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The effect of seed inoculation and fertilization on the nitrogen fixing capacity of soybean varieties

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ABSTRACT

The paper presents the results of studies on the nitrogen-fixing ability of soybean varieties depending on seed inoculation and fertilization. In today's global conditions of ecological and economic crises, the attention to the potential of agroecosystems and minimization of the use of pesticides and agrochemicals is growing. Application of advanced forms of micronutrient fertilizers and inoculants is one of the most promising methods of crop production. The improvement of soybean cultivation technology with environmentally friendly components requires scientific justification, adaptation to specific soil and climatic conditions, and an assessment of their impact on the varietal characteristics of the crop. The research established that for the maximum formation of the symbiotic apparatus indicators, including the number and mass of nodules, their intensive functioning with the formation of the highest levels of total and active symbiotic potential, and the amount of biologically fixed nitrogen, it is necessary to combine pre-sowing seed treatment (with inoculant HighCot Super, micronutrient fertilizer Wonder Micro, and the seed protectant Maxim XL) and foliar nutrition with chelated fertilizers containing macro- and microelements (Wonder Yellow and Wonder Blue) against the background of applying mineral fertilizer at the rate of $N_{20}P_{20}S_{9}$.. Under these conditions, the total number of nodules in Betina variety reached 50.4 nodules per plant, of which 43.8 were active, while in Vyshyvanka variety the total number of nodules was 48.5, with 38.3 active nodules per plant. The total and active mass of nodules in Betina variety was 586.5 and 469 mg per plant, respectively, while in Vyshyvanka variety, it was 581.3 and 465 mg per plant, respectively. Betina variety exhibited the longest total and active symbiotic period – 90.0 and 81 days, respectively, compared to Vyshyvanka variety – 88 and 79 days. The highest values of both total and active symbiotic potential were also recorded in Betina variety (37.3 and 26.2 thousand kg·days/ha) and in Vyshyvanka variety (34.8 and 24.6 thousand kg·days/ha. Similarly, the maximum amount of biologically fixed nitrogen was found in Betina variety (136.5 kg/ha) and in Vyshyvanka variety (127.7 kg/ha).

Keywords: soybean, fertilization, nutrition, nodule number, nodule mass, nitrogen fixation, symbiotic potential, nitrogen.

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the most important leguminous crops cultivated worldwide due to its wide range of applications, including feed production, the oil industry, and the food sector. The largest soybean producers are Brazil, the USA, Argentina, and China, with a total cropping area reaching 120–130 million hectares. In Europe, soybean meal and seeds are in high demand, but the region relies heavily on imports due to the limited area dedicated to legume cultivation (only 1.5% of agricultural land) compared to global needs (14.5%).

Soybean cultivation in Ukraine, where it is not a traditional crop, covered up to 1 million hectares before 2010. However, since the early 2010s, there has been a significant increase in cropping areas and yields (Kuprieieva, 2023; Biliavska at al., 2021).

Thanks to both quantitative and qualitative growth, Ukraine is currently among the world's top ten soybean producers, with a projected supply volume of 3.8 million tons, which is expected to increase due to the growing interest of agricultural producers, particularly as grain production becomes less profitable (Kobylynskyi, 2024; Branitskyi at al., 2022).

The key export markets for Ukrainian soybeans are EU countries, largely due to geographical factors, despite the current logistical challenges. Today, due to modern soybean varieties and advanced cultivation technologies, it is possible to overcome yield limitations, achieve high productivity, and expand the areas under this crop. The comprehensive adoption of all farming practices, and high-quality implementation of operations in optimal terms, ensures yields of 1.8–2.5 t/ha on non-irritated Ukrainian lands and 2.8–3.5 t/ha on irrigated lands (Kobylynskyi, 2024; Myronova at al., 2023).

The relevance of soybean cultivation in the modern world is driven by many factors (feed production, human nutrition, soil biota restoration, mitigation of climate change, etc.) and requires detailed research, especially in terms of increasing its yield. Several key factors influence soybean yield, including variety genetics, pre-sowing seed treatment, soil cultivation and crop rotation, weed control, and fertilization. Soybean yield and quality largely depend on soil and weather conditions and agrotechnical measures, including seed inoculation. Pre-sowing treatment of soybean seeds with inoculants, trace elements, fungicidal and insecticidal agents protects seeds pathogens in an aggressive soil environment. This practice ensures uniform and well-developed seedlings, which directly contributes to the preservation of the yield potential of varieties (Tytova and Dubynska, 2020; Vdovenko at al., 2024).

The introduction of energy-saving technologies for growing soybeans is crucial, as in modern farming conditions it provides additional sources of mineral nutrition for plants, ensures high and stable crop yields. Such technologies are based on the use of inoculants created on the basis of living cells of microorganisms. In the last 20–30 years, the attitude towards microbial preparations and the very idea of artificial bacterization has changed dramatically. Soybean is one of the most widely grown crops worldwide, which affects various aspects of the ecosystem. One of the most important ecological components associated with soybean cultivation are soil microbes (soil biota, including rhizobia and mycorrhizal fungi). Since soybean is the only legume species that can be associated with rhizobia and arbuscular mycorrhizal fungi, the potential for its further cultivation increases (Tytova and Dubynska, 2020; Myronova at al., 2023).

As a leguminous crop, soybean can fix free atmospheric nitrogen through symbiosis with *Bradyrhizobium japonicum* bacteria. However, *B. Japonicum* is not naturally present in European soils; therefore, soybean seeds should be inoculated to enhance nodule formation (Kobylynskyi, 2024; Didur at al., 2020).

Since nodule bacteria have not been found in the epiphytic and endophytic microbiocenosis of soybean seeds, it is obvious that for the formation of an effective soybean-rhizobial symbiosis, artificial inoculation of seeds with highly active strains of specific nodule bacteria, which are characterized by high ecological plasticity and are complementary to a wide range of modern varieties, including varieties with different ripening periods, should be a mandatory agronomic measure. This measure will contribute to maximizing the crop's genetic potential (Mykolaievskyi et al., 2016; Didur at al., 2021).

The yield-enhancing potential of inoculants for seed treatment is a scientifically proven and natural method of increasing nitrogen availability for legumes and boosting crop productivity. The use of inoculants based on resistant mycorrhizal strains, which take into account specific needs of each crop, improves the natural ability of legumes to form symbiosis with bacteria, which contributes to better nitrogen assimilation. It has been established that inoculation of soybean seeds, even with regular crop rotation and the use of mineral fertilizers, results in a yield increase of up to 10% (Drobitko et al., 2015; Razanov at al., 2018).

According to numerous scientists, soybean in symbiosis with nodule bacteria can absorb about 50–70% of the nitrogen needed. Thus, it is able to accumulate up to 80–100 kg/ha of symbiotic nitrogen in the soil after harvesting. It is one of the best-preceding crops for cereals, vegetables, and other crops. Therefore, modern agriculture is interested in producing environmentally friendly products with minimal costs and reduced environmental impact (Razanov at al., 2020).

