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Influence of biologisation of the nutrition system on the transformation of biological nitrogen and formation of soybean productivity

Abstract. Rising prices for mineral fertilisers stimulate the search for alternative ways to optimise the existing and develop new technological methods of growing crops, including soybeans. One of these approaches is the intensive use of biological ways to enhance the ability of legumes to symbiosis and natural fixation of biological nitrogen from the soil air, which will help reduce the cost of plant cultivation technology. That is why the purpose of this study was to determine the effect of biological preparations on atmospheric nitrogen fixation by soybean plants using symbiotic nodule bacteria. In these studies, the method of calculation based on active symbiotic potential and symbiotic specific activity was used to determine the amount of biologically fixed nitrogen. The study analysed the effect of some inoculants and biofertilisers intended for foliar application on the development and formation of symbiotic processes in soybean plants, namely, the specific features of the formation of both general and active symbiotic potential in the vegetation stages. The influence of symbiotic productivity on soybean grain yield was also determined. Treatment of seeds with the selected preparations for the entire period of symbiosis duration provided an increase in the total symbiotic potential and active symbiotic potential. It was found that the treatment of seeds with the inoculant Bioinoculant BTU (2 l/ha) before sowing

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was more productive. Therewith, the maximum soybean grain yield of 3.31 t/ha was recorded in areas where the preparation Bioinoculant BTU (2 l/t) was treated before sowing and two fertilising applications were made in the 3rd ternate leaf stage and in the budding stage with Helprost soybean fertiliser (2.5 l/ha). The findings of this study indicate a substantial impact of symbiotic productivity and its value on soybean grain yield. Correlation and regression analyses showed that the accumulation of biological nitrogen has a considerable impact on grain yield. Thus, the use of biological preparations is an alternative to mineral fertilisers in soybean cultivation technology and they can be implemented in the production conditions of agricultural enterprises

Keywords: inoculant treatment; foliar feeding; preparations of natural origin; symbiotic potential; yield

INTRODUCTION

Nitrogen fixation is the main function of the symbiotic system formed in legumes. The strength of this indicator is determined by the efficiency (activity) of nodule bacteria. Nitrogen fixation begins when rhizobia become bacteroids that intensively synthesise nitrogenases, the content of which can reach 30% of the total protein. Together with the plants, they also protect the nitrogenases from oxygen, meet energy requirements, and assimilate nitrogen fixation products. Considering the significant climate change and, accordingly, the development and needs of modern agriculture, it is promising to find ways to increase the productivity of nitrogen-fixing symbiotic systems and their adaptive capabilities. Specifically, it is the impact of environmental factors, including stress factors, on the relationship between plants and microorganisms, elucidation of mechanisms for increasing plant resistance and improving symbiotic activity to increase plant yields. The use of biologically active substances of natural origin has been an effective means of regulating plant growth and development, optimising their relationships with microorganisms, namely nodule bacteria, which ensure the process of biological nitrogen fixation from the air by legumes.

According to the findings of S. Didur *et al.* (2019), scientists found a positive effect on nitrogen fixation processes due to optimisation of soil acidity. It was found that the maximum dynamics in the formation of the number of nodule bacteria and their mass during the vegetation of perennial legumes was caused by pre-sowing seed treatment with the biological preparation Rhizobophyt and its combination with the plant growth regulator of natural origin Emistim C. This determines the importance of investigating the effect of biological preparations on the nitrogen fixation in legumes.

Detailed studies of the biological fixation of atmospheric nitrogen by legumes under different growing conditions, its impact on the nitrogen balance in the soil and the increase of the coefficient of biological nitrogen utilisation in agriculture are among the main tasks of intensifying agricultural production. H.V. Pantsyreva *et al.* (2020) indicated that the maximum grain yield of white lupine of the Veresnevyi variety was obtained in the experimental variants with pre-sowing seed treatment with the inoculum Rhizogumin and the growth stimulator Emistim C in combination with two foliar dressings with Emistim C. Therewith, the grain yield was 3.61 t/ha. H.M. Zabolotnyi *et al.* (2020) point out that the growth characteristics, passage of distinct stages of development of legumes and nitrogen fixation activity are determined by the genetic characteristics of the species or variety. L. Symochko (2020) and O. Tkachuk & N. Telekalo (2020) investigated the features of soil microflora, the number of soil microorganisms, their functional activity and impact on biological nitrogen fixation processes. Multiparametric indicators are recommended for assessing the environmental impact of soils: microbiological and biochemical.

