

Adaptability of soybean varieties assessed through symbiotic activity under different soil-climatic conditions

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February 16th, 2026; Accepted: August 3rd, 2026; Published: October 19th, 2026

Abstract. The purpose of this work reveals itself in distinguishing ontogenetic adaptation parameters according to the symbiotic performance indicators of soybean varieties for the introduction of such varieties into production and as source material for the development of new soybean varieties with high and stable nitrogen-fixing capacity. The research was conducted in different soil-climatic regions of Ukraine, enabling the assessment of soybean variety responses to varying ecological conditions. Indicators of the active symbiotic apparatus and the amount of biologically fixed nitrogen were determined using the Volkohon methodology. Adaptability of the researched varieties was assessed by their symbiotic potential considering the method developed by Eberhart and Russell. The study presents the scientific results on the assessment of soybean varieties by adaptability of active nodules and their mass, active symbiotic potential, and accumulation of biologically fixed nitrogen. The highest amount of biologically fixed nitrogen was recorded in such varieties as Hoverla – $101.12 \pm 0.39 \text{ kg ha}^{-1}$, Artemida – $98.07 \pm 0.38 \text{ kg ha}^{-1}$, Amethyst – $95.51 \pm 0.38 \text{ kg ha}^{-1}$ and Vezha – $93.40 \pm 0.38 \text{ kg ha}^{-1}$, respectively. Despite the different reaction of varieties to fluctuations in environmental conditions, the selected varieties were distinguished by high stability of the formation of the amount of biologically fixed nitrogen. In the Vezha and Amethyst varieties, the stability index (S_i^2) was as close to zero as possible. Although the varieties differed in their responses to environmental fluctuations, the selected Hoverla, Artemida, Amethyst and Vezha soybean varieties demonstrated high stability in biologically fixed nitrogen accumulation and were recommended for the development of new soybean varieties, considering their stable realization under different soil-climatic growing conditions.

Key words: adaptability, homeostaticity, nitrogen, nodules, plasticity, stability, variance.

INTRODUCTION

Legumes play a significant role in agriculture because their main property is the ability to accumulate nitrogen from the air and enrich the soil with it. According to the

research results, the use of nodule bacteria for the treatment of soybean seeds provides a high level of nitrogen accumulation (Tkachenko et al., 2024).

In modern agriculture, the main direction for reproducing soil fertility is often determined as the application of biological fertilizers. The use of inoculants in agriculture is less costly than the application of mineral fertilizers. Due to the property of nodule bacteria, up to 35–55 kg ha⁻¹ of nitrogen remains in the soil (Barvinchenko, 2017).

Approximately 60–150 kg ha⁻¹ of nitrogen, which accumulates after growing soybeans, by 90–100% is used by the following varieties in crop rotation, from its part mineral nitrogen, for example, by 50–60% (Hryhorieva, 2014).

The accumulated nodule bacteria remain active in the soil for 3–5 years. Nevertheless, most researchers admit the nitrogen-fixing activity of existing legume-rhizobia systems is much lower than the potential level, demonstrated by the high genetic polymorphism of wild and varietal populations of legumes in terms of symbiotic activity (Didora et al., 2015).

Soybeans undergo such important processes as photosynthesis and nitrogen fixation, which are the basis for the synthesis of vitamins, proteins, amino acids, enzymes, carbohydrates, and other compounds (Vasylenko, 2018). It is a leguminous crop, the cultivation technology of which must necessarily include bacterization of seeds (inoculation). Nitrogen fixation from the air of soybeans requires *Rhizobium japonicum* (Kirchner) Buchanan bacteria's presence in the soil for converting nitrogen gas into mineral forms available to plants (Kyrychenko et al., 2016).

But the observed amount of nodule bacteria in soybean plants is not always sufficient. Due to the fact that their sown area in Ukraine is constantly increasing and this crop is grown there where it has never been done before, it is necessary to ensure the existence of active strains of nodule bacteria in the ground. Using such bacterial fertilizers as rhizohumin, agrobacterin, chetomic, and rhizobophyte is a vital precondition for nodule bacteria activity. Under favorable conditions, soybeans can accumulate up to 150–200 kg ha⁻¹ of biological nitrogen, and also accumulate phosphorus and potassium in an accessible form. Modern varieties in symbiosis with strains of nodule bacteria can enhance output by about 10–30% (Babych & Babych-Poberezhna, 2014).

Moreover, due to the nitrogen accumulated by nodule bacteria, the productivity of subsequent crops in crop rotation increases, which makes it probable to diminish costs of nitrogen fertilizers (Kvitko et al., 2021).

The research has shown that soybean varieties can react differently to nodule bacteria. Higher nitrogen fixation happens if there is sufficient moisture supply; the yield increase was 2.5–3.1 t ha⁻¹, with lack of moisture – 0.5–0.6 t ha⁻¹. Its effect on yield due to the ripeness group of varieties was also revealed; higher growth rates occurred in late-ripening varieties (Derevianskyi & Kalenska, 2012; Sulieman & Tran, 2021; Ribeiro et al., 2022).

The research of the legumes' role in the formation of active symbiosis is of great practical importance. Considering the traits related to symbiotic nitrogen fixation (mass and number of nodules, nitrogenase activity, nitrogen accumulation, economic specificity), high variability of legumes is widely used in breeding work to create new high-yielding varieties of these crops. It is believed that due to plant breeding, the

intensity of symbiotic nitrogen fixation will go up by 300%; that should stimulate active research in this direction (Volkohon et al., 2006; Kahraman & Akgül, 2021; Mazur et al., 2023).

Thus, among the prerequisites for the vigorous plant growth, the main one is to provide them with nitrogen and enhanced synthesis of proteins necessary for cell growth processes. Accordingly, nitrogen nutrition has a significant impact on plants' photosynthetic activity. Besides, the process of photosynthesis has a decisive influence on its transformation in the plant cell. The various organic substances formed as a result of this ensure the maintenance of the plant organism at a high physiological level and, consequently, guarantee its high biological and economic suitability (Pantsyreva et al., 2023; Yatsenko et al., 2023; Mazur et al., 2023b).

Rhizobia strains ideal for agricultural production should provide a high level of symbiotic nitrogen fixation in different soil and climatic conditions on all grown varieties of this type of leguminous plant. Unfortunately, the current state of biological science does not allow designing such microorganisms and indicates the feasibility of coordinated selection of strains of nodule bacteria and varieties of leguminous plants.

In Ukraine, it is vital for soybean rhizobia, which are absent in the composition of the aboriginal soil microflora. The possibility of selecting a highly effective strain of soybean rhizobia with a wide varietal specificity has been proven experimentally (Kniaziev, 1995).

Therefore, a further increase in the effectiveness of legume-rhizobia symbiosis depends both on legume breeding varieties and on the selection of appropriate highly active rhizobia strains. Unfortunately, Ukraine has not created a purposeful system of such selection yet, but its elements are presented in the work of scientific institutions whose activities are related to the research of leguminous plants and nodule bacteria (Kniaziev, 1995; Mostovenko et al., 2022).

Modern intensive soybean varieties and selective nodule bacteria, which form an intensive symbiotic apparatus, can be satisfied with minimal consumption of it from soil reserves and fertilizers applied under the predecessor and form a high yield. However, a high intensity of nitrogen fixation and productivity of the variety can be achieved only with a successful combination of the strain of nodule bacteria and the genotype of plants.

