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MICROBIAL BIOSTIMULANTS ENHANCE SOYBEAN YIELD AND SEED QUALITY UNDER HYDROTHERMAL STRESS IN ORGANIC FARMING

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Background. In organic farming conditions under increasing frequency of hydrothermal stress, ensuring stable soybean yield and seed quality requires the use of biological preparations capable of activating plant adaptive mechanisms. The integrated application of arbuscular mycorrhizal fungi, nitrogen-fixing bacteria, and microbial biostimulants with phytohormonal activity may improve plant water status, reduce oxidative damage, and enhance seed biochemical composition. However, the effects of such multicomponent systems on yield structure components, seed protein, oil, and nitrogen content under variable hydrothermal conditions remain insufficiently studied.

Materials and Methods. Field experiments were conducted in 2022–2024 under organic farming conditions in the Left-Bank Forest-Steppe of Ukraine using the early-maturing soybean cv. Khorol. Eight treatment variants were evaluated: control, Profix, Violar, Mycofriend, Profix + Violar, Mycofriend + Profix, Mycofriend + Violar, and Mycofriend + Profix + Violar. Seed protein and oil content were determined by NIR spectroscopy; relative water content (RWC), stomatal conductance (gs), abscisic acid (ABA), and malondialdehyde (MDA) were assessed at the BBCH 61 stage. Statistical analysis included one-way ANOVA followed by Tukey's HSD test, Pearson correlation, and principal component analysis (PCA).

Results. The highest yield (2.96–3.57 t/ha) and seed quality were recorded under the Mycofriend + Profix + Violar treatment across all years, exceeding the control by 40.6–59.1%. Seed protein content increased by up to 5.7 percentage points, and oil content reached 19.3 %. Yield gains were primarily driven by an increased number of seeds per plant (up to 130), while thousand-seed weight remained relatively stable. Under hydrothermal deficit in 2024, combined treatments maintained higher RWC (up to 91.9 %), lower MDA (-47.7 % vs. control), and reduced ABA accumulation, with strong correlations confirmed between RWC and yield ($r = 0.92$; $P < 0.001$) and between ABA and gs ($r = -0.98$; $P < 0.001$).

Conclusion. The complex application of Mycofriend, Profix, and Violar in organic soybean cultivation consistently improved yield, seed nutritional quality, and physiological stress tolerance across years with contrasting hydrothermal conditions. Stabilization of plant water status and limitation of oxidative damage were identified as key mechanisms underlying productivity maintenance under drought.

Keywords: arbuscular mycorrhizal fungi, rhizobia, phytohormones, abscisic acid, malondialdehyde, relative water content

INTRODUCTION

The agricultural sector is currently facing a dual challenge posed by complex abiotic stressors and continued global population growth. Abiotic stress remains a persistent threat to agricultural productivity and may cause yield losses of up to 70 % (Biswas *et al.*, 2023). At the same time, soybean is one of the leading oilseed crops in global production and continues to show steady growth trends (USDA FAS, 2024), largely owing to the versatile use of its seeds, particularly for food and feed purposes (Jarecki & Migut, 2022). Growing demand, along with the development of new cultivars characterized by stable yields and high seed quality, continues to promote the expansion of soybean cultivation worldwide (Prusiński, 2020). However, realization of the crop's productive potential is increasingly constrained, primarily by hydrothermal instability during the growing season.

Microbial biostimulants based on arbuscular mycorrhizal fungi (AMF), rhizobia, plant growth-promoting rhizobacteria (PGPB), and phytohormones are considered a promising tool for improving soybean productivity and stress tolerance (Ahmad *et al.*, 2022; Shaffique *et al.*, 2023). Symbiotic interactions with AMF enhance phosphorus and water uptake, activate antioxidant enzymes, and reduce the intensity of lipid peroxidation, thereby stabilizing cell membranes under drought conditions (Mirshad & Puthur, 2016; Li *et al.*, 2019). Associations with *Bradyrhizobium japonicum* ensure the biological fixation of atmospheric nitrogen and stimulate root system development; however, intensification of nitrogen nutrition may be accompanied by a redistribution of assimilates from the lipid fraction in favor of the protein fraction (Carciochi *et al.*, 2019; Jarecki, 2024).

Co-inoculation with *B. japonicum* and AMF can increase yield, improve plant water status, and reduce oxidative damage to cell membranes under field water deficit conditions (Sheteiwy *et al.*, 2021; Igiehon *et al.*, 2021). The application of three-component microbial consortia can further increase seed protein and oil content, and the magnitude of this effect increases with consortium complexity (Rafique *et al.*, 2025).

Phytohormonal biostimulants complement microbial inoculants by regulating the balance between growth processes and plant defense responses. Abscisic acid (ABA) plays a key role in controlling stomatal conductance and activating antioxidant systems under water deficit (Munemasa *et al.*, 2015; Liao *et al.*, 2025), whereas auxins, cytokinins, and gibberellins optimize phytohormonal balance and enhance plant stress tolerance (Verma *et al.*, 2016; Hasanuzzaman *et al.*, 2020). The integration of these metabolites with AMF and rhizobia produces synergistic effects on key physiological and biochemical processes, thereby contributing to an improvement in crop productivity under adverse growing conditions (Chaika *et al.*, 2025).