S.Ya. Kots *et al.* (2021) and S. Tanchyk *et al.* (2021) indicate that the study of the complex use of biological preparations made based on active strains of microorganisms – nitrogen fixers to create highly effective symbiotic systems, prevention and protection of legumes from pathogens of various aetiologies is of particular relevance. Furthermore, despite all the challenges and risks facing agriculture in Ukraine, demand for organic crop production is still important. Therefore, the development of environmentally safe ways to increase the productivity of legumes based on the use of organic-mineral fertilisers and biological preparations is relevant and is an aspect that requires further research.

Leading Ukrainian scientists V. Mazur *et al.* (2021) investigate the specific features of the development and implementation of an environmentally friendly technology to produce vegetable protein based on the symbiotic interaction of highly efficient microorganisms with modern varieties of legumes. The specific features of the influence of fungicides on the formation of the symbiotic apparatus during the pre-treatment of soybean seeds were also established. The number of root nodules under Fever treatment at the stage of two true leaves was at the level of plants without treatment. During the flowering phase of soybean, the number of root nodules gradually levelled off to the control level and increased by 33% during the bean formation phase. At the same time, the weight of root nodules was 36% less than that of control plants in the phase of two true leaves. Subsequently, during the vegetation period, the root nodule weight was observed to equalise to the values of the control plants, exceeding them by 33% in the phase of bean formation.

That is why the purpose of this study was to determine the impact of biological preparations on the process of atmospheric nitrogen fixation by soybean plants using symbiotic nodule bacteria. And determination of the relationship between the indicators of fixed symbiotic nitrogen and the level of soybean grain yield in different variants of the experiment.

MATERIALS AND METHODS

Field research was conducted in 2017-2021 in the conditions of the experimental field subordinated to Vinnytsia National Agrarian University and located in the village of Ahronomichne (Vinnytsia region). The research was conducted in compliance with the provisions of the Convention on Safety and Health in Agriculture No. 184. Soil cultivation in the experiment was generally accepted for the Forest-Steppe zone of Ukraine and ensured the formation of optimal conditions for plant growth and development by maximising weed control, moisture conservation, and levelling the soil surface. The soil of the experimental field is grey forest medium loam. On the day of sowing, the seeds were inoculated with biological preparations based on active strains of nodule bacteria (*Bradyrhizobium japonicum*), and foliar fertilisation was performed in the corresponding experimental variants according to the experimental scheme (Kots, 2021).

The field experiment was designed as follows: Factor A – Seed treatment: 1) control, 2) seed treatment with BTU bio-inoculant (2 l/t), 3) seed treatment with Rhizoline (2 l/t) + Rhizosave (2 l/t), 4) seed treatment with Anderhiz (1.5 l/t). Factor B – Foliar feeding: 1) control, 2) Biocomplex BTU (1.0 l/ha), 3) Humifriend (1.0 l/ha), 4) Helprost soya (2.5 l/ha).

The size of the experimental plot is 40 m^2, and the accounting plot is 25 m^2. The replication was fourfold, and the plots are systematically placed. Climatic conditions, such as temperature and precipitation, were generally favourable for soybean growth and development in the years under study, although there were deviations from the long-term average. For the research, the Madison soybean variety was sown. The biological preparations for inoculation and foliar dressing under study are products of BTU Center. When the soil was warmed up to a depth of 10 cm to +12°C, seeds were sown at a seeding rate of 650 thous./ha and a row spacing of 45 cm. Foliar application of biological preparations in the areas defined by the scheme in the experiment was performed in the phase of the 3^{rd} ternate leaf and budding. The research was conducted according to generally accepted methodological guidelines. The number and wet weight of nodules on the roots and, accordingly, the symbiotic productivity of soybean plants were estimated based on calculations of total (TSP) and active (ASP) symbiotic potential and specific symbiosis activity (SSA) according to the method of H.S. Posypanov (1991).

$$TSP = \frac{M_1 + M_2}{2} * T, \qquad (1)$$

where *TSP* is the total symbiotic potential, thous. kg day/ha; *T* is the period between two adjacent periods of analysis, days; M_1, M_2 is the average mass of nodules for the period T, kg/ha.

$$ASP = \frac{M_1+M_2}{2} * T, \quad (2)$$

where *ASP* is the active symbiotic potential, thous. kg day/ha; *T* is the period between two adjacent periods of analysis, days; M_1, M_2 is the average mass of nodules for the period T, kg/ha.

$$SSA = \frac{N_1+N_2}{ASP_1-ASP_2}, \quad (3)$$

where *SSA* is the specific symbiosis activity, gN/kg; N_1, N_2 is the maximum use of nitrogen by plants in the corresponding variants of the experiment for separate periods or for the vegetation as a whole, kg/ha; ASP_1, ASP_2 is the active symbiotic potential in the compared variants, thous. kg day/ha.

