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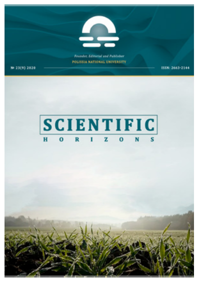

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Study of legume-rhizobia symbiosis in soybean for agroecosystem resilience

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Abstract. Research into innovative methods of regulating legume-rhizobia symbiosis is crucial for enhancing nitrogen fixation, thereby promoting soil health and increasing crop yields. This contributes to sustainable agriculture by reducing the need for chemical fertilisers and enhancing the resilience of agroecosystems. The study aimed to determine the impact of seed inoculation, environmental conditions, and varietal characteristics of soybean varieties on biological nitrogen accumulation. The research

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was conducted under the environmental conditions of Kyiv, Poltava, and Vinnytsia regions from 2010 to 2021. Cultivation practices for the soybean varieties adhered to standard regional agronomic guidelines. The findings detail the effects of seed inoculation on the dynamics of formation and productivity of soybean-rhizobial symbiosis in soils with existing native rhizobial populations. The nitrogen-fixing potential of soybean varieties under inoculation was identified, showing that inoculation enhances the efficiency of the soybean symbiotic system. It has been demonstrated that, across varied environmental conditions, seed inoculation with *Bradyrhizobium japonicum* enhances the formation and functioning of the soybean symbiotic apparatus, even in soils with existing native populations of nodule bacteria. The efficacy of seed inoculation is influenced by the hydrothermal conditions of the year, environmental factors, and soybean variety. Seed inoculation contributes to the development of a greater mass of active nodules on plant roots, positively impacting nitrogen fixation. The highest nitrogen fixation levels were observed in the soybean varieties Ametyst, Artemida, and Hoverla across different environmental conditions. Seed inoculation increased the amount of biologically fixed nitrogen in these varieties by 33.9-36.1 kg/ha. Varieties Ametyst, Artemida, and Hoverla showed a particularly strong response to inoculation with nitrogen-fixing bacteria and are recommended for cultivation in diverse environmental conditions. Innovative approaches to enhancing the efficiency of the soybean legume-rhizobia symbiosis through the use of biological inoculants based on nitrogen-fixing bacteria will enable the development of biologically-oriented cultivation technologies, promoting the resilience of agroecosystems

Keywords: nodule number and mass; nitrogen fixation; symbiotic potential; inoculation; hydrothermal coefficient; rhizobia; biologically fixed nitrogen

INTRODUCTION

Nitrogen is an essential plant nutrient, vital for biomass accumulation, phytohormonal regulation, and enzyme function. Nitrogen fixation, the process of converting atmospheric nitrogen into a plant-available form, plays a crucial role in maintaining soil fertility. The efficiency of nitrogen fixation is influenced by various factors, including the number and development of root nodules, the species of nitrogen-fixing microorganisms, the host plant, and environmental conditions. Soybean (*Glycine hispida* Maxim.) is a strategic crop for implementing the Green Deal in agriculture due to its unique ability to combine two essential processes: photosynthesis and biological nitrogen fixation. Therefore, investigating the efficiency of the legume-rhizobia symbiosis in soybeans, as influenced by varietal characteristics and environmental growing conditions, is highly relevant.

E. Kebede (2021) and S. Langyan *et al.* (2022) noted that the challenges of plant protein supply and soil fertility preservation can be addressed by cultivating optimal areas of legume crops. However, this is contingent upon ensuring effective symbiosis between legumes and rhizobia. Through the fixation of atmospheric nitrogen by symbiotic systems of legumes and rhizobia, as well as associative and free-living nitrogen-fixing microbes, approximately the same amount of biological nitrogen is annually contributed to the arable layer of the soil as is introduced through mineral nitrogen fertilisers.

Host plants are colonised by various rhizobia species differing in their virulence. Indigenous rhizobial populations in the arable layer are more mobile and virulent. However, nitrogen fixation in such legume-rhizobia symbioses is often inefficient, which is linked to the sensitivity of rhizobia to moisture conditions. According to A. Soumare *et al.* (2020), understanding the diversity of nitrogen-fixing microorganisms, their fixation mechanisms, and developing innovative biofertilizers based on this knowledge is an alternative approach to address this issue and optimise nitrogen fixation. Measures such as seed inoculation with biofertilizers before sowing, selecting drought-tolerant cultivars, and adjusting sowing dates can help maximise the potential of the legume-rhizobia symbiosis in soybeans. Optimising symbiotic nitrogen fixation is becoming increasingly important as it is an environmentally friendly and cost-effective method for maintaining soil fertility and increasing crop productivity (Abd-Alla *et al.,* 2023).

Soybeans consume more nutrients to produce a crop compared to other legumes. This legume crop absorbs mineral nutrients unevenly throughout its growth and development stages and has the ability to assimilate nitrogen from the air through symbiosis with rhizobia. Additionally, soybeans can utilise phosphorus and potassium from soil-bound, insoluble compounds and reallocate these reserves from stems to seeds. According to studies by S. Kots (2021) and O. Mazur *et al.* (2024), the absence of beneficial, specific microflora in the root zone of crops encourages colonisation by other, atypical microorganisms, including phytopathogens. Given this, the ecological and economic viability of inoculating soybeans and other crops is undeniable (Panchyshyn *et al.*, 2023).

Inoculation is particularly effective in soils not already populated by active soybean strains of *Rhizobium japonicum*. On fields where soybean has been cultivated long-term, an indigenous population of nodule bacteria develops that can spontaneously infect the roots of young plants; however, these bacteria are often low in activity and efficiency and may inhibit the effectiveness of productive strains. As a result, the use of bacterial inoculants may be ineffective in such cases. Bioinoculants are formulated with specific nodule bacteria for each type of legume crop. When an unsuitable strain is applied, it has no effect, as it cannot form nodules on a non-responsive legume plant. Research by M. Mendoza-Suárez *et al.* (2024) has shown that only competitive, specific strains of nodule bacteria should be used for soybean seed inoculation.

Given the interest in and promotion of technologies aimed at increasing nitrogen availability and legume crop productivity, seed inoculation with nitrogen-fixing bacteria is an effective tool for reducing the environmental impact of mineral fertilisers and enhancing plant nutrition (Sousa *et al.,* 2022). Using effective rhizobial strains with compatible legume varieties can decrease not only the need for nitrogen fertilisers but also the greenhouse gas emissions associated with their production and use. A better understanding of symbiotic relationships will contribute to the development of sustainable agriculture and the preservation of biodiversity.

The symbiotic relationship between legumes and rhizobia is one of the most studied models of nitrogen fixation, demonstrating a complex interaction between plants and microorganisms. Most research, including work by S. McCormick (2018) and J. Hawkins and I. Oresnik (2021), has focused on the mechanisms of nitrogen fixation, which provide benefits to both partners in the symbiosis through nitrogen and carbon exchange. The authors noted that the symbiosis between legumes and rhizobial bacteria is based on a complex sequence of morphophysiological changes in partner cells. Rhizobia interacting with plants experience various stress factors such as decreased pH, osmotic pressure, oxidative stress, and plant antimicrobial peptides. For the symbiotic process to proceed effectively, protection against oxidative stress is required at all stages of legume-rhizobia symbiosis formation (Mamenko, 2021).

However, limited attention has been paid to research on the impact of environmental conditions on the functioning of legume-rhizobia symbiosis and how stress tolerance affects the interaction between legumes and bacteria. Such research, combined with the establishment of parameters for symbiotic apparatus formation in soybeans, will help in the search for effective symbiotic systems that ensure maximum realisation of symbiotic potential and high tolerance to adverse growing conditions. This suggests that research to improve the productivity of nitrogen-fixing symbiotic systems, their adaptability to environmental conditions (including stress), and understanding the mechanisms of interaction between soybean plants and microorganisms under changing climate conditions is relevant and promising. This study aimed to determine the influence of seed inoculation, hydrothermal and edaphic conditions, and varietal characteristics of soybean varieties on the formation of biologically fixed nitrogen.

MATERIALS AND METHODS

The research was conducted under various soil and climatic conditions in Ukraine, specifically in Kyiv, Poltava, and Vinnytsia regions. In the Vinnytsia Region, the soils were represented by grey forest soils, in the Poltava Region by chernozems podzolized, and in the Kyiv Region by chernozems typical during the period 2010-2021, which differed in their hydrothermal conditions (Fig. 1).

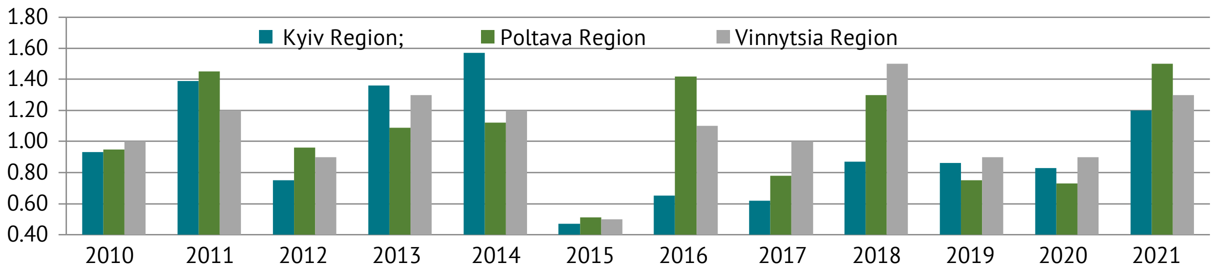

Figure 1. *Hydrothermal coefficients during the growing season (BBCH 10-99, May-September, 2010-2021)*
Source: *developed by the authors*

The research material consisted of soybean cultivars bred by the Krasnohrad Research Station of the Institute of Grain Management of the National Academy of Agrarian Sciences of Ukraine, specifically Ametyst (early-maturing); the Prykarpattia State Agricultural Research Station of the Institute of Agriculture of the Carpathian Region of the National Academy of Agricultural Sciences of Ukraine and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Hoverla (early-maturing); the Krasnohrad Research Station of the Institute of Grain Management of the National Academy of Agrarian Sciences of Ukraine and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Artemida (mid-early); the Institute of Agriculture of the Ukrainian Academy of Agrarian Sciences and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Femida (mid-season), and Zolotysta (mid-early), Oriana (mid-early); and the Institute of Feed and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine, Vezha (mid-early).

Seed inoculation was performed one day before sowing using the biopreparation Optimize 200 (2.8 L/t) based on strains of *Bradyrhizobium japonicum*. The titre of the preparation was $2x10^9$ CFU bacteria/g.

The study was conducted under conditions of a dense soybean rhizobia population, which was established in previous years by cultivating soybeans inoculated with various strains of rhizobia and bacterial preparations. To determine the presence of nodules on plant roots at different growth and development stages, soil monoliths with a diameter of 50 cm and a depth of 0-20 cm were sampled. Soybean roots were washed under water on sieves with 1 mm mesh openings. The remaining clay particles were removed with a soft brush under running water over the sieve. After the entire root was completely cleared of soil, the nodules were dried with filter paper, separated from the root, weighed, and the number of nodules with and without leghaemoglobin was determined. The active symbiotic potential (ASP) was calculated using formula 1:

$$ASP = \frac{M_1 \pm M_2}{2 \times T}, \quad (1)$$

where ASP is the active symbiotic potential, thousand kg days/ha; M_1, M_2 is the average mass of nodules with leghaemoglobin over a period of time, kg/ha; T is the period between two successive determinations, days.

The amount of biologically fixed nitrogen was determined as the product of the active symbiotic potential and the specific activity of the symbiosis. The assessment of the symbiotic apparatus was carried out according to well-known methods. Mathematical processing of the research results was performed using dispersion and correlation-regression analysis on a personal computer using specialised application packages such as MS Excel. Experimental studies of plants (both cultivated and wild), including the collection of plant material, complied with institutional, national, or international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

Nodules became visible on soybean roots 7-10 days after emergence, that is, during the formation of the first trifoliate leaf. Approximately 15-25 days after their formation, the nitrogen fixation process began and continued until plant senescence. In the early stages of soybean development, nitrogen fixation was weak, but its activity increased sharply later, reaching its maximum during flowering and pod filling. After that, it decreased as maturity approached. The lowest number of active nodules was observed at the BBCH microstage 51-59 (Table 1).