A successful solution to the problem of biological fixation of atmospheric nitrogen by soybeans can provide a significant increase in vegetable protein resources. Significant specificity of soybean varieties and bacterial strains in their symbiosis in different soil and climatic conditions has been determined. Selection for early nodule formation should be aimed either at activating the initial infection of the root hairs or at ensuring the germination of infectious strands from the hairs into the root bark. The selection of forms with increased symbiotic activity should be carried out according to direct (nitrogenase activity) or indirect (intensity of photosynthesis, chlorophyll content in leaves, degree of development of vegetative organs) traits (Kyrychenko et al., 2016).

According to observation, an acute lack of moisture in the soil leads to the death of nodules. The minimum soil moisture at which they develop is about 16% of the total moisture capacity (TM). Other researchers note that the minimum is 15–20% of the total moisture capacity of the soil. In legumes, nodules are formed in the range of 40–80% of the total moisture capacity. The optimal soil moisture is 60–70% TM (Kniaziev, 1995).

Due to the research, nitrogen fixation occurs actively if the nodules in the opening are pink and the plants are rich green. Since nodule bacteria are living organisms, it should be mentioned that their vital activity depends on weather conditions. However, the environment influences bacteria through the plant, since they live in symbiosis with it. Thus, with a lack of moisture, the intensity of photosynthesis in the plant decreases, and with waterlogging, the nodules lack oxygen (Malynovska & Kolmaz, 1997; Honcharuk et al., 2023).

The limit of critical moisture for nodulation depends on the symbiosis partners. The existence of genetic variability in resistance to most external stressors has been shown both in feeding plants and in their corresponding strains of rhizobia (Hungria & Vargas, 2000). Nodule bacteria appear more resistant to external pressures than other plants and, in arid conditions, can survive in a film of water around soil particles (Serraj & Adu-Gyamfi, 2004).

The survival and activity of microorganisms, as well as the effectiveness of the symbiosis formed with their participation, depend on many factors, particularly the physiological characteristics of macro- and microsymbionts, their natural habitat, soil type, and changes in its moisture content (Cook & Orchard, 2008). Thus, substantial reduction in the microorganisms' population under arid conditions and a rise in water stress have been shown. The unearthed effective strains are able to migrate in drought conditions over longer distances than ineffective ones. It verifies a decrease in water supply significantly reduces the number of infectious filaments in the root hairs of legumes, inhibits nodulation, along with nitrogen fixation by formed nodules (Wadisirisuk et al., 1989).

Temperature regimes play key roles in nodule bacteria and legume relationships. Active nitrogen fixation and the formation of a high yield in leguminous plants happen at substrate temperatures of 20–24 °C. A change in the temperature regime during alfalfa cultivation from 25/20 °C (day/night) to 10/7 °C in a period of up to 13 weeks led to a 50% decrease in the total and relative activity of nitrogenase (Kniaziev, 1995; López-Bellido et al., 2020).

The high nitrogen-fixing capacity, resulting from the well-developed symbiotic apparatus of plants, provides a more intensive photosynthesis process, which ultimately contributes to the accumulation of more organic matter, both in the vegetative and reproductive organs of the plant. Therefore, seed inoculation is an effective technological technique that is fully expedient in view of economics. Though, along with high nitrogen-fixing capacity, varieties are needed that will be stable in these indicators and less dependent on the effect of hydrothermal and edaphic conditions, especially during climate change. Thus, varieties stable in their traits and suitable to grow in different climatic conditions of the region are of great importance for agriculture. Under favourable conditions, greater preference belongs to strains demonstrating considerable productivity potential, especially when challenged by adverse or extreme conditions, ideally necessitate robust environmental stability as a complementary trait (Zinchenko et al., 2018; Korobko et al., 2024; Mazur et al., 2024).

At the present stage, the strategic goal of soybean breeding is to create highly adaptive strains distinguished not only by high seed yields but also by high genetic protection levels of the crop from bio- and abiotic external conditions that heavily influence outcomes and offer the chance to achieve peak efficiency in combination with high-quality seeds and nitrogen-fixing ability.

Most modern soybean varieties have a fairly high productivity potential, whose execution is limited by their poor homeostatic ability and susceptibility to detrimental environmental conditions. Plants' adaptation to new environmental conditions is achieved due to modification and genotypic variability, i. e., by restructuring the complex of the plant's physiological, biochemical, and morphoanatomical traits in ontogenesis and building new reaction norms in phylogeny. The term 'adaptability' defines the genotypes' capacity to guarantee high and stable productivity of plants in different environmental conditions (Mazur et al., 2023).

Adaptability (from the English 'adaptive' and the Latin 'adapto' – to adjust), as a property of living organisms, characterizes the adequacy (correspondence) of a plant's genotype to the actual environmental conditions over a sufficiently long period of time to maximize the realization of its potential capabilities (Vinnichenko et al., 2011). Accordingly, an adaptive variety is an ecologically plastic genotype adapted to both optimal and minimal or maximal manifestations of environmental factors (Salari et al., 2015).

Ecological stability is closely linked to the concept of plasticity, which reflects the ability of plant populations to withstand stress factors, whereas plasticity is the ability of plants to combine economical consumption with the effective use of natural resources and nutrients under specific growing conditions (Eberhart & Russell, 1966). Ecological plasticity reflects the ability of plants to effectively utilize favorable environmental factors for the stable formation of high productivity (Tai, 1971).

Today plant breeding for adaptability is especially important when weather conditions are changing rapidly, causing a strict moisture limit in regions that were previously favorable for agriculture (Chernyshenko, 2014).

Thus, the variety's adaptability to weather, soil, and economic conditions is called ecological plasticity. Plasticity has been proposed as a term that means an adaptive mechanism to environmental conditions. A high plasticity index characterizes plants that respond optimally to environmental heterogeneity (Alpert & Simms, 2002).

Consequently, the analysis shows that we can find not only the different reaction rate of growing conditions considering ecological plasticity and stability, but also identify genotypes that can realize productivity with significant changes in environmental conditions and ensure their most effective application and distribution (Zinchenko et al., 2018).

The research goal is to outline the ontogenetic adaptation parameters according to the symbiotic performance indicators of soybean varieties (Chernyshenko, 2014). So, ecological plasticity is, firstly, the strain's adaptability to weather, soil, and economic conditions. Plasticity has been interpreted as a term that means an adaptive mechanism to environmental conditions. A high plasticity index characterizes plants that respond optimally to environmental heterogeneity (Alpert & Simms, 2002; Mazur et al., 2024b).

The analysis helps not only to discover the different reaction rates of growing conditions, but also to identify genotypes that will realize productivity with significant changes in environmental conditions, ensure their most effective application and distribution (Zinchenko et al., 2018).

The research purpose reveals itself in distinguishing ontogenetic adaptation parameters according to the symbiotic performance indicators of soybean varieties for the introduction of such varieties into production and as source material for the development of new soybean varieties with high and stable nitrogen-fixing capacity.

MATERIAL AND METHODS

Climatic conditions

Research was conducted under different soil and climatic conditions of Ukraine, specifically within the so-called ‘soybean belt’, where approximately two-thirds of the country’s soybean acreage is concentrated. This region includes zones of stable and unstable soybean production on fertile soils, as well as a zone of guaranteed soybean production under irrigated conditions (Babych & Babych-Poberezhna, 2011). This zone comprises regions receiving 500–650 mm of annual precipitation, including 250–400 mm during the period from May to September and 180–200 mm during the flowering and pod formation stages (Didora, 2018).

The study was carried out during 2010–2021, a period characterized by contrasting hydrothermal conditions across different soil-climatic regions of Ukraine (Fig. 1). This made it possible to determine the response of soybean varieties to variations in environmental conditions.

A reliable assessment of variety adaptability, plasticity, and stability requires investigating the peculiarities of symbiotic activity formation under changing abiotic factors during the growing season (Adamenko, 2006). In our study, this important requirement was fulfilled, as considerable variation in the hydrothermal coefficient (HTC) was observed (Fig. 1).