Recent studies have confirmed the phenomenon of associative nitrogen fixation, emphasizing the crucial role of rhizosphere microflora in providing crops with essential nutrients. The interactions between microorganisms and plants have been extensively studied. The microorganisms convert compounds inaccessible to plants into mobile ones, which are optimal for metabolism. Therefore, plants provided with a full-fledged complex of microorganisms can receive sufficient nutrition and, as a result, realize their potential for forming high yields. However, the issue of effective compatibility of endophytic bacteria with rhizobia of leguminous crops has not yet been studied enough, although the combination of the properties of nitrogen-fixing and growth-regulating functions of the microbial community of endophytic bacteria are very valuable from an economic point of view. Therefore, an in-depth study of the mechanisms of these interactions is crucial for advancing scientific knowledge about the microbial-plant symbiosis of grain legumes, namely soybean plants (Tytova and Dubynska, 2020).

The prospects of using inoculants by farmers are driven by the rising cost of mineral fertilizers and the need to reduce their environmental impact. Research highlights the sensitivity of legumes to environmental stresses, which leads to variable yields over years. For example, low or high temperature, lack or excess water, high salinity or low pH negatively affect nodule formation, which reduces biological nitrogen fixation and the final yield. Soybeans meet 50–60% of their nitrogen demand through biological nitrogen fixation, which must be taken into account when growing high-yielding varieties that require more nutrients. Thus, the best soybean varieties yield up to 5 t/ha, while their potential yield can reach 7 t/ha. In this case, nodule formation must be highly efficient to meet the crop's nitrogen needs. Therefore, when growing high-yielding varieties, a small dose of nitrogen fertilizer may be required, but biologically fixed nitrogen should remain the primary source of this element (Kobylynskyi 2024; Tkachuk at al., 2021).

The formation of nodules on the root system of soybean and nitrogen fixation strongly depend on the environmental conditions in which the plant develops. Most associative nitrogen-fixing bacteria exhibit species specificity, so that they can form symbiotic relationships only with soybeans. The efficiency of nitrogen fixation can only be increased by using bacterial strains that exhibit higher ecological plasticity and start accumulating nitrogen effectively at the early stages of crop development (Hadzovskyi and Novytska, 2018).

To form 100 kg of seeds, soybeans require an average of 7.5 kg of nitrogen, 1.6–1.8 kg of phosphorus, and 3.0–4.5 kg of potassium in the active ingredient. The uptake of nutrients during the growing season in soybeans is uneven. Hence, from seedling emergence to flowering, plants absorb only 18% N, 15% P, and 25% K, while the majority of nutrients are consumed from budding to bean formation and grain filling – 80% N, 80% P, and 50% K. It should be noted that soybeans, like other crops, have critical periods for specific nutrients. In the initial phases of crop development (seedlings and branching), phosphorus is the most crucial, which contributes to the formation of a larger number of generative organs and the development of nodules. The largest amount of potassium is used by soybean plants in the phase of bean formation and grain filling. During germination and during the week after germination, the seedling uses nutrients from the seeds. Applying high doses of nitrogen fertilizers before sowing inhibits the development of nodules. The main part of nitrogen is used by soybean plants from the budding phase to flowering, when the vegetative mass is intensively growing. During this period, nitrogen fixation is also maximum. A significant amount of nitrogen is also used during grain filling. The rates of mineral fertilizers should be calculated based on their availability in the soil, the level of the planned harvest, etc. Phosphorus and potassium fertilizers are usually applied during the main tillage (P45–60, K45–60). The starting dose of nitrogen fertilizers (N 20–30) is given during pre-sowing tillage on poor soils and after poor unfertilized predecessors. In addition to macroelements, the growth and development of soybean plants require microelements, the most important of which are boron, molybdenum, and cobalt. The deficiency of these elements reduces yield, causes diseases, and worsens grain quality. The availability of trace elements in sufficient quantities is a key condition for intensive nitrogen fixation (Demianenko, 2014).

It is difficult to overestimate the importance of macroelements such as nitrogen, phosphorus, potassium and sulfur for soybean productivity. However, crop productivity is often limited by a deficiency of one specific trace element at a certain stage of plant development.

The use of microelements for the soybean development helps to improve metabolism, ensures the proper progression of biochemical and physiological processes under normal conditions, facilitates chlorophyll synthesis, and increases the intensity of photosynthesis. Microelements also improve plant resistance to adverse weather conditions (temperature fluctuations, moisture deficiency in the soil), protect plants from a significant number of bacterial and fungal diseases, thereby strengthening their immunity. Pre-sowing seed treatment is the most effective way to use microfertilizers in soybeans. Thus, according to the results of field studies, a positive effect of pre-sowing soybean seed treatment with microelements on field germination and plant density in crops has been determined. Pre-sowing soybean seed treatment with a mixture of Nitro-Dar and microelements resulted in the following indicators: a twofold increase in the number of nodules of nitrogen-fixing bacteria on soybean plants in the branching phase; increase nodule mass leading to the improved plant development and increased productivity (Hadzovskyi and Novytska, 2018).

The use of microfertilizers in pre-sowing soybean seed treatment has shown a positive effect on the yield structure formation. Thus, depending on the applied microfertilizers, the attachment height of the lowest pods in different experimental soybean varieties was within 13.2–15.9 cm. When seeds were treated with Active Corn Legume, the highest number of pods per plant (15.9–16.7 pods) and the weight of 1.000 seeds (167.3–190.5 g) were recorded. The yield increase depended on the soybean variety and the applied micronutrient fertilizers: VUKSAL CoMo Active – 0.22–0.28 t/ha; Nano-Mineralis – 0.47–0.56 t/ha; Active Corn Legume – 0.58–0.70 t/ha. In leguminous crops, the availability of molybdenum (Mo) plays a key role in nitrogen fixation, as it is a component of the iron-molybdenum (Fe-Mo) catalytic complex, which converts atmospheric nitrogen into ammonia.

Boron (B) availability throughout the growing season also significantly affects soybean productivity. High boron levels during soybean flowering have a positive effect on bud formation and pollination. However, the role of boron extends far beyond as it is involved in carbohydrate transport within the plant, phytohormone synthesis, and plant tissue formation and development. Manganese (Mn) availability in plants is important for the process of photosynthesis, ammonia oxidation, and nitrate reduction (Hadzovskyi and Novytska, 2018).

The combination of such microelements as Mo, Mn, and B is the basis of most modern foliar nutrition fertilizers. These fertilizers typically contain chelated microelements, and their ratio may vary depending on the crop, growth stage, and production objectives. The critical growth phases when soybeans require the highest micronutrient availability include 4–6 leaf stage, bud formation and pod formation. Ensuring available forms of microelements during these key growth phases allows soybeans to maximize their biological yield potential by increasing the number of fertile flowers and pods (Hadzovskyi and Novytska, 2018).

