treatment with 0.01 g precision. Biological yield was estimated from individual plot productivity and normalized to a standard 14% moisture content.

Statistical processing of the research results was performed using a three-factor analysis of variance (ANOVA) for a field experiment according to the methodology of Tsarenko et al. (2000).

The total sum of squares SS_y was calculated using the following formula:

$$SS_y = \sum y^2 - \frac{(\sum y)^2}{N} \quad (1)$$

where: N is the total number of observations in the experiment (N= *až bž cž n*).

The total variation was partitioned into the following components:

$$SS_y = SS_A + SS_B + SS_C + SS_{AB} + \\ +SS_{AC} + SS_{BC} + SS_{ABC} + SS_{err} \quad (2)$$

For the main factors (using factor A as an example), the sum of squares was determined as:

$$SS_A = \frac{\sum y_A^2}{b \cdot c \cdot n} - C \quad (3)$$

The sums of squares for the interaction of factors (e.g., AB) were calculated as:

$$SS_{subAB} = \frac{\sum y_{AB}^2}{c \cdot n} - C \quad (4)$$

$$SS_{AB} = SS_{subAB} - SS_A - SS_B \quad (5)$$

The triple interaction (ABC) was determined as:

$$SS_{ABC} = SS_{subABC} - SS_A - SS_B - \\ -SS_C - SS_{AB} - SS_{AC} - SS_{BC} \quad (6)$$

The residual sum of squares (experimental error) was calculated by subtraction:

$$SS_{err} = SS_y - (SS_A + SS_B + SS_C + SS_{AB} + \\ +SS_{AC} + SS_{BC} + SS_{ABC}) \quad (7)$$

The mean squares (*MS*) were calculated by dividing each sum of squares by its corresponding degrees of freedom (*df*)

$$MS_A = \frac{SS_A}{a - 1} \quad (8)$$

$$MS_{err} = \frac{SS_{err}}{N - (a \cdot b \cdot c)} \quad (9)$$

where: $(N - a{\cdot}b{\cdot}c)$ represents the degrees of freedom for the error.

To determine the significance of each factor's effect, the calculated F_{test} (F_{act}) was compared with the critical value (F_{table}):

$$F_A = \frac{MS_A}{MS_{err}} \quad (10)$$

The effect of a factor or its interaction was considered significant if $F_{test} > F_{table}$ at a significance level of $P = 0.05$

The least significant difference (LSD_{05}) was calculated using the formula:

$$\text{HIP}_{05} = t_{05} \times \sqrt{\frac{2 \cdot MS_{err}}{n_{cp}}} \quad (11)$$

where: n_{cp} – is the number of observations used to calculate the mean.

The proportion of influence of each factor on the total variance was determined as follows:

$$\eta_x^2 = \frac{SS_x}{SS_y} 100\% \quad (12)$$

where: SS_x — is the sum of squares for the respective factor SS_y — is the total sum of squares.

To quantify the relationship between biological yield (Y) and the number of productive stems (X) under the influence of biological agents, a correlation and regression analysis was performed. The tightness of the relationship was determined by the Pearson correlation coefficient (r). The parameters of the linear regression equations (Y = a + bX) were estimated using the least squares method. The reliability of the models was assessed using the coefficient of determination (R^2) and the F-$_{test}$ at a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

The climatic conditions of the research site are characterized by moderate continentality with pronounced seasonal temperature fluctuations. (Figure 1). The lowest average daily temperatures were recorded during the first decade of April 2023. Subsequent gradual warming promoted the active growth and development of winter wheat plants. May 2023 proved to be the most stable, whereas significant temperature peaks were recorded in 2024 and 2025. June

2024 and 2025 were abnormally hot. In 2023, relatively uniform precipitation was observed from April to June. Due to elevated temperatures and insufficient rainfall in June, 2024 was the most risky year, which was unfavorable for achieving high crop yields.

