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Productivity and quality indicators of soybean varieties in the conditions of the western forest-steppe of Ukraine

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Abstract. The aim of this study was to evaluate the effects of seed inoculation with the nitrogen-fixing preparation HiStick® Soy, the mycorrhiza-forming preparation Mycofriend®, and foliar application of the multicomponent fertilizer StimOrganic on the yield and quality parameters of the soybean varieties Tytan and Mozart under the agroclimatic conditions of the Western Forest-Steppe. Field, laboratory (for determining seed quality indicators), and statistical methods (for evaluating data reliability) were applied. Field experiments were conducted on grey forest surface-gleyed soils. Inoculation of soybean seeds with HiStick® Soy increased individual plant productivity: the average number of pods per plant increased by 2.1% in Tytan and 0.8% in Mozart; the number of seeds per plant increased by 2.2% and 0.58%, respectively; and the grain weight per plant increased by 3.4% and 3.1%. The highest yields were achieved when soybean seeds were treated with Mycofriend® and received foliar fertilization with StimOrganic in combination with HiStick® Soy inoculation - 3.29 t ha^{-1} for Tytan and 3.52 t ha^{-1} for Mozart. In these treatments, crude protein content in soybean seeds increased compared to the control by 1.1% in Tytan (up to 39.1%) and 1.8% in Mozart (up to 37.4%). These results can be applied in agricultural practice to enhance soybean productivity and produce high-quality grain.

Key words: varieties, soybean, inoculation, foliar feeding, yield, protein content.

INTRODUCTION

The growing popularity of soybean on the global market and the high price of soybean grain have stimulated an expansion of cultivated areas worldwide, making this crop attractive to Ukrainian farmers.

At the beginning of the 21st century, global soybean production amounted to about 176.6 million tons grown on 75.5 million hectares. To date, production has increased by 210%, reaching 371.7 million tons on an area of 136.9 million hectares. In Ukraine, in particular, a sharp increase in interest in this crop has been observed over the last two decades: the sown area expanded from 60.6 thousand ha to 1.8 million ha, while gross production increased from 64.4 thousand tons to 4.7 million tons (FAOSTAT, 2025).

Such a rapid expansion of soybean acreage has placed Ukraine among the leading soybean producers in Europe and has resulted in soybean cultivation on lands where it had not previously been grown.

Although the genetic yield potential of soybean exceeds 5.0 t ha^{-1}, the average yield in Ukraine is only about 2.5 t ha^{-1}, which is significantly lower than the potential level. Therefore, the search for effective measures to increase productivity while maintaining the profitability of soybean production is critically important for producers.

Soybean requires substantial amounts of moisture and heat. Current climate change trends, including rising average annual temperatures and decreasing precipitation (Twardosz et al., 2021; Staniak et al., 2023), together with the development of new cultivars, make it possible to shift soybean cultivation into the western regions of Ukraine. Along with the expansion of sown areas, scientific justification of cultivation practices adapted to specific climatic zones becomes particularly important. Soybean productivity and quality parameters strongly depend on soil and climatic conditions as well as agronomic practices, especially seed inoculation and fertilization systems (Kulig & Klimek-Kopyra, 2023; Serafin-Andrzejewska et al., 2024).

The problem of realizing the genetic potential of soybean remains relevant for researchers worldwide (Leggett et al., 2017; Cordeiro & Echer, 2019; Szpunar-Krok et al., 2023), as soybean accounts for more than 50% of the global legume cropping area and 68% of their total production (Herridge et al., 2008). Since soybean can meet 50–60% of its nitrogen demand through symbiosis with *Bradyrhizobium japonicum* (Salvagiotti et al., 2008), its cultivation technology traditionally involves the use of moderate nitrogen fertilizer rates. The advisability of applying 'starter' nitrogen doses and their effect on yield has long remained controversial (Albareda et al., 2009). Some researchers report that even small amounts of mineral nitrogen may suppress the formation of active nodules and have no positive effect on yield (Hungria et al., 2006; Kaschuk et al., 2016). However, most studies indicate the effectiveness of low nitrogen rates in supplying plants during the early growth stages when biological nitrogen fixation is still limited (Cordeiro & Echer, 2019). In particular, Capatana et al. (2017) demonstrated that under the conditions of southeastern Romania, mineral fertilizers had a stronger effect on yield than inoculation. It has also been established that nitrogen deficiency during seed filling negatively affects not only yield but also crude protein content (Chiluwal, 2025).

For maximum efficiency of nitrogen fixation, it is crucial to ensure an adequate population of rhizobial bacteria in the soil. These may originate either from commercial inoculants or from indigenous soil microflora (Grossman et al., 2011; Omari et al., 2022). In fields where soybean is cultivated for the first time, natural populations of *B. japonicum* are usually insufficient; therefore, inoculation is an essential practice (Thilakarathna et al., 2017; Zilli et al., 2021). The effectiveness of products such as HiStick® Soy or TURBOSOY® has been confirmed by numerous studies (Jarecki et al., 2024), although results depend on several factors, including the type of inoculant, application rate, nitrogen fertilization, and weather conditions. According to Prusiński et al. (2020), the combination of inoculation with mineral nitrogen (30 or 60 kg N ha^{-1}) resulted in higher yields than the use of inoculation or nitrogen alone. Higher efficiency of inoculation with HiStick® Soy and Nitragina combined with a fertilizer rate of 30 kg ha^{-1} was confirmed under the agroclimatic conditions of southwestern Poland (Serafin-Andrzejewska et al., 2024; Helios et al., 2025). Similar results regarding the effectiveness of HiStick® Soy were also obtained under the conditions of Ghana

(Nartey et al., 2022). According to Silva et al. (2024), the application of rhizobacteria is also effective as a foliar treatment in soybean.

A separate promising direction is the use of arbuscular mycorrhizal fungi (AMF), which stimulate plant growth and stress tolerance (Begum et al., 2023), as well as their combination with bacterial seed inoculation (Fahde, 2023; Wahab et al., 2023). Arbuscular mycorrhizae (AM) are recognized as the most widespread type of mycorrhizal symbiosis in natural ecosystems, encompassing approximately 72% of terrestrial flora, and play a key role in the functioning of the rhizosphere (Genre et al., 2020). Co-inoculation of seeds with AMF and rhizobacteria improves growth, photosynthesis, and tolerance to water stress in agricultural crops (Chen et al., 2017; Begum et al., 2022). Researchers report that the use of *Bradyrhizobium* bioinoculants and mycorrhizal fungi is effective even under drought conditions (Igiehon & Babalola, 2021; Nader et al., 2024).

One of the main indicators of yield quality is thousand-seed weight. Although this trait is largely determined by the genetic characteristics of the cultivar, optimization of the nutrient management system allows for maximum realization of this potential. It has been proven that the combined use of rhizobia and arbuscular mycorrhizal fungi ensures better seed filling even under moisture deficit conditions. In particular, Ashwin et al. (2023) emphasized the effectiveness of binary inoculation of soybean with *Bradyrhizobium liaoningense* and the arbuscular mycorrhizal fungus *Ambispora leptoticha*. Under water stress conditions, this approach resulted in a significant increase in the number and weight of pods (by 19% and 34% respectively), as well as in the number and weight of seeds per plant (by 17% and 32%).

At the same time, the effectiveness of arbuscular mycorrhizal fungi remains a subject of debate (Faye et al., 2020). The performance of AMF inoculation depends on a range of factors, including species compatibility, environmental conditions, and the level of competition with indigenous soil microflora (Verbruggen et al., 2013). This necessitates local studies to objectively assess the feasibility of mycorrhization under specific agroclimatic conditions.

