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Symbiotic productivity of soybeans depending on inoculation and fertiliser in conditions of the Right-Bank Forest-Steppe

Abstract. Given the high value of the biochemical composition of soybean seeds and the versatility of using this crop, the need for it will continue to grow, which makes it necessary to improve existing and develop new technologies for its cultivation, considering local agroclimatic resources. Therefore, this study, aiming to investigate the agroecological foundations of the use of chemical and biological techniques in modern technologies for growing soybeans, is relevant. The purpose of the study was to identify the features of the formation of symbiotic productivity of soybeans under the influence of bacterial and mineral fertiliser in the conditions of the Right-Bank Forest-Steppe of Ukraine. A field method was laid down according to the developed scheme to achieve this goal. The positive effect of mineral fertiliser and inoculation on the formation of the symbiotic apparatus of soy and its productivity was established. The smallest increase in the number of root nodules was noted for the introduction of $N_{45}P_{60}K_{60}$ – 24.7-27.3%, depending on the variety. Small initial doses of nitrogen were more effective – within the limits of N_{15-30} – they provided an increase in the number of active

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bulbs by 51.2-106.9%. Bacterisation of seeds with the complex bacterial preparation Phosphonitragine increased the number of active nodules on soybean roots by 106.8-138.6%, depending on the variety. The interaction of technological methods of mineral fertilisation and inoculation contributed to an increase in both the number of nodules with leghemoglobin – by 128.5-198.6%, and their mass – by 111.1-147.6%. The soy symbiotic apparatus was maximally developed by interacting seed inoculation factors with a bacterial preparation containing *Br. japonicum* and *B. Mucilaginosus* strains and applying $N_{30}P_{60}K_{60}+N_{15}$ in the budding phase. This technological model of crop cultivation provided the highest productivity of legume-rhizobial symbiosis of soybean plants in terms of the volume of accumulation of symbiotically fixed nitrogen – in the early-ripening soybean variety Vilshanka – 124.2 kg/ha, in the medium-ripening variety Suziriia – 130.3 kg/ha. The practical importance of the obtained results is in the improvement of varietal technologies for growing soybeans based on the complex application of seed inoculation with a bacterial preparation and the introduction of nitrogen fertilisers in retail against the background of phosphorus-potassium fertiliser

Keywords: mineral fertiliser; variety; symbiotic apparatus; active symbiotic potential; biological nitrogen

INTRODUCTION

Soy (*Glycine max*) occupies a leading place in world agriculture as a crop that can be harvested twice (protein and oil) in one growing year, is characterised by a unique biochemical composition of seeds, the versatility of use, high production growth rates, a positive effect on the qualitative composition of the soil and the ability to fix atmospheric nitrogen in interaction with nodule bacteria. Given the substantial advantages of soybeans, the need for them will continue to grow, which makes it necessary to improve existing and develop new technologies for their cultivation, considering local agroclimatic resources (Furman *et al*., 2022; Shovkova, 2022).

One of the determining factors for the formation of high and stable seed productivity of soybeans is mineral fertilisers and varietal characteristics, the share of which in the formation of the yield level reaches, respectively, 58.5-78.2 and 76.6% (Chynchyk, 2017). Pre-sowing seed inoculation can increase crop productivity by 50% or more (Kozar, 2015). Therewith, due to the symbiotic interaction with nodule bacteria, the ability of soy to independently meet its need for nitrogen is at 25-75%, which substantially reduces the economic and environmental burden when growing it (Faridula *et al*., 2015; Chynchyk, 2017). However, the effectiveness of symbiosis largely depends on the complementarity of symbiotic partners, hydrothermal resources, nitrogen nutrition conditions, etc. (Patyka *et al*., 2015; Petrychenko *et al*., 2018).