In the modern context of grain farming development, the comprehensive integration of traditional chemical fertilization methods with new biologization approaches – specifically the use of industrial mineral fertilizers alongside innovative microbiological products – is becoming increasingly relevant. It was established that their impact on the formation of productive stem counts, grain number per spike, grain mass per spike, and the biological yield of the studied cultivars allows for a scientific substantiation of the optimal elements of crop cultivation technology.

It was established that all factors and their interactions in the experiment were statistically significant (LSD_{05}). Factor B (mineral fertilization) had the most substantial impact on the formation of the yield structure parameters of the studied winter wheat cultivars. The contribution of Factor B ranged from 46.68% to 78.03%, depending on the parameter. The development of yield structure components was also determined by the biological potential of each cultivar (Factor C), which accounted for a 10.35–28.20% share of the influence. The contribution of Factor A (biological product) amounted to 1.52–12.51% (Table 2).

Throughout the research years, it was found that the yield structure parameters of the studied

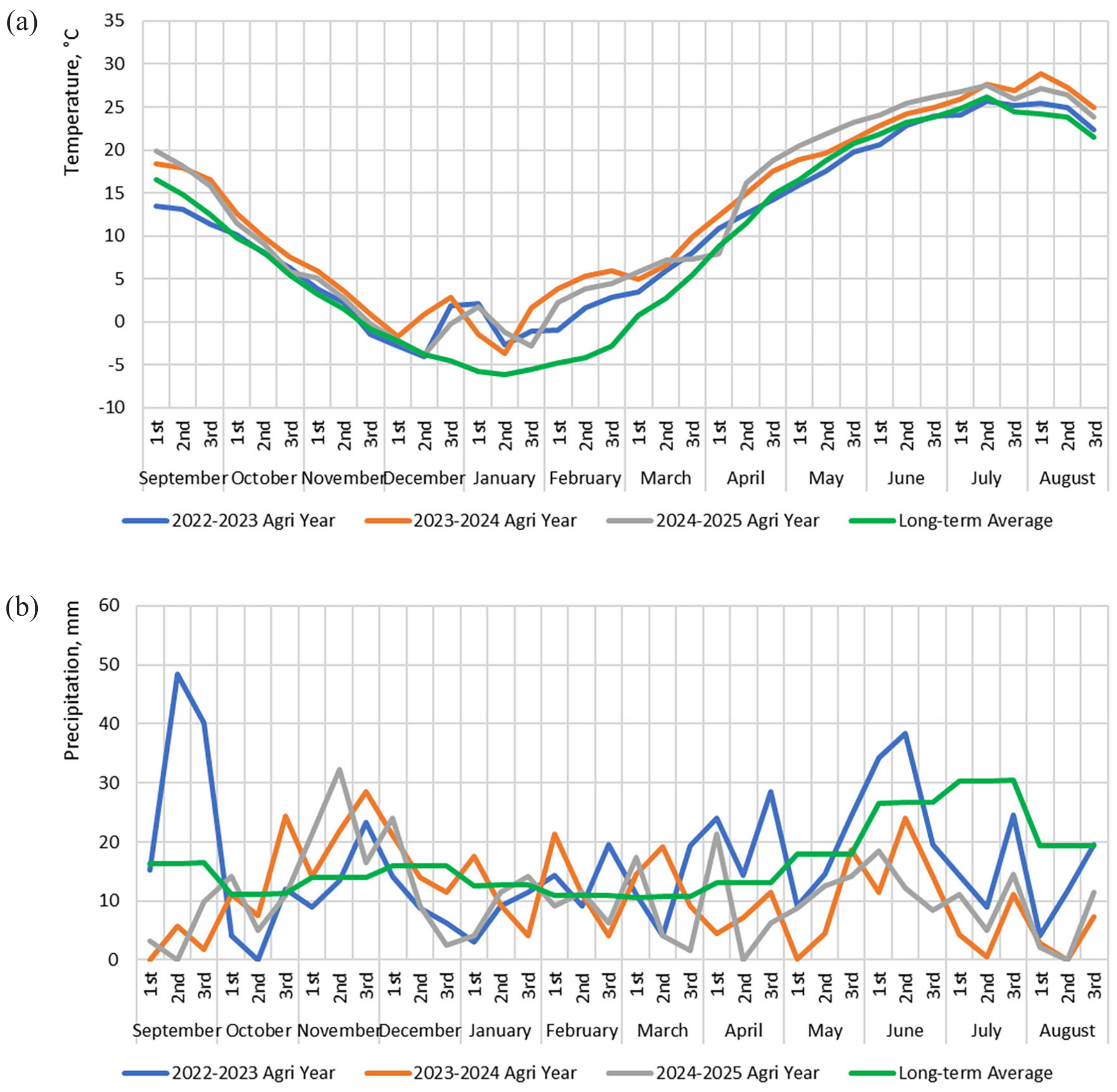

Figure 1. Meteorological conditions at the research site during the 2022–2025 agricultural years (based on data from the Bila Tserkva Meteorological Station, Ukraine (49°47' N, 30°08' E), located 11 km from Mala Vilshanka)

winter wheat cultivars (Table 2) varied depending on the experimental variant. Thus, in the control variants, where no biological products or mineral fertilizers were applied, minimum values for both quantitative and qualitative yield structure elements were observed. Specifically, the spike length ranged from 9.44 to 9.56 cm, the mass per spike was between 2.87 and 2.91 g, and the number of grains per spike was 48–51 pcs, respectively. The TGW in these variants ranged from 40.15 to 40.45 g.