Despite the extensive experimental data, information on the comparative effectiveness of mono- and multicomponent systems of microbial and phytohormonal biostimulants in terms of soybean yield, yield components, and seed quality parameters (protein, oil, and total nitrogen content) under variable hydrothermal conditions in field experiments within organic farming systems in the Left-Bank Forest-Steppe of Ukraine remains limited.

The aim of this study was to evaluate the effects of microbial biostimulants based on AMF (*Glomus* sp., *Trichoderma harzianum* + PGPB), a nitrogen-fixing inoculant (*B. japonicum*), and a phytohormonal preparation, applied separately and in different combinations, on soybean yield, yield components, seed quality, and the physiological and biochemical status of plants under variable hydrothermal conditions in an organic production system.

MATERIALS AND METHODS

Field experiments were conducted during 2022–2024 under agroecological conditions in the Left-Bank Forest-Steppe of Ukraine (Poltava region). The object of the study was the early-maturing soybean cultivar Khorol (originator – Research Institute of Soybean LLC). The soil of the experimental plots was residual solonetzic Chernozem on loess deposits. Agrochemical analysis of the arable soil layer (0–20 cm) was performed using a multiparameter photometer Palintest SK500 (Palintest Ltd., UK). The following parameters were determined: pH(KCl) – 6.3 (slightly acidic reaction); humus content – 5.2 % (high); total nitrogen – 58.6 mg/kg and available phosphorus – 78.3 mg/kg (medium supply level); exchangeable potassium – 138.4 mg/kg (high).

The experiment was conducted using a randomized block design with four replications. The total plot area was 0.3 ha, and the accounting area was 0.1 ha.

Agronomic practices complied with the regional requirements of organic soybean production technology (Chaika *et al.*, 2025) and included: (i) autumn plowing with a reversible plow after the preceding crop (spring barley); (ii) spring harrowing with a heavy drag harrow to conserve soil moisture; (iii) pre-sowing cultivation with a stubble cultivator; (iv) pre-emergence harrowing at the weed seedling stage (white thread stage) and post-emergence harrowing with a Striegel tine harrow; (v) two inter-row cultivations.

Sowing was carried out at the optimal dates for each year (April 20 – May 5) at a depth of 5 cm. Row spacing was 38 cm, and the seeding rate was 700 thousand viable seeds per hectare.

Weather conditions and precipitation dynamics were monitored annually during the soybean growing season (May–August), which allowed the degree of moisture supply to be assessed using the Selyaninov hydrothermal coefficient (HTC) (Koval & Bräuning, 2024). The soybean growing seasons of 2022–2024 were characterized by considerable variability in the hydrothermal regime (**Fig. 1**), allowing them to be classified as follows: 2022 – favorable; 2023 – extremely favorable; 2024 – stressful (hydrothermal deficit).

Three commercial preparations with different mechanisms of action and potential for synergistic interactions were selected to evaluate the effectiveness of biological agents in organic soybean production. These included: (i) Mycofriend® (BTU-Center, Ukraine) – a complex of mycorrhizal fungi (*Glomus* sp., *Trichoderma harzianum*) and rhizosphere bacteria (*Pseudomonas fluorescens*, *Streptomyces* sp., *Bacillus megaterium* var. *phosphaticum, B. mucilaginosus*, *B. subtilis*, *Enterobacter* sp.); (ii) Profix® (Certis Belchim, Belgium) containing three strains of nodule bacteria: *Bradyrhizobium japonicum* USDA442 (532 C) and *B. diazoefficiens* SEIMA 5079 and SEIMA 5080; (iii) Violar® (Bioinvest-Agro LLC, Ukraine) – a phytohormonal preparation containing auxins, cytokinins, gibberellins, abscisic acid, free amino acids, lipids, and sterols.

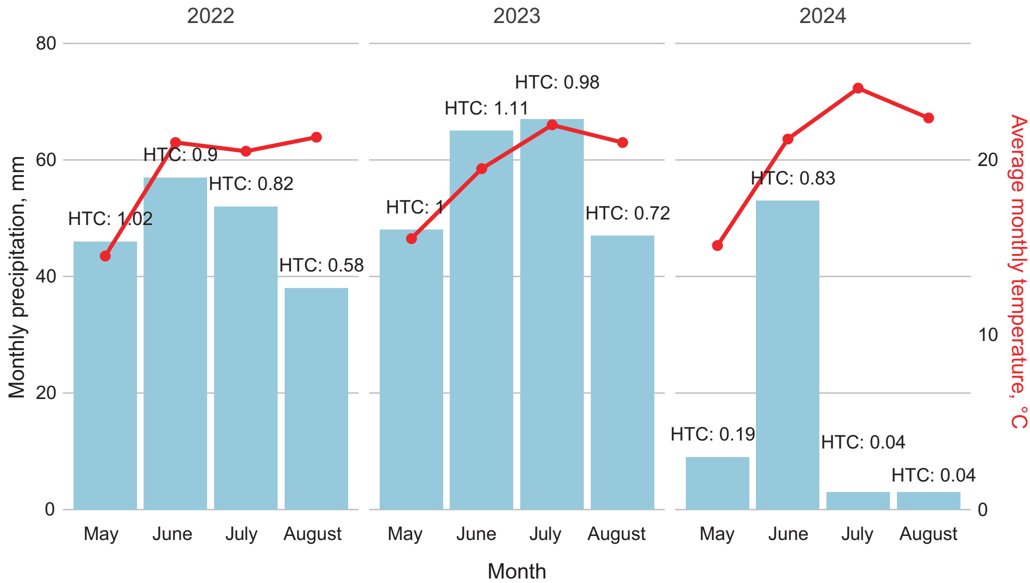

Fig. 1. Precipitation dynamics, mean monthly temperature, and the hydrothermal coefficient (HTC) in the soybean growing seasons of 2022–2024