***Table 1**. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 51-59*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	7.7	10.1	7.0	9.7	10.4	3.4	6.3	5.6	8.1	7.9	7.6	9.4
	i	12.7	15.3	12.6	15.1	16.0	7.8	11.7	10.2	13.8	12.6	12.7	14.6
Hoverla	w/i	9.0	10.8	8.0	9.9	11.2	4.0	7.7	6.1	9.0	8.2	7.9	9.7
	i	15.1	16.1	13.1	15.6	17.5	8.8	12.8	10.9	14.2	13.3	13.1	15.0
Artemida	w/i	8.3	10.6	8.2	10.5	10.5	3.7	6.6	5.5	8.6	8.1	7.9	9.8
	i	13.2	15.9	12.9	15.4	16.9	8.1	12.3	10.5	14.0	12.9	12.9	14.8
Femida	w/i	8.2	10.5	7.1	9.9	10.9	3.4	6.4	5.4	7.8	7.7	7.6	9.3
	i	12.2	14.8	12.1	14.6	15.8	7.2	10.8	9.5	12.9	12.2	12.1	14.2
Zolotysta	w/i	9.9	10.5	7.0	9.7	10.4	3.1	6.1	5.3	7.8	7.8	7.3	9.2
	i	12.1	14.4	11.7	14.4	15.3	6.9	10.5	9.4	12.6	12.1	11.8	13.9
Vezha	w/i	7.7	10.6	7.3	10.1	10.8	3.5	6.4	5.6	8.0	7.8	7.4	9.4
	i	12.4	15.1	12.3	14.8	15.8	7.5	11.4	10.1	13.2	12.4	12.4	14.6
Oriana-standart	w/i	7.2	10.4	6.4	9.1	10.4	2.9	6.0	5.0	7.3	7.0	6.9	9.3
	i	11.6	14.2	11.2	14.2	15.6	6.7	10.3	9.1	12.3	11.8	11.5	13.7
Poltava Region													
Ametyst	w/i	7.5	11.1	7.5	8.3	8.9	3.8	10.8	6.4	10.6	6.3	6.2	11.6
	i	12.6	16.5	12.6	13.7	14.1	8.3	16.5	12.4	16.4	11.8	11.3	17.8
Hoverla	w/i	7.9	11.6	8.0	8.6	9.2	4.4	11.4	8.1	11.5	7.0	6.6	12.6
	i	13.2	17.1	13.1	14.1	15.0	8.7	17.2	13.1	17.0	12.2	11.7	18.5
Artemida	w/i	8.3	11.1	8.2	9.1	9.1	3.9	11.0	7.5	11.1	6.4	6.2	11.9
	i	12.9	17.0	12.9	14.0	14.6	8.6	16.4	12.6	16.7	12.1	11.5	18.1
Femida	w/i	7.5	10.9	7.5	8.6	9.4	3.6	10.9	7.4	10.5	6.2	5.9	11.4
	i	12.0	16.1	12.4	13.4	14.1	7.8	15.7	11.9	15.7	11.5	10.8	17.2
Zolotysta	w/i	7.3	10.9	7.3	8.2	9.0	3.5	10.6	4.3	10.4	6.0	5.8	11.2
	i	11.8	15.8	12.1	13.1	13.6	7.5	15.5	10.7	15.6	11.1	10.5	16.7

Table 1. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Vezha	w/i	7.9	11.0	8.1	8.6	9.3	3.7	10.8	7.6	10.5	6.3	6.1	11.4
	i	12.5	16.2	12.5	13.5	14.1	8.0	15.9	12.1	16.1	11.6	11.1	17.4
Oriana-standart	w/i	7.3	10.6	7.0	8.1	9.0	3.2	10.5	7.1	10.0	5.8	5.5	11.3
	i	11.7	15.5	11.4	12.9	13.5	7.2	15.3	10.6	15.2	10.5	10.2	16.4
Vinnytsia Region													
Ametyst	w/i	7.7	8.5	6.5	8.4	9.1	3.6	8.4	7.3	10.9	7.7	7.2	9.3
	i	13.2	13.4	11.5	13.6	14.2	7.8	13.7	13.5	16.9	13.2	12.1	16.2
Hoverla	w/i	8.1	8.9	7.0	8.8	9.5	4.1	8.9	7.9	12.1	8.1	7.5	9.6
	i	13.9	14.1	12.0	14.0	15.1	8.4	14.1	13.8	17.8	13.7	12.6	16.9
Artemida	w/i	8.2	8.6	7.2	9.0	9.3	3.7	8.6	7.2	11.4	8.0	7.5	10.0
	i	13.5	13.7	11.7	13.8	14.5	8.0	14.0	13.8	17.3	13.4	12.3	16.7
Femida	w/i	7.7	8.4	6.4	8.7	9.6	3.4	8.4	7.1	10.6	7.5	6.8	9.2
	i	12.2	13.1	11.0	13.3	13.8	7.3	13.1	12.9	15.9	12.7	11.6	15.3
Zolotysta	w/i	7.5	8.3	6.2	8.5	9.3	3.3	8.2	7.0	10.6	7.6	6.8	9.0
	i	12.1	12.9	10.7	13.1	13.5	7.1	12.8	12.3	15.6	12.4	11.2	14.8
Vezha	w/i	8.0	8.6	7.1	8.7	9.5	3.4	8.4	7.2	10.8	7.6	7.0	9.3
	i	12.7	13.2	11.2	13.4	14.0	7.5	13.3	13.2	16.1	12.8	11.8	15.6
Oriana-standart	w/i	7.5	8.3	5.9	8.2	9.2	3.0	8.0	6.8	10.1	6.9	6.5	9.1
	i	11.9	12.8	10.4	12.8	13.3	6.9	12.5	12.0	15.2	12.1	10.9	14.6

Source: *developed by the authors*

The number of active nodules depended on seed inoculation, ecogradient (hydrothermal and edaphic conditions), and soybean variety characteristics. The highest number of active nodules was observed in Poltava Region in 2021 following seed inoculation in the varieties Hoverla (18.5 nodules), Artemida (18.1 nodules), and Ametyst (17.8 nodules). This was 5.9, 6.2, and 6.2 nodules higher, respectively, compared to untreated seeds. In Vinnytsia Region, the highest number of nodules was observed in 2018 following seed inoculation in the varieties Hoverla (17.8 nodules), Artemida (17.3 nodules), and Ametyst (16.9 nodules). This was 5.7, 5.9, and 6.0 nodules higher, respectively, compared to untreated seeds. In Kyiv Region, the highest number of nodules was observed in 2014 in the varieties Hoverla (17.5 nodules), Artemida (16.9 nodules), and Ametyst (16.0 nodules), which was 6.3, 6.4, and 6.4 nodules higher, respectively, compared to non-inoculated seeds. The lowest number of active nodules was observed in all soybean varieties in different growing zones (Kyiv, Vinnytsia, Poltava) under the most drought-prone year (2015). The number of active nodules in untreated soybean seeds varied across these regions from 2.9-3.2 per plant (variety Oriana) to 4.0-4.4 per plant (variety Hoverla). In inoculated soybean seeds, the number of active nodules ranged from 6.7-7.2 per plant (variety Oriana) to 8.4-8.8 per plant (variety Hoverla). It should be noted that across different growing years, the highest number of active nodules was observed, primarily with seed inoculation in 2021 in the Poltava Region, ranging from 16.4 per plant (variety Oriana) to 18.5 per plant (variety Hoverla). The highest number of active nodules with seed inoculation was observed in Vinnytsia Region in 2018, ranging from 15.2 per plant (variety Oriana) to 17.8 per plant (variety Hoverla). In Kyiv Region, the highest number of active nodules was observed in 2014, ranging from 15.3 per plant (variety Zolotysta) to 17.5 per plant (variety Hoverla). At the BBCH microstage 61-62, a higher number of active nodules on plant roots was established compared to the BBCH microstage 51-59 (Table 2).

Table 2*. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 61-62*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	17.0	22.0	14.5	21.0	22.8	5.0	12.5	10.6	16.8	16.4	15.7	20.2
	i	35.2	37.2	31.8	37.4	38.3	20.8	29.9	27.3	32.1	31.9	30.3	34.7
Hoverla	w/i	19.3	22.6	16.0	21.6	23.8	6.2	15.2	11.9	18.9	17.0	16.3	20.9
	i	37.5	38.9	33.8	39.0	39.9	22.4	31.7	29.1	34.8	33.1	32.3	36.8
Artemida	w/i	18.2	22.1	16.2	21.8	23.0	5.6	12.8	10.3	17.9	16.9	16.5	21.1
	i	36.0	37.8	33.1	38.2	39.1	21.6	30.7	28.4	33.3	32.3	31.0	36.1

Table 2. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Femida	w/i	16.3	21.9	14.5	21.5	23.3	5.0	12.4	10.3	16.5	15.9	14.8	20.1
	i	33.2	36.2	30.2	36.2	36.5	19.3	28.4	25.9	31.0	30.4	29.1	32.5
Zolotysta	w/i	16.6	21.9	14.2	20.9	22.8	4.0	11.9	9.8	16.3	16.0	14.9	19.9
	i	31.9	35.2	29.8	35.4	35.4	18.8	28.1	25.3	30.0	29.8	28.4	31.7
Vezha	w/i	16.7	22.1	14.9	21.5	23.1	5.0	12.5	10.4	16.6	16.3	15.1	20.2
	i	34.4	36.7	31.1	36.5	37.4	20.0	29.2	26.6	32.0	31.1	29.6	33.5
Oriana-standart	w/i	15.4	21.5	13.4	20.2	22.7	3.6	11.5	9.2	15.1	14.6	14.1	19.8
	i	31.6	34.4	29.2	34.5	34.4	18.3	27.4	24.6	29.1	28.9	27.8	30.7
Poltava Region													
Ametyst	w/i	16.4	25.5	16.2	18.2	18.8	6.7	24.9	13.3	24.1	13.1	12.9	26.4
	i	33.6	41.1	32.2	35.6	37.1	23.2	40.3	32.9	41.4	29.3	30.0	43.3
Hoverla	w/i	17.0	26.5	17.3	18.8	19.6	8.2	25.9	17.8	26.5	14.2	13.7	29.1
	i	35.0	44.0	35.5	37.8	38.8	25.2	42.6	35.2	43.5	31.4	31.4	46.6
Artemida	w/i	17.5	25.5	17.9	19.9	19.2	6.9	25.0	16.1	25.3	12.9	13.1	27.5
	i	34.4	42.5	33.6	36.9	38.2	24.4	41.1	33.6	42.5	30.1	30.4	44.8
Femida	w/i	16.7	25.3	16.2	18.6	19.7	6.2	24.8	15.8	23.7	13.0	12.1	26.5
	i	32.5	39.4	30.9	34.1	34.4	22.3	40.9	31.2	39.2	27.7	28.0	40.9
Zolotysta	w/i	15.7	25.4	15.7	18.0	19.1	5.9	24.3	15.6	23.7	12.6	11.9	25.9
	i	31.4	38.7	29.6	34.2	33.4	21.6	39.9	30.4	38.7	28.9	27.1	40.1
Vezha	w/i	16.8	25.3	17.7	18.8	19.7	6.6	24.7	16.2	24.0	13.0	12.6	26.4
	i	32.9	40.3	31.4	35.0	35.6	22.8	39.6	31.7	40.5	28.4	28.8	41.9
Oriana-standart	w/i	16.1	24.9	14.9	17.8	19.2	5.4	24.0	15.2	22.7	11.8	11.1	26.2
	i	31.0	37.8	29.4	33.2	32.9	21.0	39.2	29.9	38.2	27.1	26.4	39.5
Vinnytsia Region													
Ametyst	w/i	16.6	18.7	13.5	18.6	20.3	6.3	18.4	15.6	24.6	16.8	15.2	20.7
	i	33.7	33.6	31.0	35.6	37.0	23.0	34.6	31.2	41.9	33.0	32.0	36.6
Hoverla	w/i	17.5	19.5	14.8	19.4	21.1	7.4	19.6	17.1	26.9	17.4	15.8	21.3
	i	34.5	36.3	32.3	36.7	37.9	24.5	36.2	34.2	43.4	34.9	33.1	39.2
Artemida	w/i	18.0	19.1	15.2	19.9	21.0	6.5	18.9	15.4	26.1	17.3	16.2	21.7
	i	34.0	34.4	31.4	35.9	37.5	23.5	35.4	32.6	42.7	34.2	31.7	37.3
Femida	w/i	16.6	18.6	13.5	19.2	21.3	5.5	18.4	15.1	24.1	16.1	14.1	20.7
	i	32.5	32.8	29.6	34.7	35.9	21.9	33.5	29.7	40.4	31.1	30.4	35.1
Zolotysta	w/i	16.2	18.6	13.2	18.6	20.7	5.1	17.7	14.9	24.1	16.2	14.5	20.3
	i	31.9	32.1	29.2	34.1	35.2	21.4	32.7	29.1	39.6	32.5	29.8	34.2
Vezha	w/i	17.3	18.8	14.7	19.2	21.1	5.6	18.6	15.6	24.6	16.4	15.0	20.7
	i	33.3	33.1	30.4	35.0	36.6	22.2	33.9	30.8	41.1	31.8	31.6	36.1
Oriana-standart	w/i	16.2	18.4	12.0	17.9	20.6	4.6	17.6	14.2	23.3	14.7	13.6	20.3
	i	31.4	31.5	28.4	33.7	34.2	21.0	31.7	27.7	38.8	30.1	28.7	33.6

Source: *developed by the authors*

In the Poltava Kegion, the highest number of active nodules following seed inoculation was observed in the Hoverla variety in 2021 (46.6 nodules), 2011 (44.0 nodules), 2018 (43.5 nodules), and 2016 (42.6 nodules). This was 16.7-17.5 nodules higher compared to non-inoculated seeds. A lower number of active nodules was observed in 2014 (38.8 nodules), 2013 (37.8 nodules), 2012 (35.5 nodules), 2017 (35.2 nodules), and 2010 (35.0 nodules). This was 17.4-19.2 nodules higher compared to non-inoculated seeds. The lowest number of active nodules was observed in 2019 and 2020 (31.4 nodules) and in 2015 (25.2 nodules), which was 17.0-17.7 nodules higher compared to inoculated seeds. The most favourable hydrothermal conditions for all soybean varieties in the Poltava Region were observed in 2021. The number of active nodules following seed inoculation in the soybean varieties Hoverla, Artemida, Ametyst, Vezha, Femida, Zolotysta, and Oriana was 13.3-17.5 nodules higher compared to non-inoculated seeds. In the Kyiv Region, the lowest number of active nodules following seed inoculation was observed in 2015 for the varieties Hoverla (22.4 nodules), Artemida (21.6 nodules), Ametyst (20.8 nodules), Vezha (20.0 nodules), Femida (19.3 nodules), Zolotysta (18.8 nodules), and Oriana (18.3 nodules). This is 14.3-16.2 nodules higher compared to non-inoculated seeds of these varieties. The obtained data correlate with the values of hydrothermal coefficients in the Poltava Region during the most favourable (2021) and least favourable (2015) years. A high number of active nodules was also observed in the Vinnytsia Region. With seed inoculation in 2018, the number of active nodules in soybean varieties Hoverla (43.4 nodules), Artemida (42.7 nodules), Ametyst (41.9 nodules), Vezha (41.1 nodules), Femida (40.4 nodules), Zolotysta (39.6 nodules), and Oriana (38.8 nodules) was 15.5-17.3 nodules higher compared to non-inoculated seeds. In the Kyiv Region, the highest number of active nodules was observed in 2014 in soybean varieties Hoverla (39.9 nodules), Artemida (39.1 nodules), Ametyst (38.3 nodules), Vezha (37.4 nodules), Femida (36.5 nodules), Zolotysta (35.4 nodules), and Oriana (34.4 nodules), which was 11.7-16.1 nodules higher compared to non-inoculated seeds. At the BBCH microstage 68-69, a higher number of active nodules on plant roots was established compared to the BBCH microstage 61-62 (Table 3).