Before harvesting, a sample sheaf from each variant was selected to determine the individual productivity of the plants. Harvesting was performed according to the method of separate threshing in the phase of full ripeness, adjusted for standard moisture. The mathematical processing of the results was performed according to the method of dispersion and correlation-regression analysis using computer software packages (Excel, Statistica, Agrostat) according to the methodology of V.O. Ushkarenko *et al.* (2013). Experimental studies of plants (both cultivated and wild), including the collection of plant material, were following the institutional, national, or international guidelines. The method of calculating fixed nitrogen according to active symbiotic potential and specific symbiosis activity was used in the research. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

The specific feature of the formation of the total symbiotic potential of soybean and the impact of pre-sowing seed treatment and foliar fertilisation on this indicator are presented in Table 1.

Table 1. Dynamics of the formation of the total symbiotic potential of soybean depending on pre-sowing seed treatment and foliar fertilisation, on average for 2017-2021, thous. kg d/ha

Seed treatment	Foliar dressing	Phases of growth and development					Over the entire period of symbiosis
		3rd ternate leaf	beginning of flowering	end of flowering	full filling of seeds	physiological maturity	
Control	1	1.069	2.320	4.013	3.244	0.828	11.474
	2	1.126	2.636	4.966	4.299	1.085	14.113
	3	1.100	2.526	4.222	3.610	0.906	12.364
	4	1.108	3.222	5.544	5.140	1.150	16.164
Bio-inoculant BTU	1	1.676	4.057	6.362	5.248	1.248	18.592
	2	2.019	5.289	7.833	6.316	1.524	22.980
	3	1.986	4.813	6.844	5.743	1.253	20.641
	4	2.116	6.074	8.115	6.886	1.620	24.811
Rhizoline + Rhizosave	1	1.210	3.086	4.986	3.798	0.860	13.940
	2	1.320	4.288	5.908	5.055	1.216	17.787
	3	1.233	3.778	5.500	4.805	1.100	16.417
	4	1.347	4.876	6.926	5.910	1.467	20.526
Anderhiz	1	1.334	3.171	5.175	4.130	0.944	14.753
	2	1.464	4.476	6.582	5.520	1.311	19.353
	3	1.493	3.885	5.740	5.029	1.156	17.303
	4	1.519	5.200	7.209	5.986	1.482	21.395
V, %		23.6	27.7	20.1	20.3	20.3	21.6
Sx %		6.0	6.9	5.0	5.2	5.1	5.4

Note: without fertilisation (control); 2. Biocomplex BTU (1 l/ha); 3. Humifriend (1 l/ha); 4. Helprost soya (2.5 l/ha)
Source: developed by the authors of this paper based on own research

Based on the results obtained, it was found that the percentage of ASP in the TSP before the period of end of flowering – full seed filling, in terms of experimental variants, ranged within 83-97%, and later this ratio decreased to 41-57%, which is explained by the deterioration of nitrogen fixation conditions. During the research, data were obtained indicating the formation of the maximum indicators of the total – 4.013-8.111 thous. kg-days/ha and active symbiotic potential – 3.702-7.258 thou. kg-days/ha in the phase of the end of flowering. It was found that the formation of the level of symbiotic potential of soybean plants was significantly influenced by pre-sowing seed treatment with inoculants, which provided more active colonisation of soybean plant roots by symbiotic bacteria, activation of the process of symbiosis formation, which in turn contributed to the growth of biological nitrogen fixation by microorganisms. The data obtained in the experiment on the formation of active symbiotic potential of soybean in the dynamics under the influence of pre-sowing seed treatment and foliar feeding are presented in Table 2.

Table 2. Dynamics of formation of active symbiotic potential of soybean depending on pre-sowing seed treatment and foliar dressing, on average for 2017-2021, thous. kg d/ha

Seed treatment	Foliar dressing	Phases of growth and development					Over the entire period of symbiosis
		3rd ternate leaf	beginning of flowering	end of flowering	full seed filling	physiological maturity	
Control	1	0.876	1.998	3.702	3.134	0.405	10.116
	2	0.933	2.375	4.572	3.786	0.440	12.106
	3	0.894	2.094	4.015	3.522	0.418	10.943
	4	0.896	2.597	4.820	4.090	0.530	12.933
Bio-inoculant BTU	1	1.305	3.542	5.253	4.699	0.601	15.401
	2	1.789	5.072	6.733	5.166	0.790	19.550
	3	1.655	4.421	6.335	4.917	0.698	18.026
	4	1.818	5.590	7.258	5.260	0.804	20.730
Rhizoline + Rhizosave	1	1.120	2.717	4.149	3.644	0.460	12.091
	2	1.248	4.071	5.636	4.230	0.499	15.684
	3	1.175	3.594	5.271	4.046	0.473	14.558
	4	1.264	4.461	6.709	4.587	0.607	17.628
Anderhiz	1	1.223	3.041	4.276	3.833	0.537	12.910
	2	1.317	4.321	5.828	4.400	0.645	16.511
	3	1.271	3.756	5.532	4.251	0.554	15.364
	4	1.337	4.661	6.820	4.850	0.736	18.404
V, %		23.5	29.9	20.6	14.3	22.5	20.8
Sx %		5.9	7.5	5.1	3.6	5.6	5.0