The experimental design included eight biopreparation treatment variants described in a previous study (Chaika *et al.*, 2025): (i) control (water); (ii) Profix (Prof); (iii) Violar (Vio); (iv) Mycofriend (Myc); (v) Profix + Violar (Prof+Vio); (vi) Mycofriend + Profix (Myc + Prof); (vii) Mycofriend + Violar (Myc+Vio); (viii) Mycofriend + Profix + Violar (Myc + Prof + Vio). Seed treatment was performed before sowing (30–60 min) according to the recommended application rates, and crop spraying was carried out at the BBCH 61 stage (beginning of flowering).

To determine relative water content (RWC), one leaf from each of ten plants per plot was sampled weekly for seven weeks, starting in the second half of May. RWC was calculated using the standard formula (Patanè *et al.*, 2022).

Abscisic acid (ABA) content in leaves was determined by fluorescence spectroscopy using a PerkinElmer LS-45 spectrometer; extract preparation was performed according to the protocol described in (Li *et al.*, 2009). Stomatal conductance (gs) was measured using an SC-1 porometer (Decagon Devices, Inc., USA) with a measurement interval of 30 s in four replicates per treatment. These parameters were measured once at the BBCH 61 growth stage.

The malondialdehyde (MDA) content in leaf tissues was determined once at the BBCH 61 stage according to the method described in (Fatema *et al.*, 2023). Protein and oil contents in soybean seeds were measured at the full maturity stage (R8) after harvesting using near-infrared spectroscopy (NIR) on an AgriCheck Plus analyzer (Bruins Instruments, Germany) with a calibration model for soybean. The results were expressed as a percentage of dry matter.

The total nitrogen (N, %) content was calculated using the formula:

$$N (\%) = Protein (\%) / 5.71,$$

where 5.71 is the conversion coefficient for soybean (FAO, 2003).

Thousand seed weight (TSW) was determined at the full maturity stage (R8) using cleaned seeds. For each replicate, 1000 seeds were counted and weighed, after which the values were adjusted to a standard moisture content of 14.0 % to ensure comparability among treatments and years.

The number of seeds per plant was determined at the full maturity stage (R8) before harvesting. Ten plants were randomly selected from the central part of each plot in each replicate to avoid border effects. The plants were cut at ground level, air-dried, and manually threshed, after which the number of seeds was counted and the mean value per plant was calculated.

Plants were harvested manually from the net plot area after cutting the above-ground biomass; the yield was adjusted to 14 % moisture content and expressed in t/ha.

For each year, the mean value ($\bar{X}$) and standard error (SE) were calculated for each treatment. Differences among treatments within each year were assessed using one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test ($P < 0.05$) as the data were analyzed separately for each year to account for contrasting hydrothermal conditions, which were considered as distinct environmental scenarios rather than a uniform experimental factor. Principal component analysis (PCA) was applied to standardized data to evaluate the overall relationships among the studied variables. Correlations were assessed using Pearson's correlation coefficient (r) based on mean values ($\bar{X}$) for each year × treatment combination ($n = 24$), with statistical significance determined at $P < 0.05$. Statistical analyses and visualization were performed in RStudio® (R Core Team, version 4.4.3).

RESULTS AND DISCUSSION

Soybean seed yield and quality under bacterial and hormonal treatments. The obtained results confirmed a significant dependence of yield and seed biochemical composition on the hydrothermal conditions of the year and the biological inoculation system (**Fig. 2**). The most pronounced differences among the treatments were observed in 2024, which was characterized by a hydrothermal deficit (**Fig. 1**).

The yield from the control plots was 2.24 t/ha in 2022, 2.46 t/ha in 2023, and 1.86 t/ha in 2024 (-24.4 % compared with 2023). Monopreparations provided a yield increase of 0.26–0.56 t/ha depending on the year, with the highest absolute increase observed in 2023. Combined treatments produced a pronounced synergistic effect, and the Myc + Prof + Vio treatment showed the highest yield in all years – 3.15, 3.57, and 2.96 t/ha, respectively, exceeding the control by 40.6–59.1 %. The relative advantage of the combined treatment was the greatest in the unfavorable year of 2024.

The three-year average yield ranged from 2.19 t/ha in the control to 3.23 t/ha under the Myc + Prof + Vio treatment, corresponding to an increase of 1.04 t/ha (+47.5 %). The ranking of treatments by yield remained consistent across all study years.