The aim of the research is to determine the optimal fertilization strategies for soybean varieties in combination with foliar nutrition and pre-sowing seed treatment using inoculants, micronutrients, and seed protectants.

MATERIALS AND METHODS

The study was conducted in 2024 in the conditions of the Druzhba Agricultural Limited Liability Company, Vinnytsia district, Vinnytsia Region, Ukraine. The total area of the experimental plot is 40 m^2. The accounting area is 25 m^2. Replication is four times (Vovkodav, 2001) (Table 1).

According to the research methodology, a three-factor field experiment was established: Factor A – varieties: 1. Betina; 2. Vyshyvanka; Factor B – inoculation: 1. Without inoculation; 2. HighCot Super (1.42 l/t). Factor C – fertilization: 1. Without fertilizers (control); 2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL (1 l/t) − (background); 3. Background + Wonder Micro (1.5 l/t); 4. Background + Wonder Micro+ Wonder Yellow (2,5 kg/ha); 5. Background + Wonder Micro + Wonder Yellow + Wonder Bor (2 l/ha).

Betina variety was registered in the State Register of Ukraine in 2019. The duration of the growing season is 107-113 days. Plant height is 64.5–90.1 cm. The resistance scores are as follows: lodging resistance 8–9 points, pod shattering resistance 8–9 points, drought tolerance 8

Table 1. Experiment scheme

Soybean variety (factor A)	Inoculation (factor B)	Fertilization (factor C)
1.Betina 2.Vyshyvanka	1.Without inoculation 2. Inoculation (HighCot Super)	1.Without fertilizers (control); 2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL (seed treatment with BBCH0) − (background); 3. Background + Wonder Micro (seed treatment BBCH0) ; 4. Background + Wonder Micro+ Wonder Yellow (treatment of crops at the microstage BBCH 14-15); 5. Background + Wonder Micro+ Wonder Yellow + Wonder Bor (treatment of crops at the microstage BBCH 51-59).

points, resistance to peronospora 8–9 points, to ascochyta 8–9 points, to bacteriosis 8–9 points, to septoria 8–9 points, to fusarium 9 points. Protein content is 35.9–38.0%. Oil content is 22.5–23.8%.

Vyshyvanka variety was registered in the State Register of Ukraine in 2019. The duration of the growing season is 110 days, the potential yield is 3.5–3.7 t/ha, the protein content is 40%, it has large seeds and the mass of 1,000 seeds is 200–210 g. It is resistant to the most common diseases and cracking of beans. The average yield of the variety over the five previous years was 18.6–22.4 c/ha. The yield of the variety is 14.4–24.9 c/ha. Plant height is 68.5–82.5 cm. The resistance scores are as follows: lodging resistance 8–9 points, pod shattering resistance 8 points, drought resistance 8 points, resistance to peronosporosis 9 points, to ascochitosis 9 points, to bacteriosis 8–9 points, to septoria 9 points, to fusarium 9 points. Oil content is 21.8–22.9%.

Maxim XL fungicide. The active ingredients in Maxim XL are fludioxonil and metalaxyl-M. These substances are protective pesticides. They have a broad-spectrum antifungal effect, inhibiting and preventing the growth of mycelium by disrupting cell membrane functions, which, in turn, hinders the growth and reproduction of fungal pathogens. Mefenoxam slows down and completely suppresses the formation of proteins in pathogenic fungi, which leads to the death of the latter. Prolonged use of Maxim XL has been observed to cause resistance in some pathogens. However, in Ukraine, when used in combination with the contact pesticide fludioxonil, the resistance of the causative agent of Peronospora and Phytophtora was not detected. The use of this fungicide is justified for protection against fungal infections, soil-borne and seed-borne pathogens.

HighCot Super inoculant contains a highly effective strain 532 C of the nodule-forming bacterium *Bradyrhizobium japonicum* with a minimum titer of at least 1x1010/g, which is currently the highest indicator available on the market. The inoculant is available in a two-component liquid formulation, consisting of a bacterial solution and an extender solution that ensures bacterial nutrition on the seed surface and prolongs their viability. The application rate is 1.42 l of HighCot Super + 1.42 l of HighCot Super Extender per 1 ton of soybean seeds. HighCot Super is a unique innovative pre-inoculation technology developed by BASF, allowing for high-quality early seed inoculation, which helps to prepare the planting material in advance and saves time during spring fieldwork. This inoculant is compatible with certain fungicides and insecticides registered for soybeans, for example, Standak®Top. However, before using with other fungicides, a compatibility test must be performed. When applying microelements, it is necessary to consider their synergistic effects, ensuring that the plants receive adequate macroelements.

Wonder Yellow is a balanced universal water-soluble crystalline fast-soluble fertilizer with a high content of available forms of macro- and microelements in chelated form. It is used for foliar nutrition of most field, vegetable, and garden crops during periods of intensive plant growth and development. It is suitable for all crops during fertigation with a concentration of 0.1–0.2%.

Wonder Bor optimizes pollination and fertilization process of flowers, increases pollen viability, enhances fruits and seed formation. It improves nutrient absorption and transport of carbohydrates from leaves to roots and reproductive organs. It strengthens cellular structures and normal tissue differentiation, making them more resilient. It is used to nourish plants that are particularly sensitive to boron deficiency, including sugar beets, rapeseed, soybeans, sunflowers, fruit trees, vegetables, and potatoes.

Wonder Micro is used for foliar nutrition of all crops and treatment of the planting material. Due to the high content of amino acids, phytohormones, and microelements, it effectively stimulates metabolic processes in the plants. It provides an increase in quantitative and qualitative indicators of plant productivity. Seed treatment at the rate of 1.5 l per ton of seeds increases germinating capacity and seed germination energy. It stimulates the development of a powerful root system and improves winter hardiness of winter crops.

The number and mass of nodules were determined using the monolith method, by applying a frame measuring 300×167 mm (0.05 m^2). Thus, knowing the monolith area and the average plant density, there was determined the number and mass of nodules per plant (Volkogon, 2010).

Active symbiotic potential (ASP) was calculated by the Equation 1:

$$ASP = \frac{M\,1 + M\,2}{2} \times T \quad (1)$$

where: T is the interval between two consecutive sampling dates (days); $\frac{M\,1+M\,2}{2}$ average mass of nodules with leghemoglobin over the period T (kg/ha).

The amount of fixed nitrogen was calculated based on the active symbiotic potential, symbiosis-specific nitrogen fixation activity, following the described methodologies (Volkogon, 2010).

The harvest data was subjected to analysis of variance (Moiseichenko and Yeshchenko, 1994).