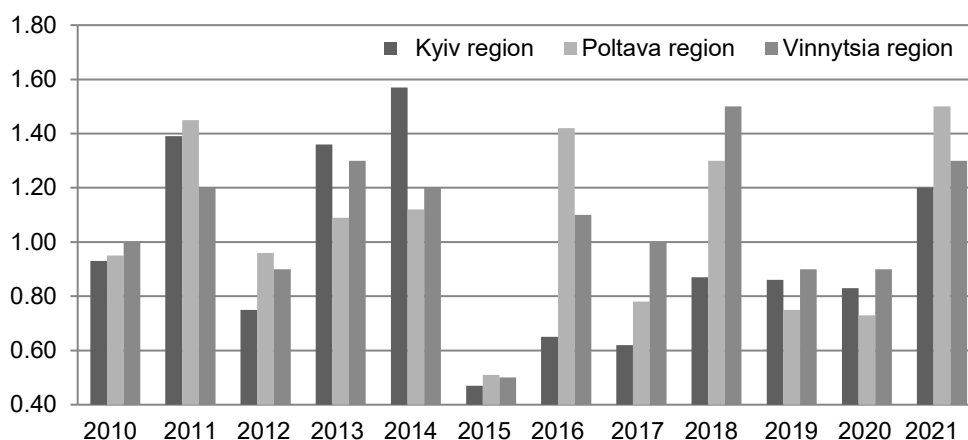


Figure 1. Hydrothermal coefficients throughout the BBCH 10-99 growing season (May–September) 2010–2021.

Low hydrothermal coefficient values were recorded in 2015, when HTC ranged from 0.4 to 0.7 (very dry conditions), in 2019, when HTC ranged from 0.8 to 1.0 (dry conditions), and in 2020, when HTC also ranged from 0.8 to 1.0 (dry conditions). These conditions affected the functioning of the symbiotic apparatus of different soybean varieties. The long-term average HTC values ranged from 1.1 to 1.3, corresponding to slightly dry conditions.

Research location

The soil cover of the experimental sites was represented by gray forest soils in Vinnytsia Region, podzolized chernozems in Poltava Region, and typical chernozems in Kyiv Region.

According to the agrochemical survey, the plow layer of the experimental field in Vinnytsia Region was characterized by the following physicochemical properties: humus content (determined by the Tyurin method) ranged from 2.02 to 2.25%; alkaline-hydrolyzable nitrogen (Cornfield method) from 60 to 67 mg kg⁻¹ of soil; available phosphorus and exchangeable potassium (Chirikov method) amounted to 149–212 and 80–92 mg kg⁻¹ of soil, respectively. The pH of the salt extract was 5.3–5.4, while hydrolytic acidity was 1.6–1.7 meq per 100 g of soil.

In Poltava Region, the soil cover of the experimental site was represented by podzolized chernozem. The humus content in the plow layer (Tyurin method) ranged from 3.07 to 3.63%. Bulk density was 1.23 g cm⁻³, and particle density was 2.7 g cm⁻³. The cation exchange capacity was 21–23 meq per 100 g of soil, and base saturation was 64%. Soil acidity was relatively low (pH 5.8–6.0), while hydrolytic acidity ranged from 1.3 to 3.5 meq per 100 g of soil. Field moisture capacity was 27.6%, and the maximum reserve of productive moisture in the 1-m soil layer reached 184 mm. Molecular moisture capacity ranged from 12.0 to 13.5%, and plasticity from 19.4 to 31.6%. The soil was moderately supplied with nitrogen, phosphorus, and potassium. The sum of absorbed bases amounted to 242–297 meq per 100 g of soil, and the degree of base saturation was 84–87%. The content of available nitrogen (Cornfield method) was 108 mg kg⁻¹, available phosphorus (Kirsanov method) 70–100 mg kg⁻¹, and available potassium (Maslova method) 120–180 mg kg⁻¹ of soil.

In Kyiv Region, the soil of the experimental site was represented by typical low-humus heavy loam chernozem characterized by the following agrochemical properties: humus content was 5.15% in the 0–20 cm layer and 4.07% in the 20–40 cm layer. The 0–20 cm layer contained 161.7 mg kg⁻¹ of easily hydrolyzable nitrogen (Cornfield method), 150.3 mg kg⁻¹ of available phosphorus (Chirikov method), and 208 mg kg⁻¹ of exchangeable potassium (Chirikov method). The soil solution reaction was slightly acidic, with a salt extract pH of 5.8. Thus, according to its main agrochemical characteristics, the soil of the experimental site was suitable for the cultivation of most agricultural crops, including soybean.

Winter wheat served as the preceding crop. Simultaneously with sowing, a complex mineral fertilizer, nitroammophoska (NPK 16–16–16), was applied.

Soybean accessions were sown in a collection nursery on four-row plots, each 1 m in length, with 45-cm row spacing and four replications (Vovkodav, 2001).

The research material consisted of soybean varieties developed by Ukrainian breeding institutions, including: Amethyst – Krasnohrad Experimental Station of the Institute of Grain Farming of the Ukrainian Academy of Agrarian Sciences; Hoverla – Precarpathian State Agricultural Experimental Station of the Institute of Agriculture of the Carpathian Region of the National Academy of Agrarian Sciences of Ukraine and the Institute of Feed Research and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine; Artemida – Institute of Feed Research and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine and Krasnohrad Experimental Station of the Institute of Grain Farming of the Ukrainian Academy of

Agrarian Sciences; Femida, Zolotysta, and Oriana – Institute of Agriculture of the Southern Region of the Ukrainian Academy of Agrarian Sciences and the Institute of Feed Research and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine; and Vezha – Institute of Feed Research and Agriculture of Podillia of the National Academy of Agrarian Sciences of Ukraine.

All soybean varieties were evaluated in all three regions. The bacterial preparation Optimize 200 (BASF, Germany) was used as an inoculant. This soybean seed treatment product stimulates natural growth processes associated with biological nitrogen fixation, thereby improving plant nutrition and development. Optimize 200 is produced using modern technology based on a pure culture of *Bradyrhizobium japonicum* and contains formulation components that extend bacterial survival on the seed surface. Lipo-chitooligosaccharides (LCOs), included in the formulation, are unique signaling molecules that enhance plant nutrition, promote the formation of productive nitrogen-fixing root nodules, and stimulate root and early shoot development. The formulation ensures a positive effect regardless of soybean variety or environmental conditions and maintains its effectiveness over an extended period. The liquid formulation allows visual quality control of the product and assessment of bacterial viability. In addition, the relatively low application rate of 2.8 L t^{-1} of seed reduces the time and resources required for treatment. The bacterial concentration was $2 \times 10^9 \text{ CFU g}^{-1}$ of product. Seed inoculation was performed one day before sowing.

METHODS

Soybean cultivation in previous years contributed to the establishment of a population of nodule bacteria and their enrichment through the application of bacterial preparations (inoculants). The presence of nodules on soybean roots was determined at different growth and developmental stages using soil monoliths with a depth of 0–20 cm and a diameter of 50 cm. Soybean roots were carefully washed through sieves with a mesh size of 1 mm.