Soybeans are a demanding crop for the availability of nutrients in the soil. For the formation of 1 centner of the seeds of its plant, according to Lykhochvor *et al*. (2016), 6.5-7.5 kg of nitrogen, 1.3-1.7 kg of phosphorus, and 1.8-2.2 kg of potassium are consumed. According to other researchers (Bahmat & Chynchyk, 2010; Melnyk & Romanko, 2015), the need for these macronutrients is even higher: nitrogen is needed in the amount of – 7.2-10.0 kg, phosphorus – 1.7-4.0 kg, potassium – 2.2-4.4 kg, which explains the positive reaction of soybeans to the application of mineral fertilisers in an easily accessible form. The greatest need of plants for nitrogen is due to the high protein content of soy seeds. Due to their ability to assimilate atmospheric nitrogen in symbiosis with nitrogen-fixing nodule bacteria, soybeans can fix up to 180 kg/ha or more of biological nitrogen, which is also characterised by good assimilation by subsequent crops and no negative impact on ecological balance (Didora, 2018).

As a result, soybean plants can partially or completely meet their nitrogen needs, which allows growing them with only minimal doses of nitrogen fertilisers or their complete absence (Faridula, *et al*., 2015; Didora, 2018;). However, the efficiency of fixing molecular nitrogen from the atmosphere due to the symbiotic interaction between soybean plants and nodule bacteria is not always high, which is due to the influence of various abiotic, biotic, and anthropogenic factors on them, for example, lack or excess of moisture, low or high temperatures, high acidity of the soil solution, mineral nutrition conditions, etc. (Petrychenko *et al*., 2018). High symbiotic performance is provided only by a well-developed and highly active symbiotic apparatus (Patyka *et al*., 2015; Petrychenko *et al*., 2018), the formation of which largely depends on the reasonable selection of symbiotic partners (Patyka *et al*., 2015; Nakei *et al*., 2022), since microbial-plant interaction is not always characterised by high productivity in terms of the amount of fixed atmospheric nitrogen, which is associated with the high varietal specificity of soybeans to nodule bacterial strains (Petrychenko *et al*., 2018; Didora, 2019).

An important agrotechnical measure that contributes to the formation of a highly productive soy-rhizobial symbiosis is the cultivation of soybeans based on bacterial and mineral nutrition (Chynchyk, 2017; Shovkova, 2022). For example, applying phosphorus-potassium fertilisers positively affects the increase in the number of nodules and the productivity of symbiosis in general (Ciampitti & Salvagiotti, 2018). As for the combined use of inoculants and nitrogen minerals, the opinions of the scientific community are ambiguous (Faridula *et al*., 2015; Kobak *et al*., 2017; Chynchyk, 2017). It is believed that small starting doses of nitrogen, in the range of 15–30 kg/ha, have a positive effect on the process of nodule formation on the soybean roots in the initial growing season of plants (Patyka *et al*., 2015; Furman *et al*., 2022). Higher doses of nitrogen fertilisers inhibit the formation of the symbiotic system, reduce its effectiveness, and can lead to the complete termination of symbiotic relationships (Moldovan, 2018; Furman *et al*., 2022;). The ambiguity of opinions regarding the feasibility of applying nitrogen fertilisers for soybeans is due to the complexity and multi-stage formation and functioning of various legume-rhizobial structures (Chekhova & Chekhov, 2019; Shevnikov *et al*., 2022).

Effective use of the bioclimatic potential of the region in the cultivation of soybeans is possible only if the development and introduction into production of such technologies for its cultivation that maximally correspond to the genetic characteristics of the variety and consider the complex interaction of the plant organism with hydrothermal and soil resources (Petrychenko *et al*., 2018; Shevnikov *et al*., 2022).

Today, breeders have created many high-tech and highly productive soybean varieties, however, the level of realisation of their genetic potential of productivity is substantially determined by the soil and climatic conditions of a particular growing area and adapted cultivation technology, which is especially important in the context of climate change (Petrychenko *et al*., 2018).

Since soybeans are characterised by a strong reaction to the length of the day, the most suitable for its cultivation is the geographical zone, the width of which is 160-240 km in the direction from South to North. The displacement of geographical space leads to changes in the duration of the vegetation period, productivity, qualitative composition of seeds, adaptive properties, symbiotic productivity, and response to stress factors (Petrychenko *et al.*, 2018; Didora, 2019).