Processing of experimental data and statistical analysis of the results were performed on a PC using MS Excel 2019 software (Microsoft, USA) and Statistica 12.6 (Dell Technologies, USA) using built-in statistical functions. Statistical functions are functional software modules that implement individual statistical formulas (calculation of average values, correlation coefficient, *etc*.), and can be used in formulas. The small sample method was used. The method of small samples provided for the determination of the arithmetic mean values (x) and the deviation of the arithmetic mean values (± Sx). The data in the tables are presented in the form of x ± Sx (mean ± standard deviation). Statistical evaluation of differences was performed using Student's t-test. The difference was considered significant if the calculated criterion for the reliability of the difference (experimental) is equal to or exceeds the standard value of the Student's t-test.The results of the average values were considered statistically significant at * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (Moiseichenko and Yeshchenko, 1994).

Measuring-weighing and monolith method was used to determine the size of the symbiotic apparatus of soybean and establish the amount of biologically fixed nitrogen; statistical and mathematical method was used to determine the reliability and accuracy of the obtained research results.

RESULTS AND DISCUSSION

Due to the activity of nodule bacteria on the roots, soybean enriches the soil with nitrogen, improves its structure and fertility, and serves as a valuable predecessor for other crops in crop rotation. However, for nodule bacteria to function effectively, it is essential to create optimal conditions for their vital activity. Observing the dynamics of nodule formation, we found out that the number of rhizobial nodules increased throughout the growing season. One of the most effective method for enhancing the efficiency of legume-rhizobial symbiosis is the use of preparations based on active strains of nodule-forming bacteria (Volkogon et al, 2010).

The development of a strong symbiotic apparatus of leguminous crops depends not only on the effective interaction of the genotypes of the host plant and nodule bacteria under specific growing conditions but also on certain agronomic practices, including the use of bacterial inoculations, the type of inoculant and the method of its application, mineral fertilizatation and methods of applying microfertilizers,use of plant growth regulators, etc. (Patyka et al., 1993; Kots et al., 2010; Kots et al. 2011).

The studies examined the influence of seed inoculation and fertilization on the features of the symbiotic apparatus formation in soybean plants. The results showed that the number and mass of nodules in the soybean root system depended primarily on the applied cultivation technologies and varietal characteristics.

The study of the process of the soybean symbiotic apparatus formation revealed that the number of nodules increased, starting from the microstage BBCH 51-59, reaching its peak at the microstage BBCH 68-69, and then decreased at the microstage BBCH 80-90.

To assess quantitative characteristics of nitrogen fixation in soybean, we counted active nodules on the plant roots. Active nodules were identified as those with a pink color, indicating the presence of leghemoglobin (Korobko et al., 2024). Leghemoglobin regulates oxygen supply and protects one of the natural enzymes – nitrogenase – from degradation (Mazur et al., 2024).

The lowest total number of nodules was observed in the control variant at the microstage BBCH 51-59, where no seed inoculation was applied and amounted to 14.3 nodules per plant, of which 7.2 were active, in Betina variety, and 12.4, of which 5.8 were active, in Vyshyvanka variety (Table 2 and Table 3).

The application of mineral fertilizer at the rate of $N_{20}P_{20}S_9$, as well as seed treatment with Maxim XL, contributed to an increase in the total number of nodules in Betina variety to 15.5 nodules per plant, of which 8.4 were active, and in Vyshyvanka variety to 13.6 nodules per plant, of which 6.9 were active. This represents an increase of 1.2 and 1.1 nodules compared to the control variant. When treating seeds with Wonder Micro microelements against the background of the application of mineral fertilizer and seed treatment, the total number of nodules per plant increased to 16.6, of which 9.3 were active, in Betina variety and 14.7, of which 7.5 were active, in Vyshyvanka variety,

Table 2. The influence of seed inoculation and fertilization on the dynamics of the total number of nodules (nodules per plant) on soybean roots, 2024

Variety	Fertilization	Microstage							
		BBCH 51-59		BBCH 61-62		BBCH 68-69		BBCH 80-90	
		Inoculation							
		w/i	i	w/i	i	w/i	i	w/i	i
Betina	1. Without fertilizers (control)	14.3±0.3	25.0 ±0.5	23.7 ±0.5	35.4 ±0.7	31.6 ±0.6	43.2 ±0.9	17.7 ±0.4	29.5 ±0.5
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background))	15.5 ±0.3	26.0 ±0.5	25.6 ±0.5	37.7 ±0.7	33.8 ±0.6	45.9 ±0.9	19.3 ±0.4	31.4 ±0.5
	3. Background + Wonder Micro	16.6 ±0.3	26.7 ±0.5	26.8 ±0.5	39.9 ±0.7	35.3 ±0.6	47.7 ±0.9	20.4 ±0.4	33.3± 0.6
	4. Background + Wonder Micro+ Wonder Yellow	17.5 ±0.3	27,3 ±0.5	27.5 ±0.5	40.5 ±0.7	36.1 ±0.6	49.2 ±0.9	21.6 ±0.4	34.5 ±0.6
	5. Background + Wonder Micro+ Wonder Yellow + Wonder Bo	17.5 ±0.3	27.3 ±0.5	27.9 ±0.5	40.8 ±0.7	37.8 ±0.6	50.4± 0.9	22.3 ±0.4	35.6 ±0.6
Vyshy-vanka	1. Without fertilizers (control)	12.4 ±0.2	23.1 ±0.4	21.8 ±0.4	33.3 ±0.6	29.5 ±0.5	41.1 ±0.8	15.8 ±0.3	27.4 ±0.4
	2. $N_{20}p_{20}S_9$ + seed treatment with Maxim XL – (background)	13.6 ±0.2	24.1 ±0.4	23.7 ±0.4	35.6 ±0.6	31.7 ±0.5	43.8 ±0.8	17.2 ±0.3	29.3 ±0.4
	3. Background + Wonder Micro	14.7 ±0.2	24.8 ±0.4	24.9 ±0.4	37.8 ±0.6	33,2 ±0.5	45.6 ±0.8	18.3 ±0.3	31.2 ±0.5
	4. Background + Wonder Micro+ Wonder Yellow	15.3 ±0.2	25.4 ±0.4	25.6 ±0.4	38.6 ±0.6	34.2 ±0.5	47.1 ±0.8	19.5 ±0.3	32.4± 0.5
	5. Background + Wonder Micro+ Wonder Yellow+ + Wonder Bo	15.3 ±0.2	25.4 ±0.4	25.8 ±0.4	38.9 ±0.6	35.7 ±0.5	48.5± 0.8	20.2 ±0.3	33.5± 0.5

which is 1.1 and 1.3 and 2.1 and 1.7 nodules more compared to the control variant. This increase is attributed to better microelement availability, compared to previous experimental treatments.

Seed inoculation with HighCot Super significantly increased the number of nodules per plant compared to fertilization. Seed inoculation with the preparation based on the highly effective strain 532 C of the nodule bacterium *Bradyrhizobium japonicum* increased both the total number of nodules and their active part by 10.7 and 10.3 nodules per plant, respectively, in Betina variety, and in Vyshyvanka variety by 10.7 and 10.0 nodules per plant in the control variant.