Knowing the area of the monolith and the average plant density, the number and fresh weight of nodules per plant were determined (Volkohon et al., 2010). The active symbiotic potential (ASP) was calculated using the following formula: $\text{ASP} = (M_1 + M_2)/2 \times T$, where T is the period between two consecutive sampling dates, days; $(M_1 + M_2)/2$ is the average weight of leghemoglobin-containing nodules during period T , kg ha^{-1} . The amount of fixed nitrogen was calculated based on the active symbiotic potential and the specific activity of symbiosis according to the methodology described by Volkohon (Volkohon et al., 2010). The ecological adaptability parameters of soybean varieties were calculated according to the method of Eberhart and Russell (Eberhart & Russell, 1966). The linear regression coefficient (b_i) and the variance of deviations from the regression line (stability parameter S^2) were determined. According to this methodology, the stability variance (S^2) indicates the reliability with which a variety expresses the plasticity characterized by the regression coefficient b_i , which reflects the genotype's response to changes in growing conditions. The higher the value of this coefficient ($b_i > 1$), the greater the sensitivity of the variety to environmental changes. When $b_i < 1$, the variety exhibits a weaker response to variations in environmental conditions. A value of $b_i = 1$, or close to unity, indicates complete correspondence between the variation of the trait and changes in growing conditions.

Homeostaticity (Hom) and the agronomic stability coefficient (As) were determined according to the methodology of Khomenko (Khomenko et al., 2016).

A structural analysis of yield components was performed on 25 plants from each replication. The collection samples were harvested manually, followed by threshing. Under laboratory conditions, the following morphobiological traits were determined: plant height (cm), 1,000-seed weight (g), grain yield (g m⁻²), and plant productivity (g plant⁻¹).

RESULTS AND DISCUSSION

As the process, nitrogen fixation takes place in special formations – nodules, which are small thickenings on the roots, populated by colonies of bacteria of the genus *Rhizobium* (Honcharuk et al., 2023).

The results of the contrast hydrothermic regime's impact during the period of research have been reflected in the expression of the test conditions over the years of research and their interaction with the variety and conditions in the expression and weight of active nodules, active symbiotic potential, and biological fixation of nitrogen (Table 1–6). In particular, the reliability (according to Fisher's criterion) of the interaction of the variety and the conditions of testing over the period of research and test conditions over the years of research in the variant of dispersion processing of the results of the number and weight of active nodules, active symbiotic potential, and biological fixation of nitrogen. In its turn, this enabled evaluation of soybean varieties using various methods for assessing environmental stability and plasticity.

While forming the first trifoliate leaf (7–10 days after germination), the nodules become noticeable on the roots of soybeans. The nitrogen fixation process begins in 15–25 days after their formation, and it lasts until the aging of plants. At the initial phases of soybean development, nitrogen fixation proceeds weakly. Later its activity increases significantly, the maximum values of which are noted during flowering and filling of beans. During ripening, it decreases again. The maximum values of which are noted during flowering and filling of beans (Table 1).

A significant increase of active nodules occurred at the microstage BBCH 68-69. Maximum quantities were in Hoverla – 21.67 ± 0.14 pcs., Artemida – 21.21 ± 0.14 pcs., Vezha – 20.65 ± 0.14 pcs., Amethyst – 20.39 ± 0.14 pcs. Considering their reactions to hydrothermal and edaphic changes of growing conditions, they belong to plastic ($b_i = 1$) and low-plastic ($b_i < 1$). For example, the plasticity coefficient of Hoverla is 0.88, Artemida – 1.0, Vezha – 0.99 and Amethyst – 0.98. In the researched strains, the stability index (S_i^2) was close to zero, namely, with a minimum deviation from the plasticity coefficient slope.

These varieties possess the highest agronomic stability (As) and the lowest coefficients of variation (V, %), which were noticed in Hoverla – 75.86 and 21.14%, Artemida – 74.88 and 25.12%, Vezha – 74.39 and 25.61%, Amethyst – 74.32 and 25.68%.

The highest indicators resistant to adverse environmental conditions has been confirmed in the sequence of their distribution and the homeostatic nature of type 1 (Hom1) and type 2 (Hom2). The highest homeostatic traits of the first (Hom1) and second types (Hom2) were noted in Hoverla – 4.14 and 0.18; Artemida – 3.98 and 0.18; Vezha – 3.91 and 0.18; Amethyst – 3.89 and 0.18. The variety's adaptability to weather, soil, and economic conditions was called ecological plasticity.

Table 1. Parameters of ecological stability and plasticity of soybeans by active nodules (pcs. plant⁻¹) on roots at the microstage BBCH 68-69, 2010–2021

Variat	Number of nodules, pcs. plant ⁻¹	Coefficient			Stability index (Si2)	Homeostaticity		Components	
	Year. Test points	Ecological plasticity (bi)	Agronomic stability (As), %	Variations (V). %		Hom 1	Hom 2	a _i	λ _i
Amethyst	20.39 + 0.14	0.98	74.32	25.68	0.22	3.89	0.18	-0.03	0.46
Hoverla	21.67 + 0.14	0.88	75.86	24.14	0.39	4.14	0.18	-0.04	0.54
Artemida	21.21 + 0.14	1.00	74.88	25.12	0.24	3.98	0.18	0.02	0.52
Femida	20.37 + 0.14	1.01	73.67	26.33	0.09	3.79	0.17	0.04	0.32
Zolotysta	20.05 + 0.15	1.01	73.11	26.89	0.05	3.72	0.17	0.05	0.28
Vezha	20.65 + 0.14	0.99	74.39	25.61	0.10	3.91	0.18	0.01	0.32
Oriana	19.55 + 0.15	1.03	71.74	28.26	0.20	3.54	0.16	0.11	0.45
Factor	F f	F t							
Variety	10,538.4	2.19							
Conditions	283.0	1.54							
Interaction variety – conditions	20.0	1.39							

Table 2. Parameters of ecological stability and plasticity of soybeans by active nodules (pcs. plant⁻¹) on roots at the microstage BBCH 68-69, 2010–2021

Variety	Number of nodules, pcs. plant ⁻¹	Coefficient			Stability index (Si ²)	Homeostaticity		Components	
	Year. Test points	Ecological plasticity (bi)	Agronomic stability (As). %	Variations (V). %		Hom 1	Hom 2	a _i	λ _i
Amethyst	37.21 + 0.15	1.00	85.57	14.43	0.08	6.93	0.29	0.03	1.19
Hoverla	39.21 + 0.15	1.03	85.99	14.01	0.14	7.14	0.30	0.09	1.48
Artemida	38.17 + 0.15	1.00	85.92	14.08	0.09	7.10	0.30	0.03	1.41
Femida	35.64 + 0.15	1.00	84.98	15.02	0.05	6.66	0.28	0.02	1.05
Zolotysta	34.76 + 0.14	0.98	84.91	15.09	0.09	6.63	0.29	-0.03	1.29
Vezha	36.41 + 0.15	1.00	85.26	14.74	0.05	6.79	0.48	0.03	1.13
Oriana	34.03 + 0.14	0.98	84.51	15.49	0.27	6.45	0.29	-0.02	1.95
Factor	F f	F t							
Variety	28,576.2	2.19							
Conditions	517	1.54							
Interaction variety – conditions	3.2	1.39							

Plasticity has been proposed as a term that means an adaptive mechanism to environmental conditions. A high plasticity index characterizes plants that respond optimally to environmental heterogeneity (Alpert & Simms, 2002).

During inoculation of soybean seeds, a significant increase was noted in quantities of nodules on plants at the microstage BBCH 68-69, the most of nodules happened in Hoverla – 39.21 ± 0.14 pcs., Artemida – 38.17 ± 0.15 pcs., Amethyst – 37.21 ± 0.15 pcs., Vezha – 36.41 ± 0.15 pcs. (Table 2).

Considering reactions to hydrothermal regime changes, we classified these plant strains as highly plastic ($b_i > 1$) and plastic ($b_i = 1$). The plasticity coefficient (b_i) of Hoverla is 1.03, Artemida – 1.0, Amethyst – 1.0, and Vezha – 1.0.