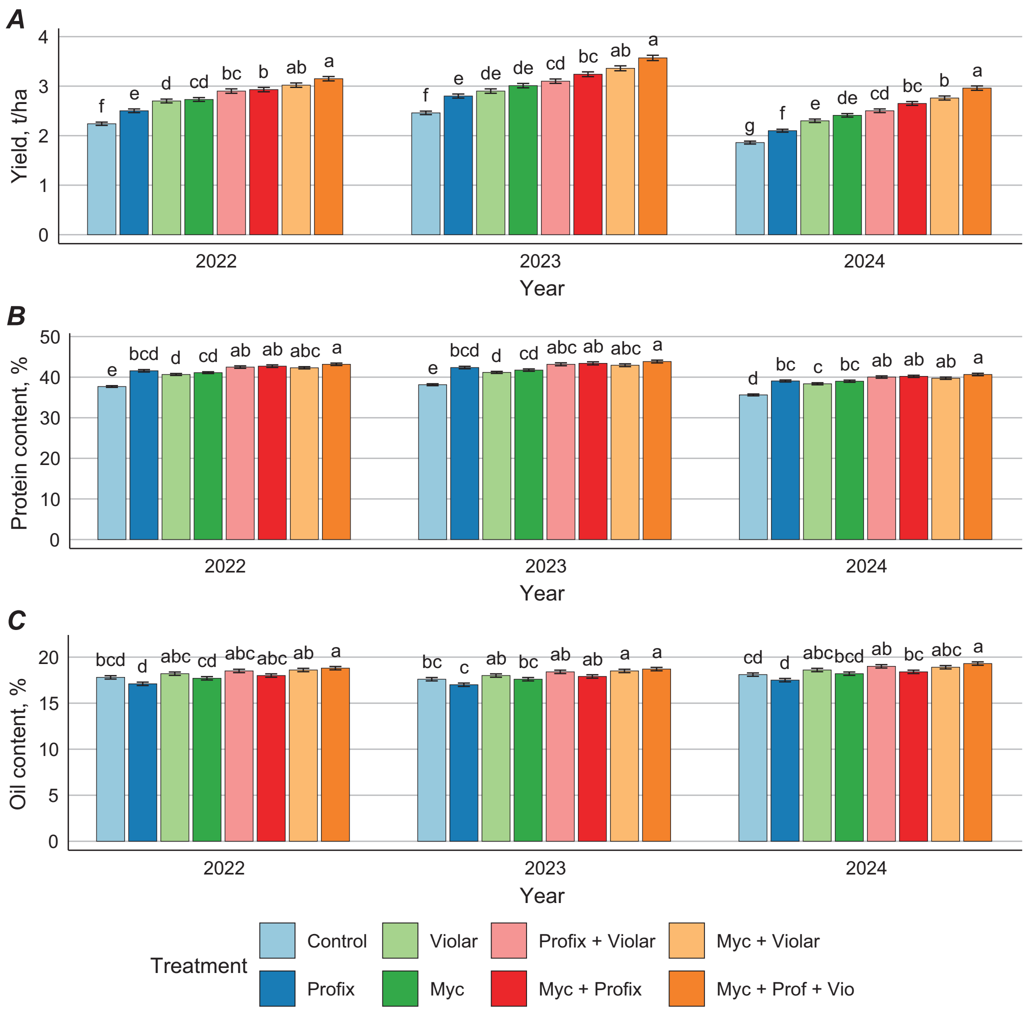

Fig. 2. Effects of microbial and hormonal seed treatments on (***A***) yield, (***B***) seed protein content, and (***C***) seed oil content of soybean under organic farming conditions (2022–2024)

Note: Mean ± SE; different letters indicate significant differences (Tukey's HSD, $P < 0.05$)

The seed protein content increased with the application of biological preparations. In the control treatment, it ranged from 35.63 to 38.14 %, whereas under the combined treatments it reached 41.66–42.56 %, depending on the treatment combination and the year. The highest values were recorded under the Myc + Prof + Vio treatment (43.17 % in 2022, 43.85 % in 2023, and 40.66 % in 2024), exceeding the control by 5.0–5.7 percentage points. Even in the dry year of 2024, the relative advantage of the combined treatments was maintained.

Changes in oil content under the application of biological preparations showed a different trend compared with changes in protein content. Profix application slightly reduced oil content (17.0–17.5 %), indicating a redistribution of assimilates toward protein synthesis. In contrast, Violar treatments contributed to an increase in this parameter.

The highest oil content was again recorded under the Myc + Prof + Vio treatment (18.8–19.3 %), exceeding the control by 1.0–1.2 percentage points.

In 2024, the overall oil content in the seeds tended to increase, which is consistent with the typical soybean response to water deficit. At the same time, the combined treatments maintained a high protein content without pronounced antagonism between the two parameters.

Thus, the relative advantage of the combined treatments across all parameters was the most pronounced under the stressful conditions of 2024, indicating an enhanced synergistic effect of the biopreparation consortium (Myc + Prof + Vio) under hydrothermal deficit conditions.

Structural components of soybean yield. Yield variability was primarily associated with changes in the number of seeds per plant, whereas the thousand-seed weight showed comparatively lower variation (**Fig. 3**).