Note: 1. without fertilisation (control); 2. Biocomplex BTU (1 l/ha); 3. Humifriend (1 l/ha); 4. Helprost soya (2.5 l/ha)
Source: developed by the authors of this paper based on own research

Thus, analysing the generalised data for the years of research, considering the duration of the entire symbiotic period, seed treatment with Rhizolineh (2 l/t) + Rhizosave (2 l/t) and Anderhiz (1.5 l/t) contributed to an increase in the indicators of TSP and ASP, respectively, by 2.466-3.280 thous. kg d/ha and 1.975-2.794 thous. kg d/ha compared to the data on the control variant without inoculation. The pre-sowing treatment of seeds with the inoculant Bioinoculant BTU (2 l/ha) proved to be more productive, with an increase in the level of total symbiotic potential compared to the control of 7.118 thous. kg-days/ha, and active 5.285 thous. kg-days/ha.

The research results suggest that one of the ways to mobilise internal reserves of nitrogen fixers to achieve maximum intensification of the biological nitrogen fixation, apart from seed inoculation, is foliar dressing, which improves the physiological activity of nodule bacteria, improves physiological and biochemical processes that take place during the fusion of inert nitrogen molecules and their conversion into compounds available to plants, resulting in an increase in the value of active symbiotic potential.

Foliar application of Biocomplex BTU biological preparation (1.0 l/ha) provided an increase in TSP and ASP, depending on pre-sowing seed inoculation, by 2.639-4.599 thous. kg-days/ha and 1.990-4.149 thous. kg-days/ha, respectively. Somewhat lower efficiency was observed when using a complex fertiliser based on potassium humate Humifriend (1.0 l/ha) for foliar dressing, with an increase in the TSP and ASP compared to the control of 0.890-2.550 thous. kg-days/ha and 0.827-2.625 thous. kg-days/ha, depending on the variants for pre-sowing seed treatment. The use of Helprost Soya fertiliser (2.5 l/ha) for foliar fertilisation increased these indicators by 4.691-6.642 thous. kg-days/ha and 2.817-5.537 thous. kg-days/ha, respectively.

Based on the results of the study, it was found that on average in 2017-2021, the amount of biologically fixed nitrogen was the lowest in the control, i.e., without seed inoculation and foliar feeding, and amounted to 49.7 kg/ha. Pre-sowing treatment of seeds with Bioinoculant BTU (2 l/t) increased the accumulation of biologically fixed nitrogen by 26 kg/ha, treatment with Rhizoline (2 l/t) + Rhizosave (2 l/t) – by 10.1 kg/ha, and the use of Anderhiz inoculant (1.5 l/t) increased this indicator by 13.8 kg/ha, respectively, compared to the untreated variants.

Foliar feeding of plants had a positive effect on photosynthesis performance, which led to a better supply of carbohydrates to plants and nodules used for biological nitrogen fixation, increased the value of symbiotic potential, and as a result, had an intensive impact on nitrogen fixation performance. According to the research results, it was found that foliar fertilisation in the phase of the 3rd ternate leaf and again in the budding phase with the biological preparation Biocomplex BTU (1.0 l/ha) increased nitrogen fixation by 9.8-20.4 kg/ha (59.5-96.5 kg/ha), depending on seed inoculation. The level of nitrogen fixation was 53.9-88.7 kg/ha, which is 4.1-12.9 kg/ha more than in the control variants where foliar fertilisation was performed using a complex fertiliser based on potassium humate Humifriend (1.0 l/ha) (Fig. 1).