These varieties demonstrate the highest agronomic stability coefficients (A_s) and, accordingly, the lowest coefficients of variation (V , %), especially in Hoverla – 85.99 and 14.1%, Artemida – 95.92 and 14.08%, Amethyst – 85.57 and 14.43%, Vezha – 85.26 and 14.74%. In these soybean varieties, the stability index (Si^2) was as close to zero; the deviation from the plasticity coefficient slope was minimal. Confirmation of the classification of soybeans by the agronomic stability coefficient (A_s) and the coefficient of variation (V , %) is represented by the sequence of varieties' distribution according to homeostaticity of type 1 (Hom1) and type 2 (Hom2): Hoverla – 7.14 and 0.30; Artemida – 7.10 and 0.30; Amethyst – 6.93 and 0.29; Vezha – 6.79 and 0.48. Lower agronomic stability coefficients (A_s) were noted in the following varieties: Oriana – 84.51%, Femida – 84.98% and Zolotysta – 84.91%. Correspondingly higher variation coefficients (V , %) appear in Oriana – 15.49%, Femida – 15.02% and Zolotysta – 15.09%, respectively.

The efficiency of legume-rhizobia symbiosis depends on the formation and functioning of the symbiotic apparatus, for the assessment of which is most often used, besides the quantity indicators of nodules and their mass on one plant. However, not all root nodules are capable of nitrogen fixation, but only those that contain a red pigment – leghaemoglobin (Mazur et al., 2024).

The maximum indicators of the active mass of nodules were reached at the microstage BBCH 68-69, compared to other microstages on the scale of development phases (Table 3). Nodule mass showed its peak activity, irrespective of whether inoculation was applied or not.

The highest active mass of nodules without seed inoculation was noted in such varieties as Hoverla – 247.30 ± 1.63 mg plant⁻¹, Artemida – 239.50 ± 1.64 mg plant⁻¹, Amethyst – 235.70 ± 1.66 mg plant⁻¹, and Vezha – 234.33 ± 1.64 mg plant⁻¹.

Therefore, in the variant of the experiment without inoculation, these varieties showed a conservative reaction, the plasticity coefficient ($b_i < 1$), ensuring the stable implementation of the corresponding active mass of nodules, which depended to a lesser extent on alterations in edaphic and hydrothermal growing conditions. The highest agronomic stability coefficients (A_s), and the lowest variation coefficients (V) confirmed our outcomes, particularly Hoverla – 75.59 and 24.41%, Artemida – 74.63 and 25.37%, Amethyst – 73.99 and 26.01%, Tower – 74.16 and 25.84%. Furthermore, these varieties demonstrated superior performance when it came to mitigating the impact of unfavorable external conditions. The measure used to assess the variety's homeostatic capacity was their aptitude to maintain limited fluctuation in the quantity of active nodules present on the plant. This, in essence, classified the varieties based on their

homeostaticity; specifically, due to Hom 1 and Hom 2 classifications, according to which Hoverla – 4.11 and 0.02, Artemida – 3.94 and 0.02, Vezha – 3.87 and 0.02, Amethyst – 3.84 and 0.02, respectively, were the finest among them all.

The assessment of ecological stability and plasticity is more clearly presented, supplemented by a graph (Fig. 2), which confirmed that the varieties coordinated in zone 1 are genotypes with increased responses to improving hydrothermal and edaphic growing conditions, namely Oriana and Zolotysta.

The varieties of zone 2 are marked by medium plasticity. The varieties with the coordinates in the third zone are marked by a low reaction to alterations in the agricultural background of cultivation; they include Amethyst, Artemida, and Vezha. The strains of zone 3 are marked by a conservative reaction to alterations in the agricultural background of cultivation; they include Hoverla and Vezha.

The maximum indicators of the active mass of nodules were achieved by inoculating seeds at the microstage BBCH 68-69, compared to other analyzed microstages on the scale of soybean development phases (Table 4).

Among the researched varieties, the maximum active mass of the nodules was noted in such varieties as Hoverla – $427.62 \pm 1.62 \text{ mg plant}^{-1}$, Artemida – $416.21 \pm 1.58 \text{ mg plant}^{-1}$, Amethyst – $405.61 \pm 1.58 \text{ mg plant}^{-1}$, and Vezha – $396.72 \pm 1.58 \text{ mg plant}^{-1}$.

Considering the reaction to the improvement of hydrothermal and edaphic conditions, these varieties belong to both high-plastic ($b_i > 1$), plastic ($b_i = 1$), and low-plastic ($b_i < 1$). Especially, plasticity coefficients of Hoverla are 1.03, Artemida – 1.00, Amethyst – 1.00 and Vezha – 0.99. The selected varieties provided the highest stable implementation of forming the active mass of nodules on the plant, which changed to a lesser extent under the influence of environmental conditions. The varieties' highest agronomic stability coefficients (A_s) and lowest coefficients of variation among the researched varieties (V , %) were Hoverla – 85.98 and 14.02%, Artemida – 85.91 and 14.09%, Amethyst – 85.57 and 14.43%, Vezha – 85.30 and 14.70%, confirming our conclusions. Confirmation of the higher resistance of plants and the genotype's ability to neutralize the effects of adverse conditions are homeostatic indicators. Considering a similar sequence, we observed the varieties' classification by homeostatic Hom1 and Hom2 properties: Hoverla – 7.13 and 0.03, Artemida – 7.09 and 0.03, Amethyst – 6.92 and 0.02, and Vezha – 6.80 and 0.02. Furthermore, alongside a full investigation into the ecological stability and flexibility assessment.

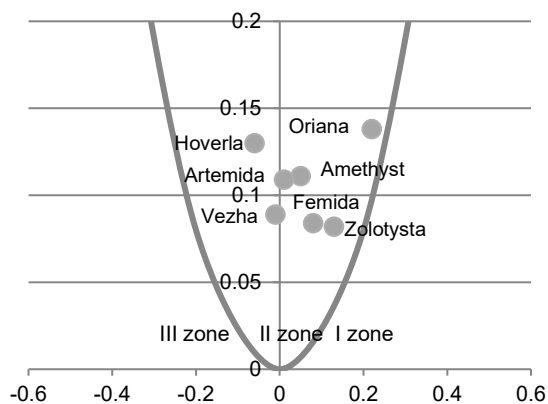


Figure 2. Classification of soybeans by stability (λ) and plasticity (a_i), mass of active nodules (mg plant^{-1}) on roots at the microstage BBCH 68-69 without inoculation.

The graph presented in Fig. 3 corroborates this: the varieties grouped within zone 1 showcase genotypes characterized by an enhanced reaction to improvements in hydrothermal and edaphic conditions suitable for growth, most notably the Hoverla variety.

In zone 2, by coordinates, there are varieties which belong to medium plastic, namely Amethyst, Femida, Artemida, Vezha. The varieties located in zone 3 are low-plastic and marked by a conservative reaction to alterations in hydrothermal and edaphic growing conditions, they include Zolotysta and Oriana. So, the size of the active symbiotic apparatus and operation duration depended on hydrothermal and edaphic conditions, seed inoculation, and varietal characteristics, which determined amounts of biologically fixed nitrogen by soybean crops.

In the variant without seed inoculation (Table 5), we observed a lower amount of biologically fixed nitrogen, and it varied in the researched varieties from 56.68 ± 0.46 to $65.06 \pm 0.44 \text{ kg ha}^{-1}$.