A moderate increase in productive traits was observed in all cultivars across the variants where biological products and mineral fertilizers were applied. The best performance was recorded for the 'KWS Spencer' cultivar in the variant treated with Rizofos Liq (1.5 L/t) + Premax (0.3 L/t) alongside the $N_{12}P_{12}K_{12}$ fertilization rate. It was established that the spike length increased to 9.63 cm (0.73% higher than the control), the spike mass reached 3.59 g, and the number of grains per spike rose to 59 (compared to 51 in the control). The grain mass per spike reached 2.77 g (2.41 g in the control), while the TGW increased to 47.73 g, which is 17.99% higher than the control variant. The number of productive stems increased by 21.25% compared to the control. Under these conditions, the yield amounted to 7.4 t/ha, representing a 23.33% increase over the control samples.

A similar trend was observed in the variants with other cultivars. In our opinion, this indicates the stimulation of reproductive processes in plants under the bio-organic protection system.

Specifically, in the cultivation of the 'Maurizio' cultivar, despite a slight increase in spike length (by 0.04 cm), the application of Rizofos Liq (1.5 L/t) + Premax (0.3 L/t) alongside $N_{12}P_{12}K_{12}$ fertilization promoted an increase in spike mass by 0.67 g (23.10%), the number of grains per spike by 5 (10.00%), grain mass per spike by 0.34 g (14.16%), and the TWG by 7.31 g (18.09%) compared to the control. Furthermore, the number of productive stems increased by 14 pcs/m (17.95%). Ultimately, these factors ensured a biological yield of 6.80 t/ha, which exceeded the variant without fertilizers and biological products by 1.5 t/ha (28.30%). This demonstrates the superior responsiveness of this cultivar to the application of biological products and fertilization.

When cultivating the 'Matchball' cultivar under similar conditions, an increase in yield structure parameters was also recorded. Despite a slight increase in spike length (0.07 cm), there was an increase in spike mass by 0.55 g (19.03%), grain number per spike by 6 (12.24%), grain mass per spike by 0.25 g (10.46%), TWG by 4.32 g (10.69%), and the number of productive stems by 15 pcs/m (20.00%) relative to the control. Ultimately, this ensured a biological yield of 6.10 t/ha, which exceeded the variant without fertilizers and biological products by 1.1 t/ha (22.00%).