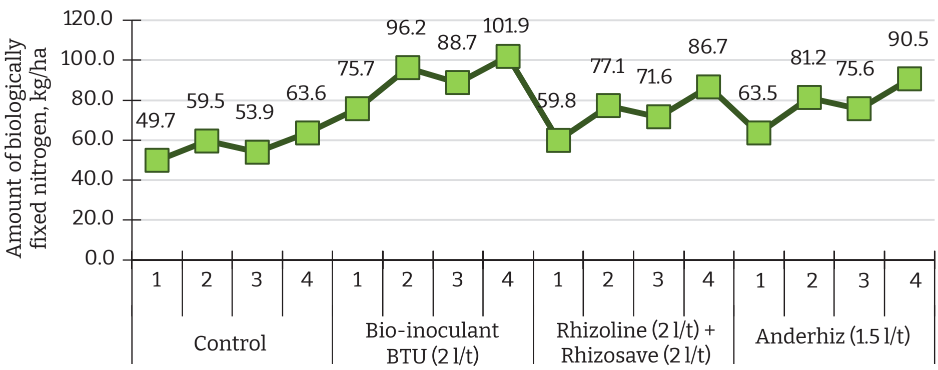

Figure 1. Amount of biologically fixed nitrogen depending on seed treatment and foliar fertilisation, on average for 2017-2021, kg/ha

Note: 1. without fertilisation (control); 2. Biocomplex BTU (1 l/ha); 3. Humifriend (1 l/ha); 4. Helprost soya (2.5 l/ha)

Source: compiled by the authors of this study

The most intensive fixation of biological nitrogen by soybean plants was observed in those areas of the experiment, where the organo-mineral fertiliser Helprost soybean (2.5 l/ha) was used for foliar feeding. In these variants, depending on the pre-sowing seed treatment, the amount of biologically fixed nitrogen was 63.6-101.9 kg/ha, which is 13.8-26.2 kg/ha more than in the control. These studies on the grey forest soils of the Right-Bank Forest-Steppe showed that soybean grain yields strongly depend on the climatic conditions of the year under study and the factors under study, namely pre-sowing inoculation of the seed and foliar dressing. It was found that the average grain yields for 2017-2021 ranged from 2.47 to 3.31 t/ha (Fig. 2).

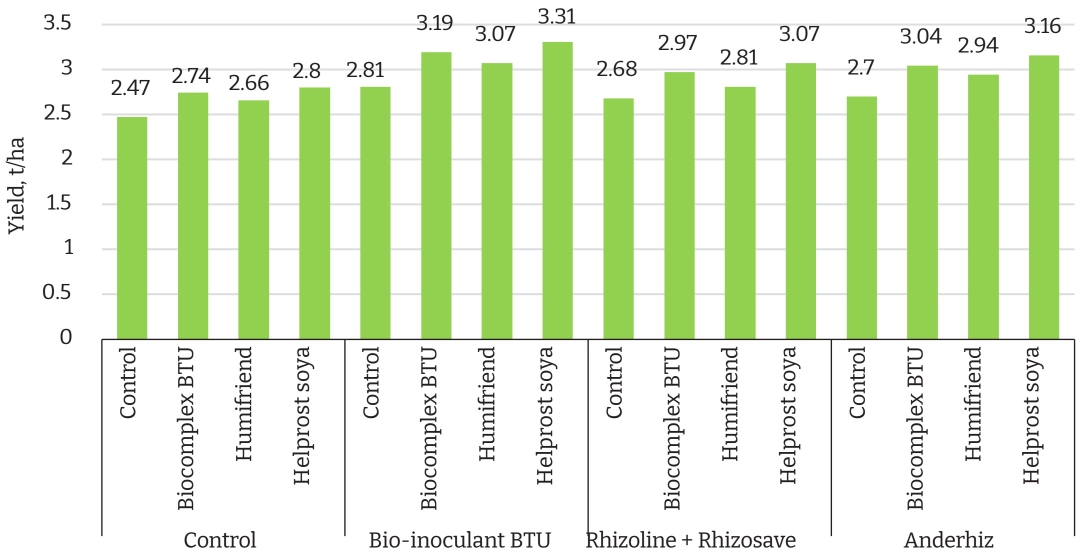

Figure 2. Soybean grain yield depending on pre-sowing seed treatment and foliar feeding, average for 2017-2021, t/ha

Source: compiled by the authors of this study

In the variant where soybean seeds were treated with the inoculant Bioinoculant BTU (2 l/t) before sowing and two foliar fertilisations were performed in the phase of 3 leaves and budding with the organo-mineral fertiliser Helprost soybean (2.5 l/ha), the maximum soybean grain yield was 3.31 t/ha, which is 0.84 t/ha (34.0%) more than in the control without pre-sowing seed treatment and foliar dressing. The symbiotic productivity of crops had a significant impact on soybean grain yield. Thus, statistical analysis of the data revealed a significant impact of the amount of biological nitrogen accumulation on grain yield. A regression equation can be used to describe this relationship between grain yield and the amount of biological nitrogen accumulated in the soil:

$$\gamma = 1{,}2618 + 0{,}022 \times \chi, \quad (4)$$

where *Y* is the grain yield, t/ha; X is the amount of biological nitrogen accumulated in the soil, kg/ha.