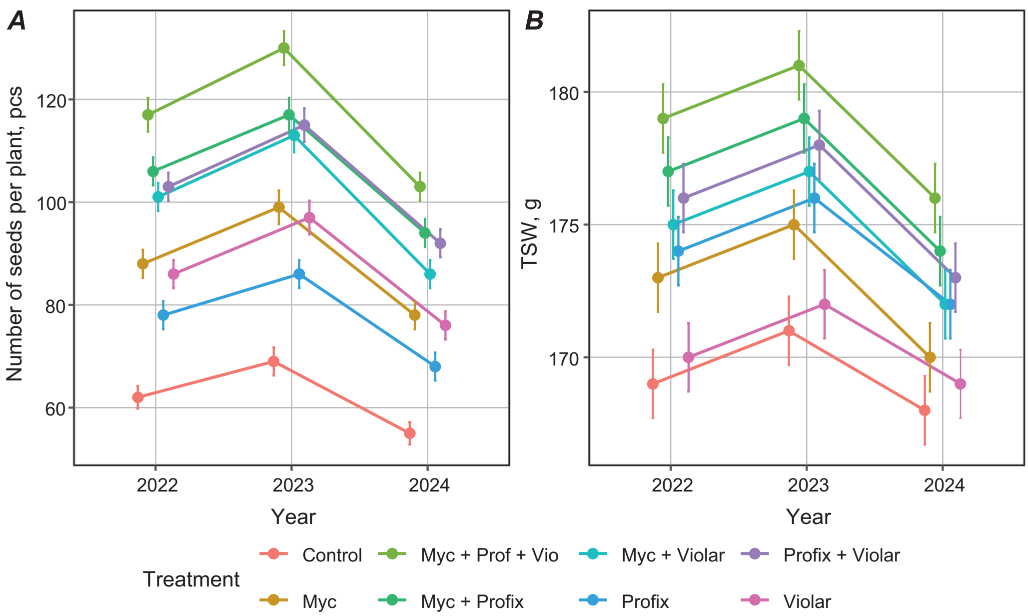

Fig. 3. Effects of microbial and hormonal seed treatments on (***A***) number of seeds per plant and (***B***) thousand-seed weight (TSW) of soybean under organic farming conditions (2022–2024)
Note: Mean ± SE; different letters indicate significant differences (Tukey's HSD, $P < 0.05$)

The number of seeds per plant in the control was 62, 69, and 55 in 2022–2024, respectively. Biological treatments significantly increased this parameter, particularly under combined applications. The highest values were observed under the Myc + Prof + Vio treatment (117, 130, and 103 seeds per plant), exceeding the control by 48–61 seeds per plant, depending on the year. In 2024, the reduction in the number of seeds per plant was the main factor contributing to lower yield in the control.

The thousand seed weight ranged from 168–171 g in the control to 176–181 g in the combined treatments. The highest values were recorded under the Myc + Prof + Vio treatment (179, 181, and 176 g), exceeding the control by 8–10 g. The interannual variability of this parameter was less pronounced compared with the variation in the seed number.

Therefore, the yield gain was determined primarily by an increase in the yield reproductive component (the number of seeds per plant), while the TSW performed a stabilizing function.

Total nitrogen content in soybean seed. The total nitrogen content depended on both the year and the inoculation system (**Fig. 4**). The highest values were recorded in 2023, whereas the lowest were observed in 2024.

In the control samples, the nitrogen content was 6.60, 6.68, and 6.24 % in 2022–2024, respectively. The biological preparations increased this value to 6.84–7.52 %, with the highest levels observed under the Myc+Prof+Vio treatment (7.56, 7.68, and 7.12 %). The increase compared with the control amounted to 0.88–1.00 percentage points.

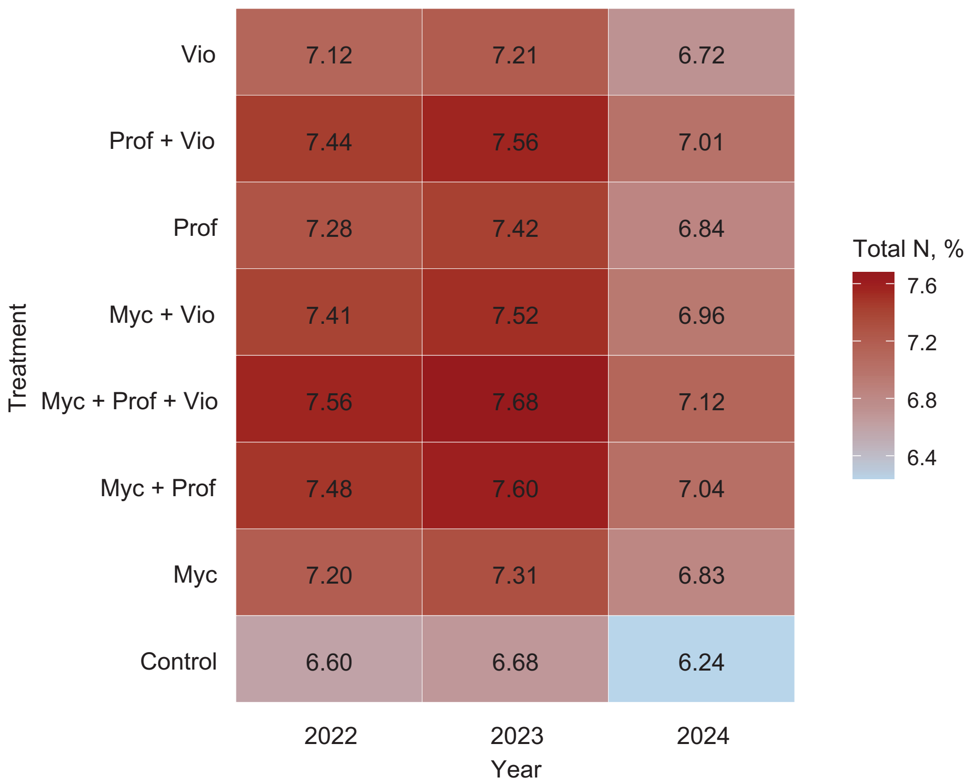

Fig. 4. Total nitrogen content in soybean seed under microbial and hormonal seed treatments in organic farming conditions (2022–2024)

In 2024, the decline in nitrogen content was more pronounced in the control samples, whereas under the combined treatment, its level remained relatively stable, indicating a partial mitigation of water deficit effects. The dynamics of total nitrogen changes were consistent with the changes in protein content, suggesting a synchronous response of nitrogen metabolism to the action of biological preparations.