In the experiment variant, where seed treatment with the inoculant and microelements Wonder Micro was carried out against the background of fertilization and seed treatment, the highest symbiotic apparatus formation was observed in Betina variety by 10.1 and 11.5 nodules per plant, respectively, and in Vyshyvanka variety by 10.1 and 10.2 nodules per plant.

Crop treatment with Wonder Yellow at microstage BBCH 14–15, combined with HighCot Super seed inoculation against the background of fertilization and seed treatment at microstages 61–62 ensured the formation of the highest indicators of the symbiotic apparatus, namely the total number of nodules in Betina variety was 40.5 nodules per plant, of which 33.8 nodules per plant were active and in the Vyshyvanka variety – 38.6 nodules per plant, of which 28.3 nodules per plant were active. These values were 13.0 and 13.3 nodules per plant (Betina variety) and 13.0 and 11.4 nodules per plant (Vyshyvanka) higher compared to non-inoculated variant. Spraying soybean crops with a solution of a multicomponent chelated

Microfertilizer improved nodule formation by enhancing the penetration of nodule bacteria into the tissues of the root system. The maximum values of the symbiotic apparatus of soybean varieties were recorded at microstage 68-69 in the experiment variant, where the combined treatment of crops with Wonder Yellow at microstages BBCH 14–15 and Wonder Bor at microstages BBCH 51–59 was carried out against the background of seed treatment with the inoculant HighCot Super, the application of mineral fertilizer at the rate of $N_{20}P_{20}S_9$, as well as seed treatment with Maxim XL. In particular, the total number of nodules in Betina variety was 50.4, of which 43.8 were active per plant, and in Vyshyvanka variety it was 48.5, of which 38.3 were active per plant. This is higher compared to non-inoculated variant by 12.6 and 13.6 nodules per plant and 12.8 and 12.9 nodules per plant, respectively.

Table 3. Influence of seed inoculation and fertilization on the dynamics of the active nodule number (nodules per plant) on the soybean roots, 2024

Variety	Fertilization	Microstage							
		BBCH 51–59		BBCH 61–62		BBCH 68–69		BBCH 80–90	
		Inoculation							
		w/i	i	w/i	i	w/i	i	w/i	i
Betina	1.Without fertilizers (control)	7.2 ±0.1	17.5 ±0.3	16.5 ±0.3	27.3 ±0.5	24.5 ±0.4	36.1 ±0.7	11.2 ±0.2	19.3 ±0.3
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	8.4 ±0.1	19.3 ±0.3	18.4 ±0.3	29.6 ±0.5	25.9 ±0.4	38.3 ±0.7	12.4 ±0.2	21.5 ±0.3
	3. Background + Wonder Micro	9.3 ±0.1	20.8 ±0.3	20.0 ±0.3	32.1 ±0.5	28.1 ±0.4	40.3 ±0.7	13.5 ±0.2	22.2± 0.3
	4. Background + Wonder Micro+ Wonder Yellow	9.8 ±0.1	21.5 ±0.3	20.5 ±0.3	33.8 ±0.5	29.6 ±0.4	42.5 ±0.7	14.7 ±0.2	24.1 ±0.4
	5. Background + Wonder Mikro+ Wonder Yelow +Wonder Bor	9.9 ±0.1	21.5 ±0.3	20.5 ±0.3	33.9 ±0.5	30.2 ±0.4	43.8± 0.7	15.6 ±0.2	25.2 ±0.4
Vyshy-vanka	1.Without fertilizers (control)	5.8± 0.1	15.8 ±0.3	14.9 ±0.3	25.4 ±0.5	22.6 ±0.4	34.2 ±0.7	9.9 ±0.2	17.7 ±0.3
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	6.9 ±0.1	16.9 ±0.3	15.8 ±0.3	26.9 ±0.5	23.9 ±0.4	35.5 ±0.7	11.1 ±0.2	19.0± 0.3
	3. Background + Wonder Micro	7.5 ±0.1	17.7 ±0.3	16.7 ±0.3	27.7 ±0.5	25,1 ±0.4	36.4 ±0.7	12.2 ±0.2	21.1 ±0.4
	4. Background + Wonder Micro+ Wonder Yellow	8.0 ±0.1	18.5 ±0.3	16.9 ±0.3	28.3 ±0.5	25.3 ±0.4	37.4 ±0.7	13.4 ±0.2	22.5 ±0.4
	5. Background + Wonder Micro+ Wonder Yellow + Wonder Bo	8.0 ±0.1	18.5 ±0.3	16.9 ±0.3	28.6 ±0.5	25.4 ±0.4	38.3 ±0.7	14.1 ±0.2	23.4 ±0.4
	LSD0.05 total LSD0.05 variety LSD0.05 fertilization LSD0.05 inoculation	3.19 1.14 0.18 1.09		3.91 1.26 0.23 1.23		4.01 1.38 0.27 1.33		3.28 1.32 0.24 1.31	

At the microstage of BBCH 80–90, a significant decrease in the number of nodules was recorded, which was associated with biological aging and the natural decline in the nodule life cycle. However, the highest total number of nodules was recorded in this variant of the research in Betina variety – 35.6, of which 25.2 were active per plant, and in Vyshyvanka variety – 33.5, of which 23.4 were active per plant. These values were 13.3 and 9.6 nodules per plant (Betina) and 13.3 and 9.3 nodules per plant (Vyshyvanka) higher than in the non-inoculated variant.

In addition, another significant indicator of the nitrogen fixation efficiency by soybeans is the mass of nodules and the duration of their functioning.

It is well known that the mass of nodules varies depending on the phase of plant development and the conditions of their cultivation and can remain stable for no more than 7–10 days. The studies confirm that atmospheric nitrogen fixation occurs only in those nodules that contain leghemoglobin.

Therefore, it is most important to consider the mass of nodules containing leghemoglobin, while the total mass should only be considered as a measure of the symbiotic apparatus activity. The degree of the symbiotic apparatus activity depends on the average mass of nodules (Korobko et al., 2024; Yatsenko et al., 2023; Mostovenko et al., 2022; Mazur et al., 2023).

The study results showed that the total mass of nodules increased in the first half of the growing season, reaching its peak at the microstage BBCH 68-69.

The lowest values of the total and active mass of nodules were recorded in the control variant at the microstage BBCH 51–59, where no inoculation was applied and amounted to 32.6 mg/plant in Betina variety, of which 19.6 mg/plant were active, and 29.2 mg/plant in Vyshyvanka variety, of which 17.5 mg/plant were active (Table 4 and Table 5).