Optimization of cultivation practices aimed at maximizing the genetic yield potential of modern soybean cultivars under changing climate conditions remains a priority in agronomic research. The economic efficiency and return on investment of innovative practices, including seed inoculation and optimized fertilization strategies, are decisive for their adoption in agricultural production. Therefore, the aim of this study was to evaluate the effects of pre-sowing inoculation and foliar fertilization on soybean yield formation and seed quality under the agroclimatic conditions of the Western Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The research was conducted in 2023–2024 on the experimental fields of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine on grey forest surface-gleyed coarse-silty light loam soil. Agrochemical indicators of the 0–20 cm soil layer (before the establishment of the experiment) were as follows: pH (salt extract) - 4.8–5.2; soil organic matter content

(SOM) - 1.97–2.2% (determined by the Tyurin method, DSTU 7855:2015 (2015)); easily hydrolyzable nitrogen - 99.0–114.2 mg kg^{-1} soil (according to the Kornfield method, DSTU 7863:2015 (2015)); available phosphorus - 95.2–101.1 mg kg^{-1} and exchangeable potassium - 107.1–112.0 mg kg^{-1} soil (according to the Kirsanov method, DSTU 4405:2005 (2005)).

Apart from the studied factors, the agronomic practices in the experiments were standard for the Forest-Steppe zone. The precursor crop was winter wheat. Plot arrangement was systematic with displacement; the number of replications was three; sowing plot area was 52 m²; accounting plot area was 25.0 m². Soybean was cultivated on the experimental fields for the first time.

Fertilization was applied at a rate of $N_{30}P_{60}K_{90}$. Mineral fertilizers were applied as ammonium nitrate (N–34%), single superphosphate (P_2O_5–19.5%), and Kalimag (K_2O–28%).

The study investigated the productivity of soybean varieties Mozart and Tytan (factor A); seed without inoculation and with pre-sowing treatment using HiStick® Soy (4 kg t^{-1}) (factor B); treatments: water (control); pre-sowing seed treatment with Mycofriend® (1.5 L t^{-1}) (Mycofriend®); foliar fertilization with StimOrganic for oil and leguminous crops (1.0 L ha^{-1}) **(**StimOrganic**)** at BBCH stages 12 and 51 (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie); pre-sowing seed treatment with Mycofriend (1.5 L t^{-1}) + foliar fertilization with StimOrganic for oil and leguminous crops (1.0 L ha^{-1}) (M+SO) at BBCH stages 12 and 51 (factor C).

The objects of the study were two soybean cultivars originating from different breeding centers and differing in biological characteristics and growth habit.

Mozart (bred by DSV, Germany) is an early-maturing cultivar (maturity group 000, CHU 2350) with a semi-determinate growth habit. The length of the growing period ranges from 111 to 122 days. Plant height is 80–85 cm, and the height of the lowest pod attachment is 10–13 cm. The potential seed yield is up to 4.0 t ha^{-1}. The cultivar is characterized by a high protein content (42.5–42.8%) and a thousand seed weight (TSW) of 170–200 g (Information and Reference System 'Sort', http://sort.sops.gov.ua/cultivar/view/832).

Tytan (bred by the Plant Breeding and Genetics Institute – National Center of Seed and Cultivar Investigation, Institute of Feed Research and Agriculture of Podillya, National Academy of Agrarian Sciences of Ukraine, Ukraine) is a medium-early cultivar (CHU 2350–2500). The growth habit ranges from semi-determinate to indeterminate. The growing period lasts 112–123 days. Plant height is 75–85 cm, with the lowest pod attached at a height of 10–13 cm. The potential seed yield is higher, reaching up to 5.5 t ha^{-1}. Protein content ranges from 40 to 42%, and TSW varies between 180 and 220 g (Information and Reference System 'Sort', http://sort.sops.gov.ua/cultivar/view/14722).

The main characteristics of the commercial products used in the experiment are presented below.

HiStick® Soy (BASF, Ludwigshafen, Germany) is a peat-based seed inoculant containing live *Bradyrhizobium japonicum* bacteria (strain 532 C) with a minimum concentration of 2 × 10^9 CFU g^{-1}. The product was applied as a seed treatment at a rate of 400 g per 100 kg of seed to enhance biological nitrogen fixation.

Mycofriend® (BTU-Center, Ukraine) is a complex mycorrhizal biological product. It contains mycorrhizal fungi (*Glomus* VS, *Trichoderma harzianum*), rhizospheric microorganisms (*Streptomyces* sp., *Pseudomonas fluorescens*), and phosphate-mobilizing bacteria (*Bacillus megaterium* var. *phosphaticum*, *Bacillus subtilis*, *Bacillus mucilaginosus*, *Enterobacter* sp.). The total number of viable microorganisms ranges from $(1.0–1.5) \times 10^8$ CFU mL^{-1}. The product also contains biologically active compounds, including phytohormones, vitamins, and amino acids.

StimOrganic (TM 'StimOrganic', Ukraine) is a specialized fulvo-humic micronutrient fertilizer intended for foliar application. It contains a complex of micronutrients chelated with HEDP (1-hydroxyethylidene-1,1-diphosphonic acid) and humic substances. The composition (g L^{-1}) is as follows: N – 80; P_2O_5 – 10; K_2O – 25; B – 40; Zn – 5; Cu – 5; Fe – 8; Mg – 12; Mn – 4; Mo – 0.5; humic acids – 65; and fulvic acids – 52.4. The product is certified for use in organic farming (Organic Standard) in accordance with EU Regulations No. 834/2007 and 889/2008.

The seeding rate was 550,000 viable seeds ha^{-1}. For sowing, the quantitative rate was converted into physical weight by mathematical recalculation based on the 1,000-seed weight and laboratory germination. Laboratory germination of soybean seed was determined annually at the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine, in the Certified Laboratory of Agrochemistry and Analytical Research (Certificate No. RL 009/22), operating in compliance with DSTU ISO 10012:2005.

Yield structure accounting (number of plants, pods per plant, seeds per pod) was carried out using sample sheaves. At the same time, grain quality assessment (crude protein and oil content) was performed using a Spectran 119 M near-infrared analyzer. Harvesting was conducted separately for each plot with a Sampo-130 breeding combine. Seed yield was expressed on a 12% moisture content basis.

The statistical data were analyzed using analysis of variance (ANOVA) with the Jamovi software (Version 2.6, 2024). Data were compared using the Tukey test. Differences between samples were considered statistically significant at $p < 0.05$. Data in the tables are presented as an arithmetic mean with standard deviation ($x \pm SD$).

Economic calculations were based on market prices for 2024 according to offers from commercial suppliers. Currency conversion was performed using an exchange rate of EUR 1 = 41.99 UAH. The purchase price of soybean seed was 556.32 € t^{-1}, while the selling price was 422.24 € t^{-1}.

In the cost structure, mineral fertilizers accounted for the largest share, amounting to 344.79 € ha^{-1}. This included expenditures for phosphorus fertilizers (131.60 € ha^{-1}), potassium fertilizers (118.89 € ha^{-1}), and ammonium nitrate (83.82 € ha^{-1}). The cost of the HiStick® Soy inoculant was 19.81 € ha^{-1}, while the cost of the Mycofriend® biological product was 5.36 € ha^{-1}. Foliar fertilization with StimOrganic, including application costs, was estimated at 13.10 € ha^{-1}.

The highest additional costs were recorded in the fourth experimental treatment (M + SO): 18.46 € ha^{-1} in the non-inoculated variant and 38.27 € ha^{-1} when the HiStick® Soy inoculant was applied.

Weather conditions during the study years were characterised by elevated temperatures during the soybean growing season and uneven precipitation distribution (Hydrometeorological Station of the Institute of Agriculture of the Carpathian Region, Obroshyne observation site) (Figs 1 and 2). These weather conditions enabled an objective assessment of the tolerance of the studied cultivars to environmental stress factors.