In this regard, an urgent and timely scientific task is to correct the technology of growing modern soybean varieties, considering the requirements of the culture for life factors.

The purpose of the study was to establish the influence of seed bacterisation and the norms and timing of mineral fertiliser application on the formation of symbiotic productivity of soybeans in the Forest-Steppe of Right-Bank Ukraine.

MATERIALS AND METHODS

The study was conducted during 2013-2015 in the experimental field of the state enterprise "Experimental Farm "Salivonkivske" of the Institute of Bioenergy Crops and Sugar Beet of the National Academy of Agrarian Sciences of Ukraine. The soil of the experimental site is typical low-humus chernozem with a humus content in the arable layer of 4.56%, easily hydrolysed nitrogen (DSTU 7863:2015 , 2016) – 155-161 mg/kg of soil, mobile phosphorus (DSTU 4115-2002 , 2003) – 44-54 mg/kg potassium exchange rate – 95-107 mg/kg of soil, the pH of salt extract is 6.7-7.2.

The field experiment was conducted according to the scheme: factor A – variety: Vilshanka (early-ripening) and Suziriia (medium-ripening) of selection of the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences"; Factor B – pre-sowing seed treatment: without inoculation, Phosphonitragine; factor C – fertiliser: without fertilisers (control), $P_{60}K_{60}$, $N_{15}P_{60}K_{60}$, $N_{30}P_{60}K_{60}$, $N_{45}P_{60}K_{60}$, $P_{60}K_{60}+N_{15}$, $N_{15}P_{60}K_{60}+N_{15}$, $N_{30}P_{60}K_{60}+N_{15}$.

Soybean sowing was conducted in the first half of May in a wide-row way with a row spacing of 45 cm when the soil warmed up at a seed depth of up to 10-12°C. The predecessor is winter wheat. The repetition is fourfold. Placement of options is systematic. Phosphorous and potash fertilisers (granulated superphosphate and potash salt) were applied for the main tillage at the rate of $P_{60}K_{60}$; nitrogen (ammonium nitrate) – for pre-sowing cultivation and top dressing of soybean plants in the budding phase in accordance with the experiment scheme.

Seed inoculation was conducted on the day of sowing with a complex bacterial preparation for agricultural purposes certified in Ukraine – Phosphonitragine (developed by the National Scientific Centre "Institute of Agriculture of the National Academy of Agrarian Sciences"), which contains strains of nodule bacteria (*Br. japonicum*) and phosphatmobilising microorganisms (*B. mucilaginosus*). Seed bacterisation was conducted in accordance with the requirements specified in the recommendations for this type of work (Recommendations for effective application..., 1997). Since the seeds were treated with Maxim XL 035 FS mordant (1 L/t of seeds) 14 days before sowing, the bacterial load level was doubled and amounted to 400 thousand cells per 1 seed.

Planning of the experiment scheme, laying of the field experiment, placement of variants and repetitions was conducted in accordance with the requirements and recommendations set out in the manual "Fundamentals of scientific research in agronomy" (Yeshchenko, 2005). Sampling to determine the size of the symbiotic apparatus was conducted by the method of monoliths (Posypanov, 1993) in the main phenological phases of soybean development, the onset of which was determined by the visual method according to the "Methodology of State variety testing of agricultural crops" (2000).

The total number and mass of nodules, the number and mass of active nodules, the active symbiotic potential, and the amount of biologically fixed nitrogen were determined according to Posypanova (1993) methods.

Weather conditions during the years of the study were characterised by a substantial difference both in years and in relation to long-term averages. In 2013, depending on the duration of the growing season of plants, their growth and development took place at an average daily temperature of 19.1-19.8°C, the sum of active temperatures (>10,°C) – 2036.3-2258.7°C and precipitation amounts – 251.4-334.0 mm. In 2014, the values of these indicators were, respectively, 18.6-19.5°C, 2020.4-2216.7°C, and 308.7-337.2 mm; in 2015 – 21.1-21.6°C, 2040.5-2324.4°C, and 135.3-166.5 mm. In general, in the last year of the study, the hydrothermal coefficient for the growing season was 0.6-0.7, while the optimal value for this crop was 1.0-1.7 (Petrychenko *et al.*, 2018).