The correlation coefficient was r = 0.938, and the adjusted coefficient of determination, respectively, was $r^2 = 0.879$. O. Tkachuk & N. Telekalo (2020) showed that under conditions of growing field crops with insufficient fertilisation and the absence of legumes, there is a gradual decrease in the content of organic matter and nitrogen in the soil. This process is caused not only by mechanical tillage and intensification of oxidation processes, but also by the removal of nitrogen with the crops. Thus, the consumption of humus (mineralisation) during grain cultivation reaches 0.5-0.7 and even 1.0 t ha^{-1}, including 25-50 kg ha^{-1} of nitrogen. Under row crops, and especially in conditions of clean vapours, there is a further increase in the mineralisation of organic matter and a growing nitrogen deficit in the soil (1.5-2.0 t ha^{-1}, including 75-100 kg ha^{-1} of nitrogen), which subsequently leads to a general deterioration in the physical, physicochemical properties, and nutritional regime of the soil.

According to the findings of S. Tanchyk *et al*. (2021), nitrogen replenishment through symbiotic and associative nitrogen fixation is effective in the system of short crop rotations on chernozem. Against the background of fertiliser use and high crop yields, the consumption of biological nitrogen due to nitrogen fixation in pea crop rotations is 261-294 kg ha^{-1}, soybeans – 312 kg ha^{-1}, and perennial grasses (alfalfa) – 468 kg ha^{-1}. The introduction of a legume component into the crop rotation allows compensating for 40-89% of the nitrogen consumption from fertilisers and soil for subsequent crops through nitrogen fixation. According to the research results, the amount of biologically fixed nitrogen by soybean plants was 63.6-101.9 kg/ha, with the best results obtained in variants using foliar dressing with organic-mineral fertiliser. This suggests that the priority measure for the efficient use of biological nitrogen by legumes in agriculture should be a scientifically sound structure of sown areas with an optimal share of these crops and the use of biological factors to intensify cultivation technology.

The findings of V.F. Petrichenko *et al*. (2017) and H.M. Zabolotnyi *et al*. (2020) show that the most powerful fixers of biological nitrogen in crop production are perennial legumes such as clover, sainfoin, alfalfa, with a nitrogen fixation factor of 0.7-0.8. During the growing season, these crops accumulate between 30 and 38 kg of biological nitrogen per tonne of dry matter. In general, perennial legumes involve 100 to 300 kg ha^{-1} of nitrogen in the biological cycle, of which 75-200 kg is a net product for the plant; the rest is consumed by the plant from the soil. The assimilative capacity of legumes is somewhat lower than that of perennial legumes. The nitrogen fixation rate ranges from 0.4 to 0.5, with the rest of the nitrogen being used from the soil. For every tonne of dry matter of the main and by-products, lupine and fodder beans absorb 20-27 kg of nitrogen from the air; peas, soybeans, and others absorb 10-15 kg of nitrogen. A considerable part of biological nitrogen (sometimes up to 90%) during the growing season is concentrated in the above-ground mass, usually removed from the field, while the rest stays in the soil in roots and post-harvest residues, causing nitrogen to be added to the soil after mineralisation. The present study on the influence of the nutrition system on the transformation of biological nitrogen and the formation of soybean crop productivity indicates that intensive fixation of biological nitrogen by soybean plants occurs when foliar dressing with organic-mineral fertiliser is performed. In other words, to improve nitrogen fixation rates, specifically to increase the amount of biologically fixed nitrogen in legumes and soybeans, it is necessary to introduce measures of pre-sowing seed treatment and foliar dressing during the growing season with biological preparations and organo-mineral fertilisers into the crop cultivation technology.

I.M. Didur *et al*. (2019) confirms the dependence of the amount of nitrogen fixed symbiotically on the mass of root nodules with leghaemoglobin and the duration of their functioning, i.e., the period from the appearance of leghaemoglobin in the nodules to its transition to choleglobin. The indicator of active symbiotic potential ASP combines these two criteria of nitrogen fixation. The ASP for the growing season is determined by the sum of the ASP indicators for individual periods. Similarly, the total symbiotic potential of the TSP is calculated, which factors in the mass of all nodules. This indicator has a more theoretical value and is determined in cases where there is a need to determine the effect of individual environmental factors on symbiosis activity. According to the findings of O. Litvinova *et al*. (2021), the factors under study have a more intense effect on the weight of the nodules with leghaemoglobin than on their total weight. Accordingly, the formation of the indicator of active symbiotic potential is more intensively influenced. However, the data of the authors' research strongly suggest that pre-sowing treatment of seeds with the inoculant Bioinoculant BTU (2 l/ha) led to an increase in the level of total symbiotic potential compared to the control at the level of 7.118 thous. kg-days/ha, and active symbiotic potential at the level of 5.285 thous. kg-days/ha.