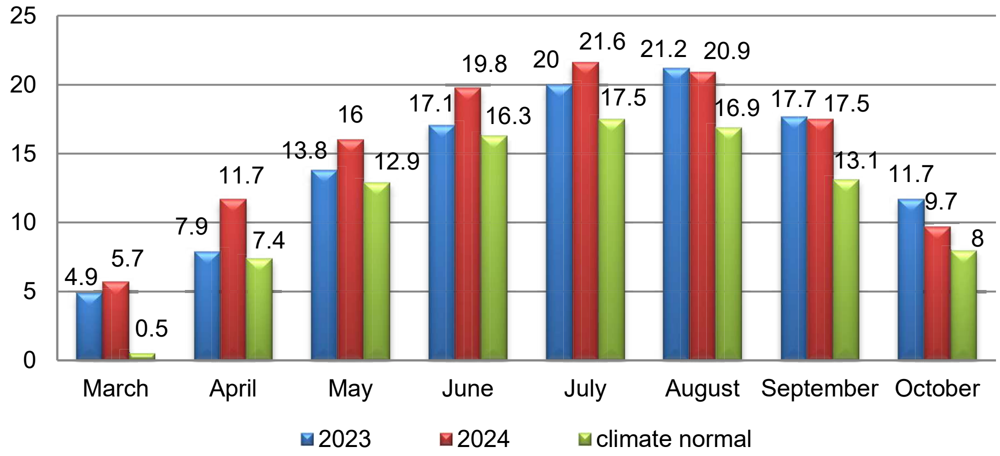

Figure 1. Mean monthly air temperatures (°C) in 2023–2024.

Fig. 1 presents a comparative analysis of mean monthly air temperatures (°C) in 2023–2024 relative to the long-term climatic norm. In both years of the study, air temperatures consistently exceeded the long-term average values, with the greatest deviations observed during the summer months. In 2023, air temperature remained above the climatic norm throughout the entire growing season, with the highest value recorded in August (21.2 °C), which exceeded the norm (17.5 °C) by 3.7 °C.

The year 2024 was characterized by even more pronounced warming at the beginning and in the middle of the growing season. In particular, a substantial deviation was recorded in May, when the mean air temperature reached 16.0 °C compared with the long-term norm of 12.9 °C. The warmest month of the entire study period was July 2024, with a mean temperature of 21.6 °C, exceeding the climatic norm (17.5 °C).

The presented data clearly confirm the general warming trend, as actual air temperatures in both years remained above long-term average values during almost the entire soybean growing cycle.

Monthly rainfall totals during the soybean growing season differed notably from long-term averages, with both surpluses and deficits recorded.Analysis of the data presented in Fig .2 indicates an alternation of periods of excessive moisture with prolonged dry spells.

The highest precipitation was recorded in July 2023 (134 mm), which corresponded to 131.4% of the long-term average. This ensured adequate soil moisture during the flowering and early pod formation stages.

The start of the 2024 growing season was critically dry; in May, only 12.8 mm of precipitation fell (15.0% of the norm), negatively affecting the uniformity of seedling emergence. In contrast, June was excessively wet, receiving 119.1 mm of rainfall (128.0% of the norm).

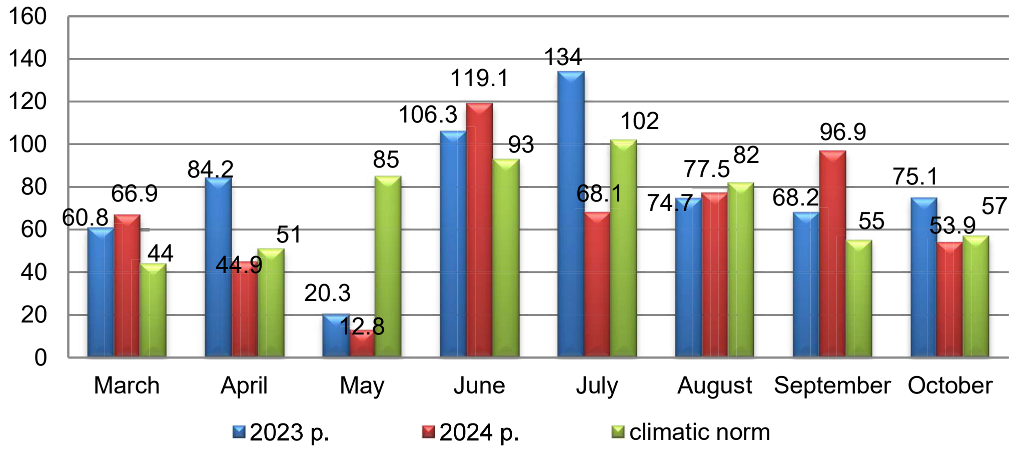

Figure 2. Total precipitation during the soybean growing season (mm) in 2023–2024.

These meteorological data indicate that the conditions during the study allowed a preliminary evaluation of the adaptive potential of soybean cultivars under temperature and water stress.

RESULTS AND DISCUSSION

The study evaluated the effects of seed inoculation (HiStick® Soy and Mycofriend®) and foliar fertilization (StimOrganic) on yield components and seed quality of soybean cultivars.

The results of the study confirmed the high effectiveness of inoculation. In the control plots (without inoculation), the number of pods per plant was 22.3 for Tytan and 23.5 for Mozart. Inoculation led to an increase in the number of pods by 2.2% in Tytan and 0.8% in Mozart, the number of seeds per plant by 2.2% and 0.6%, the grain weight per plant by 3.4% and 3.1%, and the 1000-seed weight (TSW) by 1.4–2.0% (Table 1).

A positive effect on individual yield components was also observed with foliar application of the micronutrient fertilizer StimOrganic, which resulted in an increase in the number of pods per plant by 0.6–0.8, the number of seeds per plant by 1.1–1.7, and seed weight per plant by 0.24–0.72.

Tukey's multiple comparison test confirmed that all differences between inoculated and non-inoculated treatments were statistically significant ($p < 0.05$), as indicated by asterisks in Table 1. Additionally, differences among treatment variants (C, M, SO, M+SO) were significant, as shown by distinct letters (a–d) within each column. These results demonstrate that both inoculation and the choice of treatment combination significantly influence soybean yield components.

Overall, inoculation with HiStick® Soy, particularly when combined with the M+SO treatment, enhanced pod and seed formation, increased seed mass, and improved TSW. These findings highlight the effectiveness of integrating biological inoculants with optimized agronomic practices to maximize soybean productivity.

Table 1. Yield components of soybean plants

Variant	Pods plant^{-1}, pcs.		Seeds from plant^{-1}, pcs.		Seed weight plant^{-1}, g		1,000-seed weight, g	
	Inoc-	Inoc+	Inoc-	Inoc+	Inoc-	Inoc+	Inoc-	Inoc+
Tytan								
Control	22.3 ± 0.28[a]	22.7 ± 0.14[a]*	48.4 ± 0.15[a]	49.7 ± 0.76[a]*	8.50 ± 0.03[a]	8.69 ± 0.06[a]*	174.3 ± 3.89[a]	176.6 ± 1.41[a]*
Mycofriend®	22.7 ± 0.13[b]	23.1 ± 0.33[b]*	49.1 ± 0.24[b]	50.3 ± 0.56[b]*	8.61 ± 0.06[b]	8.88 ± 0.28[b]*	175.8 ± 3.7[b]	178.3 ± 1.69[b]*
StimOrganic	22.9 ± 0.46[c]	23.5 ± 0.81[c]*	49.5 ± 0.41[c]	50.8 ± 0.82[c]*	8.74 ± 0.23[c]	9.10 ± 0.17[c]*	177.3 ± 2.55[c]	179.9 ± 0.74[c]*
M+SO	23.3 ± 0.77[d]	23.9 ± 1.08[d]*	50.7 ± 0.68[d]	51.3 ± 0.52[d]*	9.01 ± 0.29[d]	9.26 ± 0.09[d]*	177.9 ± 2.35[d]	180.6 ± 0.3[d]*
Mean	22.8	23.3	49.4	50.5	8.7	9.0	176.3	178.8
Mozart								
Control	23.5 ± 0.24[a]	23.7 ± 0.22[a]*	50.2 ± 0.29[a]	50.9 ± 0.35[a]*	9.17 ± 0.43[a]	9.72 ± 0.23[a]*	186.7 ± 7.08[a]	191.5 ± 4.72[a]*
Mycofriend®	24.0 ± 0.7[b]	24.2 ± 0.65[b]*	51.5 ± 0.1[b]	51.6 ± 0.1[b]*	9.73 ± 0.06[b]	9.96 ± 0.22[b]*	188.8 ± 5.48[b]	192.8 ± 4.6[b]*
StimOrganic	24.2 ± 0.29[c]	24.3 ± 0.37[b]*	51.9 ± 0.55[c]	52.0 ± 0.48[c]*	9.89 ± 0.39[c]	10.02 ± 0.33[c]*	189.9 ± 6.12[c]	193.1 ± 4.35[c]*
M+SO	24.4 ± 0.52[d]	24.7 ± 0.67[c]*	52.1 ± 0.33[d]	52.4 ± 0.52[d]*	10.04 ± 0.25[d]	10.25 ± 0.12[d]*	191.7 ± 6.88[d]	194.7 ± 4.9[d]*
Mean	24.0	24.2	51.4	51.7	9.7	10.0	189.3	193.0