In the variants where the 'Vidrada' cultivar was grown, the lowest values for the winter wheat yield structure parameters were recorded. Following the application of Rizofos Liq (1.5 L/t) + Premax (0.3 L/t) and $N_{12}P_{12}K_{12}$ fertilization, the spike length increased by 0.16 cm, spike mass by 0.54 g (18.82%), grain number per spike by 6 (12.50%), grain mass per spike by 0.23 g (9.79%), TWG by 1.57 g (3.91%), and the number of productive stems by 16 pcs/m (22.86%) relative to the control. The biological yield of the 'Vidrada' winter wheat cultivar amounted to 5.7 t/ha, which was 0.9 t/ha (18.75%) higher than the variant without fertilizers and biological products.

In other experimental variants, a slightly lower increase in yield structure parameters and biological yield was observed across all studied cultivars. The lowest yield growth (4.00%) was recorded for the 'Matchball' cultivar in the variant with the application of the 'Mycofriend' biological product at a rate of 1.5 L/t and $N_{24}P_{24}K_{24}$ fertilization.

The results of the correlation and regression analysis (Figures 2, 3) indicate a positive, very strong, direct linear correlation between the formation of the number of productive stems per linear meter and the biological yield of all studied winter wheat cultivars in the experiment (Figure 2).

The correlation coefficients (r) range from 0.93943 to 0.98574, which, according to the Chaddock scale, indicates a functional proximity of the parameters. This confirms that the density of the productive stem stand is one of the key factors in yield formation in this experiment. Notably, the 'Vidrada' cultivar demonstrates the highest stability (r = 0,98574).

For the studied winter wheat cultivars, a direct positive strong and very strong correlation was established between the 1.000-kernel weight and the biological yield (Figure 3). The correlation coefficients (r = 0,8631…0,95221) indicate a substantial influence of grain size on the formation of biological yield. Regarding the TWG parameter, the 'Maurizio' cultivar proved to be the most stable.

Table 2. Influence of experimental factors on the yield structure parameters of winter wheat cultivars (average for 2023–2025)