Applying mineral fertilizer at the rate of $N_{20}P_{20}S_9$ and seed treatment with Maxim XL contributed to an increase in both the total and active mass of nodules in Betina variety to 40.3, of which 24.2 were active, and in Vyshyvanka variety to 36.8, of which 24.2 were active mg/plant. These values are higher compared to the control variant by 7.7 and 4.6; 7.6 and 4.6 mg/plant, respectively. Against the background of mineral fertilizer application and seed treatment, the application of

Table 4. The influence of seed inoculation and fertilization on the dynamics of the total mass of nodules (mg/plant) on soybean roots, 2024

Variety	Foliar nutrition	Microstage							
		BBCH 51–59		BBCH 61–62		BBCH 68–69		BBCH 80–90	
		Inoculation							
		w/i	i	w/i	i	w/i	i	w/i	i
Betina	1.Without fertilizers (control)	32.6 ±0.8	43.4 ±1.0	245.7 ±9.0	415.0 ±15.0	344.3 ±11.0	515.0 ±17.0	48.6	76.6
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	40.3 ±0.9	48.0 ±1.0	261.4 ±10.0	443.8 ±15.0	362.9 ±12.0	528.8 ±17.0	51.4	81.5
	3. Background + Wonder Micro	44.8 ±0.9	50.6 ±1.1	278.6 ±11.0	461.3 ±16.0	378.6 ±12.0	545.0 ±17.0	61.7	89.8
	4. Background + Wonder Micro + Wonder Yellow	46.0 ±0.9	51.0 ±1.1	282.9 ±11.0	483.8 ±16.0	391.4 ±13.0	567.5 ±17.0	68.6	93.3
	5. Background + Wonder Micro + Wonder Yellow + Wonder Bo	46.0 ±0.9	51.0 ±1.1	284.3 ±11.0	487.5 ±16.0	411.4 ±14.0	586.3 ±17.0	72.3	100.4
Vyshy–vanka	1. Without fertilizers (control)	29.2 ±0.7	40.3 ±1.0	234.3 ±9.0	397.5 ±14.0	327.1 ±11.0	496.3	44.3	72.5
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	36.8 ±0.8	44.9 ±1.0	248.6 ±9.0	415.0 ±15.0	338.6 ±11.0	515.0	47.1	76.3
	3. Background + Wonder Micro	41.3 ±0.9	47.4 ±1.0	261.4 ±10.0	438.8 ±16.0	355.7 ±12.0	533.8	50.0	83.8
	4. Background + Wonder Micro + Wonder Yellow	42.0 ±0.9	48.3 ±1.0	264.3 ±10.0	441.3 ±16.0	374.3 ±12.0	551.3	54.3	89.4
	5. Background + Wonder Micro + Wonder Yellow + Wonder Bo	42.0 ±0.9	48.3 ±1.0	265.7 ±10.0	443.8 ±16.0	391.4 ±13.0	581.3	57.9	94.9
	LSD0.05 total	4.17		5.02		5.08		3.71	
	LSD0.05 variety	1.52		1.39		1.48		1.42	
	LSD0.05 fertilization	0.26		0.28		0.31		0.23	
	LSD0.05 inoculation	1.43		1.38		1.47		1.42	

Wonder Micro microelements to treat seeds provided an increase in both the total and active mass of nodules per plant to 44.8 mg/plant in Betina variety, of which 26.9 mg/plant was active, and 41.3 mg/plant in the Vyshyvanka variety, of which 24.8 mg/plant was active, which was 12.2 and 7.3; 12.1 and 7.3 mg/plant more compared to the control variant. This increase is attributed to better microelement availability compared to previous experimental treatments.

There was observed the advantage of the effect of pre-sowing bacterization of seeds with HighCot Super on both the total and active mass of nodules compared to fertilization. Thus, in the control variant, both the total and active number of nodules increased by 10.8 and 10.8 mg/plant in Betina variety, as well as by 11.1 and 10.7 mg/plant in the control variant in Vyshyvanka variety.

In the experimental variant, where against the background of fertilization and seed treatment with Maksym XL, seeds were treated with HighCot Super inoculant and Wonder Micro trace elements, there was observed an increase in total and active nodule mass by 5.8 and 8.5 mg/plant in Betina variety and by 6.1 and 8.4 mg/plant in Vyshyvanka variety.

At microstage BBCH 61-62, an increase in the indicators of symbiotic apparatus of both total and active mass of nodules was observed when treating crops with Wonder Yellow, a chelated fertilizer of macro- and microelements, in combination with pre-sowing bacterization and seed treatment against the background of fertilization in Betina variety – 483.8 mg/plant, of which 387 mg/plant were active, and in Vyshyvanka variety – 441.3 mg/plant, of which 353 mg/plant were active. This is higher compared to the option without seed inoculation by 200.9 and 189 mg/plant and 177.0 and 168 mg/plant.

The maximum total and active mass of nodules of soybean varieties was observed at microstage BBCH 68-69 in the experimental variant, where the combined treatment of crops with chelated water-soluble fertilizers based on

macro- and microelements Wonder Yellow and Wonder Bor was applied against the background of seed treatment with HighCot Super inoculant, application of mineral fertilizer at the

Table 5. Influence of seed inoculation and fertilization on the dynamics of active nodule mass (mg/plant) on soybean roots, 2024

Variety	Foliar nutrition	Microstage							
		BBCH 51–59		BBCH 61–62		BBCH 68–69		BBCH 80–90	
		Inoculation							
		w/i	i	w/i	i	w/i	i	w/i	i
Betina	1. Without fertilizers (control)	19.6 ±0.5	30.4 ±0.7	172 ±6	332 ±9	241 ±8	412 ±14	34 ±1	61.3 ±2
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	24.2 ±0.6	33.6 ±0.8	183 ±7	355 ±11	254 ±9	423 ±15	36 ±1	65.2 ±2
	3. Background + Wonder Micro	26.9 ±0.7	35.4 ±0.9	195 ±8	369 ±11	265 ±9	436 ±16	43 ±2	71.8 ±2
	4. Background + Wonder Micro + Wonder Yellow	27.8 ±0.7	36.0 ±1.0	198 ±8	387 ±12	274 ±9	454 ±16	48 ±2	74.6 ±2
	5. Background + Wonder Micro + Wonder Yellow + Wonder Bor	27.8 ±0.7	36.0 ±0.6	199 ±9	390 ±12	288 ±9	469 ±16	50.6 ±2	80.3 ±2
Vyshy–vanka	1. Without fertilizers (control)	17.5 ±0.4	28.2 ±0.6	164 ±5	318 ±8	229 ±8	397 ±11	31 ±1	58 ±2
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	22.1 ±0.5	31.4 ±0.7	174 ±6	332 ±9	237 ±8	412 ±14	33 ±1	61 ±2
	3. Background + Wonder Micro	24.8 ±0.6	33.2 ±0.8	183 ±7	351 ±10	249 ±9	427 ±16	35 ±2	67 ±2
	4. Background + Wonder Micro + Wonder Yellow	26.0 ±0.6	34.3 ±0.8	185 ±7	353 ±11	262 ±9	441 ±16	38 ±2	71.5 ±2
	5. Background + Wonder Micro + Wonder Yellow + Wonder Bor	26.0 ±0.6	34.3 ±0.8	186 ±8	355 ±11	274 ±9	465 ±16	40.5 ±2	75.9 ±2
	LSD0.05 total LSD0.05 variety LSD0.05 fertilization LSD0.05 inoculation	4.05 1.46 0.21 1.39		4.92 1.28 0.25 1.32		5.01 1.37 0.28 1.36		3.37 1.31 0.21 1.33	