Note. Inoc–: without HiStick® Soy; Inoc+: with HiStick® Soy. Different letters (a–d) within a column indicate significant differences (*Tukey*'s test, $p < 0.05$). *Significant effect of inoculation within a treatment.

The obtained data are fully consistent with the results of the analysis of variance (ANOVA) (Table 2). A statistically significant impact of all studied factors (year, variety, treatment, and inoculation) on yield structure indicators was established.

Table 2. Analysis of variance (ANOVA) of factor interactions and soybean yield components

Trait	Pods plant^{-1}		Seeds from plant^{-1}		Seed weight plant-1		1,000-seed weight	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Y	270.95	<0.001	0.42	0.520	153.96	<0.001	2,566.86	<0.001
T	74.71	<0.001	102.44	<0.001	91.12	<0.001	139.0	<0.001
V	437.95	<0.001	418.55	<0.001	1,325.55	<0.001	9,758.06	<0.001
I	46.01	<0.001	83.77	<0.001	100.71	<0.001	562.01	<0.001
Y × T	16.77	<0.001	1.44	0.238	3.27	0.026	6.49	<0.001
V × Y	0.11	0.742	52.83	<0.001	20.01	<0.001	537.56	<0.001
I × Y	4.28	0.042	0.07	0.789	2.15	0.147	165.91	<0.001
V × T	0.56	0.644	2.75	0.048	3.27	0.026	2.6	0.058
I × T	0.22	0.88	2.18	0.097	1.48	0.226	3.29	0.025
I × V	7.45	0.008	27.27	<0.001	0.05	0.821	13.77	<0.001

Note. Year (Y), Treatment (T), Variety (V), Inoculation (I), Year × Treatment (Y × T), Variety × Year (V × Y), Inoculation × Year (I × Y), Variety × Treatment (V × T), Inoculation × Treatment (I × T), Inoculation × Variety (I × V).

Analysis of variance revealed that cultivar was the primary determinant of all traits, with the largest effect on TSW ($F = 9{,}758.06$), while environmental conditions (year) significantly affected pod number and seed weight. Agronomic practices, including treatment and inoculation, significantly influenced all measured components ($p < 0.001$), with inoculation exerting the strongest effect on TSW ($F = 562.01$), reflecting enhanced nutrient assimilation and seed filling. Interactions between variety and year were significant for seed number and TSW, indicating differential cultivar responses to environmental conditions, whereas the non-significant Variety × Treatment interaction for TSW ($p = 0.058$) suggests a generally uniform response to the applied treatments.

Overall, these results highlight that integrating seed inoculation with optimized agronomic practices reliably enhances soybean yield and seed quality across diverse environmental conditions.

Soybean yield varied significantly with cultivar and agronomic practices (Table 3). Mozart consistently outyielded Tytan, with control plots (Inoc–) producing 3.10 t ha^{-1} versus 2.88 t ha^{-1} in Tytan. Seed inoculation with HiStick® Soy increased yield by 0.09–0.13 t ha^{-1}, Mycofriend® by 0.12–0.16 t ha^{-1}, and foliar fertilization with StimOrganic by 0.18–0.24 t ha^{-1}.

Table 3. Soybean yield by cultivar** (t ha^{-1})

Variants	Tytan		Mozart	
	noc-	noc+	noc-	noc+
Control	2.88 ± 0.18^{a}	3.01 ± 0.19^{a}*	3.1 ± 0.05^{a}	3.19 ± 0.02^{a}*
Mycofriend®	3.0 ± 0.13^{b}	3.13 ± 0.16^{b}*	3.23 ± 0.03^{b}	3.35 ± 0.03^{b}*
StimOrganic	3.08 ± 0.13^{c}	3.19 ± 0.15^{c}*	3.31 ± 0.02^{c}	3.43 ± 0.02^{c}*
M+ SO	3.17 ± 0.12^{d}	3.29 ± 0.07^{d}*	3.39 ± 0.06^{d}	3.52 ± 0.01^{d}*
$LSD_{0.05}$	0.04	0.05	0.03	0.06

Note. Inoc–: without HiStick® Soy; Inoc+: with HiStick® Soy. Different letters (a–d) within a column indicate significant differences (*Tukey*'s test, $p < 0.05$). ** – yield at 12% moisture.

The highest yields were achieved with the combined application of all treatments (M+SO + inoculation), reaching 3.52 t ha^{-1} for Mozart and 3.29 t ha^{-1} for Tytan. All treatment variants differed significantly from each other and the control (Tukey's test, $p < 0.05$), with yield increases exceeding $LSD_{0.05}$ values (0.03–0.06 t ha^{-1}).

ANOVA confirmed that variety ($F = 1{,}164.31$), year ($F = 389.19$), treatment ($F = 383.44$), and inoculation ($F = 337.76$) all had highly significant effects on yield ($p < 0.001$). Significant interactions were observed for Variety × Year ($F = 349.68$) and Year × Treatment ($F = 21.72$), indicating differential cultivar responses and weather-dependent treatment effectiveness, whereas other interactions were non-significant, suggesting a generally uniform response to agronomic practices across cultivars (Table 4).

Table 4. ANOVA results for factor effects and interactions on soybean yield

Trait	Y	T	V	I	Y × T	V × Y	I × Y	V × T	I × T	I × V
F	389.19	383.44	1,164.31	337.76	21.72	349.68	0.07	1.28	0.363	0.59
p	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.798	0.287	0.780	0.443

Note. Year (Y), Treatment (T), Variety (V), Inoculation (I), Year × Treatment (Y × T), Variety × Year (V × Y), Inoculation × Year (I × Y), Variety × Treatment (V × T), Inoculation × Treatment (I × T), Inoculation × Variety (I × V).

No significant interactions were observed for Inoculation × Variety (I × V, $p = 0.443$) or Variety × Treatment (V × T, $p = 0.287$), indicating that both cultivars respond positively to inoculation and combined fertilization regardless of genotype.

Biochemical analysis using infrared spectroscopy revealed patterns in seed composition depending on cultivar and agronomic practices (Table 5). The Tytan cultivar exhibited a higher baseline protein content (38.0%) compared to Mozart (35.6%). Solo application of Mycofriend® increased protein content by 0.1–0.2%, while StimOrganic contributed an increase of 0.4%; however, their integrated use (M+SO+Inoc+) yielded the maximum increment of 0.6–0.8% relative to the uninoculated control. Under the M+SO+Inoc+ treatment, protein content reached 39.1% in the Tytan variety and 37.4% in the Mozart variety, corresponding to increases of 1.1% and 1.8%, respectively, relative to the uninoculated control. Differences among all treatment variants were statistically significant (Tukey's test, $p < 0.05$).