RESULTS AND DISCUSSION

Analysis of the field experiment results indicates a positive influence of the examined technological methods of growing soybeans on the formation of its symbiotic apparatus. It was established that on the root system of plants of the Vilshanka and Suziriia varieties examined in the experiment, the number of nodules increased intensively before the onset of the phenological phase of seed filling, further on, with the approach of the physiological ripeness phase, their number gradually decreased (Table 1). This pattern was observed both in relation to the total number of root nodules and in relation to their active part.

Table 1. Dynamics of the number of nodules on the roots of soybean plants depending on inoculation and norms and terms of application of mineral fertilisers (average for 2013-2015), pcs./plant

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Vilshanka Variety							
Without fertilisers (control)	n/i	10.1	6.6	14.2	11.9	18.2	14.5
	i	25.1	20.5	29.6	25.2	39.8	34.6
$P_{60}K_{60}$	n/i	13.5	10.2	19.4	17.1	25.4	21.2
	i	28.3	23.8	32.4	26.8	41.5	36.4
$N_{15}P_{60}K_{60}$	n/i	16.0	12.5	21.1	17.9	26.2	23.5
	i	28.9	24.1	32.7	27.3	43.1	37.8
$N_{30}P_{60}K_{60}$	n/i	19.2	15.6	22.2	18.2	31.5	27.3
	i	29.5	24.5	33.4	27.7	45.2	40.0
$N_{45}P_{60}K_{60}$	n/i	12.6	8.4	17.8	13.2	24.5	19.4
	i	17.7	12.0	23.1	17.6	33.4	27.0
$P_{60}K_{60}+N_{15}$	n/i	13.7	10.4	20.2	17.7	26.2	23.6
	i	28.2	23.7	32.6	27.1	44.3	38.6
$N_{15}P_{60}K_{60}+N_{15}$	n/i	16.2	12.7	22.8	19.4	33.2	29.4
	i	28.7	23.8	34.3	29.0	50.0	42.8
$N_{30}P_{60}K_{60}+N_{15}$	n/i	19.4	15.8	25.2	20.8	34.5	30.0
	i	29.0	23.6	35.4	29.4	51.3	43.3
Suziriia variety							
Without fertilisers (control)	n/i	11.8	8.1	20.5	18.1	24.5	20.7
	i	26.7	22.2	38.1	34.8	48.3	42.8
$P_{60}K_{60}$	n/i	15.9	12.4	26.3	24.2	33.1	28.7
	i	30.8	26.5	41.6	36.1	52.2	47.3
$N_{15}P_{60}K_{60}$	n/i	21.1	17.6	29.1	25.7	35.2	31.3
	i	32.6	27.6	43.2	37.5	53.0	47.8

Table 1, Continued

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Suziriia variety							
$N_{30}P_{60}K_{60}$	n/i	25.2	21.4	32.2	27.9	38.4	33.9
	i	35.6	30.4	44.8	38.7	54.1	48.3
$N_{45}P_{60}K_{60}$	n/i	14.7	10.1	25.7	21.6	29.3	24.0
	i	21.1	16.7	33.6	26.4	40.9	33.8
$P_{60}K_{60}+N_{15}$	n/i	16.0	12.6	27.1	24.7	36.0	32.3
	i	30.8	26.0	42.8	36.6	53.8	48.0
$N_{15}P_{60}K_{60}+N_{15}$	n/i	21.0	17.4	33.2	29.7	40.2	35.9
	i	32.3	27.2	46.1	40.7	56.5	50.3
$N_{30}P_{60}K_{60}+N_{15}$	n/i	24.9	21.1	34.6	29.9	41.4	36.8
	i	35.2	29.6	47.2	41.0	57.1	51.0
$HIP_{0.05}$ total $HIP_{0.05}$ variety $HIP_{0.05}$ fertiliser $HIP_{0.05}$ inoculation		3.44 1.23 2.57 1.23		4.05 1.39 3.08 1.39		5.21 1.56 3.46 1.56	