Physiological and biochemical indicators of soybean productivity. PCA-based analysis of relationships between physiological parameters and yield revealed a clear differentiation of treatments depending on the year hydrothermal conditions (**Fig. 5**).

The first principal component (Dim1, 84.7 %) represented a gradient associated with water balance and oxidative stress: the vectors of RWC, gs, and yield were oriented within the same quadrant, whereas ABA and MDA were in the opposite one.

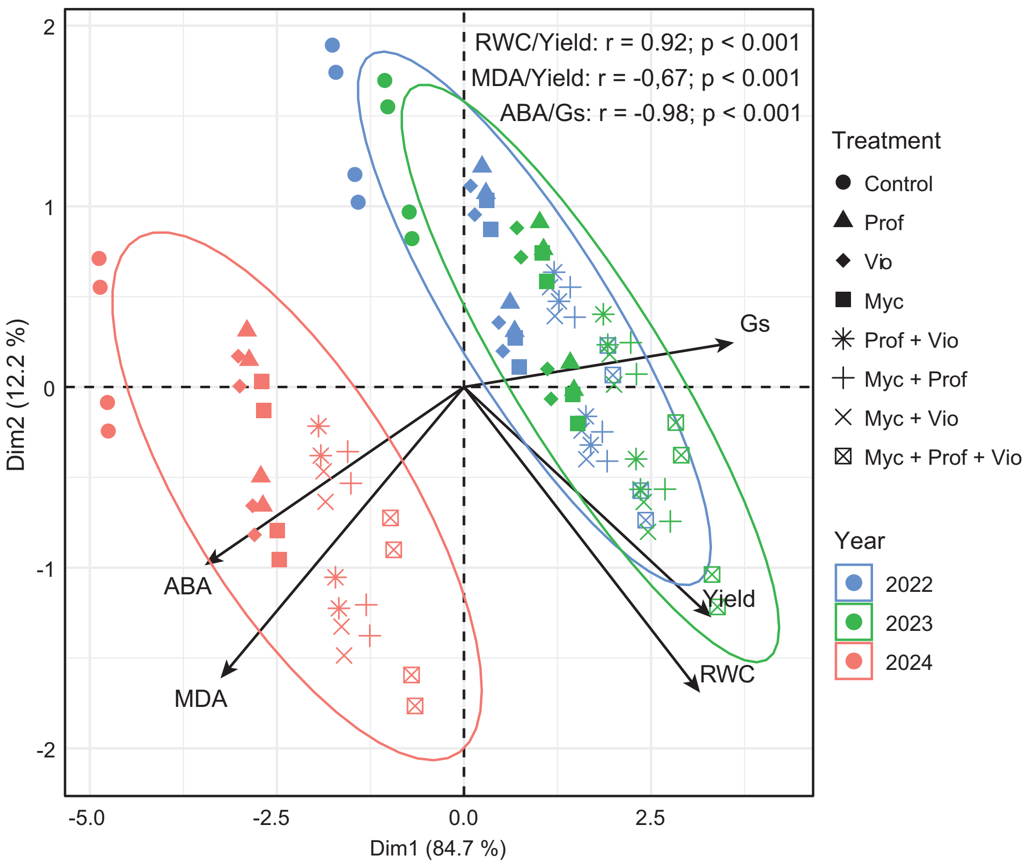

Fig. 5. Principal component analysis (PCA) of physiological traits (ABA, MDA, RWC, gs) and yield in soybean (2022–2024)

Note: Dim1 and Dim2 explain 84.7 % and 12.2 % of total variance, respectively. Vectors denote variable loadings. Pearson correlation coefficients (r) and associated P values are provided

In 2024, which was characterized by a hydrothermal deficit, control plants showed an increase in ABA content to 8.5 nmol/g and MDA to 17.93 µg/g, along with a decrease in RWC to 69.7 % and gs to 0.19 mol/m²·s; this was accompanied by a yield reduction to 1.86 t/ha. Under the Myc + Prof + Vio treatment, these parameters remained at markedly better levels: ABA – 5.6 nmol/g, MDA – 9.37 µg/g (−47.7 % compared with the control), RWC – 91.9 % (+22.2 percentage points), and gs – 0.39 mol/m²·s. In the more favorable years of 2022–2023, the differences among treatments were less pronounced; however, the ranking of treatments remained consistent.

Correlation analysis quantitatively confirmed these relationships: a strong positive correlation was found between RWC and yield (r = 0.92; P < 0.001), a negative correlation between MDA and yield (r = -0.67; P < 0.001), and a very strong negative correlation between ABA and gs ($r = -0.98$; $P < 0.001$), indicating a key role of ABA-dependent mechanisms in the regulation of transpiration under hydrothermal stress.

Our results agree with data on the synergistic effects of microbial consortia on soybean productivity. M. Rafique *et al.* (2025) showed that three-component inoculation increased yield by 20.5 % and the protein and oil contents by 8.78 % and 10.52 %, respectively, with the effect intensifying with increasing consortium complexity.