Table 5. Soybean seed quality parameters

Variants	Protein content, %		Oil content, %		Fiber content, %	
	Inoc-	Inoc+	Inoc-	Inoc+	Inoc-	Inoc+
Tytan						
C	38.0 ± 3.67^{a}	$38.4 \pm 3.38^{a*}$	23.1 ± 1.52^{a}	23.0 ± 1.06^{a}	5.9 ± 2.01^{a}	$5.9 \pm 2.01^{a*}$
M	38.2 ± 3.51^{b}	$38.6 \pm 3.38^{b*}$	23.1 ± 1.25^{a}	23.0 ± 1.1^{a}	5.6 ± 1.76^{ab}	$5.7 \pm 1.86^{b*}$
SO	38.5 ± 3.52^{c}	$38.8 \pm 3.58^{c*}$	23.4 ± 1.19^{b}	$23.3 \pm 1.01a^{b}$	5.5 ± 1.72^{bc}	$5.6 \pm 1.86^{b*}$
M+SO	38.8 ± 3.84^{d}	$39.1 \pm 3.71^{d*}$	23.5 ± 1.06^{c}	23.4 ± 1.23^{c}	5.4 ± 1.61^{c}	$5.3 \pm 1.75^{bc*}$
Mozart						
C	35.6 ± 5.55^{a}	$36.8 \pm 4.55^{a*}$	22.9 ± 1.44^{a}	23.0 ± 1.47^{a}	5.9 ± 2.08^{a}	$6.0 \pm 2.01^{a*}$
M	35.7 ± 5.66^{b}	$37.0 \pm 4.53^{b*}$	23.0 ± 1.32ab	$23.2 \pm 1.3a^{b}$	5.8 ± 2.01^{ab}	$5.8 \pm 2.12^{ab*}$
SO	36.0 ± 5.72^{c}	$37.2 \pm 4.67^{c*}$	23.1 ± 1.3^{bc}	23.3 ± 1.29^{b}	5.8 ± 2.12^{b}	$5.7 \pm 2.09^{b*}$
M+SO	36.2 ± 5.55^{d}	$37.4 \pm 5.0^{d*}$	23.2 ± 0.16^{c}	$23.6 \pm 0.42^{c*}$	5.7 ± 2.01^{b}	$5.6 \pm 2.16^{b*}$

Note. Inoc–: without HiStick® Soy; Inoc+: with HiStick® Soy. Different letters (a–d) within a column indicate significant differences (*Tukey*'s test, $p < 0.05$). *Significant effect of inoculation within a treatment.

Oil content was less affected by inoculation but increased with fertilization, with the highest value (23.6%) recorded in Mozart under M+SO+Inoc+. In Tytan, inoculation slightly reduced oil content while increasing protein concentration.

The application of integrated agronomic practices reduced fiber content by 0.4–0.6%, which is beneficial for improving digestibility and overall feed value. In Tytan, fiber content decreased from 5.9% to 5.3%, while in Mozart it decreased from 6.0% to 5.6%.

The most efficient approach combined Mycofriend® seed treatment and StimOrganic foliar fertilization with HiStick® Soy inoculation (M+SO+Inoc+), maximizing yield (Tytan: 3.29 t ha^{-1}; Mozart: 3.52 t ha^{-1}) and protein content (Tytan: 39.1%; Mozart: 37.4%).

ANOVA (Table 6) showed that seasonal conditions (Y) had a critical effect on all seed quality traits, confirming that protein, oil, and fiber synthesis strongly depend on temperature and moisture during grain filling. Variety (V) was highly significant for protein and fiber ($F = 1{,}685.55$ and 54.77, $p < 0.001$, respectively) but not for oil ($F = 0.18$, $p = 0.672$). Inoculation (I) significantly increased protein content ($F = 245.54$, $p < 0.001$) and oil content to a lesser, non-significant extent ($F = 2.43$, $p = 0.123$), while fiber content was unaffected ($F = 0.24$, $p = 0.623$). Treatment (T) had a highly significant effect on all traits (protein $F = 34.50$; oil $F = 10.9$; fiber $F = 48.28$; $p < 0.001$).

Table 6. ANOVA results for factor effects and interactions on soybean quality

Trait	Protein content		Oil content		Fibre content	
	F	*p*	*F*	*p*	*F*	*p*
Y	24,983.47	<0.001	1,223.99	<0.001	19,540.0	<0.001
T	34.50	<0.001	10.9	<0.001	48.28	<0.001
V	1,685.55	<0.001	0.18	0.672	54.77	<0.001
I	245.54	<0.001	2.43	0.123	0.24	0.623
Y × T	4.46	0.006	20.61	<0.001	5.23	0.002
V × Y	820.94	<0.001	2.43	0.123	90.98	<0.001
I × Y	91.21	<0.001	0.50	0.481	3.89	0.052
V × T	0.325	0.81	0.619	0.605	4.14	0.009
I × T	0.175	0.913	0.192	0.903	1.54	0.210
I × V	80.49	<0.001	5.13	0.026	0.243	0.623

Note. Year (Y), Treatment (T), Variety (V), Inoculation (I), Year × Treatment (Y × T), Variety × Year (V × Y), Inoculation × Year (I × Y), Variety × Treatment (V × T), Inoculation × Treatment (I × T), Inoculation × Variety (I × V).

Interactions were mostly non-significant, except for Year × Treatment (Y × T), which affected oil ($F = 20.61$, $p < 0.001$), indicating that fertilization effects vary with weather conditions, and Variety × Treatment (V × T) for fiber ($F = 4.14$, $p = 0.009$), reflecting cultivar-specific responses. No significant Variety × Treatment interaction was observed for protein or oil ($p > 0.6$), indicating a stable response of both cultivars to the applied treatments.

Overall, these results highlight the dominant role of seasonal conditions, alongside treatment and cultivar, in determining soybean seed quality, with inoculation contributing primarily to protein accumulation.

Table 7. Soybean protein and oil yields (t ha^{-1})

Variants	Protein, t ha^{-1}		Oil, t ha^{-1}	
	Inoc-	Inoc+	Inoc-	Inoc+
Tytan				
Control	1.09 ± 0.04^{a}	1.15 ± 0.03^{a}*	0.66 ± 0.08^{a}	0.69 ± 0.07^{a}*
Mycofriend®	1.14 ± 0.05^{b}	1.21 ± 0.05^{b}*	0.69 ± 0.07^{b}	0.72 ± 0.07^{b}*
StimOrganic	1.18 ± 0.06^{c}	1.24 ± 0.06^{c}*	0.72 ± 0.07^{c}	0.75 ± 0.07^{c}*
M+ SO	1.23 ± 0.08^{d}	1.29 ± 0.1^{d}*	0.75 ± 0.06^{d}	0.77 ± 0.06^{d}*
Average	1.16	1.22	0.71	0.73
Mozart				
Control	1.10 ± 0.15^{a}	1.17 ± 0.14^{a}*	0.71 ± 0.05^{a}	0.73 ± 0.05^{a}*
Mycofriend®	1.16 ± 0.17^{b}	1.24 ± 0.14^{b}*	0.74 ± 0.05^{b}	0.78 ± 0.05^{b}*
StimOrganic	1.19 ± 0.19^{c}	1.27 ± 0.17^{c}*	0.76 ± 0.04^{c}	0.80 ± 0.04^{c}*
M+ SO	1.23 ± 0.2^{d}	1.32 ± 0.18^{d}*	0.78 ± 0.01^{d}	0.83 ± 0.01^{d}*
Average	1.17	1.25	0.75	0.79

Note. Inoc–: without HiStick® Soy; Inoc+: with HiStick® Soy. Different letters (a–d) within a column indicate significant differences (*Tukey*'s test, $p < 0.05$). *Significant effect of inoculation within a treatment.