We observed the highest amount of biologically fixed nitrogen in Hoverla – $65.06 \pm 0.44 \text{ kg ha}^{-1}$, Artemida – $62.79 \pm 0.45 \text{ kg ha}^{-1}$, Amethyst – $61.64 \pm 0.44 \text{ kg ha}^{-1}$, and Vezha – $61.0 \pm 0.44 \text{ kg ha}^{-1}$. Thanks to alterations in edaphic and hydrothermal conditions, these soybean varieties were certainly conservative, the plasticity coefficient ($bi < 1$).

Therefore, under different climatic and soil forces, without inoculation of seeds, accumulation of the maximum amount of biologically fixed nitrogen probable due to the strains' conservative reactions to environmental fluctuations, which causes high stable indicators. High agronomic stability coefficients (As) and correspondingly low variation coefficients (V , %) confirmed the conclusions noted in the given strains, particularly Hoverla – 74.75 and 25.25%, Artemida – 73.69 and 26.31%, Amethyst – 73.31 and 26.69%, Vezha – 73.25 and 26.75%. Moreover, these varieties had a higher ability to neutralize the aftereffect of adverse ecological forces, distinguished in the sequence of homeostatic distribution of type 1 (Hom1) and type 2 (Hom2), especially Hoverla – 3.96 and 0.06, Artemida – 3.80 and 0.06, Amethyst – 3.75 and 0.05, Vezha – 3.74 and 0.06.

We observed the highest amount of biologically fixed nitrogen in the sample where seed inoculation underwent (Table 6).

Biologically fixed nitrogen differed from 87.05 ± 0.37 to $101.12 \pm 0.39 \text{ kg ha}^{-1}$. In the given varieties, the highest amount of biologically fixed nitrogen was noted in Hoverla – $101.12 \pm 0.39 \text{ kg ha}^{-1}$, Artemida – $98.07 \pm 0.38 \text{ kg ha}^{-1}$, Amethyst – $95.51 \pm 0.38 \text{ kg ha}^{-1}$, and Vezha – $93.40 \pm 0.39 \text{ kg ha}^{-1}$. According to their reactions to alterations in edaphic and hydrothermal conditions, these varieties belonged to highly-plastic strains ($bi > 1$), particularly, Hoverla – 1.03, and Artemida – 1.02; to plastic ($bi = 1$), Amethyst; to low-plastic ($bi < 1$), particularly Vezha – 0.99.

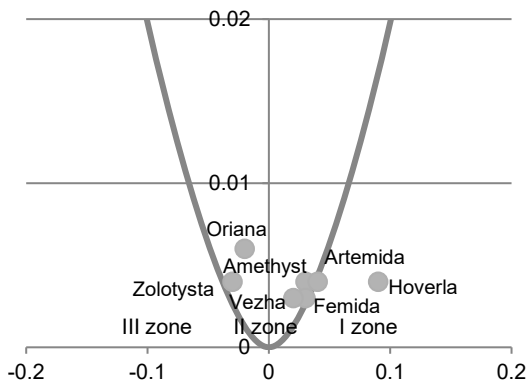


Figure 3. Classification of soybeans by stability (λ), plasticity (ai), mass of active nodules (mg plant^{-1}) on roots at the microstage BBCH 68-69 with inoculation.

Table 5. Parameters of soybeans' ecological stability and plasticity by biologically fixed nitrogen (kg ha⁻¹), 2010–2021

Variety	Amounts of biologically fixed nitrogen, kg ha ⁻¹	Coefficient			Stability index (Si ²)	Homeostaticity		Components	
	Year. Test points	Ecological plasticity (bi)	Agronomic stability (As), %	Variations (V), %		Hom 1	Hom 2	a _i	λ _i
Amethyst	61.64 ± 0.44	0.99	73.31	26.69	2.09	3.75	0.05	0.04	0.54
Hoverla	65.06 ± 0.44	0.99	74.75	25.25	3.71	3.96	0.06	-0.02	0.70
Artemida	62.79 ± 0.45	0.99	73.69	26.31	2.31	3.80	0.06	0.08	0.56
Femida	60.04 ± 0.45	1.01	72.30	27.70	1.27	3.61	0.06	0.19	0.40
Zolotysta	58.63 ± 0.45	1.01	71.65	28.35	1.12	3.53	0.05	0.19	0.37
Vezha	61.00 ± 0.44	0.99	73.25	26.75	1.06	3.74	0.06	-0.04	0.48
Oriana	56.68 ± 0.46	1.02	70.21	29.79	2.53	3.36	0.05	0.35	0.44
Factor	F f	F t							
Variety	81,260.2	2.19							
Conditions	344	1.54							
Interaction variety – conditions	17	1.39							

Table 6. Parameters of soybeans' ecological stability and plasticity by biologically fixed nitrogen within 2010–2021

Variety	Amounts of biologically fixed nitrogen, kg ha ⁻¹	Coefficient			Stability index (Si ²)	Homeostaticity		Components	
	Year. Test points	Ecological plasticity (bi)	Agronomic stability (As), %	Variations (V), %		Hom 1	Hom 2	a _i	λ _i
Amethyst	95.51 ± 0.38	1.00	85.36	14.64	0.24	6.83	0.11	0.04	1.39
Hoverla	101.12 ± 0.39	1.03	85.73	14.27	1.27	7.01	0.10	0.22	1.08
Artemida	98.07 ± 0.38	1.02	85.52	14.48	0.73	6.91	0.11	0.13	1.92
Femida	91.37 ± 0.38	0.99	84.76	15.24	0.47	6.56	0.11	0.01	1.35
Zolotysta	89.30 ± 0.37	0.98	84.72	15.28	0.83	6.54	0.11	-0.12	1.17
Vezha	93.40 ± 0.38	0.99	85.11	14.89	0.24	6.72	0.11	0.01	1.31
Oriana	87.05 ± 0.37	0.97	84.37	15.63	0.76	6.39	0.11	-0.14	0.74
Factor	F f	F t							
Variety	128,899.3	2.19							
Conditions	2,452.1	1.54							
Interaction variety – conditions	13.4	1.39							

Despite the different reactions of strains to fluctuations in environmental conditions, the selected varieties showed high stability in forming the biologically fixed nitrogen. Since the selected varieties demonstrated the best agronomic stability coefficients (As) and the lowest variation coefficients (V, %), especially Hoverla – 85.73 and 14.27%, Artemida – 85.52 and 14.48%, Amethyst – 85.36 and 14.64%, Vezha – 85.11 and 14.89%. These particular types of plants additionally exhibited a greater resilience against detrimental environmental factors.

This assertion was corroborated by the sequential patterns observed in the homeostatic distributions of the initial (Hom 1) and subsequent (Hom2) varieties, particularly, Hoverla – 7.01 and 0.10, Artemida – 6.91 and 0.11, Amethyst – 6.83 and 0.11, Vezha – 6.72 and 0.11.

In Vezha and Amethyst the stability index (Si^2) was as close to zero as possible; namely, in these strains deviation from the angle of inclination of the plasticity coefficient was minimal.

In the figure, the graphic image additionally confirmed that the varieties within zone 1 are highly plastic and respond well to improving edaphic and hydrothermal growing environments, chiefly Artemida and Hoverla (Fig. 4).

The varieties placed in zone 2 are medium-plastic, namely Amethyst, Femida, and Vezha. The varieties in zone 3 are conservative in their reactions to alterations in edaphic and hydrothermal growing conditions, particularly Zolotysta and Oriana.

Thus, among the prerequisites for the vigorous plant growth, the main one is to provide them with nitrogen and enhanced synthesis of proteins necessary for cell growth processes. Accordingly, nitrogen nutrition has a significant impact on plants' photosynthetic activity. Besides, the process of photosynthesis has a decisive influence on its transformation in the plant cell.