***Table 3**. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 68-69*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	20.3	25.3	17.6	24.2	25.9	8.3	15.9	13.9	20.0	19.7	18.9	23.4
	i	36.3	40.9	34.8	37.9	41.0	24.3	34.5	30.6	38.8	36.3	35.7	40.1
Hoverla	w/i	22.5	26.0	19.2	24.9	26.8	9.6	18.5	15.3	22.2	20.4	19.6	24.2
	i	38.8	43.7	36.4	41.2	43.9	26.2	36.1	32.7	41.2	38.3	37.9	42.5
Artemida	w/i	21.6	25.5	19.6	25.3	26.2	8.8	16.2	13.8	21.3	20.3	19.8	24.5
	i	37.8	41.8	35.7	38.9	41.9	25.2	35.5	31.9	39.5	37.8	36.8	41.3
Femida	w/i	19.8	25.2	17.8	24.8	26.6	8.1	15.9	13.6	19.6	19.2	18.0	23.4
	i	35.4	39.5	33.1	36.5	39.8	22.8	32.2	29.3	36.5	34.6	34.1	38.5
Zolotysta	w/i	19.8	25.1	17.4	24.3	26.0	7.3	15.3	13.2	19.5	19.4	18.2	23.1
	i	35.0	38.5	32.0	35.5	38.9	22.1	31.7	28.5	35.7	33.7	33.6	37.7
Vezha	w/i	20.0	25.4	18.3	24.8	26.5	8.2	15.9	13.9	19.9	19.5	18.5	23.5
	i	35.9	40.2	34.2	36.9	40.9	23.6	33.7	29.8	37.8	35.5	34.7	39.4
Oriana-standart	w/i	18.8	24.9	16.7	23.7	26.1	6.9	15.0	12.8	18.5	17.9	17.4	23.2
	i	34.4	39.4	31.2	34.4	39.5	21.7	31.0	27.9	34.4	32.3	32.8	36.9
Poltava Region													
Ametyst	w/i	19.5	28.7	19.6	21.5	22.2	9.9	28.2	16.6	27.5	16.3	16.1	29.8
	i	36.8	45.1	36.9	39.4	39.3	26.1	45.0	35.7	45.5	33.7	32.7	48.2
Hoverla	w/i	20.3	29.6	20.8	22.2	22.9	11.3	29.3	21.0	29.7	17.5	17.0	32.3
	i	38.5	47.1	38.9	41.4	41.1	27.6	46.7	38.4	47.4	35.7	35.1	50.3
Artemida	w/i	20.7	28.7	21.2	23.2	22.7	10.2	28.5	19.5	28.8	16.3	16.2	30.8
	i	37.6	45.8	37.8	40.7	40.3	26.6	45.4	37.2	46.6	34.7	34.1	49.2
Femida	w/i	19.6	28.4	19.4	22.1	23.1	9.4	28.2	19.3	27.1	16.2	15.4	29.7
	i	35.1	43.7	35.1	37.6	38.5	24.7	43.4	35.0	43.9	32.3	31.1	46.7
Zolotysta	w/i	19.0	28.3	19.0	21.4	22.6	9.1	27.6	18.9	27.0	15.7	15.1	29.4
	i	34.3	43.1	34.3	36.4	37.5	23.7	42.4	34.1	42.8	31.4	31.1	44.6
Vezha	w/i	20.2	28.6	20.9	22.1	23.0	9.7	28.2	19.6	27.4	16.3	15.9	29.8
	i	35.9	44.3	36.6	38.3	38.7	25.3	44.2	35.2	44.9	32.9	31.8	47.4
Oriana-standart	w/i	19.0	28.1	18.3	21.0	22.6	8.4	27.3	18.5	26.0	15.0	14.3	29.5
	i	33.6	41.9	33.3	35.4	37.0	22.8	41.7	33.1	41.8	30.4	30.2	44.1
Vinnytsia Region													
Ametyst	w/i	20.0	22.0	16.8	21.9	23.7	9.4	21.8	18.8	28.0	20.0	18.5	23.9
	i	36.6	38.5	33.5	38.4	40.2	25.5	38.6	35.7	46.0	36.0	34.6	40.3
Hoverla	w/i	20.8	22.7	18.0	22.6	24.4	10.7	22.9	20.2	30.2	20.7	19.2	24.7
	i	38.1	40.3	35.6	39.9	41.9	26.7	40.3	37.9	47.8	37.9	35.6	42.4
Artemida	w/i	21.2	22.2	18.4	23.0	24.2	9.7	22.1	18.7	29.3	20.6	19.4	25.0
	i	37.2	39.5	34.7	39.3	41.3	26.3	39.3	36.5	46.9	36.8	34.8	41.3
Femida	w/i	20.1	21.9	16.6	22.5	24.6	8.8	21.8	18.5	27.6	19.5	17.6	23.9
	i	35.0	37.3	32.1	35.8	38.8	24.1	37.2	33.7	44.1	34.0	33.1	38.4
Zolotysta	w/i	19.5	21.8	16.2	22.0	24.1	8.5	21.2	18.1	27.5	19.7	17.8	23.6
	i	33.8	36.6	31.2	34.7	37.8	23.3	36.5	32.5	43.4	33.4	32.3	37.4
Vezha	w/i	20.7	22.1	18.1	22.5	24.5	8.9	21.8	18.8	27.9	19.8	18.1	24.0
	i	35.8	37.9	32.7	36.9	39.6	24.7	37.8	34.5	44.7	35.0	33.9	39.3
Oriana-standart	w/i	19.5	21.6	15.5	21.4	24.1	7.8	20.9	17.7	26.5	18.2	17.0	23.7
	i	34.3	35.5	30.7	33.7	37.0	22.5	35.3	31.5	42.4	32.5	31.9	36.4

***Source:** developed by the authors*

The highest number of active nodules was observed in the Poltava Region in 2021 with seed inoculation of varieties Hoverla (50.3 nodules), Artemida (49.2 nodules), Ametyst (48.2 nodules), Vezha (47.4 nodules), Femida (46.7 nodules), Zolotysta (44.6 nodules), and Oriana (44.1 nodules). This is 14.6-18.4 nodules higher compared to non-inoculated seeds. In the Poltava Region, on the roots of Hoverla, Artemida, and Ametyst varieties, the highest number of active nodules formed in 2021 (48.2-50.3 nodules), 2018 (45.5-47.4 nodules), 2011 (45.1-45.8 nodules), 2016 (45.0-46.7 nodules), 2013 (39.4-41.4 nodules), 2014 (39.3-41.1 nodules), 2012 (36.9-38.9 nodules), 2010 (36.8-38.5 nodules), 2019 (33.7-35.7 nodules), 2020 (32.7-35.1 nodules), and 2015 (26.1-27.6 nodules), compared to other varieties. In the non-inoculated variants, the number of active nodules on these varieties decreased by 16.2-19.2 nodules depending on the year of cultivation.

A high number of active nodules was observed in the Vinnytsia Region in 2018 with seed inoculation of varieties Hoverla (47.8 nodules), Artemida (46.9 nodules), Ametyst (46.0 nodules), Vezha (44.7 nodules), Femida (44.1 nodules), Zolotysta (43.4 nodules), and Oriana (42.4 nodules). This was 15.9-18.0 nodules higher compared to non-inoculated seeds. In the Kyiv Region, the highest number of active nodules was observed in 2014 with seed inoculation of varieties Hoverla (43.9 nodules), Artemida (41.9 nodules), Ametyst (41.0 nodules), Vezha (40.9 nodules), Femida (39.8 nodules), Zolotysta (38.9 nodules), and Oriana (39.5 nodules). This was 13.2-17.1 nodules higher compared to non-inoculated seeds. The lowest number of active nodules in the Kyiv Region was observed in 2015 with seed inoculation of varieties Hoverla (26.2 nodules), Artemida (25.2 nodules), Ametyst (24.3 nodules), Vezha (23.6 nodules), Femida (22.8 nodules), Zolotysta (22.1 nodules), and Oriana (21.7 nodules). This was 14.7-16.6 nodules higher compared to non-inoculated seeds. During soybean maturation, a decrease in nitrogen fixation was observed. At the BBCH microstage 80-90, a lower number of active nodules was observed on soybean roots compared to the BBCH microstage 68-69 (Table 4).

***Table 4**. Number of active nodules (number/plant) on soybean roots depending on the variety, seed inoculation, and environmental conditions at the BBCH microstage 80-90*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	10.2	12.4	9.8	11.7	13.3	6.1	9.0	8.5	11.2	10.7	10.3	12.4
	i	15.6	19.0	14.7	17.5	20.2	8.7	13.4	12.6	17.0	16.3	15.7	19.0
Hoverla	w/i	12.2	14.0	11.1	12.7	14.5	7.2	10.8	9.3	12.3	11.4	11.1	12.9
	i	18.5	21.4	16.9	19.6	22.4	10.6	16.7	14.2	18.7	17.2	16.8	20.9
Artemida	w/i	10.9	13.7	11.5	13.7	13.6	6.8	9.5	8.4	11.7	11.0	10.9	13.2
	i	15.6	22.1	17.4	21.2	20.8	9.9	14.2	12.6	17.8	16.6	16.6	20.4
Femida	w/i	10.8	13.2	9.9	12.6	13.8	6.0	9.2	8.2	10.6	10.3	10.1	12.4
	i	16.3	21.3	14.8	19.4	21.1	8.6	13.6	12.3	16.2	15.7	15.2	19.2
Zolotysta	w/i	12.9	13.1	9.7	12.3	13.1	5.6	8.6	7.9	10.5	10.5	9.6	12.0
	i	18.7	20.1	14.5	19.7	20.3	8.0	13.7	11.8	15.7	15.8	14.6	18.4
Vezha	w/i	10.0	13.2	9.8	13.3	13.7	6.7	9.1	8.6	11.0	10.3	9.8	12.5
	i	15.1	20.3	14.9	20.1	21.1	9.6	13.6	12.7	16.6	15.6	14.7	19.1
Oriana-standart	w/i	9.6	12.9	8.7	11.6	13.2	5.2	8.4	7.5	9.9	9.3	9.1	12.2
	i	14.5	19.8	13.0	17.5	20.4	7.5	12.5	11.2	14.8	14.2	13.6	18.3
Poltava Region													
Ametyst	w/i	10.2	14.3	10.1	10.6	11.5	6.4	13.2	9.4	13.4	9.3	8.8	14.8
	i	15.4	22.0	15.2	16.2	18.4	9.3	20.4	14.0	20.5	14.2	13.4	22.6
Hoverla	w/i	11.3	15.0	10.7	11.6	11.9	7.3	14.4	11.1	14.5	10.0	9.8	16.1
	i	17.2	23.1	16.3	17.9	19.2	10.8	22.0	16.8	22.2	15.9	14.7	24.8
Artemida	w/i	11.5	14.4	10.8	12.3	11.7	6.6	13.8	10.5	14.0	9.4	8.7	15.3
	i	18.4	22.2	17.2	18.7	18.8	10.5	21.1	15.9	21.6	14.9	13.9	23.5
Femida	w/i	10.1	13.6	10.5	11.0	12.3	5.9	13.6	10.4	13.1	9.2	8.1	13.9
	i	15.2	20.8	15.8	16.6	17.9	8.4	20.8	15.6	20.3	13.7	12.1	21.6
Zolotysta	w/i	9.8	13.5	9.9	10.4	11.4	5.7	12.9	7.3	12.9	9.0	7.8	13.1
	i	14.7	20.6	14.8	15.5	17.3	8.2	19.7	12.0	19.7	13.4	11.9	20.5
Vezha	w/i	10.9	14.0	10.6	11.1	12.1	6.2	13.3	10.6	13.2	9.3	8.5	14.0
	i	16.6	21.4	16.2	16.8	18.3	9.0	20.4	16.0	20.2	14.1	12.6	21.4
Oriana-standart	w/i	9.7	13.1	9.4	10.2	11.5	5.3	12.7	10.1	12.4	8.0	7.4	13.1
	i	14.5	20.2	14.0	15.3	17.6	7.6	19.3	15.2	19.1	12.3	11.2	20.3
Vinnytsia Region													
Ametyst	w/i	10.5	11.1	9.2	10.9	11.4	6.2	11.1	10.3	13.9	10.5	10.0	11.9
	i	16.9	16.8	13.7	16.4	17.3	9.0	17.2	15.7	21.3	17.8	15.2	18.2