Mono-inoculation with rhizobia was associated with lower oil content, reflecting the classical antagonistic relationship between protein and oil accumulation under intensified nitrogen nutrition (Carciochi *et al.*, 2019; Jarecki, 2024). At the same time, co-inoculation of rhizobia with arbuscular mycorrhizal fungi (AMF) can partially mitigate this antagonism through the synergy of nitrogen, phosphorus, and water nutrition (Igiehon *et al.*, 2021).

It should be noted that the establishment of mycorrhizal symbiosis is sensitive to soil moisture conditions during early plant development. Despite the hydrothermal deficit observed in 2024, periods of sufficient moisture supply during the early growing season (**Fig. 1**) supported the initial formation of symbiotic associations. Once established, arbuscular mycorrhizal fungi are known to maintain functional activity under drought, contributing to improved plant water status under subsequent stress conditions.

The observed pattern is consistent with the current understanding that under water deficit, the processes of flowering, pollination, and pod formation are the most vulnerable (Fatema *et al*., 2023; Poudel *et al*., 2023). M. S. Sheteiwy *et al.* (2021) reported that co-inoculation with AMF and *B. japonicum* under drought conditions increased the pod number by 28–34 % and the seed number by 30–36 %, which was accompanied by a yield increase of 25–32 %. N. O. Igiehon *et al.* (2021) also confirmed that the productivity gain under co-inoculation was realized mainly through an increase in seed weight per plant, rather than through a substantial increase in the individual seed weight.

Thus, biological preparations support the plants' reproductive potential primarily by optimizing the numerical components of yield structure. These agronomic effects are consistent with earlier findings demonstrating the productivity and economic benefits of microbial–hormonal treatments in organic soybean cultivation under climate variability (Chaika & Korotkova, 2025), where the highest-performing treatment (Myc + Prof + Viol) increased profit to 1575 €/ha and profitability to 369.0 %, confirming that the yield gain offsets the treatment costs.

The increase in seed total nitrogen content directly explains the rise in protein content, since soybean protein is a function of nitrogen accumulation and remobilization during the reproductive period (Carciochi *et al.*, 2019). M. Rafique *et al.* (2025) reported that three-component inoculation increased plant nitrogen nutrition by 7.33 %, which correlated with a higher yield. O. Stajković-Srbinović *et al.* (2020) also confirmed that *Bradyrhizobium* inoculation increased N uptake and raised yield up to 125 % compared with the control. The relative stability of nitrogen content under the combined treatments during the dry 2024 season indicates a partial mitigation of the negative effects of water deficit on symbiotic nitrogen fixation due to the synergistic action of AMF and rhizobia.

The present results are in accordance with experimental evidence on the role of biostimulants in maintaining plant water status and limiting oxidative damage under drought conditions. M. S. Sheteiwy *et al.* (2021) and N. Begum *et al.* (2023) reported that AMF inoculation or its co-inoculation with *Bradyrhizobium* increased RWC by 8–12 % and reduced MDA by 20–37 %. P. P. Mirshad & J. T. Puthur (2016) and J. Li *et al.* (2019) found that AMF enhance the catalase activity and superoxide dismutase, thereby reducing MDA content by 30–50 %. The strong negative correlation between ABA and stomatal conductance ($r = -0.98$; $P < 0.001$) confirms the key role of ABA-dependent signaling cascades in the regulation of transpiration under hydrothermal stress (Munemasa *et al.*, 2015; Liao *et al.*, 2025).

Although abscisic acid is known to induce stomatal closure under water deficit, the reduced ABA levels observed in treated plants in this study did not result in impaired water conservation. On the contrary, treated plants maintained higher RWC and adequate gs, indicating a more balanced regulation of transpiration rather than excessive water loss. This suggests that biostimulant application may optimize hormonal signaling, allowing plants to maintain both water status and photosynthetic activity under stress conditions.

Modulation of hormonal signaling ensured an optimal balance between limiting transpiration and maintaining photosynthetic activity, which was reflected in the RWC stabilization and a reduction in lipid peroxidation intensity (Hasanuzzaman *et al.*, 2020). This relationship between physiological indicators of photosynthetic activity and crop productivity has also been demonstrated in previous studies (Ahmed *et al.*, 2023). Thus, the stabilization of plant water status and the limitation of oxidative damage are key mechanisms supporting soybean productivity under moisture deficit conditions.

Despite the robustness of the three-year dataset, the results of this study should be interpreted with consideration of certain limitations. The experiments were conducted at a single location within the Left-Bank Forest-Steppe of Ukraine under specific soil and climatic conditions, which may limit the direct extrapolation of the findings to other agroecological zones. In addition, only one soybean cultivar (Khorol) was evaluated, and the response to biostimulant treatments may vary depending on genotype. Therefore, further multi-site and multi-year studies involving soybean cultivars of different maturity groups across diverse soil–climatic conditions are required to confirm the broader applicability of the observed effects.

CONCLUSION

Three-year field experiments revealed that the combined application of the biological preparations Mycofriend + Profix + Violar under organic farming conditions ensured the highest yield of the soybean Khorol cultivar in all study years, reaching 3.15–3.57 t/ha.

The yield increase of 40.6–59.1 % was primarily associated with a greater number of seeds per plant (103–130 vs. 55–69 in the control), whereas the TSW varied within a narrower range (176–181 g vs. 168–171 g).

Complex inoculation promoted an increase in seed protein content to 40.66–43.85 % (+5.0–5.7 percentage points compared with the control) and oil content to 18.8–19.3 % (+1.0–1.2 percentage points), as well as an increase in total nitrogen by 0.88–1.00 percentage points. In contrast to rhizobial mono-inoculation, which was accompanied by a decrease in oil content, the combined treatments partially mitigated the antagonistic relationship between the protein and lipid fractions.