rate of $N_{20}P_{20}S_9$ and seed treatment with Maxim XL. Thus, it was 586.3 mg/plant in Betina variety, of which 469 mg/plant were active, and 581.3 mg/plant in Vyshyvanka variety, of which 465 mg/plant were active. This was higher compared to the variant without seed inoculation by 174.9 and 181 mg/plant and 189.9 and 191 mg/plant, respectively.At the microstage BBCH 80-90, a significant decrease in the nodule mass was observed, which is associated with the process of extinction of the nodule life cycle. However, it should be noted that the highest, both total and active, number of nodules was recorded in this variant of the research in Betina variety – 100.4 mg/plant, of which 80.3 mg/plant were active, and in Vyshyvanka variety – 94.9 mg/plant, of which 75.9 mg/plant were active. This is higher compared to the variant without seed inoculation by 28.1 and 29.7 and 37.0 and 35.4 mg/plant, respectively.

The application of microfertilizers in the experimental variants during the growing season positively affected the number of total and active nodules.

In addition to the mass of root nodules with leghemoglobin, the amount of symbiotically fixed nitrogen depends on the duration of their functioning, i.e. the time period from the leghemoglobin formation in the nodules to its degradation into choleglobin. The active symbiotic potential (ASP) combines these two criteria of nitrogen fixation (Mazur et al., 2023; Korobko et al., 2024; Yatsenko et al., 2023; Mazur et al., 2024).

Having determined the dynamics of the nodule mass accumulation on the roots of soybean varieties and the duration of symbiosis in the experiment, we calculated the indicators of the total and active symbiotic potentials depending on the influence of the factors studied. These results align with the findings of studies by other scientists.

An important indicator of the state of legume-rhizobia symbiosis during the growing season is the total and active symbiotic potential, the values of which depend on the duration of the symbiotic apparatus. Total symbiosis duration is determined from the appearance of the first nodules on soybean roots until their complete decomposition, while the active symbiosis duration is determined from the appearance of red pigment in the nodules until its destruction (Honcharuk, 2023; Mazur et al., 2024; Mazur et al., 2023).

The ASP during the growing season is determined by the sum of ASP values for individual periods. Similarly, the total symbiotic potential (TSP) is calculated by considering the mass of all nodules. This indicator has a more theoretical significance and is determined in cases where it is necessary to show the influence of individual environmental factors on the activity of symbiosis, since they affect the mass of nodules with leghemoglobin more than their total mass (Mazur et al., 2023; Korobko et al., 2024; Yatsenko et al., 2023; Mazur et al., 2024).

The formation of both total and active symbiotic potential was determined primarily by seed inoculation and fertilization (Table 6).

It was established that pre-sowing seed treatment with inoculant significantly influenced the formation of the level of symbiotic potential of soybean plants. It ensured a more active colonization of soybean plant roots with symbiotic bacteria, activation of the process of symbiosis formation, which in turn contributed to an increase in the amount of biological nitrogen fixation by microorganisms.

Indicators of total and active symbiotic potential are determined by both the total and active mass of nodules and their duration. Pre-sowing bacterization of seeds extended the duration of both total and active symbiosis in Betina soybean variety from 3 to 4 days and in Vyshyvanka soybean variety by 4 days, respectively. The longest period of both total and active symbiosis was recorded in the experiment variant, where the combined treatment of crops with water-soluble fertilizers based on macro- and microelements Wonder Yellow and Wonder Bor was carried out against the background of seed treatment with HighCot Super inoculant, application of mineral fertilizer at the rate of $N_{20}P_{20}S_9$ and seed

Treatment with maxim XL in Betina variety – 90.0 and 81 days, in Vyshyvanka variety – 88 and 79 days, respectively. This is higher compared to the absolute control by 7 and 8, as well as 8 days, respectively. In addition, this variant showed the highest indicators of both total and active symbiotic potential, in particular in Betina variety – 37.3 and 26.2 thousand kg·days/ha, and in Vyshyvanka variety – 34.8 and 24.6 thousand kg·days/ha, which is higher compared to the control variant by 18.3, 14.9 and 17.8; 14.2 thousand kg·days/h, respectively.

Based on the conducted studies, it was found that pre-sowing seed treatment significantly improved the symbiotic productivity of soybean agrophytocenosis. Seed inoculation with highly effective strains of nodule bacteria enables the realization of up to 15–50% of the symbiotic nitrogen-fixing potential, and the remaining reserve can be utilized through the optimization of

Table 6. The influence of seed inoculation and fertilization on the dynamics of formation of the total and active symbiotic potential, thousand kg·days/ha, 2024

Variety	Foliar nutrition	Duration of symbiosis, days				Symbiotic potential, thousand kg·days/ha			
		Total		Active		Total		Active	
		w/i	i	w/i	i	w/i	i	w/i	i
Betina	1.Without fertilizers (control)	83± 1.2	86± 1.2	73± 1.0	77± 1.1	19.0± 0.7	31.0± 0.9	11.3± 0.4	21.2± 0.8
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	84± 1.2	87± 1.3	74± 1.0	78± 1.1	20.3± 0.8	32.7± 0.9	12.1± 0.4	22.5± 0.8
	3. Background + Wonder Micro	85± 1.2	88± 1.3	75± 1.0	79± 1.1	21.9± 0.8	34.2± 0.9	13.0± 0.5	23.7± 0.8
	4. Background + Wonder Micro+ Wonder Yellow	86± 1.2	89± 1.3	76± 1.0	80± 1.1	22.8± 0.9	36.0± 0.9	13.1± 0.5	25.1± 0.9
	5. Background + Wonder Micro+ Wonder Yellow + Wonder Bo	87± 1.2	90± 1.3	77± 1.0	81± 1.1	23.8± 0.9	37.3± 0.9	14.1± 0.5	26.2± 0.9
Vyshy–vanka	1.Without fertilizers (control)	80± 1.1	84± 1.3	71± 1.0	75± 1	17.0± 0.8	28.9± 0.8	10.4± 0.4	19.7± 0.7
	2. $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background)	81± 1.1	85± 1.3	72± 1.0	76± 1	18.1± 0.7	30.4± 0.9	11.4± 0.4	20.9± 0.8
	3. Background + Wonder Micro	82± 1.1	86± 1.3	73± 1.0	77± 1.1	19.2± 0.8	32.1± 0.9	11.9± 0.4	22.3± 0.8
	4. Background + Wonder Micro+ Wonder Yellow	83± 1.1	87± 1.3	74± 1.0	78± 1.1	20.2± 0.8	33.2± 0.9	12.5± 0.4	23.2± 0.8
	5. Background + Wonder Micro+ Wonder Yellow + Wonder Bo	84± 1.2	88± 1.3	75± 1.1	79± 1.1	21.2± 0.9	34.8± 0.9	13.2± 0.5	24.6± 0.9