Table 4. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Hoverla	w/i	11.2	11.9	10.1	12.1	12.7	6.9	12.2	11.1	15.3	11.3	10.7	12.8
	i	18.0	18.2	15.4	18.6	19.6	10.3	18.5	16.8	23.5	17.3	16.6	19.5
Artemida	w/i	11.5	11.3	10.4	12.2	12.1	6.2	11.7	10.1	14.5	10.9	10.4	12.5
	i	17.4	17.3	15.6	18.5	18.4	9.0	17.6	15.4	22.1	16.6	15.6	19.1
Femida	w/i	10.4	10.9	9.0	11.7	12.8	5.7	11.1	9.6	13.4	10.0	9.3	11.6
	i	16.7	16.4	13.6	17.3	19.5	8.1	16.8	14.5	20.8	16.0	14.2	17.5
Zolotysta	w/i	10.1	10.6	8.7	11.1	11.9	5.5	10.7	9.5	13.2	10.2	9.2	11.2
	i	16.3	16.2	13.0	16.6	18.0	7.8	16.5	14.4	20.4	15.6	13.7	17.1
Vezha	w/i	10.9	11.0	9.9	11.4	12.5	5.8	11.0	9.8	13.7	10.3	9.7	11.8
	i	17.5	16.8	14.8	17.3	19.2	8.2	16.6	14.7	21.2	15.6	14.5	18.2
Oriana-standart	w/i	10.0	10.5	8.2	10.6	11.6	5.1	10.4	9.2	12.6	9.2	8.7	11.4
	i	16.1	16.4	12.3	16.2	17.8	7.2	15.8	13.9	19.4	13.7	13.2	17.4

Source: *developed by the authors*

At BBCH microstage 80-90, a general trend of maintaining higher nitrogen fixation rates was observed in the same top-performing treatments as in the previous microstages (BBCH 61-62 and BBCH 68-69). The highest number of active nodules was observed in the Poltava Region in 2021 with seed inoculation of varieties Hoverla (24.8 nodules), Artemida (23.5 nodules), Ametyst (22.6 nodules), Femida (21.6 nodules), Vezha (21.4 nodules), Zolotysta (20.5 nodules), and Oriana (20.3 nodules). This was 7.2-8.7 nodules lower compared to non-inoculated seeds. The lowest number of active nodules was observed in the Kyiv Region in 2015 with seed inoculation of varieties Hoverla (10.6 nodules), Artemida (9.9 nodules), Vezha (9.6 nodules), Ametyst (8.7 nodules), Femida (8.6 nodules), Zolotysta (8.0 nodules), and Oriana (7.5 nodules). This was 2.3-3.4 nodules lower compared to non-inoculated seeds. To assess the effectiveness of the legume-rhizobia symbiosis, not only the number but also the mass of active nodules per plant is used. At BBCH microstage 51-59 in the Poltava Region in 2021, the highest active nodule mass was established in varieties Hoverla (68.6 mg), Artemida (66.9 mg), and Ametyst (65.7 mg) with seed inoculation (Table 5).

Table 5*. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 51-59*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Kyiv Region													
Ametyst	w/i	33.9	44.4	30.9	42.5	45.8	14.7	27.3	24.4	34.7	34.1	32.8	40.8
	i	46.9	56.6	46.7	55.7	59.2	28.7	43.4	37.6	50.9	46.6	46.9	53.9
Hoverla	w/i	38.7	46.4	34.4	42.6	48.2	17.2	33.1	26.2	38.7	35.3	34.0	41.7
	i	52.9	59.5	48.4	57.8	62.3	32.4	47.1	40.2	52.6	49.1	48.3	55.6
Artemida	w/i	35.7	45.7	35.3	45.2	45.2	15.9	28.4	23.7	37.0	34.8	34.0	42.1
	i	47.8	58.7	47.8	56.9	60.9	29.8	45.6	38.7	51.7	47.9	47.6	54.8
Femida	w/i	35.5	45.2	30.5	42.6	46.9	14.6	27.5	23.2	33.5	33.1	32.7	40.0
	i	45.2	54.7	44.7	53.9	58.4	26.8	39.8	35.2	47.9	45.1	44.9	52.7
Zolotysta	w/i	42.6	45.3	30.1	41.7	44.7	13.3	26.2	22.8	33.5	33.5	31.4	39.6
	i	44.6	53.2	43.4	53.2	56.7	25.7	38.7	34.8	46.8	44.6	43.7	51.6
Vezha	w/i	33.1	45.6	31.4	43.4	46.4	15.1	27.5	24.1	34.4	33.5	31.8	40.4
	i	45.8	55.9	45.6	54.6	58.6	27.9	40.9	37.2	48.7	45.9	45.8	53.9
Oriana-standart	w/i	31.0	44.7	27.5	39.1	44.7	12.5	25.8	21.5	31.6	30.1	29.7	40.0
	i	43.0	52.7	41.4	52.8	57.7	24.8	38.2	33.6	45.5	43.7	42.5	50.8
Poltava Region													
Ametyst	w/i	33.3	48.7	33.3	37.7	39.3	17.3	47.4	32.5	46.6	28.1	27.7	53.9
	i	46.8	60.9	46.7	50.6	51.8	30.6	59.7	45.8	60.7	43.7	41.7	65.7
Hoverla	w/i	35.0	51.0	35.4	38.0	40.6	19.9	50.0	35.8	50.5	31.1	29.4	55.2
	i	48.7	63.4	48.2	52.3	53.1	32.1	62.7	48.4	62.9	45.3	43.4	68.6
Artemida	w/i	35.7	47.7	35.3	39.1	39.2	16.8	47.3	32.3	47.7	27.5	26.7	51.2
	i	47.9	62.8	47.8	51.7	52.6	31.9	60.8	46.5	61.8	44.6	42.6	66.9
Femida	w/i	32.3	46.9	32.3	37.0	40.4	15.5	46.9	31.8	45.2	26.7	25.4	49.0
	i	44.5	59.3	45.7	49.4	52.4	28.9	58.2	44.0	58.2	42.4	39.8	63.6

Table 5. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Zolotysta	w/i	31.4	46.8	31.4	35.3	38.7	15.1	45.6	18.5	44.7	25.8	24.9	48.2
	i	43.6	58.6	44.9	48.3	50.4	27.6	57.4	39.6	57.6	40.9	38.7	61.9
Vezha	w/i	34.0	47.3	34.8	37.0	40.0	15.9	46.4	32.7	45.2	27.1	26.2	49.0
	i	46.3	59.7	46.1	49.9	51.1	29.7	58.9	44.9	59.4	43.1	40.9	64.4
Oriana-standart	w/i	31.4	45.6	30.1	34.8	38.7	13.8	45.2	30.5	43.0	24.9	23.7	48.6
	i	43.2	57.5	42.3	47.6	49.8	26.5	56.6	39.1	56.4	38.8	37.6	60.8
Vinnytsia Region													
Ametyst	w/i	39.1	38.6	28.0	38.1	39.1	18.5	39.1	38.4	49.9	38.1	38.0	48.0
	i	49.0	49.4	42.6	50.4	52.6	28.7	50.8	50.1	62.4	48.9	44.9	59.8
Hoverla	w/i	34.8	38.3	30.1	37.8	40.9	17.6	38.3	34.0	52.0	34.8	32.2	41.3
	i	50.9	51.3	44.5	51.8	54.2	30.9	52.3	51.2	66.0	50.6	46.7	62.4
Artemida	w/i	35.3	37.0	31.0	38.7	40.0	15.9	37.0	31.0	49.0	34.4	32.3	43.0
	i	49.3	50.6	43.4	50.9	53.1	29.6	51.6	50.9	63.9	49.7	45.6	61.8
Femida	w/i	33.1	36.1	27.5	37.4	41.3	14.6	36.1	30.5	45.6	32.3	29.2	39.6
	i	45.0	48.5	40.8	49.2	50.9	26.9	48.4	47.6	58.7	46.9	43.1	56.7
Zolotysta	w/i	32.3	35.7	26.7	36.6	40.0	14.2	35.3	30.1	45.6	32.7	20.2	38.7
	i	44.3	47.9	39.5	48.4	50.1	26.3	47.5	45.4	57.9	45.8	41.5	54.8
Vezha	w/i	34.4	37.0	30.5	37.4	40.9	14.6	36.1	31.0	46.4	32.8	30.1	40.0
	i	46.8	48.8	41.9	49.7	51.8	27.6	49.1	48.7	59.5	47.5	43.8	58.3
Oriana-standart	w/i	32.3	35.7	25.4	35.3	39.6	12.9	34.4	29.2	43.4	29.7	28.0	39.1
	i	44.3	47.2	38.4	47.2	49.2	25.4	46.2	44.3	56.4	44.7	40.3	53.9

Source: *developed by the authors*

In the non-inoculated variants, the active nodule mass decreased by 11.8-15.7 mg/plant depending on the variety. A high active nodule mass with seed inoculation was also observed in 2011 on the roots of varieties Hoverla (63.4 mg), Artemida (62.8 mg), and Ametyst (60.9 mg), which was 12.2-15.1 mg/plant higher compared to the non-inoculated variants. In 2016 and 2018, a high active nodule mass was observed with seed inoculation in varieties Hoverla (62.7 and 62.9 mg, respectively), Artemida (60.8 and 61.8 mg, respectively), and Ametyst (59.7 and 60.7 mg), which was 12.3-14.1 mg/plant higher compared to the non-inoculated variants. The highest active nodule mass was observed in the Vinnytsia Region in 2018 in varieties Hoverla (66.0 mg), Artemida (63.9 mg), and Ametyst (62.4 mg). In the non-inoculated variants, this value decreased by 12.5-15.7 mg/plant. In the Kyiv Region, the highest active nodule mass was observed in 2014 in varieties Hoverla (62.3 mg), Artemida (60.9 mg), and Ametyst (59.2 mg). In the non-inoculated variants, this value decreased by 13.4-15.7 mg/plant.

The formation of higher active nodule mass on the roots of soybean plants in different regions, depending on the favourable growing year, is supported by the hydrothermal coefficient values for each zone. The lowest active nodule mass following seed inoculation was observed in the Kyiv Region in 2015, which ranged from 24.8 mg/plant (Oriana) to 32.4 mg/plant (Hoverla). In the non-inoculated variants, this indicator decreased by 12.3-15.2 mg/plant. The lowest active nodule mass was also observed in 2015 in the conditions of the Vinnytsia and Poltava regions. Following seed inoculation, this value ranged from 25.4-26.5 mg/plant (Oriana) to 30.9-32.1 mg/plant (Hoverla). In the non-inoculated variants, the active nodule mass decreased by 12.2-13.3 mg/plant. An increase in active nodule mass was noted at the BBCH microstage 61-62 across all experimental variants (Table 6).

Table 6*. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 61-62*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	182.8	235.4	155.9	224.7	243.3	53.5	134.0	113.4	179.8	176.1	169.7	217.5
	i	386.7	409.4	349.6	411.2	421.3	228.6	328.7	300.5	353.4	350.5	333.8	381.8
Hoverla	w/i	210.4	246.3	172.8	233.3	259.4	67.0	164.2	127.8	204.1	183.6	174.7	225.7
	i	412.3	427.8	371.8	428.9	438.7	245.9	348.9	319.8	383.1	362.7	354.8	404.5
Artemida	w/i	191.6	235.9	170.6	231.6	246.1	59.9	137.0	110.2	192.4	181.7	166.6	220.0
	i	395.6	416.5	364.4	419.8	429.6	237.8	337.6	312.3	366.7	355.4	340.9	397.2