The various organic substances formed ensure the maintenance of plant organisms at a high physiological level and, consequently, guarantee their high biological and economic suitability. Rhizobia strains ideal for agricultural production should provide a high level of symbiotic nitrogen fixation in different soil and climatic conditions on all grown varieties of this type of leguminous plant. Unfortunately, the current state of biological science does not allow designing such microorganisms and indicates the feasibility of coordinated selection of strains of nodule bacteria and varieties of leguminous plants (Volkohon et al., 2006).

It is vital for soybean rhizobia, which are absent in the composition of the aboriginal soil microflora. The possibility of selecting a highly effective strain of soybean rhizobia with a wide varietal specificity has been proven experimentally (Kniaziev, 1995; Tkachuk & Verhelis, 2021).

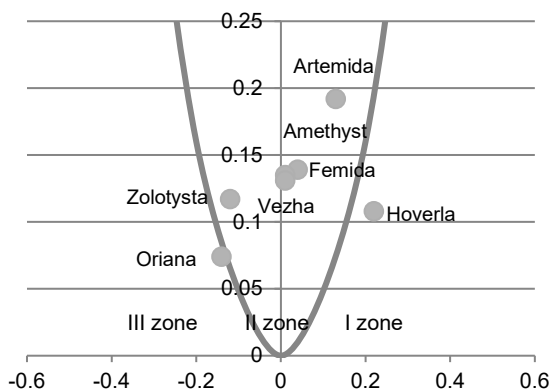


Figure 4. Classification of soybeans by stability (λ), plasticity (ai), biologically fixed nitrogen ($kg\ ha^{-1}$) with inoculation.

Therefore, a further increase in the effectiveness of legume-rhizobia symbiosis depends both on legume breeding varieties and on the selection of appropriate highly active rhizobia strains. Unfortunately, Ukraine has not created a purposeful system of such selection yet, but its elements are presented in the work of scientific institutions whose activities are related to the research of leguminous plants and nodule bacteria (Kniaziev, 1995; Tkachuk et al., 2024).

Modern intensive soybean varieties and selective nodule bacteria, which form an intensive symbiotic apparatus, can be satisfied with minimal consumption of it from soil reserves and fertilizers applied under the predecessor and form a high yield. However, a high intensity of nitrogen fixation and productivity of the variety can be achieved only with a successful combination of the strain of nodule bacteria and the genotype of plants. A successful solution to the problem of biological fixation of atmospheric nitrogen by soybeans can provide a significant increase in vegetable protein resources. Significant specificity of soybean varieties and bacterial strains in their symbiosis in different soil and climatic conditions has been determined. Selection for early nodule formation should be aimed either at activating the initial infection of the root hairs or at ensuring the germination of infectious strands from the hairs into the root bark. The selection of forms with increased symbiotic activity should be carried out according to direct (nitrogenase activity) or indirect (intensity of photosynthesis, chlorophyll content in leaves, degree of development of vegetative organs) traits (Kyrychenko et al., 2016).

According to observation, an acute lack of moisture in the soil leads to the death of nodules. The minimum soil moisture for their development is approximately 16% of total moisture capacity (TM). Other researchers note that the minimum is 15–20% of the soil's TM. In legumes, nodules are formed in the range of 40–80% of TM. The optimal soil moisture is 60–70% (Kniaziev, 1995; Kaletnik et al., 2020).

Due to the research, nitrogen fixation occurs actively if the nodules in the opening are pink, and the plants are rich green. Since nodule bacteria are living organisms, their vital activity depends on weather conditions. However, the environment influences bacteria through the plant, since they both live in symbiosis. Thus, with a lack of moisture, the intensity of photosynthesis in the plant decreases, and with waterlogging, the nodules lack oxygen (Malynovska & Kolmaz, 1997; Honcharuk et al., 2023).

The limit of critical moisture for nodulation depends on the symbiosis partners. The existence of genetic variability in resistance to most external stressors has been shown both in feeding plants and in their corresponding strains of rhizobia (Hungria & Vargas, 2000). Nodule bacteria appear better resistant to external forces than others, and, in arid conditions, can survive in a film of water around soil particles (Serraj & Adu-Gyamfi, 2004).

The survival and activity of microorganisms, as well as the effectiveness of the symbiosis formed with their participation, depend on many factors, particularly the physiological characteristics of macro- and microsymbionts, their natural habitat, soil type, and changes in its moisture content (Cook & Orchard, 2008). Thus, substantial reduction in the microorganisms' population under arid conditions, and a rise in water stress has been shown, the unearthed effective strains are able to migrate in drought conditions over longer distances than ineffective ones, it verifies a decrease in water supply significantly reduces the number of infectious filaments in the root hairs of legumes, inhibits nodulation, along with nitrogen fixation by formed nodules (Wadisirisuk et al., 1989).

Temperature regimes play key roles in nodule bacteria and legume relationships. Active nitrogen fixation and the formation of a high yield in leguminous plants happen at substrate temperatures of 20–24 °C. A change in the temperature regime during alfalfa cultivation from 25/20 °C (day/night) to 10/7 °C in a period of up to 13 weeks led to a 50% decrease in the total and relative activity of nitrogenase (Kniaziev, 1995).

The high nitrogen-fixing capacity, resulted from the well-developed symbiotic apparatus of plants, provides a more intensive photosynthesis process, which ultimately contributes to the accumulation of more organic matter, both in the vegetative and reproductive organs of the plant. Therefore, seed inoculation is an effective technological technique that is fully expedient in view of economics. Though, along with high nitrogen-fixing capacity, varieties are needed that will be stable in these indicators and less dependent on the effect of hydrothermal and edaphic conditions, especially during climate change. Thus, varieties stable in their traits and suitable to grow in different climatic conditions of the region are of great importance for agriculture. Under favorable conditions, greater preference belongs to strains demonstrating considerable productivity potential, especially when challenged by adverse or extreme conditions, ideally necessitating robust environmental stability as a complementary trait (Zinchenko et al., 2018).

At the present stage the strategic goal of soybean breeding is to create highly adaptive strains distinguished not only by high seed yields, but also have high genetic protection levels of the crop from bio- and abiotic external conditions heavily influence outcomes and offer the chance to achieve peak efficiency in combination with high quality seeds and nitrogen-fixing ability.

Most modern soybean varieties have a fairly high productivity potential, whose execution is limited by their poor homeostatic ability and susceptibility to detrimental environmental conditions. The term ‘adaptability’ defines the genotypes’ capacity to guarantee high and stable productivity of plants in different environmental conditions. Plants’ adaptation to environmental conditions is achieved due to modification and genotypic variability, i. e., by restructuring the complex of the plant’s physiological, biochemical, and morphoanatomical traits in ontogenesis and building new reaction norms in phylogeny (Mazur et al., 2024).

Today plant breeding for adaptability is especially important when weather conditions are changing rapidly, causing a strict moisture limit in regions previously favorable for agriculture (Chernyshenko, 2014; Kaletnik et al., 2020b; Okrushko et al., 2025).

The variety’s adaptability to weather, soil, and economic conditions was called ecological plasticity. Plasticity has been proposed as a term that means an adaptive mechanism to environmental conditions. A high plasticity index characterizes plants that respond optimally to environmental heterogeneity (Alpert & Simms, 2002). Consequently, the analysis shows that we can find the different reaction rates of growing conditions considering ecological plasticity and stability, identify genotypes that can realize productivity with significant changes in environmental conditions, and ensure their most effective application and distribution (Zinchenko et al., 2018).