Factor A, use of biological preparations	Factor B, fertilizer application dose	Spike length, cm	Mass per spike, g	Number of grains per spike, psc.	Grain mass per spike,g	TGW, g	Number of productive stems per linear meter, psc	Biological yield, t/ha
Factor C, winter wheat cultivar								
KWS Spencer								
Control (no biological treatment)	No fertilization	9.56	2.91	51	2.41	40.45	80	6.0
Mycofriend 1.5 L/t	$N_{12}P_{12}K_{12}$	9.57	3.43	58	2.64	43.34	87	6.7
Mycofriend 1.5 L/t	$N_{24}P_{24}K_{24}$	9.56	3.42	57	2.63	43.33	86	6.7
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{12}P_{12}K_{12}$	9.63	3.59	59	2.77	47.73	97	7.4
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{24}P_{24}K_{24}$	9.60	3.47	56	2.68	44.48	89	7.1
Groundfix 3.0 L/ha	$N_{12}P_{12}K_{12}$	9.61	3.59	59	2.76	47.69	96	7.3
Groundfix 3.0 L/ha	$N_{24}P_{24}K_{24}$	9.60	3.47	57	2.68	44.48	90	7.2
Maurizio								
Control (no biological treatment)	No fertilization	9.56	2.90	50	2.40	40.41	78	5.3
Mycofriend 1.5 L/t	$N_{12}P_{12}K_{12}$	9.56	3.40	56	2.63	43.33	85	5.6
Mycofriend 1.5 L/t	$N_{24}P_{24}K_{24}$	9.56	3.39	56	2.63	43.34	84	5.7
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{12}P_{12}K_{12}$	9.60	3.57	57	2.75	47.72	92	6.8
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{24}P_{24}K_{24}$	9.60	3.45	55	2.66	44.46	87	6.3
Groundfix 3.0 L/ha	$N_{12}P_{12}K_{12}$	9.60	3.57	55	2.74	47.69	91	6.7
Groundfix 3.0 L/ha	$N_{24}P_{24}K_{24}$	9.60	3.44	55	2.66	44.46	89	6.3
Matchball								
Control (no biological treatment)	No fertilization	9.54	2.89	49	2.39	40.40	75	5.0
Mycofriend 1.5 L/t	$N_{12}P_{12}K_{12}$	9.57	3.32	52	2.44	43.34	80	5.5
Mycofriend 1.5 L/t	$N_{24}P_{24}K_{24}$	9.56	3.30	52	2.44	42.25	80	5.2
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{12}P_{12}K_{12}$	9.61	3.44	55	2.64	44.72	90	6.1
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{24}P_{24}K_{24}$	9.60	3.35	53	2.51	42.26	85	5.5
Groundfix 3.0 L/ha	$N_{12}P_{12}K_{12}$	9.60	3.42	54	2.63	43.68	90	6.0
Groundfix 3.0 L/ha	$N_{24}P_{24}K_{24}$	9.60	3.40	53	2.51	42.46	85	5.6
Vidrada								
Control (no biological treatment)	No fertilization	9.44	2.87	48	2.35	40.15	70	4.8
Mycofriend 1.5 L/t	$N_{12}P_{12}K_{12}$	9.47	3.22	52	2.44	41.34	78	5.3
Mycofriend 1.5 L/t	$N_{24}P_{24}K_{24}$	9.46	3.20	52	2.44	41.25	77	5.2
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{12}P_{12}K_{12}$	9.60	3.41	54	2.58	41.72	86	5.7
Rizofos Liq 1.5 L/t + Premax 0.3 L/t	$N_{24}P_{24}K_{24}$	9.50	3.31	53	2.50	41.26	81	5.5
Groundfix 3.0 L/ha	$N_{12}P_{12}K_{12}$	9.60	3.40	54	2.58	41.68	86	5.7
Groundfix 3.0 L/ha	$N_{24}P_{24}K_{24}$	9.50	3.30	53	2.50	41.46	80	5.5
Least significant difference								
Evaluation of the significance of partial differences								
$LSD_{05}A$		0.0093	0.0131	0.8750	0.0087	0.0379	1.2374	0.0461
$LSD_{05}B$		0.0033	0.0032	1.2600	0.0031	0.0326	3.2600	0.0330
$LSD_{05}C$		0.0180	0.0128	2.1346	0.0111	0.0638	1.7482	0.0706
Evaluation of main effects significance								
$LSD_{05}A$		0.0027	0.0038	0.2526	0.0025	0.0109	0.3572	0.0133
$LSD_{05}B$		0.0036	0.0030	0.4490	0.0029	0.0114	0.3806	0.0195
$LSD_{05}C$		0.0060	0.0043	0.7115	0.0037	0.0213	0.5827	0.0235
Share of influence of factors, %								
A		11.86	1.52	7.47	9.19	10.79	12.51	7.15

B	47.01	78.03	62.68	57.00	46.68	51.14	57.76
C	20.33	10.35	22.13	22.39	21.21	27.85	28.20
AB	6.01	0.07	1.93	0.45	4.58	0.43	0.96
AC	3.60	9.20	3.17	5.93	8.93	0.29	1.32
BC	6.23	0.76	0.51	4.61	5.41	6.26	3.59
ABC	3.15	0.04	1.13	0.24	2.39	0.30	0.76
Residual influence of factors	1.81	0.03	0.98	0.19	0.01	1.22	0.26