Note: *n/i – seeds with no inoculation; i – inoculated seeds

Thus, in the budding phase, the total number of nodules on plants of the control variant was 10.1 pcs./plant in the Vilshanka variety and 11,8 pcs./plant in the Suziriia variety, of which there were 6.6 and 8.1 active nodules on one plant, respectively. Improvement of phosphorus-potassium nutrition conditions due to the introduction of $P_{60}K_{60}$ contributed to an increase in the total number of nodules – by 3.4-4.1 pcs./plant, depending on the variety, including their active part – by 3.6 and 4.3 pcs./plant. A more intensive increase in the number of root nodules was observed when applying full mineral fertiliser – by 2.5-13.1 (total number) and 1.8-13.4 pcs./plant (active bulbs). However, the effect of such fertiliser on the formation of a symbiotic apparatus varied substantially depending on the norms and timing of nitrogen fertiliser application.

It was determined that small starting doses of nitrogen are within the limits of N_{15-30} had a positive effect on the formation of root nodules, the total number of which increased by 58.4-113.6%, of which the active part – by 89.3-164.2%. The application of N_{45} against the background of $P_{60}K_{60}$ had a positive, but not so pronounced effect, as a result of which the increase in the total number of nodules relative to absolute control in the Vilshanka variety was only 24.8%, in the Suziriia variety – 24.6%, including active ones, respectively, 27.3 and 24.7%. The intensity and size of the symbiotic apparatus were determined by inoculation with Phosphonitragine rather than by applying mineral fertilisers. Pre-sowing bacterisation of soybean seeds with a complex preparation containing *Br. japonicum* and *B. Mucilaginosus* stains provided an increase in the total number of nodules and their active component in the early-ripening Vilshanka variety, respectively, by 148.5 and 210.1%, in the medium-ripening Suziriia variety – by 126.3 and 174.1%.

The most effective agricultural method for the formation of a well-developed symbiotic system in plants of the examined soybean varieties was the combined effect of seed inoculation and mineral fertilisers with the norm of $N_{30}P_{60}K_{60}$. The interaction of these factors provided an increase in the total number of root nodules in the Vilshanka variety by 192.1%, and in the Suziriia variety – by 201.7%, of which active ones – by 271.2 and 275.3%, respectively.

Before the onset of the seed filling phase, when the symbiotic apparatus of soybeans reached its maximum development, there was a certain redistribution between the variants of the experiment. As at the first stages of soy-rhizobial symbiosis formation, the smallest number of nodules was formed in areas of absolute control (without inoculation and mineral fertilisers) – 18.2 pieces were formed in the Vilshanka variety per plant, in the Suziriia variety – 24.5 pcs./plant. Among all other variants of the experiment scheme, the least developed symbiotic apparatus was in plants grown in areas where $N_{45}P_{60}K_{60}$ was applied – the increase in the total number of nodules and their active part was 4.8-6.3 and 3.3-4.9 pcs./plant or 19.6-34.6 and 16.0-3.8%, respectively. investigating the interaction of mineral fertiliser and bacterisation factors, it was established that the smallest increase in root nodules was also noted for the introduction of $N_{45}P_{60}K_{60}$ – 15.2-16.4 pcs./plant (total quantity) and 12.5-13.1 pcs./plant (active ingredients) or 67.0-83.5 and 63.3-86.2%, respectively. Of all the fertiliser options, the separate application of nitrogen fertilisers against the background of $P_{60}K_{60}$ had the most positive effect on the formation of root nodules, both with and without inoculation.

The most favourable conditions for the formation of root nodules were formed according to the technological model of soybean cultivation, which provided for inoculation of seeds with a complex bacterial preparation containing nodule bacteria and fosformobilising microorganisms and the introduction of $N_{30}P_{60}K_{60} + N_{15}$. In this variant, the increase in the total number of root nodules and their active part in the Vilshanka variety was 33.1 and 28.8 pcs./plant or 181.9 and 198.6%, respectively. The Suziriia variety had a similar relationship – 32.6 and 30.3 pcs./plant or 133.1 and 146.9%.