P. Boyko *et al*. (2019) argue that one of the ways to solve the problem of nitrogen deficiency in the soil is the use of biological features of legumes, including soybeans, which, using symbiotic nodule bacteria, can fix significant amounts of atmospheric nitrogen. To date, scientists have developed ways to not only effectively use the nitrogen-fixing capacity of this crop, but also to simultaneously mobilise hard-to-reach forms of phosphorus in the soil. O. Demyanyuk *et al*. (2019) and O.M. Kolisnyk *et al*. (2020) point out that the use of modern bacterial preparations, which, apart from symbiotic nodule bacteria, also contain phosphorus-mobilising microorganisms, can mobilise hard-to-reach forms of phosphorus.

Scientists such as L.I. Onufran & V.I. Netis (2017) argue that photosynthetic processes, which synthesise carbohydrates that serve as a source of energy for complex nitrogenase reactions of N_2 reduction, have a considerable impact on the course and activity of symbiotic nitrogen fixation. In other words, plants, through interaction with nodule bacteria, provide them with photosynthetic products, and under these conditions, they receive biologically fixed nitrogen. According to the findings of V. Mazur *et al*. (2021) and I. Gorodiska *et al*. (2018) found that nodule bacteria are biological stimulants, and therefore, apart from the ability to "fix" molecular nitrogen from the air and leave it in the soil bound in compounds easily accessible to plants, they can synthesise amino acids, vitamins, and some biologically active substances. The findings strongly suggest that one of the ways to mobilise internal reserves of nitrogen fixers to achieve maximum intensification of the biological nitrogen fixation, apart from seed inoculation, is foliar dressing, which improves the physiological activity of nodule bacteria, improves physiological and biochemical processes that take place during the fusion of inert nitrogen molecules and their conversion into compounds available to plants, resulting in an increase in the value of active symbiotic potential.

V. Mazur *et al.* (2021) note that the activity and viability of nodules on the root system in legumes, including soybeans, depends on hydrothermal factors, species and variety, mineral nutrition and soil moisture in spring and the first half of summer, soil temperature of 22-26°C, which contribute to the cyclical processes of photosynthesis and biological nitrogen fixation. This feature is also confirmed by the authors' research results. It was noted that the maximum formation of the active symbiotic potential of soybean, depending on pre-sowing seed treatment and foliar fertilisation, occurred in the flowering phase of plants with a subsequent decrease in this indicator during the vegetation of soybean crops. Under conditions of low soil temperature, there is a considerable slowdown in the work of nodule bacteria.

Scientific studies by P.S. Vyshnivskyi & O.V. Furman (2020), V.F. Petrichenko *et al.* (2017) and H.M. Zabolotnyi *et al.* (2020) reflect the dependence of the symbiotic apparatus of legumes and its intensity of development not only on the effective interaction of host plant genotypes and symbiotic microorganisms under certain growing conditions, but also on the fact that it can be influenced by certain technological methods of cultivation. Namely, the use of bacterial preparations and foliar feeding. When studying the influence of these technological methods, the authors found that pre-sowing seed treatment with the preparation Bioinoculant BTU (2 l/t) increased the accumulation of biologically fixed nitrogen by 26 kg/ha, treatment with Rhizoline (2 l/t) + Rhizosave (2 l/t) – by 10.1 kg/ha, and the use of Anderhiz inoculant (1.5 l/t) increased this indicator, respectively, by 13.8 kg/ha compared to the variants without treatment.

Researchers are interested in identifying and investigating the morphogenesis of nodules with the rhizobial system of legumes. O. Tkachuk & N. Telekalo (2020) proved that the expansion of the area under legumes in intensive crop rotation will have a positive impact on the agro-ecological state of the soil. The researchers draw attention to the possibility of accumulating a large amount of mineral nitrogen in the soil with by-products after soybean cultivation – 38.4 kg/ha. Among the legumes investigated by scientists, soybeans have the highest symbiotic nitrogen fixation capacity of 120 kg/ha. The most intensive fixation of biological nitrogen by soybean plants in the study of the authors was noted in those variants where foliar dressing with the organo-mineral fertiliser Helprost soybean (2.5 l/ha) was carried out. In these variants, depending on the pre-sowing seed treatment, the amount of biologically fixed nitrogen was 63.6-101.9 kg/ha, which is 13.8-26.2 kg/ha more than in the control.