Table 6. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Femida	w/i	172.8	232.1	155.2	231.1	249.3	53.7	132.7	109.7	176.6	170.1	155.4	215.1
	i	364.8	398.5	332.7	397.8	402.3	212.3	312.8	285.4	340.9	334.6	319.8	357.9
Zolotysta	w/i	177.6	233.2	150.5	221.5	241.5	42.0	126.7	103.9	172.8	171.5	157.9	207.0
	i	351.2	387.6	327.9	389.7	389.8	206.5	309.5	277.6	329.8	327.8	312.7	348.7
Vezha	w/i	178.7	236.5	160.9	230.1	247.2	54.0	133.8	111.3	177.6	175.1	161.6	216.1
	i	377.8	404.1	341.6	401.2	411.5	219.7	321.4	292.4	351.6	342.3	325.5	368.6
Oriana-standart	w/i	161.7	225.8	140.7	212.1	236.1	37.8	120.8	96.6	158.4	153.3	146.6	203.9
	i	347.9	378.8	321.6	379.5	378.9	201.3	301.2	270.7	319.8	317.9	305.7	337.5
Poltava Region													
Ametyst	w/i	189.3	279.4	189.2	208.1	208.4	79.9	269.4	188.3	268.3	148.2	139.4	297.1
	i	369.8	452.1	354.7	391.5	408.3	254.9	443.4	362.4	455.8	322.7	329.8	476.7
Hoverla	w/i	192.8	288.9	196.1	221.9	212.7	88.6	279.7	193.5	288.9	151.9	147.3	317.2
	i	384.5	484.5	390.8	415.6	426.7	276.7	468.9	386.7	478.9	345.8	345.6	512.5
Artemida	w/i	190.8	274.9	195.1	216.9	205.4	74.2	268.8	173.2	273.2	137.8	140.2	298.4
	i	378.1	467.9	369.6	406.7	419.8	268.2	451.6	369.9	467.5	331.2	334.7	492.4
Femida	w/i	178.7	271.0	173.3	199.8	214.7	66.7	266.1	169.1	254.8	139.1	128.6	285.7
	i	357.9	433.4	339.6	374.5	378.9	245.6	450.1	343.5	431.2	304.6	307.9	449.8
Zolotysta	w/i	163.3	271.8	168.0	192.6	204.4	63.1	257.6	166.9	253.6	133.6	125.7	277.1
	i	345.6	425.6	325.9	376.6	367.5	237.9	439.6	334.6	425.6	317.6	297.6	441.5
Vezha	w/i	179.8	271.2	191.2	203.0	214.1	70.3	264.8	175.0	258.2	139.1	133.8	283.0
	i	361.4	443.4	345.5	384.5	391.5	250.8	435.5	348.9	445.2	312.5	316.7	461.0
Oriana-standart	w/i	169.1	261.5	156.5	185.1	205.4	56.6	252.0	162.6	240.6	123.9	116.0	280.3
	i	341.2	415.6	323.8	365.7	361.6	230.6	431.0	328.8	420.4	297.8	290.1	434.7
Vinnytsia Region													
Ametyst	w/i	187.6	210.7	159.7	211.1	219.2	67.7	197.4	178.9	287.2	188.9	168.2	228.5
	i	370.6	369.5	341.5	391.7	406.7	253.4	380.4	343.2	461.2	362.9	352.2	402.3
Hoverla	w/i	188.1	211.2	160.6	209.9	226.8	80.7	211.7	186.4	292.1	188.6	169.9	229.2
	i	379.8	399.8	354.8	403.6	416.7	269.8	398.7	376.5	477.8	383.4	364.5	423.2
Artemida	w/i	194.4	205.5	164.6	215.7	224.7	70.2	203.4	164.8	280.6	185.8	175.0	236.5
	i	374.5	378.6	345.6	394.5	412.3	258.9	388.9	358.8	469.5	375.7	348.9	410.5
Femida	w/i	178.6	200.0	144.9	207.4	230.0	58.9	198.2	161.3	259.3	172.4	150.9	221.5
	i	357.7	361.2	325.5	381.4	394.6	240.9	368.7	326.4	444.7	342.1	334.9	385.6
Zolotysta	w/i	172.5	199.0	139.9	199.0	221.5	54.6	188.5	158.7	257.9	173.8	155.2	217.2
	i	351.2	353.4	321.4	374.9	387.5	235.6	359.8	319.9	435.6	357.8	327.8	376.7
Vezha	w/i	185.1	202.3	159.2	205.4	225.8	59.9	199.0	167.5	264.2	176.1	160.8	223.6
	i	366.7	364.5	334.7	384.8	402.1	244.5	373.4	338.6	452.4	350.1	347.8	397.6
Oriana-standart	w/i	171.7	196.9	126.0	187.9	218.4	48.3	186.6	150.5	244.7	154.4	142.8	215.2
	i	345.6	346.7	312.9	370.3	376.5	230.9	348.7	305.1	426.4	331.5	315.7	369.3

Source: *developed by the authors*

The highest active nodule mass was observed in the conditions of the Poltava Region following seed inoculation for the varieties Hoverla, Artemida, and Ametyst in 2021 (476.7-512.5 mg), 2018 (455.8-478.9 mg), 2011 (452.1-484.5 mg), 2016 (443.4-468.9 mg), and 2014 (408.3-426.7 mg). In the non-inoculated variants, the active nodule mass on the roots of these varieties decreased by 172.7-214.4 mg/plant, depending on the growing year. In the Vinnytsia Region, the highest active nodule mass following seed inoculation was noted for the varieties Hoverla, Artemida, and Ametyst in 2018 (461.2-477.8 mg), 2021 (402.3-423.2 mg), 2014 (406.7-416.7 mg), and 2013 (391.7-403.6 mg/plant). This was higher compared to the non-inoculated variants by 173.8-194.0 mg/plant, depending on the growing year. In the Kyiv Region, the highest active nodule mass following seed inoculation was observed for the varieties Hoverla, Artemida, and Ametyst in 2014 (421.3-438.7 mg), 2013 (411.2-428.9 mg), 2011 (409.4-427.8 mg), and 2010 (386.7-412.3 mg). In the non-inoculated variants, this indicator decreased by 174.0-204.0 mg/plant, depending on the growing year. The lowest active nodule mass following seed inoculation in the conditions of the Kyiv Region was observed in 2015. This value ranged from 201.3 mg (Oriana) to 245.9 mg (Hoverla), which was 163.5 and 178.9 mg/plant higher compared to the non-inoculated variants. In the Poltava and Vinnytsia regions, the lowest active nodule mass following seed inoculation was also recorded in 2015 on the roots of all soybean varieties. This value ranged from 230.6 to 276.7 mg and from 230.9 to 269.8 mg/plant, respectively. In the non-inoculated variants, the active nodule mass on the roots of soybean plants decreased by 174.0-189.1 mg/plant, depending on the growing region. Thus, in all regions where a significant precipitation deficit and the lowest hydrothermal coefficient values were observed throughout the study years, the formation of the lowest active nodule mass and nodule count was noted. The highest values of active nodule mass on the roots of soybean varieties were achieved in all experimental variants at the BBCH microstage 68-69 (Table 7).

***Table 7**. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 68-69*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	223.3	283.4	201.5	275.9	295.3	93.0	183.0	158.5	230.2	225.6	217.2	266.8
	i	395.6	445.8	379.5	413.2	446.5	265.4	376.0	334.0	423.0	396.0	389.5	437.6
Hoverla	w/i	254.5	286.0	220.8	283.9	305.0	105.6	209.1	172.9	254.8	234.4	225.8	278.3
	i	422.5	476.5	396.7	448.9	482.9	285.6	394.0	356.0	449.0	423.0	413.7	463.0
Artemida	w/i	240.6	284.6	213.4	277.9	288.5	96.8	186.3	157.2	244.9	233.7	217.9	272.2
	i	412.3	455.7	388.7	423.8	462.1	274.9	387.0	348.0	431.0	412.0	401.0	449.8
Femida	w/i	221.8	282.2	202.9	282.2	302.7	90.6	182.9	156.4	224.6	218.9	206.3	266.3
	i	385.6	430.8	360.9	397.8	440.9	248.9	351.0	319.0	398.0	377.0	371.3	419.2
Zolotysta	w/i	219.8	281.1	200.1	277.1	296.4	82.9	176.0	151.8	223.3	221.0	208.9	263.3
	i	381.4	419.8	348.6	386.6	423.6	241.2	345.0	311.0	389.0	367.8	366.6	411.3
Vezha	w/i	226.0	284.5	210.5	282.7	301.8	91.5	183.2	158.2	228.9	224.3	211.5	270.3
	i	391.4	437.9	372.3	402.3	439.7	256.7	367.0	325.0	412.0	387.0	378.6	428.9
Oriana-standart	w/i	212.4	278.9	192.1	269.9	297.0	78.5	172.5	147.2	209.1	203.8	199.6	264.5
	i	374.6	429.6	340.5	375.4	439.8	236.4	338.0	304.0	375.0	352.9	357.6	402.4
Poltava Region													
Ametyst	w/i	238.3	327.2	237.1	257.6	258.9	108.9	328.6	199.3	318.9	186.6	188.3	347.0
	i	401.2	491.2	402.4	429.8	428.7	284.0	491.0	389.0	496.0	367.0	356.7	525.7
Hoverla	w/i	242.4	336.0	245.0	272.9	259.2	123.2	335.5	239.4	338.6	200.4	194.7	369.2
	i	419.8	513.8	423.8	450.9	447.8	301.3	509.0	419.0	517.0	389.0	382.6	547.8
Artemida	w/i	237.0	326.0	241.7	265.9	257.2	111.2	325.8	221.9	327.2	185.5	183.6	348.4
	i	409.6	498.7	411.7	443.5	439.6	289.4	495.0	406.0	508.0	378.0	371.5	536.4
Femida	w/i	224.4	322.1	219.2	251.5	262.0	101.5	322.0	219.3	307.3	183.9	174.2	335.6
	i	382.3	476.7	382.6	409.8	419.8	269.0	473.0	381.0	479.0	352.0	338.4	508.9
Zolotysta	w/i	216.8	321.8	214.7	242.7	256.5	92.3	314.6	213.6	305.9	178.0	170.9	330.8
	i	374.4	469.5	373.4	396.7	409.1	258.0	462.0	372.0	467.0	342.0	338.9	486.5
Vezha	w/i	231.3	324.9	237.5	251.1	260.1	105.2	321.5	223.6	310.4	185.0	179.8	336.7
	i	391.5	482.8	398.7	417.7	421.3	276.0	482.0	384.0	489.0	359.0	346.8	516.7
Oriana-standart	w/i	216.2	318.9	205.0	237.5	255.6	90.3	308.5	209.1	291.2	168.0	160.2	333.4
	i	366.5	456.6	362.9	385.5	403.6	249.0	454.0	361.0	456.0	331.0	329.2	481.0
Vinnytsia Region													
Ametyst	w/i	227.6	249.7	199.7	247.7	267.8	108.5	256.6	219.8	337.5	229.8	207.9	281.0
	i	398.4	419.8	365.4	418.9	438.6	278.0	421.0	389.0	501.0	392.0	376.9	439.0
Hoverla	w/i	236.9	257.7	204.5	256.3	276.0	116.6	260.8	229.3	342.8	236.0	217.8	280.3
	i	414.8	438.9	387.9	434.6	456.7	291.0	439.0	413.0	520.8	413.2	387.8	462.0
Artemida	w/i	241.3	252.4	208.8	262.0	273.9	104.8	250.2	211.9	332.3	234.2	221.2	284.0
	i	405.6	430.7	378.7	428.7	449.8	287.0	428.0	398.0	511.2	401.0	379.5	450.0
Femida	w/i	228.9	248.6	188.2	255.0	278.7	95.0	247.3	209.5	313.0	219.4	197.6	270.6
	i	381.5	406.7	349.6	389.9	423.4	263.0	405.0	367.0	481.0	371.0	361.0	419.0
Zolotysta	w/i	220.7	247.2	183.1	249.0	273.1	91.8	239.6	204.5	311.6	222.4	200.1	265.7
	i	368.9	398.5	340.5	378.6	411.9	254.0	398.0	354.0	473.0	364.0	352.0	408.0
Vezha	w/i	235.6	251.1	206.3	254.5	277.3	96.1	246.8	213.0	316.7	223.7	203.1	271.2
	i	389.7	413.6	356.7	402.5	431.2	269.0	412.0	376.0	487.0	382.0	369.0	428.0
Oriana-standart	w/i	220.4	244.7	172.1	239.9	272.6	83.5	234.1	199.0	299.5	203.8	190.4	267.8
	i	374.3	387.4	334.1	367.4	403.1	245.0	385.0	343.0	462.0	354.0	348.0	397.0

***Source:** developed by the authors*

In the conditions of the Poltava Region, the highest active nodule mass was recorded in 2021, where, following seed inoculation, it ranged from 481.0 mg/plant (Oriana) to 547.8 mg/plant (Hoverla). That year, the highest active nodule mass following seed inoculation was observed on the roots of the soybean varieties Hoverla (547.8 mg), Artemida (536.4 mg), Ametyst (525.7 mg), Vezha (516.7 mg), and Femida (508.9 mg). In the non-inoculated variants, this value decreased by 173.7-188.0 mg/plant, depending on the variety. High values of active nodule mass were also observed in 2011 and 2018, following seed inoculation, for the varieties Hoverla (513.0 and 517.0 mg), Artemida (498.7 and 508.0 mg), and Ametyst (491.2 and 496.0 mg). These values were 164.0-180.8 mg/plant higher compared to the non-inoculated variants, depending on the variety and year. In the Poltava Region, high active nodule mass was observed in 2016 following seed inoculation in the soybean varieties Hoverla (509.0 mg), Artemida (495.0 mg), and Ametyst (491.0 mg). These values were 162.4-173.5 mg/plant higher compared to the non-inoculated variants. In the conditions of the Vinnytsia Region, the highest values of active nodule mass were recorded in 2018 following seed inoculation for the soybean varieties Hoverla (520.8 mg), Artemida (511.2 mg), and Ametyst (501 mg/plant). These values were 163.5-178.09 mg/plant higher compared to the non-inoculated variants. In the Kyiv Region, the highest values of active nodule mass were observed in 2014 in the variants where seed inoculation was carried out for the soybean varieties Hoverla (482.9 mg), Artemida (462.1 mg), and Ametyst (446.5 mg/plant). These values were 151.2-177.9 mg/plant higher compared to the non-inoculated variants. The lowest active nodule mass was recorded in the conditions of the Kyiv Region in 2015 on the roots of all soybean varieties. This value ranged from 236.4 mg/plant (Oriana) to 285.6 mg/plant (Hoverla) following seed inoculation, which was 157.9-180.0 mg/plant higher compared to the non-inoculated variants. At the BBCH microstage 80-90, a decrease in active nodule mass was observed on the roots of the soybean plants (Table 8).