Agronomic interventions increased protein and oil yield per hectare (Table 7). For protein, HiStick® Soy alone increased yields by 0.05–0.09 t ha^{-1}, while Mycofriend® raised protein to 1.15–1.21 t ha^{-1} in Tytan and 1.17–1.25 t ha^{-1} in Mozart. Foliar StimOrganic further enhanced protein yields by 0.09–0.10 t ha^{-1}, and oil yields by 0.02–0.03 t ha^{-1} compared to unfertilized treatments. The combined application of HiStick® Soy + Mycofriend® + StimOrganic (M+SO+Inoc+**)** produced the highest protein and oil yields (Tytan: 1.29 t ha^{-1} protein, 0.77 t ha^{-1} oil; Mozart: 1.32 t ha^{-1} protein, 0.83 t ha^{-1} oil).

Tukey's test confirmed that each step of technological intensification led to statistically significant yield increases ($p < 0.05$). The highest protein and oil yields were achieved with the combined treatment (Inoculation + Mycofriend® + StimOrganic).

Year (Y) was the strongest influencing factor, while Variety (V) significantly affected both traits, especially oil content, indicating its higher genetic determination (Table 8).

Table 8. ANOVA results for factor effects and interactions on soybean protein and oil yields

Trait	Protein yield		Oil yield	
	F	*p*	*F*	*p*
Year (Y)	5,156.82	<0.001	1,672.29	<0.001
Treatment (T)	415.04	<0.001	233.53	<0.001
Variety (V)	51.77	<0.001	440.29	<0.001
Inoculation (I)	598.52	<0.001	190.70	<0.001
Year × Treatment	45.32	<0.001	38.32	<0.001
Variety × Year	1,243.12	<0.001	153.13	<0.001
Inoculation × Year	0.815	0.49	0.289	0.592
Variety × Treatment	0.57	0.639	38.32	<0.001
Inoculation × Treatment	0.815	0.490	0.87	0.461
Inoculation × Variety	16.24	<0.001	2.06	0.155

Inoculation had a highly significant effect on protein yield ($F = 598.52, p < 0.001$) and increased oil yield mainly through the enhancement of overall seed yield ($F = 190.70$, $p < 0.001$). Mycofriend® and StimOrganic also significantly increased protein ($F = 415.04$). The strong Variety × Year interaction ($F = 1,243.12$) highlights the seasonal dependence of protein potential. Overall, inoculation and integrated fertilization act as stabilizing factors, substantially enhancing protein harvest per hectare.

The application of agrotechnical practices under the soil and climatic conditions of the Western Forest-Steppe of Ukraine had a positive effect on the quantity and quality of soybean yields, as well as the economic indicators of its production. The economic evaluation of the varieties Tytan and Mozart showed that seed inoculation with *Bradyrhizobium japonicum* in combination with the bioproducts Mycofriend®, StimOrganic, and the M+SO complex significantly increased gross yield (1,271–1,393 € ha^{-1} Tytan and 1,360–1,486 € ha^{-1} Mozart) compared to the control. The highest effect was observed with M+SO combined with inoculation, indicating a synergistic effect between biological products and symbiotic nitrogen fixation. The additional costs for bioproducts (19.81–38.27 € ha^{-1} with inoculation) were fully compensated by the increased yield and gross income (Table 9).

Table 9. Economic Indicators of Soybean Cultivation, Averages for 2023–2024

Variants	Gross production value, € ha⁻¹		Additional costs, € ha⁻¹		Net income, € ha⁻¹		Profitability ratio, %		Return on investment (ROI), € €⁻¹	
	Inoc-	Inoc+	Inoc-	Inoc+	Inoc-	Inoc+	Inoc-	Inoc+	Inoc-	Inoc+
Tytan										
Control	1,216	1,271	-	19.81	489	519	67.3	69.0	1.67	1.69
Mycofriend®	1,267	1,322	5.36	26.17	535	562	73.1	73.9	1.73	1.74
StimOrganic	1,301	1,351	13.1	32.91	561	586	75.8	76.6	1.76	1.77
M+SO	1,339	1,393	18.46	38.27	594	641	79.7	85.2	1.80	1.85
Mozart										
Control	1,309	1,360	-	19.81	582	614	80.1	82.3	1.8	1.82
Mycofriend®	1,381	1,436	5.36	26.17	649	684	88.7	91.0	1.89	1.91
StimOrganic	1,393	1,444	13.1	32.91	653	684	88.2	90.0	1.88	1.9
M+SO	1,423	1,486	18.46	38.27	678	721	91.0	94.2	1.91	1.94

Seed inoculation with *Bradyrhizobium japonicum* combined with Mycofriend®, StimOrganic, and particularly the M+SO complex significantly improved the economic efficiency of soybean cultivation. For the Tytan variety, gross production value reached 1,393 € ha^{-1}, net income 641 € ha^{-1}, and profitability 85.2%. The Mozart variety exhibited superior economic performance, with a gross production value of 1,486 € ha^{-1}, a net income of 721 € ha^{-1}, and a profitability of 94.2%. Specifically, the Return on Investment (ROI) reached 1.94 € for every 1 € invested when inoculated with the M+SO complex. These findings highlight the economic viability of integrating seed inoculation and biological products into soybean cultivation under the conditions of the Western Forest-Steppe of Ukraine and underscore the advantage of the Mozart variety over Tytan.

The improvement of soybean cultivation technology is relevant not only for Ukrainian researchers but also constitutes an important research subject for European scientists, due to the relatively short period (approximately 150 years) during which soybean has been cultivated in Europe (Wenda-Piesik & Ambroziak, 2022). Variety selection, fertilization systems, and seed inoculation remain key factors in assessing soybean yield potential. Research results clearly indicate that soybean productivity and quality traits directly depend on agrotechnical practices. Each studied element of the cultivation technology had a positive effect on the individual plant productivity and overall yield, which is statistically confirmed by the study results. Soybean yield in this study ranged from 2.88 to 3.52 t ha^{-1} and depended on the fertilization system, seed inoculation, and variety. The study confirmed the effectiveness of the combined application of HiStick® Soy seed inoculation, Mycofriend® treatment, and SO fertilization. Yield increases compared to the control were 14.2% for the Tytan variety and 13.5% for the Mozart variety.

The economic value of soybean is determined not only by yield but also by the biochemical composition of the seeds, particularly protein and oil content (Chiozza et al., 2025; Zelaya Arce et al., 2025). Our results align with previous studies that highlight the positive effects of inoculation and the use of mycorrhizal fungi on the formation of yield components, increased productivity, and improved quality traits of crops (Adesemoye & Kloepper, 2009; Cely et al., 2016; Basiru et al., 2020).

Specifically, increases in yield, protein content, and thousand-seed weight due to soybean inoculation have been confirmed by studies conducted in Belgium (Pannecoucque et al., 2022). Similar results were obtained by Panasiewicz et al. (2023) in the southeastern Baltic region, where inoculation of the Aldana soybean variety with *B. japonicum* was combined with the application of 30–60 kg N ha^{-1}. Positive trends in productivity and grain quality under combined inoculation and foliar fertilization have also been reported by Di Mauro et al. (2023) and Serafin-Andrzejewska et al. (2024). Furthermore, Furman (2021) emphasizes the effectiveness of combined application of mineral fertilizers and seed inoculation with *B. japonicum* and *B. mucilaginosus* strains in increasing raw protein and oil yield.

In summary, the studied agronomic measures had a significant impact on yield structure, total productivity, and seed quality. The results of the present study confirmed the high agronomic and economic efficiency of HiStick® Soy inoculation, Mycofriend® seed treatment, and SO fertilization, ensuring a high return on investment (ROI).