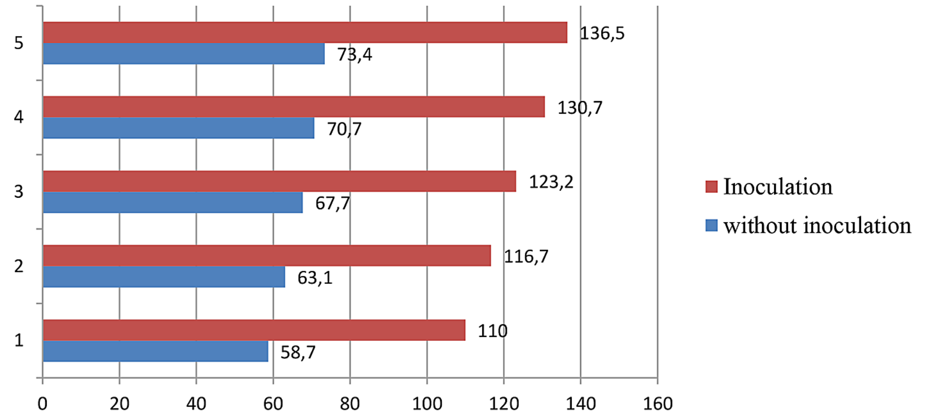

Figure 1. Amount of biologically fixed nitrogen in Betina soybean variety, kg/ha: 1. – without fertilizers (control); 2. – $N_{20}P_{20}S_9$ + seed treatment with Maxim XL – (background); 3. – Background + Wonder Micro; 4. – Background + Wonder Micro+ Wonder Yellow; 5. – Background + Wonder Micro+ Wonder Yellow + Wonder Bor

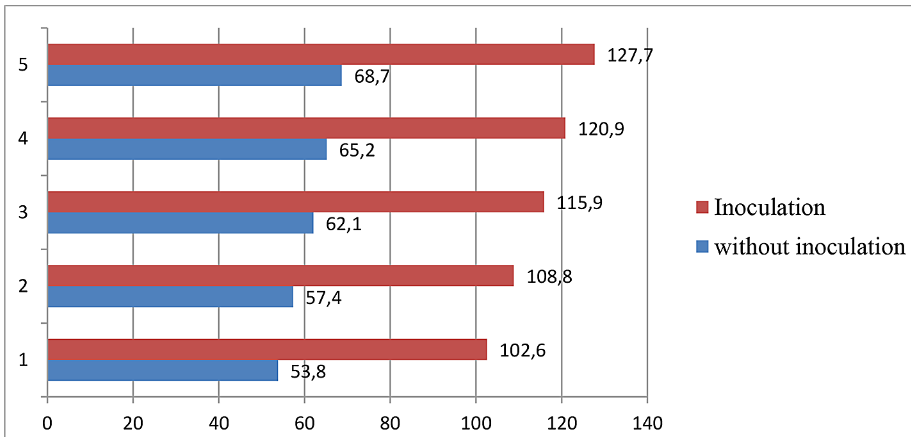

Figure 2. Amount of biologically fixed nitrogen in Vyshyvanka soybean variety, kg/ha, where HighCot Super seed inoculation was used and crops were treated with water-soluble fertilizers based on macro- and microelements Wonder Yellow and Wonder Bor against the background of mineral fertilizer application at the rate of $N_{20}P_{20}S_9$ and seed treatment with Maxim XL These values were higher compared to the absolute control by 77.8 and 73.9 kg/ha, respectively

conditions for the symbiosis functioning (Mazur et al., 2023; Korobko et al., 2024; Yatsenko et al., 2023; Mazur et al., 2024).

An essential condition for effective nitrogen fixation is the availability of a sufficient amount of microelements (molybdenum, boron, magnesium, iron, cobalt) during soybean growth and development. To meet the needs of soybean plants for microelements, microfertilizers containing nutrients in an accessible and easily digestible form are applied.

The highest amount of biologically fixed nitrogen (Betina variety – 136.5 kg/ha and Vyshyvanka – 127.7 kg/ha) was recorded in soybean plants in the experimental variants with the highest symbiotic potential (Fig. 1 and Fig. 2), The largest amount of nitrogen was recorded by plants of Betina variety, which was characterized by a longer symbiosis period and higher indicators of active symbiotic potential.

CONCLUSIONS

The highest indicators of the symbiotic apparatus of soybean varieties were recorded at microstage 68–69 in the experiment variant, where the combined crop treatment with Wonder Yellow at microstages BBCH 14–15 and Wonder Bor at microstages BBCH 51–59 was carried out against the background of seed treatment with HighCot Super inoculant, application of mineral fertilizer at the rate of $N_{20}P_{20}S_9$, as well as seed treatment with Maxim XL, in particular, the total number of nodules in Betina variety was 50.4, of which 43.8 nodudes per plant were active, and in Vyshyvanka variety – 48.5, of which 38.3 nodudes per plant were active. This is higher compared to the variant without seed inoculation by 12.6 and 13.6 nodules per plant and 12.8 and 12.9 nodules per plant, respectively.

In the same variant, the maximum total and active mass of nodules was observed in Betina variety – 586.5, of which 469 mg/plant were active, and in Vyshyvanka variety – 581.3, of which 465 mg/plant were active. This is higher compared to the variant without seed inoculation by 174.9 and 181 mg/plant and 189.9 and 191 mg/plant, respectively. The longest period of both total and active symbiosis was recorded in Betina variety – 90.0 and 81 days, and in Vyshyvanka variety – 88 and 79 days, respectively. This is higher compared to the absolute control by 7 and 8 and 8 days, respectively. The highest indicators of both total and active symbiotic potential were recorded, in particular in Betina variety – 37.3 and 26.2 thousand kg·days/ha and in Vyshyvanka variety – 34.8 and 24.6 thousand kg·days/ha, which is higher compared to the control variant by 18.3, 14.9, and 17.8, 14.2 thousand kg·days/ha, respectively. The maximum amount of biologically fixed nitrogen was recorded in Betina variety – 136.5 kg/ha and Vyshyvanka variety – 127.7 kg/ha. These results were 77.8 kg/ha (Betina) and 73.9 kg/ha (Vyshyvanka) higher compared to the absolute control.

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