***Table 8**. Active nodule mass (mg/plant) on soybean roots depending on variety, seed inoculation, and environmental conditions at the BBCH microstage 80-90*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	44.9	50.5	39.5	46.7	52.1	25.4	39.6	37.4	49.3	47.1	45.3	54.6
	i	81.9	88.5	81.5	95.6	90.2	62.3	75.5	76.0	84.0	81.0	80.1	90.1
Hoverla	w/i	56.1	63.0	47.7	55.9	62.4	32.4	46.4	40.0	52.9	49.0	47.7	55.5
	i	90.1	101.0	90.7	100.8	104.3	71.2	85.1	84.0	89.0	87.2	87.2	95.3
Artemida	w/i	49.0	60.3	50.6	61.7	59.8	29.9	40.9	34.4	51.5	48.4	48.0	56.8
	i	81.1	97.3	87.6	99.6	98.7	67.8	78.5	78.0	86.0	83.1	84.5	93.4
Femida	w/i	47.0	56.8	41.6	54.2	59.3	25.2	39.6	32.8	44.5	43.3	43.4	52.1
	i	84.0	92.8	75.6	90.2	91.3	57.0	73.4	71.0	79.0	75.6	73.0	86.2
Zolotysta	w/i	54.2	53.7	37.8	51.7	49.8	23.0	34.4	30.7	42.0	45.2	39.5	48.0
	i	91.2	89.7	71.8	87.6	85.8	55.1	70.1	68.0	75.0	73.0	71.3	82.1
Vezha	w/i	43.0	55.4	39.2	58.5	57.5	28.8	39.1	36.1	47.3	42.1	41.2	53.8
	i	78.0	93.4	76.2	94.4	88.5	59.6	74.0	75.0	82.0	78.1	76.0	90.3
Oriana-standart	w/i	39.5	51.6	33.1	46.4	51.5	20.8	31.9	28.5	38.8	37.2	36.4	50.0
	i	73.5	85.6	69.1	82.4	87.6	51.4	67.5	63.0	72.0	70.3	68.6	79.9
Poltava Region													
Ametyst	w/i	42.8	62.9	42.4	44.5	43.7	26.9	57.6	36.7	57.6	38.1	38.7	62.2
	i	79.8	99.9	80.4	89.4	86.7	63.5	96.1	89.0	95.0	81.3	74.2	95.4
Hoverla	w/i	48.6	69.0	48.2	52.2	52.4	32.1	64.4	46.5	62.4	43.0	44.1	70.8
	i	86.5	108.0	91.2	101.1	96.2	71.0	102.0	87.0	104.0	89.4	83.0	106.7
Artemida	w/i	50.6	64.8	49.7	56.6	50.3	28.4	60.7	43.1	60.2	39.5	37.4	65.8
	i	84.6	102.8	88.7	95.5	89.3	66.2	97.0	82.0	98.1	84.2	76.5	102.3
Femida	w/i	41.4	55.8	45.2	47.3	54.1	23.6	58.5	41.6	56.3	35.9	33.2	55.6
	i	77.4	92.8	78.2	85.3	81.1	59.3	92.1	79.0	89.2	72.3	69.4	89.5
Zolotysta	w/i	39.2	54.0	40.6	42.6	45.6	22.2	52.9	27.0	55.5	34.2	31.2	51.1
	i	75.2	91.0	76.6	78.6	77.6	58	87.6	63.0	86.4	68.7	65.3	85.6
Vezha	w/i	46.9	60.2	46.6	48.8	52.0	25.4	55.4	45.6	56.8	37.2	35.7	57.4
	i	83.9	98.2	79.6	87.7	85.0	61.2	93.9	81.0	93.3	76.5	72.6	92.2
Oriana-standart	w/i	37.8	51.1	36.7	40.8	47.2	20.1	50.8	39.4	53.3	29.6	28.9	49.8
	i	73.8	86.1	72.7	76.9	75.2	56.0	86.1	72.0	83.6	64.1	62.7	81.1
Vinnytsia Region													
Ametyst	w/i	44.1	46.6	38.6	46.9	45.6	26.7	48.2	44.3	59.8	45.2	41.0	53.6
	i	80.1	83.6	80.6	87.9	83.5	62.5	84.8	76.0	96.0	81.3	78.3	88.7
Hoverla	w/i	48.2	52.4	43.4	52.0	55.9	30.4	54.9	48.8	68.9	48.6	47.1	58.9
	i	87.2	92.4	85.4	98.0	94.8	69.2	94.0	85.0	107.2	88.5	85.4	104.5

Table 8. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Artemida	w/i	50.6	48.6	44.7	52.5	52.0	26.0	51.5	42.4	63.8	46.9	43.7	56.3
	i	87.6	87.6	82.7	91.5	89.0	63.5	89.2	80.0	102.4	84.6	81.2	96.8
Femida	w/i	42.6	44.7	36.9	50.3	55.0	22.8	46.6	38.4	57.6	43.0	36.3	49.9
	i	78.6	79.7	73.9	86.3	81.0	58.0	81.8	74.0	90.1	75.2	73.1	82.3
Zolotysta	w/i	40.4	42.4	34.8	47.7	48.4	21.5	42.8	37.1	54.1	43.9	35.0	44.8
	i	76.4	77.4	70.8	83.7	77.3	57.6	77.9	72.0	87.0	73.1	70.5	78.4
Vezha	w/i	46.9	47.3	42.6	49.0	52.5	23.8	45.1	40.2	57.5	44.3	38.8	51.9
	i	83.9	81.3	77.6	85.0	81.4	59.2	82.6	76.0	94.3	79.8	75.6	85.6
Oriana-standart	w/i	39.0	41.0	32.0	45.6	44.1	19.4	40.6	35.0	50.4	39.6	33.9	47.9
	i	74.0	75.0	68.0	81.5	75.2	55.1	76.1	69.0	85.0	70.2	68.1	75.7

Source: *developed by the authors*

Nitrogen fixation gradually decreases as soybean plants approach maturity. However, the best variants identified in earlier microstages of the soybean development scale continued to yield higher values even at the latest microstage, BBCH 80-90. The highest mass of active nodules at BBCH microstage 80-90 was observed in the conditions of the Poltava Region. For seed-inoculated varieties, such as Hoverla, Artemida, and Ametyst, the active nodule mass in 2021 ranged from 95.4 to 106.7 mg/plant; in 2011, from 99.9 to 108.0 mg/plant; in 2018, from 95.0 to 104.0 mg/plant; in 2016, from 96.1 to 102.0 mg/plant; and in 2013, from 89.4 to 101.1 mg/plant. In the non-inoculated variants, this value decreased by 33.2 to 48.9 mg/plant, depending on the year of cultivation. High values of active nodule mass were also recorded in the Vinnytsia Region with seed inoculation in 2018, for the soybean varieties Hoverla (107.2 mg/plant), Artemida (102.4 mg/plant), and Ametyst (96.0 mg/plant). These values were 36.2 to 38.6 mg/plant higher than in the non-inoculated variants. High active nodule mass was also observed in 2021 for the varieties Hoverla (104.5 mg), Artemida (38.6 mg), and Ametyst (36.2 mg/plant). In the Kyiv Region, the highest active nodule mass was observed in 2014 for seed-inoculated varieties, with Hoverla (104.3 mg), Artemida (98.7 mg), and Ametyst (90.2 mg/plant). These values were 38.1 to 41.9 mg/plant higher than in the non-inoculated variants. The studies recorded the highest active symbiotic potential in the Poltava Region in 2021 for seed-inoculated soybean varieties: Hoverla (25,109 thousand kg·day/ha), Artemida (24,267 thousand kg·day/ha), Ametyst (23,522 thousand kg·day/ha), and Vezha (22,868 thousand kg·day/ha). These values were 5,824 to 6,456 thousand kg·day/ha higher than in the non-inoculated variants (Table 9).

Table 9*. Active symbiotic potential (ASP) on soybean roots, depending on variety, seed inoculation, and environmental conditions at BBCH microstage 51-90, thousand kg·day/ha*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	11,311	14,313	10,019	13,780	14,863	4,405	9,018	7,820	11,550	11,295	10,874	13,510
	i	18,664	20,255	17,368	20,006	20,644	11,723	16,549	15,102	18,158	17,597	17,016	19,335
Hoverla	w/i	13,013	14,839	11,100	14,373	15,667	5,188	10,545	8,592	12,855	11,749	11,280	14,047
	i	20,008	21,472	18,437	21,116	21,718	12,715	17,611	16,141	19,480	18,460	18,097	20,450
Artemida	w/i	12,092	14,544	10,891	14,282	14,845	4,732	9,205	7,661	12,295	11,676	10,895	13,779
	i	19,138	20,791	18,050	20,488	21,185	12,234	17,043	15,682	18,700	18,008	17,466	20,018
Femida	w/i	11,124	14,334	10,084	14,252	15,342	4,330	8,989	7,595	11,224	10,902	10,238	13,406
	i	17,911	19,795	16,492	19,284	19,938	10,904	15,666	14,336	17,330	16,761	16,207	18,310
Zolotysta	w/i	11,330	14,266	9,840	13,864	14,815	3,825	8,564	7,306	11,067	11,029	10,287	13,086
	i	17,589	19,253	16,100	18,843	19,348	10,582	15,412	13,942	16,795	16,388	15,888	17,845
Vezha	w/i	11,276	14,464	10,386	14,329	15,239	4,434	9,010	7,745	11,430	11,144	10,467	13,580
	i	18,259	20,081	16,924	19,532	20,204	11,287	16,152	14,725	17,890	17,176	16,541	18,843
Oriana-standart	w/i	10,464	14,014	9,305	13,352	14,762	3,569	8,297	6,978	10,292	9,994	9,721	13,102
	i	17,043	19,040	15,731	18,296	19,033	10,284	15,023	13,537	16,245	15,842	15,495	17,350
Poltava Region													
Ametyst	w/i	11,852	16,737	11,805	12,856	12,897	5,436	16,486	10,527	16,162	9,377	9,267	17,698
	i	18,205	22,369	17,792	19,449	19,890	12,780	22,023	17,988	22,442	16,373	16,278	23,522

Table 9. Continued

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hoverla	w/i	12,158	17,308	12,297	13,725	13,155	6,147	17,031	12,050	17,267	9,974	9,720	18,920
	i	19,033	23,796	19,347	20,672	20,873	13,803	23,156	19,089	23,592	17,509	17,268	25,109
Artemida	w/i	11,996	16,643	12,202	13,503	12,907	5,421	16,442	11,045	16,563	9,165	9,109	17,811
	i	18,664	23,010	18,521	20,202	20,427	13,308	22,347	18,307	23,014	16,832	16,671	24,267
Femida	w/i	11,195	16,280	11,002	12,558	13,305	4,889	16,236	10,856	15,521	9,071	8,518	16,983
	i	17,532	21,478	17,039	18,599	18,825	12,209	21,883	17,120	21,358	15,460	15,284	22,378
Zolotysta	w/i	10,624	16,254	10,675	12,057	12,780	4,511	15,740	10,291	15,438	8,752	8,325	16,586
	i	17,016	21,113	16,479	18,345	18,257	11,797	21,337	16,370	20,977	15,616	14,896	21,745
Vezha	w/i	11,534	16,453	11,942	12,634	13,198	5,104	16,135	11,179	15,690	9,131	8,840	16,999
	i	17,905	21,957	17,453	19,045	19,263	12,499	21,622	17,368	21,991	15,873	15,727	22,868
Oriana-standart	w/i	10,692	15,911	10,079	11,721	12,780	4,281	15,405	10,373	14,692	8,173	7,763	16,705
	i	16,753	20,544	16,166	17,838	17,959	11,412	20,943	16,222	20,610	14,778	14,485	21,373
Vinnytsia Region													
Ametyst	w/i	11,555	12,709	10,002	12,657	13,408	5,197	12,697	11,150	17,152	11,659	10,523	14,190
	i	18,233	18,552	16,867	19,282	19,924	12,609	18,929	17,255	22,709	17,947	17,320	20,016
Hoverla	w/i	11,893	13,063	10,265	12,986	13,998	5,752	13,215	11,634	17,583	11,882	10,927	14,234
	i	18,878	19,876	17,667	20,045	20,689	13,416	19,892	18,722	23,719	18,981	17,982	21,263
Artemida	w/i	12,192	12,718	10,503	13,285	13,820	5,100	12,662	10,558	16,932	11,742	11,067	14,448
	i	18,587	19,053	17,211	19,567	20,345	12,919	19,363	17,914	23,229	18,511	17,324	20,583
Femida	w/i	11,359	12,420	9,337	12,865	14,129	4,523	12,386	10,344	15,806	10,950	9,738	13,616
	i	17,546	18,052	16,041	18,556	19,301	11,938	18,286	16,404	21,800	16,923	16,484	19,100
Zolotysta	w/i	10,948	12,316	9,041	12,473	13,668	4,317	11,888	10,117	15,673	11,088	9,812	13,290
	i	17,141	17,666	15,724	18,159	18,863	11,650	17,848	15,974	21,361	17,230	16,086	18,595
Vezha	w/i	11,769	12,593	10,283	12,789	13,960	4,593	12,354	10,604	16,015	11,180	10,143	13,714
	i	18,043	18,273	16,448	18,802	19,642	12,154	18,540	16,931	22,194	17,395	17,020	19,654
Oriana-standart	w/i	10,895	12,175	8,283	11,937	13,514	3,896	11,639	9,769	14,972	10,057	9,313	13,373
	i	17,003	17,269	15,324	17,819	18,375	11,334	17,302	15,327	20,889	16,265	15,618	18,171