Under the hydrothermal deficit conditions of 2024, the Myc + Prof + Vio seed treatment ensured an RWC of 91.9 % (+22.2 percentage points compared with the control), reduced MDA content by 47.7 %, and lowered ABA to 5.6 nmol/g, while maintaining higher stomatal conductance (gs 0.39 mol/m²·s). Strong correlations were observed between RWC and yield (r = 0.92; P < 0.001) and between ABA and gs (r = -0.98; P < 0.001), confirming the key role of plant water status and ABA-dependent regulation of transpiration in determining soybean productivity under stress conditions.

Thus, the combined application of Mycofriend + Profix + Violar can be recommended as an effective biological strategy for maintaining soybean yield and seed quality in organic production systems under variable hydrothermal condition.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: the authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Animal Rights: this article does not contain any studies with animal subjects performed by any of the authors.

AUTHOR CONTRIBUTIONS

Conceptualization, [T.C.; I.K.]; methodology, [T.C.]; validation, [T.C.; I.K.]; formal analysis, [V.L.; A.R.]; investigation, [V.L.; A.R.; O.M.]; resources, [V.L.]; data curation, [A.R.; O.M.]; writing – original draft preparation, [T.C.; I.K.]; writing – review and editing, [T.C; I.K.]; visualization, [T.C.; V.L.] supervision, [T.C.].

All authors have read and agreed to the published version of the manuscript.

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МІКРОБНІ БІОСТИМУЛЯТОРИ ПІДВИЩУЮТЬ ВРОЖАЙНІСТЬ І ЯКІСТЬ НАСІННЯ СОЇ ЗА ГІДРОТЕРМІЧНОГО СТРЕСУ В ОРГАНІЧНОМУ ЗЕМЛЕРОБСТВІ

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Обґрунтування. У системі органічного землеробства і зростання частоти проявів гідротермічного стресу забезпечення стабільної врожайності сої та високої якості насіння потребує застосування біологічних препаратів, здатних активувати адаптивні механізми рослин. Комплексне застосування арбускулярних мікоризних грибів, азотфіксуючих бактерій і мікробних біостимуляторів з фітогормональною активністю може зменшити окислювальне пошкодження, покращити водний статус рослин та покращити біохімічний склад насіння. Водночас вплив таких багатокомпонентних систем на елементи структури врожаю, вміст білка, жиру й азоту в насінні за мінливих гідротермічних умов досліджено недостатньо.

Матеріали і методи. Польові досліди проводили у 2022–2024 рр. в умовах органічного землеробства Лівобережного Лісостепу України із використанням ранньостиглого сорту сої Хорол. Оцінювали вісім варіантів обробки: контроль, Profix, Віолар, Мікофренд, Profix + Віолар, Мікофренд + Profix, Мікофренд + Віолар та Мікофренд + Profix + Віолар. Вміст білка та жиру в насінні визначали методом ближньої інфрачервоної спектроскопії (БІС). Відносний вміст води в листках (ВВВ), продихову провідність (ПП), вміст абсцизової кислоти (АБК) та малонового діальдегіду (МДА) визначали у фазі BBCH 61. Статистичну обробку результатів проводили з використанням однофакторного дисперсійного аналізу (ANOVA) з тестом Тьюкі HSD, кореляційного аналізу Пірсона й аналізу головних компонент (PCA).

Результати. Найвищу врожайність (2,96–3,57 т/га) та найкращі показники якості насіння в усі роки досліджень зафіксовано на варіанті Mycofriend + Profix + Violar, що перевищувало контроль на 40,6–59,1 %. Особливо виражений ефект комплексної інокуляції спостерігали за умов дефіциту вологи, коли різниця між контрольними й обробленими варіантами зростала. Вміст білка в насінні зростав до 5,7 відсоткових пунктів, а вміст жиру досягав 19,3 %. За комплексного застосування препаратів не спостерігали різкого антагонізму між накопиченням білка та жиру, що свідчить про більш збалансоване формування біохімічного складу насіння. Приріст урожайності зумовлювало переважно збільшення кількості насінин на рослині (до 130 шт.), тоді як маса 1000 насінин лишалася відносно стабільною. Основний внесок у формування врожайності забезпечувало підвищення реалізації репродуктивного потенціалу рослин. За умов гідротермічного дефіциту у 2024 р. комбіновані обробки давали вищі значення ВВВ (до 91,9 %), нижчий вміст МДА (-47,7 % порівняно з контролем) та зменшене накопичення АБК. Встановлено тісні кореляційні зв’язки між ВВВ і врожайністю ($r = 0,92$; $P < 0,001$) та між АБК і ПП ($r = -0,98$; $P < 0,001$).

Висновки. Комплексне застосування препаратів Мікофренд, Profix і Віолар у технології вирощування органічної сої забезпечувало стабільне підвищення врожайності, покращення харчової цінності насіння та зростання фізіологічної стійкості рослин до стресу в роки з контрастними гідротермічними умовами. Ключовими механізмами підтримання продуктивності за умов дефіциту вологи є стабілізація водного статусу рослин і обмеження інтенсивності оксидативного ушкодження.

Ключові слова: арбускулярні мікоризні гриби, ризобії, фітогормони, абсцизова кислота, малоновий діальдегід, відносний вміст води

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