CONCLUSIONS

The integrated application of HiStick® Soy seed inoculation and the bioproducts Mycofriend® and StimOrganic significantly enhanced both the yield and quality of soybean seeds under the conditions of the Western Forest-Steppe of Ukraine. The highest productivity was recorded in the Mozart cultivar using the combined treatment scheme (3.52 t ha^{-1}), which was accompanied by an increase in protein content to 37.4–39.1% and a decrease in fiber content. ANOVA results confirmed the dominant influence of genotype and seasonal weather conditions on yield formation, while demonstrating the stable effectiveness of biological treatments across both cultivars ($p > 0.05$ for the V×T interaction).

Future research prospects include conducting a comparative analysis of the productivity of the newest soybean genotypes and optimizing technological cultivation elements. This will allow for expanding the scientific understanding of the crop's adaptive potential, mitigating the impact of destructive biotic and abiotic factors, and ensuring stable, high-quality seed yields under global climate change.

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REFERENCES

Adesemoye, A.O. & Kloepper, J.W. 2009. Plant–microbes interactions in enhanced fertilizer-use efficiency. *Applied Microbiology and Biotechnology* **85**(1), 1–12. doi: 10.1007/s00253-009-2196-0

Albareda, M., Rodríguez-Navarro, D.N. & Temprano, F.J. 2009. Soybean inoculation: Dose, N fertilizer supplementation and rhizobia persistence in soil. *Field Crops Research* **113**(3), 352–356. https://doi.org/10.1016/j.fcr.2009.05.013

Ashwin, R., Bagyaraj, D.J. & Mohan Raju, B. 2023. Ameliorating the drought stress tolerance of a susceptible soybean cultivar, MAUS 2, through dual inoculation with selected rhizobia and AM fungus. *Fungal Biology and Biotechnology* **10**(1), 10. doi: 10.1186/s40694-023-00157-y

Basiru, S., Mwanza, H.P. & Hijri, M. 2020. Analysis of arbuscular mycorrhizal fungal inoculant benchmarks. *Microorganisms* **9**(1), 81. https://doi.org/10.3390/microorganisms9010081

Begum, N., Wang, L., Ahmad, H., Akhtar, K., Roy, R., Khan, M.I. & Zhao, T. 2022. Co-inoculation of arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria improves growth and photosynthesis in tobacco under drought stress by up-regulating antioxidant and mineral nutrition metabolism. *Microbial Ecology* **83**(4), 971–988. https://doi.org/10.1007/s00248-021-01815-7

Begum, N., Xiao, Y., Wang, L., Li, D., Irshad, A. & Zhao, T. 2023. Arbuscular mycorrhizal fungus *Rhizophagus irregularis* alleviates drought stress in soybean overexpressing the GmSPL9d gene by promoting photosynthetic apparatus and regulating the antioxidant system. *Microbiological Research* **273**. https://doi.org/10.1016/j.micres.2023.127398

Capatana, N., Bolohan, C. & Marin, D. 2017. Research regarding the influence of mineral fertilization along with *Bradyrhizobium japonicum* on soybean grain yield (*Glycine max* (L.) Merrill) under the conditions of south-east Romania. *Scientific Papers. Series A. Agronomy* **60**, 207–214. https://agronomyjournal.usamv.ro/pdf/2017/Art33.pdf

Cely, M.V., de Oliveira, A.G., de Freitas, V.F., de Luca, M.B., Barazetti, A.R., dos Santos, I.M., ... & Andrade, G. 2016. Inoculant of arbuscular mycorrhizal fungi (*Rhizophagus clarus*) increases yield of soybean and cotton under field conditions. *Frontiers in Microbiology* **7**, 720. https://doi.org/10.3389/fmicb.2016.00720

Chen, S., Zhao, H., Zou, C., Li, Y., Chen, Y., Wang, Z., ... & Ahammed, G.J. 2017. Combined inoculation with multiple arbuscular mycorrhizal fungi improves growth, nutrient uptake and photosynthesis in cucumber seedlings. *Frontiers in Microbiology* **8**. doi: 10.3389/fmicb.2017.02516

Chiluwal, A. 2025. US soybean seed protein concentrations – Current status, challenges, and some potential crop management solutions. *Agronomy Journal* **117**(1). doi: 10.1002/agj2.21731

Chiozza, M.V., Shook, J.M., Van der Laan, L., Singh, A.K. & Miguez, F.E. 2025. Comprehensive assessment of soybean seed composition from field trials spanning 22 US states and 24 years: Predictive insights. *Crop Science* **65**. https://doi.org/10.1002/csc2.70142

Cordeiro, C.F.D.S. & Echer, F.R. 2019. Interactive effects of nitrogen-fixing bacteria inoculation and nitrogen fertilization on soybean yield in unfavorable edaphoclimatic environments. *Scientific Reports* **9**. https://doi.org/10.1038/s41598-019-52131-7

Di Mauro, G., Schwalbert, R., Prado, S.A., Saks, M.G., Ramirez, H., Costanzi, J. & Parra, G. 2023. Exploring practical nutrition options for maximizing seed yield and protein concentration in soybean. *European Journal of Agronomy* **146**. doi: 10.1016/j.eja.2023.126794

DSTU 7855:2015. Soil quality. Determining the group composition of humus according to Tyurin’s method as modified by Kononova and Belchikova. State Standard of Ukraine.

DSTU 7863:2015. Soil quality. Determination of easily hydrolyzable nitrogen by the Kornfield method. State Standard of Ukraine.

DSTU 4405:2005. Soil quality. Determination of mobile compounds of phosphorus and potassium by the Kirsanov method (modified by the National Center of IGA). State Standard of Ukraine.

DSTU ISO 10012:2005. Measurement management systems – Requirements for measurement processes and measuring equipment. State Standard of Ukraine.

FAOSTAT. 2025. Crops and livestock products. https://www.fao.org/faostat/en/#data/QCL (accessed on 10 December 2025).

Fahde, S., Boughribil, S., Sijilmassi, B. & Amri, A. Rhizobia. 2023. A Promising Source of Plant Growth-Promoting Molecules and Their Non-Legume Interactions: Examining Applications and Mechanisms. *Agriculture* **13.** doi: 10.3390/agriculture13071279

Faye, A., Stewart, Z.P., Ndung’u-Magiroi, K., Diouf, M., Ndoye, I., Diop, T., ... & Lesueur, D. 2020. Testing of commercial inoculants to enhance P uptake and grain yield of promiscuous soybean in Kenya. *Sustainability* **12**(9), 3803.

Furman, O. 2021. Influence of mineral fertilizers and inoculation on the formation of individual and seed productivity of soybean in conditions of the Right-Bank Forest-Step. *Feeds and Feed Production* **91**, 82–92. https://doi.org/10.31073/kormovyrobnytstvo202191-07

Genre, A., Lanfranco, L., Perotto, S. & Bonfante, P. 2020. Unique and common traits in mycorrhizal symbioses. *Nature Reviews Microbiology* **18**(11), 649–664. doi: 10.1038/s41579-020-0402-3

Grossman, J.M., Schipanski, M.E., Sooksanguan, T., Seehaver, S. & Drinkwater, L.E. 2011. Diversity of rhizobia in soybean (*Glycine max* (Vinton)) nodules varies under organic and conventional management. *Applied Soil Ecology* **50**, 14–21. https://doi.org/10.1016/j.apsoil.2011.08.003

Helios, W., Serafin-Andrzejewska, M., Kozak, M. & Lewandowska, S. 2025. Impact of nitrogen fertilisation and inoculation on soybean nodulation, nitrogen status, and yield in a central European climate. *Agriculture* **15**. https://doi.org/10.3390/agriculture15151654

Herridge, D.F., Peoples, M.B. & Boddey, R.M. 2008. Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil* **311**(1–2), 1–18. doi: 10.1007/s11104-008-9668-3