Source: *developed by the authors*

In the Poltava Region, high values of active symbiotic potential were recorded in 2011 for seed-inoculated soybean varieties: Hoverla – 23,796; Artemida – 23,010; Ametyst – 22,369; and Vezha – 21,957 thousand kg·day/ha. In the non-inoculated variants, this value decreased by 5,504 to 6,488 thousand kg·day/ha. In 2018, high values of active symbiotic potential were also observed for seed-inoculated varieties Hoverla, Artemida, Ametyst, and Vezha, which were 6,301 to 6,451 thousand kg·day/ha higher compared to the non-inoculated variants. The increase in active symbiotic potential can be explained by the high values of the hydrothermal coefficient in these years of research. In the Vinnytsia Region, the active symbiotic potential in 2018 for seed-inoculated varieties Hoverla, Artemida, Ametyst, and Vezha ranged from 22,194 to 23,719 thousand kg·day/ha, which was 5,557 to 6,297 thousand kg·day/ha higher compared to the non-inoculated variants. In 2021, for seed-inoculated varieties Hoverla, Artemida, and Ametyst, this indicator increased by 5,826 to 7,029 thousand kg·day/ha compared to the non-inoculated variants. In the Kyiv Region, the highest values of active symbiotic potential were recorded in 2014 for the soybean varieties Hoverla (21,718), Artemida (21,185), Ametyst (20,644), and Vezha (20,204 thousand kg·day/ha). These values were 4,965 to 6,340 thousand kg·day/ha higher compared to the non-inoculated variants. The lowest values of active symbiotic potential were observed in 2015 in the Kyiv Region. For seed-inoculated varieties, this indicator ranged from 10,284 (variety Oriana) to 12,715 (variety Hoverla), which was directly related to the lowest values of the hydrothermal coefficient in that year. The most significant positive effect on the formation of the active symbiotic potential indicator was achieved through the use of seed inoculation. This promoted a more intensive colonisation of soybean plant roots by symbiotic bacteria, leading to an increase in the number of nodules and their potential mass, which in turn contributed to a higher symbiotic potential. The magnitude of the active symbiotic apparatus was influenced by hydrothermal and edaphic conditions, seed inoculation, and the variety, all of which had a significant impact on the amount of biologically fixed nitrogen in soybean crops (Table 10).

Table 10. *Amount of biologically fixed nitrogen depending on variety, seed inoculation, and ecological growing conditions, kg/ha*

Variety	Inoculation	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1	2	3	4	5	6	7	8	9	10	11	12	13	14
Kyiv Region													
Ametyst	w/i	58.8	74.4	52.1	71.8	77.3	22.9	46.9	40.7	60.1	58.7	56.5	70.3
	i	97.1	105.3	90.3	104.0	107.3	60.9	86.1	78.5	94.4	91.5	88.5	100.5
Hoverla	w/i	67.7	77.2	57.7	74.7	81.5	27.0	54.8	44.7	66.8	61.1	58.7	73.0
	i	104.0	111.7	95.9	109.8	112.9	66.1	91.6	83.9	101.3	96.0	94.1	106.3
Artemida	w/i	62.9	75.6	56.6	74.3	77.2	24.6	47.9	39.8	63.9	60.7	56.7	71.7
	i	99.5	108.1	93.9	106.5	110.2	63.6	88.6	81.5	97.2	93.6	90.8	104.1
Femida	w/i	57.8	74.5	52.4	74.1	79.8	22.5	46.7	39.5	58.4	56.7	53.2	69.7
	i	93.1	102.9	85.8	100.3	103.7	56.7	81.5	74.6	90.1	87.2	84.3	95.2
Zolotysta	w/i	58.9	74.2	51.2	72.1	77.0	19.9	44.5	38.0	57.5	57.4	53.5	68.0
	i	91.5	100.1	83.7	98.0	100.6	55.0	80.1	72.5	87.3	85.2	82.6	92.8
Vezha	w/i	58.6	75.2	54.0	74.5	79.2	23.1	46.9	40.3	59.4	57.9	54.4	70.6
	i	94.9	104.4	88.0	101.6	105.1	58.7	84.0	76.6	93.0	89.3	86.0	98.0
Oriana-standart	w/i	54.4	72.9	48.4	69.4	76.8	18.6	43.1	36.3	53.5	52.0	50.6	68.1
	i	88.6	99.0	81.8	95.1	99.0	53.5	78.0	70.4	84.5	82.4	80.6	90.2
Poltava Region													
Ametyst	w/i	61.6	87.0	61.4	66.9	67.1	28.3	85.7	54.7	84.0	48.8	48.2	92.0
	i	94.7	116.3	92.5	101.1	103.4	66.5	114.5	93.5	116.7	85.1	84.6	122.3
Hoverla	w/i	63.2	90.0	63.9	71.4	68.4	32.0	88.6	62.7	89.8	51.9	50.5	98.4
	i	98.9	123.7	100.6	107.5	108.5	71.8	120.4	99.3	122.7	91.0	89.8	130.6
Artemida	w/i	62.4	86.5	63.5	70.2	67.1	28.2	85.5	57.4	86.1	47.7	47.4	92.6
	i	97.1	119.7	96.3	105.0	106.2	69.1	116.2	95.2	119.7	87.5	86.7	126.2
Femida	w/i	58.2	84.7	57.2	65.3	69.2	25.4	84.4	56.4	80.7	47.2	44.3	88.3
	i	91.2	111.6	88.6	96.7	97.9	63.5	113.8	89.0	111.1	80.4	79.5	116.4
Zolotysta	w/i	55.2	84.5	55.5	62.7	66.5	23.5	81.8	53.5	80.3	45.5	43.3	86.2
	i	88.5	109.8	85.7	95.4	94.9	61.3	111.0	85.1	109.1	81.2	77.5	113.1
Vezha	w/i	60.0	85.6	62.1	65.7	68.6	26.5	83.9	58.1	81.6	47.5	46.0	88.4
	i	93.1	114.2	90.8	99.0	100,2	65.0	112.4	90.3	114.4	82.5	81.8	118.9
Oriana-standart	w/i	55.6	82.7	52.4	61.0	66.6	22.3	80.1	53.9	76.4	42.5	40.4	86.9
	i	87.1	106.8	84.1	92.8	93.4	59.3	108.9	84.4	107.2	76.8	75.3	111.1
Vinnytsia Region													
Ametyst	w/i	60.1	66.1	52.0	65.8	69.7	27.0	66.0	58.0	89.2	60.6	54.7	73.8
	i	94.8	96.5	87.7	100.3	103.6	65.6	98.4	89.7	118.1	93.3	90.1	104.1
Hoverla	w/i	61.8	67.9	53.4	67.5	72.8	29.9	68.7	60.5	91.4	61.8	56.8	74.0
	i	98.2	103.4	91.9	104.2	107.6	69.8	103.4	97.4	123.3	98.7	93.5	110.6
Artemida	w/i	63.4	66.1	54.6	69.1	71.9	26.5	65.8	54.9	88.0	61.1	57.5	75.1
	i	96.6	99.0	89.5	101.7	105.8	67.2	100.7	93.2	120.8	96.3	90.1	107.0
Femida	w/i	59.1	64.6	48.6	66.9	73.5	23.5	64.4	53.8	82.2	56.9	50.6	70.8
	i	91.2	93.9	83.4	96.5	100.4	62.1	95.1	85.3	113.4	88.0	85.7	99.3
Zolotysta	w/i	56.9	64.0	47.1	64.9	71.1	22.4	61.8	52.6	81.5	57.7	51.0	69.1
	i	89.1	91.9	81.8	94.4	98.2	60.6	92.7	83.1	111.1	89.6	83.6	96.7
Vezha	w/i	61.2	65.5	53.5	66.5	72.6	23.9	64.2	55.1	83.3	58,1	52.7	71.3
	i	93.8	95.0	85.7	97.8	102.1	63.2	96.4	88.0	115.4	90.5	88.5	102.2
Oriana-standart	w/i	56.7	63.3	43.6	62.1	70.3	20.3	60.5	50.8	77.9	52,3	48.4	69.5
	i	88.4	89.8	79.7	92.7	95.5	58.9	90.0	79.7	108.6	84.6	81.2	94.5

Source: *developed by the authors*

The highest values of biologically fixed nitrogen were recorded in the Poltava Region in the experimental variant where seed inoculation was applied in 2021 for the varieties Hoverla (130.6 kg/ha), Artemida (126.2 kg/ha), Ametyst (122.3 kg/ha), and Vezha (118.9 kg/ha). These values were 30.3–33.6 kg/ha higher compared to the non-inoculated variants. High levels of biologically fixed nitrogen were also observed in 2011 for the varieties Hoverla (123.7 kg/ha), Artemida (119.7 kg/ha), Ametyst (116.3 kg/ha), and Vezha (114.2 kg/ha). These values were higher by 33.7, 33.2, and 29.3 kg/ha, respectively, compared to the non-inoculated variants. Similarly, high levels of biologically fixed nitrogen were observed in 2018 for the varieties: Hoverla (122.7 kg/ha), Artemida (119.7 kg/ha), and Ametyst (116.7 kg/ha). These values were higher than those in the non-inoculated variants by 32.9, 33.6, and 32.7 kg/ha, respectively. It is worth noting the relatively high amounts of biologically fixed nitrogen in 2016 in the experimental variants with seed inoculation for the varieties: Hoverla (120.4 kg/ha), Artemida (116.2 kg/ha), and Ametyst (114.5 kg/ha). These values were higher by 31.8, 30.7, and 28.8 kg/ha, respectively, compared to the non-inoculated variants. In the Vinnytsia Region, high levels of biologically fixed nitrogen were recorded in 2018 with seed inoculation for the varieties Hoverla (123.3 kg/ha), Artemida (120.8 kg/ha), and Ametyst (118.1 kg/ha). In the non-inoculated variants, this value decreased by 28.9-32.8 kg/ha. The lowest amount of biologically fixed nitrogen was observed in 2015 with seed inoculation. This value ranged from 53.5 kg/ha (variety Oriana) to 71.8 kg/ha (variety Hoverla), which was 34.9-39.8 kg/ha higher compared to the non-inoculated variants. Seed inoculation with nitrogen-fixing bacteria has a significant impact on nitrogen fixation (Fig. 2).

Seed inoculation had the most significant impact on biological nitrogen fixation, accounting for 96.89% of the variation. Hydrothermal conditions contributed 2.3% and varietal differences 0.76%. The interaction effects of these factors on biological nitrogen fixation did not exceed 1%. The average amount of biologically fixed nitrogen with and without seed inoculation under various soil and hydrothermal conditions for different soybean varieties is presented in Figure 3.

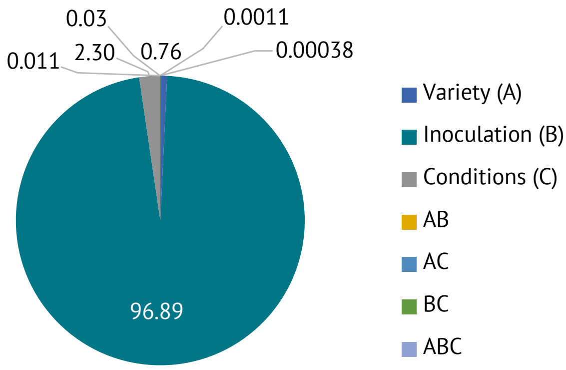

***Figure 2**. The contribution of factors and their interactions to nitrogen fixation in soybean plants*
***Source:** developed by the authors*

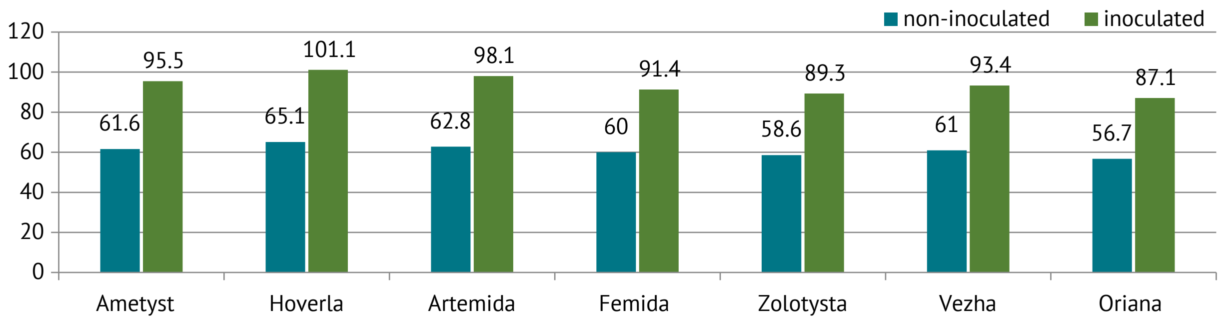

***Figure 3**. Average amount of biologically fixed nitrogen under different ecological conditions of cultivation*
***Source:** developed by the authors*

The highest amount of biologically fixed nitrogen was recorded in the Hoverla variety, both in the non-inoculated variant (65.1 kg/ha) and with seed inoculation (101.2 kg/ha). For the Ametyst and Artemida varieties, the amount of biologically fixed nitrogen with seed inoculation was 95.5 and 98.1 kg/ha, respectively. Seed inoculation increased the amount of biologically fixed nitrogen by 36.1 kg/ha (Fig. 4).