Thus, the symbiotic productivity of crops has a significant impact on soybean grain yield. The dependence of the soybean symbiotic apparatus and the intensity of its development is determined not only by the effective interaction of the host plant genotype and symbiotic microorganisms under certain growing conditions, but also by the influence of certain technological methods of cultivation. Specifically, the use of bacterial preparations and foliar dressing.

CONCLUSIONS

Cultivating leguminous crops enables the replenishment of nitrogen through symbiotic and associative nitrogen fixation. One of the alternative ways to optimise existing developments and new technological methods of growing crops is to intensify the use of biological methods to enhance the ability of legumes to symbiosis and natural fixation of biological nitrogen from the soil air. The shortage of mineral fertilisers and the rapid and constant increase in their cost are driving research in this area.

As a result of the experiment on grey forest soils of the Right-Bank Forest-Steppe, the maximum value of the total 24.811 thousand kg-days/ha and the active symbiotic potential of 20.730 thous. kg-day/ha of soybean plants, for the entire period of symbiosis, was formed under the conditions of a combination of pre-sowing seed treatment with Bioinoculant BTU (2 l/t) and foliar feeding with organo-mineral fertiliser Helprost soybean (2.5 l/ha). The highest amount of biological nitrogen in the atmosphere of 101.9 kg/ha of soybean plants was observed in those variants of the experiment where foliar feeding with organo-mineral fertilizer Helprost soybean (2.5 l/ha) was performed against the background of seed inoculation with Biocomplex BTU (1.0 l/ha). Therewith, the value of symbiotic productivity had a significant impact on soybean grain yield. Thus, the correlation and regression analysis revealed a close relationship between the amount of biological nitrogen accumulation and grain yield. The data obtained indicate that the use of biological preparations is a viable alternative to mineral fertilisers in soybean cultivation. The effect of the biological preparations and organic-mineral fertiliser under study on symbiotic nitrogen fixation by soybean plants is a confirmation of this. That is why one of the priority measures for the efficient use of biological nitrogen from legumes in agriculture should be a scientifically sound structure of sown areas with an optimal share of these crops. A promising area for future research is a detailed study of the specific features of symbiotic nitrogen fixation in legumes under the biologisation of their nutrition system.

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CONFLICT OF INTEREST

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Вплив біологізації системи живлення на трансформацію біологічного азоту та формування продуктивності посівів сої

Анотація. Зростання цін на мінеральні добрива стимулює пошук альтернативних шляхів оптимізації існуючих та розробки нових технологічних прийомів вирощування сільськогосподарських культур, зокрема сої. Одним із таких підходів є інтенсивне застосування біологічних шляхів посилення здатності бобових культур до симбіозу і природної фіксації біологічного азоту із ґрунтового повітря, що сприятиме здешевленню технології вирощування рослин. Саме тому метою досліджень було визначення впливу біологічних препаратів на процес фіксації атмосферного азоту за допомогою симбіотичних бульбочкових бактерій рослинами сої. У цих дослідженнях для визначення кількості біологічно фіксованого азоту використовувався метод обчислення за активним симбіотичним потенціалом та симбіотичною питомою активністю. В ході дослідження було проаналізовано дію ряду препаратів для інокуляції та біодобрив, призначених для листкового підживлення, на розвиток та формування симбіотичних процесів в рослинах сої, а саме – особливості формування по фазах вегетації як загального, так і активного симбіотичного потенціалу. Також визначено вплив величини симбіотичної продуктивності на урожайність зерна сої. Оброблення насіння обраними препаратами за весь період тривалості симбіозу забезпечила зростання загального симбіотичного потенціалу та активного симбіотичного потенціалу. Встановлено, що оброблення насіння інокулянтом Біоінокулянт БТУ (2 л/га) перед посівом виявилось більш продуктивним. При цьому показник максимальної урожайності зерна сої 3,31 т/га зафіксований на ділянках, де до посіву проводили обробку препаратом Біоінокулянт БТУ (2 л/т) а, також, здійснювали два лситкових підживлення добривами у фазу 3-го трійчастого листка та у фазу бутонізації добривом Хелпрост соя (2,5 л/га). Результати дослідження свідчать про суттєвий вплив симбіотичної продуктивності та її величини на урожайність зерна сої. Кореляційний та регресійний аналізи показали, що накопичення біологічного азоту має значний вплив на врожайність зерна. Таким чином, використання біологічних препаратів є альтернативою мінеральним добривам в технології вирощування сої і вони можуть впроваджуватися у виробничих умовах сільськогосподарських підприємств

Ключові слова: обробка інокулянтом; листкові підживлення; препарати природнього походження; симбіотичний потенціал; урожайність