Hungria, M., Franchini, J.C., Campo, R.J., Crispino, C.C., Moraes, J.Z., Sibaldelli, R.N., Mendes, I.C. & Arihara, J. 2006. Nitrogen nutrition of soybean in Brazil: Contributions of biological N2 fixation and N fertilizer to grain yield. *Canadian Journal of Plant Science* **86**(4), 927–939. https://doi.org/10.4141/P05-098

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

Information and Reference System 'Sort', http://sort.sops.gov.ua/cultivar/view/832

Information and Reference System 'Sort', http://sort.sops.gov.ua/cultivar/view/14722

Jarecki, W., Borza, I.M., Rosan, C.A., Vicas, S.I. & Domuța, C.G. 2024. Soybean response to seed inoculation with *Bradyrhizobium japonicum* and/or nitrogen fertilization. *Agriculture* **14**(7). https://doi.org/10.3390/agriculture14071025

Kaschuk, G., Nogueira, M.A., De Luca, M.J. & Hungria, M. 2016. Response of determinate and indeterminate soybean cultivars to basal and topdressing N fertilization compared to sole inoculation with *Bradyrhizobium*. *Field Crops Research* **195**, 21–27. doi: 10.1016/j.fcr.2016.05.010

Kulig, B. & Klimek-Kopyra, A. 2023. Sowing date and fertilization level are effective elements increasing soybean productivity in rainfall deficit conditions in Central Europe. *Agriculture* **13**(1), 115. https://doi.org/10.3390/agriculture13010115

Leggett, M., Diaz-Zorita, M., Koivunen, M., Bowman, R., Pesek, R., Stevenson, C. & Leister, T. 2017. Soybean response to inoculation with *Bradyrhizobium japonicum* in the United States and Argentina. *Agronomy Journal* **109**(3), 1031–1038. doi: 10.2134/agronj2016.04.0214

Nader, A.A., Hauka, F.I.A., Afify, A.H. & El-Sawah, A.M. 2024. Drought-tolerant bacteria and arbuscular mycorrhizal fungi mitigate the detrimental effects of drought stress induced by withholding irrigation at critical growth stages of soybean (*Glycine max*, L.). *Microorganisms* **12**(6). https://doi.org/10.3390/microorganisms12061123

Nartey, E., Darko, D., Sulemana, N. & Assibey, E. 2022. Efficacy of HiStick® Soy in soybean nodulation in two Alfisols of Ghana. *Frontiers in Sustainable Food Systems* **6**. https://doi.org/10.3389/fsufs.2022.1004090

Omari, R.A., Yuan, K., Anh, K.T., Reckling, M., Halwani, M., Egamberdieva, D., ... & Bellingrath-Kimura, S.D. 2022. Enhanced soybean productivity by inoculation with indigenous *Bradyrhizobium* strains in agroecological conditions of northeast Germany. *Frontiers in Plant Science* **12**. https://doi.org/10.3389/fpls.2021.707080

Panasiewicz, K., Faligowska, A., Szymańska, G., Ratajczak, K. & Sulewska, H. 2023. Optimizing the amount of nitrogen and seed inoculation to improve the quality and yield of soybean grown in the southeastern Baltic region. *Agriculture* **13**(4), 407. doi: 10.3390/agriculture13040798

Pannecoucque, J., Goormachtigh, S., Ceusters, N., Bodé, S., Boeckx, P. & Roldán-Ruiz, I. 2022. Soybean response and profitability upon inoculation and nitrogen fertilisation in Belgium. *European Journal of Agronomy* **132**. https://doi.org/10.1016/j.eja.2021.126390

Prusiński, J., Baturo-Cieśniewska, A. & Borowska, M. 2020. Response of soybean (*Glycine max* (L.) Merrill) to mineral nitrogen fertilization and *Bradyrhizobium japonicum* seed inoculation. *Agronomy* **10**(9). https://doi.org/10.3390/agronomy10091300

Salvagiotti, F., Cassman, K.G., Specht, J.E., Walters, D.T., Weiss, A. & Dobermann, A. 2008. Nitrogen uptake, fixation and response to fertilizer N in soybeans: A review. *Field Crops Research* **108**(1), 1–13. https://doi.org/10.1016/j.fcr.2008.03.001

Serafin-Andrzejewska, M., Jama-Rodzeńska, A., Helios, W., Kozak, M., Lewandowska, S., Zalewski, D. & Kotecki, A. 2024. Influence of nitrogen fertilization, seed inoculation and the synergistic effect of these treatments on soybean yields under conditions in south-western Poland. *Scientific Reports* **14**. https://doi.org/10.1038/s41598-024-57008-y

Silva, R.K.S., Silva, P.F.M., Nascimento, L.M., Araújo, T.A.N. & Vendruscolo, E.P. 2024. How do rhizobacteria species influence the growth and yield of soybean in a tropical environment? *Agronomy Research* **22**(S2), 703–711. https://doi.org/10.15159/AR.24.032

Staniak, M., Szpunar-Krok, E. & Kocira, A. 2023. Responses of soybean to selected abiotic stresses-Photoperiod, temperature and water. *Agriculture* **13**(1), 146. https://doi.org/10.3390/agriculture13010146

Szpunar-Krok, E., Bobrecka-Jamro, D., Pikuła, W. & Jańczak-Pieniążek, M. 2023. Effect of nitrogen fertilization and inoculation with *Bradyrhizobium japonicum* on nodulation and yielding of soybean. *Agronomy* **13**(5), 513. https://doi.org/10.3390/agronomy13051341

The jamovi project. 2024. *jamovi* (Version 2.6) [Computer software]. https://www.jamovi.org

Thilakarathna, M.S. & Raizada, M.N. 2017. A meta-analysis of the effectiveness of diverse rhizobia inoculants on soybean traits under field conditions. *Soil Biology and Biochemistry* **105**, 177–196. https://doi.org/10.1016/j.soilbio.2016.11.022

Twardosz, R., Walanus, A. & Guzik, I. 2021. Warming in Europe: Recent trends in annual and seasonal temperatures. *Pure and Applied Geophysics* **178**, 4021–4032. doi: 10.1007/s00024-021-02860-6

Verbruggen, E., van der Heijden, M.G., Rillig, M.C. & Kiers, E.T. 2013. Mycorrhizal fungal establishment in agricultural soils: Factors determining inoculation success. *New Phytologist* **197**(4), 1104–1109. https://doi.org/10.1111/j.1469-8137.2012.04348.x

Wahab, A., Muhammad, M., Munir, A., Abdi, G., Zaman, W., Ayaz, A., ... & Reddy, S.P.P. 2023. Role of arbuscular mycorrhizal fungi in regulating growth, enhancing productivity, and potentially influencing ecosystems under abiotic and biotic stresses. *Plants* **12**(17). https://doi.org/10.3390/plants12173102

Wenda-Piesik, A. & Ambroziak, K. 2022. The choice of soybean cultivar alters the underyielding of protein and oil under drought conditions in Central Poland. *Applied Sciences* **12**(15). https://doi.org/10.3390/app12157830

Zelaya Arce, M.S., Lago Tagliapietra, E.L., Minussi Winck, J.E., Ferigolo Alves, A., Schmidt Dalla Porta, F., Broilo Facco, T., ... & Zanon, A.J. 2025. Assessing genetics, biophysical, and management factors related to soybean seed protein variation in Brazil. *European Journal of Agronomy* **165**. https://doi.org/10.1016/j.eja.2025.127541

Zilli, J.É., Pacheco, R.S., Gianluppi, V., Smiderle, O.J., Urquiaga, S. & Hungria, M. 2021. Biological N2 fixation and yield performance of soybean inoculated with *Bradyrhizobium*. *Nutrient Cycling in Agroecosystems* **119**(3), 323–336. doi: 10.1007/s10705-021-10128-7