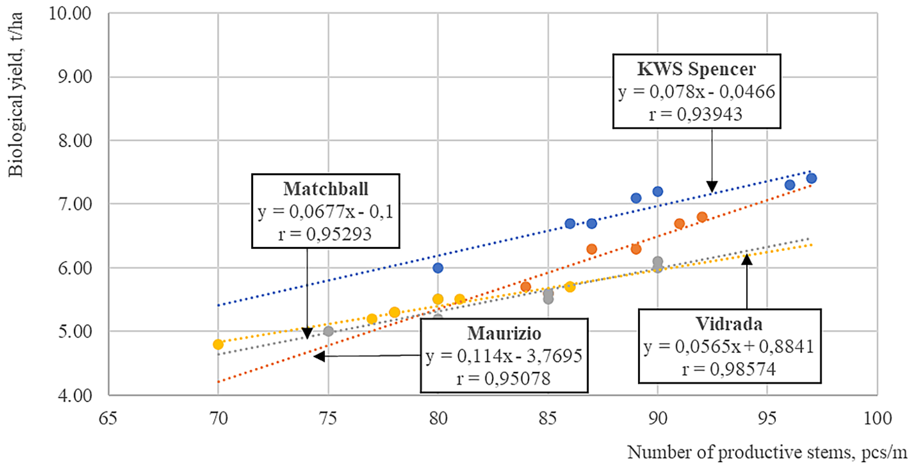

Figure 2. Correlation-regression model of the dependence of winter wheat biological yield on the number of productive stems under the influence of biologization elements (average for 2023–2025)

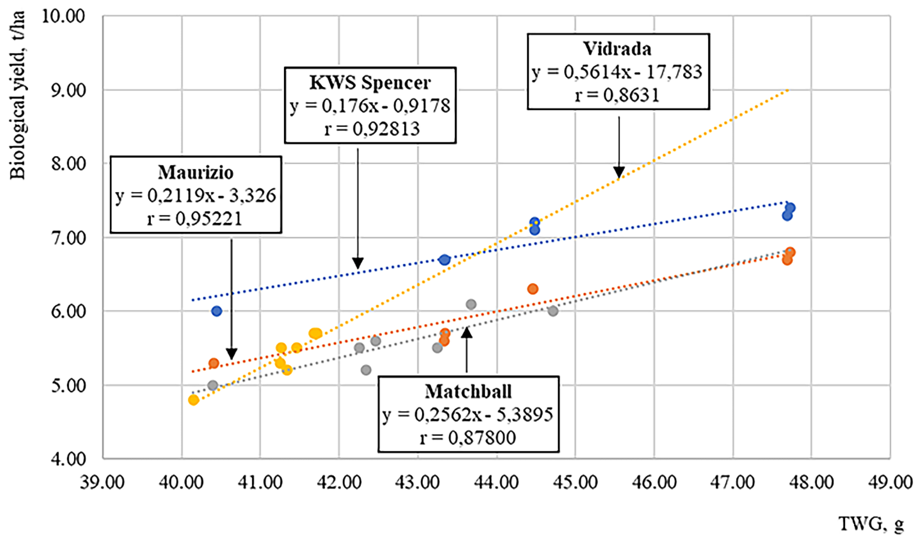

Figure 3. Correlation-regression model of the dependence of winter wheat biological yield on the 1.000-grain weight (average for 2023–2025)

CONCLUSIONS

The use of biological products in winter wheat cultivation technology under the conditions of the South-Western Forest-Steppe of Ukraine demonstrates their significant effectiveness in increasing productivity and improving the yield structure parameters. Research results confirm that the implementation of seed treatment with biologicals (Rhizofos Liq 1.5 l/t + Premax 0.3 l/t; Mycofriend 1.5 l/t) or the application of Groundfix (3.0 l/ha) during sowing, combined with mineral fertilizers at a rate of $N_{12}P_{12}K_{12}$, promotes the realization of the biological potential of the studied winter wheat varieties by improving plant mineral nutrition in the early stages. This creates a reliable foundation for better winter hardiness and active spring tillering.

The application of Groundfix soil biofertilizer (3.0 l/ha) directly during sowing in combination with a moderate dose of mineral fertilizers ($N_{12}P_{12}K_{12}$) facilitates the mobilization of poorly soluble nutrients from the soil. This allows for the maximum realization of the genetic potential of modern winter wheat varieties even under unstable moisture conditions.

It was established that the increase in biological yield, which ranged from 4.00 to 28.30%, is achieved due to a synergistic effect: an increase in the density of the productive stem stand (the number of productive stems per linear meter) and an increase in grain filling, as confirmed by a positive correlation with the 1000-grain weight.

The use of biological products allows for an increase in the utilization rate of active ingredients from mineral fertilizers, making the cultivation technology more environmentally safe and economically viable for farms in the South-Western Forest-Steppe.

The results obtained can be applied in the production conditions of agricultural enterprises of various ownership forms.

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