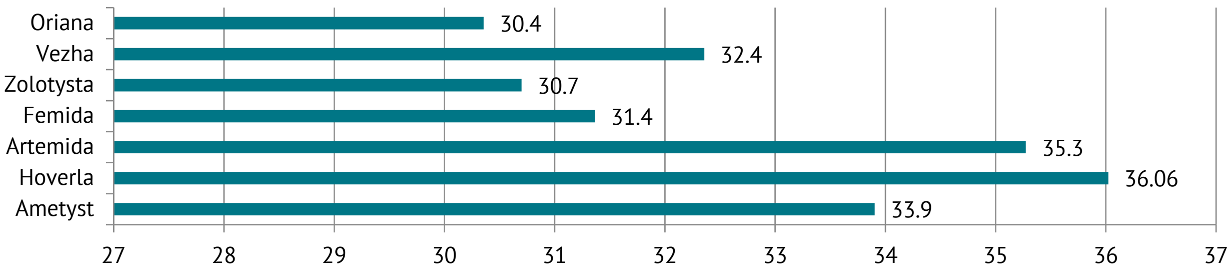

***Figure 4**. Increase in the amount of biologically fixed nitrogen depending on seed inoculation and the response of soybean varieties, kg/ha*
***Source:** developed by the authors*

Seed inoculation in the Artemida variety led to an increase in biologically fixed nitrogen by 35.3 kg/ha. In the Ametyst variety, the amount of biologically fixed nitrogen increased by 33.9 kg/ha compared to the non-inoculated variant. Thus, the selected soybean varieties – Hoverla, Artemida, and Ametyst – showed a strong response to treatment with nitrogen-fixing bacteria, which facilitated the influx of biologically fixed nitrogen. These varieties are recommended for cultivation in various ecological conditions to support the effective functioning of the soybean's legume-rhizobia symbiosis, which will contribute to the increased resilience of agroecosystems.

DISCUSSION

Legumes are competitive crops due to their environmental and socio-economic benefits, such as nitrogen fixation, soil enrichment with high-quality organic matter, promotion of nutrient cycling, and water retention in the soil. *Rhizobium* bacteria play a crucial role in nitrogen fixation and sustainable agriculture (Soumare et al., 2020). Rhizobia colonise the root system of legumes, forming nodules where nitrogen fixation occurs, converting atmospheric nitrogen into a plant-available form (Coba de la Pena *et al.,* 2018). nodules are primarily formed on the main root, where they are larger in size and mass. Most of them are located in the topsoil. Under favourable conditions, a single plant can form 21 to 80 or more nodules (Roy Choudhury *et al.,* 2019). The number and mass of active nodules on plant roots, especially during periods of peak photosynthetic activity, are important indicators of successful legume-rhizobia symbiosis (Savala *et al.*, 2022). According to research by M. Vasconcelos *et al.* (2024), biological nitrogen fixation by legumes varies from 21 to 389 kg/ha. This is corroborated by the results obtained from the study of the impact of the investigated factors on biological nitrogen fixation in soybean plants, which varied from 36.3 to 130.6 kg/ha.

The activity of rhizobia is influenced by weather conditions that affect the bacteria through the plant, as they live in symbiosis. Water scarcity slows down plant photosynthesis, while waterlogging causes oxygen deficiency in nodules, reducing nitrogen fixation rates (Sinclai & Nogueira, 2018). The current research has established a relationship between nodule formation on soybean roots and the hydrothermal coefficient of the growing region. During periods of moisture deficiency across all years of the study, the lowest mass and number of nodules were observed. The increase in the number of active nodules on plant roots depending on the growth stage of soybeans aligns with the findings of other researchers (Cigelske *et al.*, 2020). In the studies by A. Korobko *et al.* (2024), the highest number of active nodules on soybean roots was also confirmed at the BBCH microstage 68-69. The study also highlighted a decrease in the number of active nodules on plant roots during soybean maturation.

The publication by D. Krutylo *et al.* (2021) highlights the dependence of the diversity of local rhizobia on the environmental conditions of the growing region and host plant genotypes. According to B. Cigelske *et al.* (2020), the average number of nodules per plant varied significantly among different soybean varieties depending on the growing year. The researchers attributed this variation to factors such as soil type, preceding crop, rainfall, and soil nitrogen levels. This confirms the data obtained on the variation in the number of nodules depending on the region and year of cultivation of soybean varieties. In the studies of C.E.N. Savala *et al.* (2022), the soybean variety TGx 1904-6F formed more nodules than the variety Storm. This number varied depending on the year and growing region. Overall, the application of bioinoculants promoted greater nitrogen uptake by plants in areas with the lowest abundance of native rhizobia.

Seed inoculation of soybean varieties resulted in a significant increase in both the number (by 10-45%) and mass (by 11-86%) of nodules on plant roots. Researchers have also reported increased levels of symbiotic nitrogen fixation (by 1.2-4.2 times) and seed weight per plant (by 6-29%), depending on the soybean variety (Krutylo, 2023). The experimental data obtained regarding the increase in the number of active nodules on soybean roots following inoculation with bio-preparations is confirmed by the results of other researchers. The increase in both the number and mass of nodules on soybean roots upon inoculation with *Rhizobia* has been observed in studies by Z. Getachew Gebrehana and L. Abeble Dagnaw (2020) and R. Omari *et al.* (2022). In the article by E. Szpunar-Krok *et al.* (2023), the relationship between increased nodule number and mass following inoculation with *Bradyrhizobia* soybean varieties is discussed. The maximum formation of active nodule mass on the roots of different soybean varieties in the studies is consistent with the findings of other researchers (Korobko *et al.*, 2024).

N.M. Gitonga *et al.* (2021) found that some soybean varieties responded better to inoculation than others. The variety SC Squire showed a positive response to seed inoculation with rhizobia across all studied parameters, compared to the varieties SB 19 and Gazelle. This is confirmed by the results obtained from the study of the impact of seed inoculation on the formation of the legume-rhizobia symbiosis in soybeans and atmospheric nitrogen fixation. D. Miljaković *et al.* (2022) also highlighted the impact of soybean inoculation with *Bradyrhizobia* on increased plant height, nodule number, and nodule mass. In the studies of C.E.N. Savala *et al.* (2022), nodule mass per plant increased from 7.7 to 167.6 mg for two soybean varieties, depending on growing conditions. Scientists believe that the effectiveness of inoculants in symbiosis depends on the compatibility of the strain with a specific soybean variety. An assessment of the symbiotic effectiveness of eight *Bradyrhizobium* strains with five soybean varieties (Gishama, Awassa-95, Boshe, Hawassa-04, and Jalale) showed a significant impact on nodule number and mass (Beruk *et al.,* 2024). The formation of a legume-rhizobia symbiosis induces specific responses that enhance the functional level of the host plant's metabolism and improve its adaptive properties to adverse growing conditions (Nyzhnyk & Kots, 2023). According to M.D. Nakei *et al.* (2024), the effectiveness of soybean-rhizobia symbiosis depends on the rhizobium species, variety characteristics, and biotic factors. This is corroborated by the obtained data concerning the variation in inoculation effectiveness across different soybean varieties inoculated with the same strain.

For the effective functioning of the soybean-rhizobia symbiosis, careful selection of symbiotic partners is necessary, requiring continuous updating of soybean varieties and nitrogen-fixing bacterial strains. According to T. Nyzhnyk and S. Kots (2023), the resilience of the soybean-rhizobia symbiosis to water deficit depends on the active participation of both symbiotic partners, as well as the ability of the host plant and bacteria to activate adaptive defence systems for regulating key enzymatic processes involved in the metabolism of phenolic compounds. Therefore, the research findings confirm those of other scientists regarding the influence of inoculation, varietal characteristics, and ecological growing conditions on the formation of the legume-rhizobia symbiosis in soybeans. Optimising the management of biological nitrogen fixation is crucial for addressing the challenges of providing plants with nitrogen, reducing the use of nitrogen fertilisers, and preserving soil fertility. The use of sustainable alternatives will contribute to sustainable agriculture and biodiversity conservation.

CONCLUSIONS

The number of active nodules formed on plants across different years of research primarily depended on the hydrothermal coefficient of the soybean growing region and its varietal characteristics. The highest number of active nodules at BBCH microstage 51-59 was formed on the roots of soybean varieties in the Poltava Region in 2021, Vinnytsia Region in 2018, and Kyiv Region in 2014 on the varieties Hoverla, Artemida, and Ametyst, after seed inoculation with the biopreparation Optimize 200. At BBCH microstage 61-62, an increase in the number of active nodules on the roots of different soybean varieties was observed after seed inoculation compared to BBCH microstage 51-59, depending on the year and growing region. The highest number of active nodules on the roots of different soybean varieties after seed inoculation was recorded at BBCH microstage 68-69, depending on the year and growing region. In the Poltava Region under favourable conditions (2021), the number of active nodules after seed inoculation ranged from 46.7 to 50.3 mg/plant depending on the variety, which is 17.0-18.4 more compared to non-inoculated variants. At BBCH microstage 80-90, a decrease in the number of active nodules on the roots of different soybean varieties was observed compared to the previous microstages (BBCH 61-62 and BBCH 68-69).

The highest active nodule mass at BBCH microstage 51-59 was observed on plant roots in Poltava Region in 2021, Vinnytsia Region in 2018, and Kyiv Region in 2014, specifically on the varieties Hoverla, Artemida, and Ametyst following seed inoculation. These findings are supported by the hydrothermal coefficient values for each region during the favourable growing year. An increase in active nodule mass was observed at BBCH microstage 61-62 across all varieties following seed inoculation compared to BBCH microstage 51-59, depending on the year and growing region. The maximum active nodule mass on soybean roots was recorded at BBCH microstage 68-69 in Poltava, Vinnytsia, and Kyiv regions. The most favourable hydrothermal conditions for all soybean varieties were observed in 2021 in Poltava Region. The mass of active nodules following seed inoculation ranged from 508.9 to 547.8 mg/plant, depending on the variety, which is 173.7-188.0 mg/plant higher compared to non-inoculated variants. At BBCH microstage 80-90, a decrease in active nodule mass on the roots of different soybean varieties was observed compared to the previous microstages.

Seed inoculation had the greatest impact on the formation of active symbiotic potential. The increase in active symbiotic potential in certain years of the study can be explained by high hydrothermal coefficient values. The highest active symbiotic potential was determined in soybean varieties Hoverla, Artemida, Ametyst, and Vezha. Cultivation of soybean varieties Ametyst, Artemida, and Hoverla contributed to the maximum accumulation of biologically fixed nitrogen when using seed inoculation with nitrogen-fixing bacteria under various ecological conditions. Biological nitrogen fixation by soybean varieties was significantly dependent on seed inoculation (96.89%). Varieties Ametyst, Artemida, and Hoverla provided the highest amount of biologically fixed nitrogen (95.5-101.2 kg/ha) when seeds were inoculated. With seed inoculation of varieties Ametyst, Artemida, and Hoverla, biological nitrogen fixation increased by 33.9-36.1 kg/ha compared to the non-inoculated variant. The results of this study confirm the prospects for further research on the effectiveness of legume-rhizobia symbiosis under the influence of seed inoculation in various ecological conditions, which will contribute to increasing the sustainability of agroecosystems.

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None.

CONFLICT OF INTEREST

None.

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Дослідження бобово-ризобіального симбіозу сої для стійкості агроекосистем

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Анотація. Дослідження інноваційних методів регуляції бобово-ризобіального симбіозу є важливим для покращення азотфіксації, що сприяє збереженню здоров›я ґрунтів та підвищенню врожайності. Це забезпечує стале сільське господарство, знижуючи потребу в хімічних добривах і підвищуючи стійкість агроекосистем. Метою роботи було з'ясувати вплив інокуляції насіння, екологічних умов і сортових особливостей сортів сої на накопичення біологічного азоту. Дослідження проводили у екологічних умовах Київської, Полтавської та Вінницької областей протягом 2010-2021 рр. Агротехніка вирощування сортів сої була загальноприйнята для умов регіонів дослідження. Наведено результати досліджень впливу інокуляції насіння на динаміку формування та продуктивність соєво-ризобіального симбіозу за наявності в ґрунті фонових популяцій ризобій сої. Визначено азотфіксувальний потенціал сортів сої за дії інокуляції. Інокуляція підвищує ефективність симбіотичної системи сої. Доведено, що в різних екологічних умовах інокуляція насіння Bradyrhizobium japonicum покращує формування і функціонування симбіотичного апарату сої навіть на фоні ґрунтової популяції бульбочкових бактерій. Дія інокуляції насіння залежить від гідротермічного режиму року, екологічних умов і сорту сої. Застосування інокуляції насіння сприяє формуванню більшої маси активних бульбочок на коренях рослин, що позитивно вплинуло на азотфіксацію. Найвищі показники азотфіксації встановлено у сортів сої Аметист, Артеміда і Говерла у різних екологічних умовах. Інокуляція насіння забезпечила збільшення кількості біологічного азоту цих сортів на 33.9-36.1 кг/га. Сорти сої Аметист, Артеміда і Говерла відзначилися вищою реакцією на інокуляцію насіння азотфіксувальними бактеріями і рекомендуються для вирощування у різних екологічних умовах. Інноваційні рішення підвищення ефективності функціонування бобово-ризобіального симбіозу сої за використання біологічних препаратів на основі азотфіксувальних бактерій дозволять розробити біологізовані технології вирощування культури для стійкості агроекосистем

Ключові слова: кількість і маса бульбочок; азотфіксація; симбіотичний потенціал; інокуляція; гідротермічний коефіцієнт; ризобії; біологічно-фіксований азот