The research goal is to outline the ontogenetic adaptation parameters according to the symbiotic performance indicators of soybean varieties (Chernyshenko, 2014). So, ecological plasticity is, firstly, the strain’s adaptability to weather, soil, and economic conditions. Plasticity has been interpreted as a term that means an adaptive mechanism to environmental conditions. A high plasticity index characterizes plants that respond

optimally to environmental heterogeneity (Alpert & Simms, 2002). The analysis helps not only to discover the different reaction rates of growing conditions but also to identify genotypes that will realize productivity with significant changes in environmental conditions, ensure their most effective application and distribution (Zinchenko et al., 2018).

It was established (Table 7) that the highest yield under different soil and climatic conditions was obtained by the soybean variety Hoverla, averaging $2.2 \pm 0.02 \text{ t ha}^{-1}$. This indicates that the genotype of this variety exhibited the greatest correspondence to the actual environmental conditions over an extended period, allowing the fullest realization of its genetic potential. Hoverla also demonstrated the highest plasticity coefficient ($b_i = 1.39$), indicating superior adaptability to both optimal and limiting manifestations of environmental factors compared with the other varieties included in the study.

Its stability variance (S_i^2) was very close to zero (0.02), reflecting a high level of stability. Similar yield performance ($2.1 \pm 0.01 \text{ t ha}^{-1}$) and adaptability parameters were recorded for the variety Artemida, with a plasticity coefficient of $b_i = 1.01$ and a stability variance of $S_i^2 = 0.01$.

According to the applied classification, the varieties Artemida, Hoverla, and Amethyst were assigned to the fifth rank based on yield performance. These varieties were characterized by a regression coefficient (b_i) greater than 1 and a stability variance (S_i^2) approaching zero. Therefore, it can be concluded that they perform best under favorable growing conditions and exhibit high stability. These varieties are recommended for cultivation under conditions of intensive and high-input agricultural management.

The varieties Femida, Zolotysta, Oriana, and Vezha were assigned to the second rank according to yield performance. Their plasticity coefficients (b_i) were less than 1, while the stability variance (S_i^2) remained close to zero. The agronomic stability coefficient (A_s) exceeded 70% for all soybean varieties studied, classifying them as stable according to this criterion.

However, the highest homeostaticity values (Hom_1 and Hom_2) were recorded for the variety Vezha, reaching 8.62 and 8.51, respectively. A comprehensive analysis of the ecological plasticity and stability of the genotypes based on the a_i and λ components, presented graphically (Fig. 5), demonstrated that the varieties Amethyst, Hoverla, and Artemida, located in Zone I, belong to the group of genotypes with a high response to changes in growing conditions. Consequently, these varieties are recommended for cultivation under high-input agricultural systems. However, under low-input conditions, their yield decreases substantially.

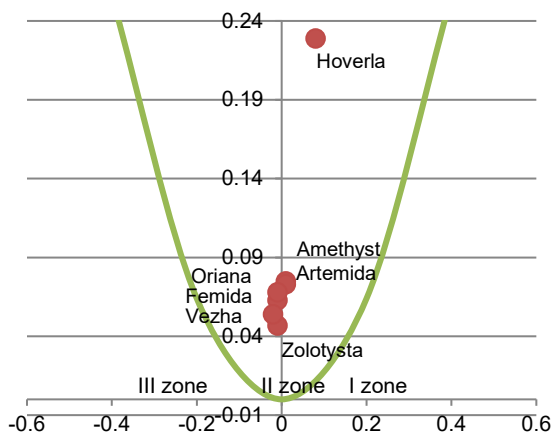


Figure 5. Classification of soybean varieties into classes according to plasticity (a_i) and stability (λ) of yield (t ha^{-1}) with inoculation.

Table 7. Parameters of soybeans' ecological stability and plasticity by the yield (t ha⁻¹) within 2010–2021

Variety	Average yield, t ha ⁻¹	Coefficient			Stability index (Si ²)	Homeostaticity		Components	
	Year. Test points	Ecological plasticity (bi)	Agronomic stability (As), %	Variances (V), %		Hom 1	Hom 2	a _i	λ _i
Amethyst	1.95 ± 0.01	1.02	86.1	13.9	0.07	7.19	6.04	0.01	0.75
Hoverla	2.2 ± 0.02	1.39	82.6	17.4	0.02	5.76	4.11	0.08	2.29
Artemida	2.1 ± 0.01	1.01	86.9	13.1	0.01	7.64	6.53	0.01	0.73
Femida	1.88 ± 0.01	0.89	87.6	12.4	0.01	8.08	8.98	-0.01	0.63
Zolotysta	1.82 ± 0.01	0.91	87.1	12.9	0.004	7.71	7.62	-0.01	0.47
Vezha	1.92 ± 0.01	0.87	88.2	11.8	0.04	8.62	8.51	-0.02	0.54
Oriana	1.77 ± 0.01	0.91	86.5	13.5	0.01	7.39	7.86	-0.01	0.68
Factor	F f	F t							
Variety	2,360.1	2.19							
Conditions	102.4	1.54							
Interaction variety – conditions	10.31	1.39							

In contrast, the varieties Femida, Zolotysta, Oriana, and Vezha, positioned in Zone II of the coordinate system, exhibited a more conservative response to environmental variation. The location of these varieties corresponds to the so-called marginal zone, situated at the boundaries between Zones III and II and between Zones II and I. This positioning may indicate the presence of an intrinsic reserve of plasticity and stability within these genotypes and highlights the need for their further investigation.

CONCLUSIONS

Following seed inoculation, the highest number of nodules (pcs. plant⁻¹) and fresh weight of active nodules (mg plant⁻¹) at the BBCH 68-69 growth stage were recorded in the soybean varieties Artemida (38.17 ± 0.15 and 416.21 ± 1.58 , respectively), Amethyst (37.21 ± 0.15 and 405.61 ± 1.58), Vezha (36.41 ± 0.15 and 396.72 ± 1.58), and Hoverla (39.27 ± 0.15 and 427.62 ± 1.62).

The highest amounts of biologically fixed nitrogen were observed in the varieties Hoverla (101.12 ± 0.39 kg ha⁻¹), Artemida (98.07 ± 0.38 kg ha⁻¹), Amethyst (95.51 ± 0.38 kg ha⁻¹), and Vezha (93.40 ± 0.38 kg ha⁻¹). The variety Amethyst was assigned to Rank III, characterized by $b_i = 1$ and $S_i^2 = 0$, indicating a favorable response to improved growing conditions combined with high stability. The variety Vezha was assigned to Rank II, characterized by $b_i < 1$ and $S_i^2 = 0$, indicating superior performance under unfavorable environmental conditions while maintaining high stability.

The highest grain yields were achieved by the varieties Hoverla (2.2 ± 0.02 t ha⁻¹), Artemida (2.1 ± 0.01 t ha⁻¹), and Amethyst (1.95 ± 0.01 t ha⁻¹). These varieties demonstrated the best performance under favorable growing conditions and were characterized by high stability ($b_i > 1$, $S_i^2 = 0$). Therefore, the varieties exhibiting the greatest nitrogen-fixing capacity also achieved the highest yield levels.

Despite differences in their responses to environmental fluctuations, the selected varieties were characterized by high stability in the accumulation of biologically fixed nitrogen. This was confirmed by their high agronomic stability coefficients (A_s) and low coefficients of variation (V , %). Consequently, the soybean varieties Hoverla, Artemida, Amethyst, and Vezha are recommended for commercial cultivation and for use in soybean breeding programs aimed at developing new varieties. This recommendation is based on their superior biological nitrogen fixation, high yield potential, and stable performance across diverse soil and hydrothermal growing conditions.

Thus, the cultivation of the highly adaptable soybean varieties Artemida, Amethyst, and Hoverla can ensure highly efficient soybean production under a wide range of soil and hydrothermal conditions.

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