An important characteristic of the process of formation of the symbiotic apparatus of soybeans is the mass of root nodules (Table. 2). According to the average research results, it was established that the dynamics of the formation of the total mass of nodules and their active part, depending on the action and interaction of the examined factors, was similar to the dynamics of changes in their number.

Table 2. Dynamics of the raw mass of nodules on the roots of soybean plants depending on inoculation and the norms and terms of mineral fertiliser application (average for 2013-2015), g/plant

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Vilshanka Variety							
Without fertilisers (control)	n/i	0.29	0.19	0.45	0.39	0.61	0.51
	i	0.67	0.46	0.97	0.85	1.27	1.07
$P_{60}K_{60}$	n/i	0.34	0.23	0.58	0.52	0.78	0.66
	i	0.75	0.51	1.04	0.92	1.32	1.12
$N_{15}P_{60}K_{60}$	n/i	0.41	0.28	0.65	0.59	0.86	0.73
	i	0.79	0.56	1.06	0.96	1.36	1.16

Table 2, Continued

Fertiliser	Inoculation	Phase of plant growth and development					
		budding		full bloom		filling seeds	
		total	active users	total	active users	total	active users
Vilshanka Variety							
$N_{30}P_{60}K_{60}$	n/i	0.52	0.36	0.77	0.70	0.92	0.78
	i	0.84	0.58	1.08	0.98	1.39	1.19
$N_{45}P_{60}K_{60}$	n/i	0.30	0.20	0.53	0.46	0.73	0.60
	i	0.47	0.28	0.80	0.69	0.97	0.78
$P_{60}K_{60}+N_{15}$	n/i	0.36	0.24	0.63	0.56	0.87	0.75
	i	0.76	0.50	1.05	0.94	1.37	1.17
$N_{15}P_{60}K_{60}+N_{15}$	n/i	0.43	0.30	0.79	0.72	0.95	0.81
	i	0.77	0.54	1.10	1.01	1.43	1.23
$N_{30}P_{60}K_{60}+N_{15}$	n/i	0.54	0.38	0.86	0.80	0.97	0.83
	i	0.82	0.55	1.14	1.06	1.45	1.26
Suziriia variety							
Without fertilisers (control)	n/i	0.33	0.22	0.61	0.52	0.77	0.63
	i	0.78	0.53	1.23	1.07	1.49	1.22
$P_{60}K_{60}$	n/i	0.38	0.26	0.84	0.72	0.87	0.72
	i	0.84	0.58	1.30	1.15	1.61	1.33
$N_{15}P_{60}K_{60}$	n/i	0.56	0.39	0.93	0.84	0.98	0.81
	i	0.90	0.64	1.37	1.23	1.68	1.39
$N_{30}P_{60}K_{60}$	n/i	0.68	0.48	1.05	0.93	1.11	0.92
	i	0.95	0.70	1.43	1.28	1.75	1.46
$N_{45}P_{60}K_{60}$	n/i	0.35	0.23	0.78	0.67	0.83	0.68
	i	0.54	0.37	1.10	0.93	1.24	0.98
$P_{60}K_{60}+N_{15}$	n/i	0.39	0.27	0.87	0.77	1.00	0.83
	i	0.84	0.56	1.33	1.18	1.71	1.42
$N_{15}P_{60}K_{60}+N_{15}$	n/i	0.53	0.38	1.09	0.96	1.21	1.01
	i	0.89	0.61	1.47	1.33	1.81	1.52
$N_{30}P_{60}K_{60}+N_{15}$	n/i	0.67	0.46	1.15	1.05	1.29	1.07
	i	0.91	0.66	1.52	1.39	1.84	1..56
$HIP_{0.05}$ total $HIP_{0.05}$ variety $HIP_{0.05}$ fertiliser $HIP_{0.05}$ inoculation		0.10 0.03 0.06 0.03		0.13 0.05 0.08 0.05		0.12 0.04 0.09 0.04	

Note: *n/i – seeds with no inoculation; i – inoculated seeds

In the budding phase, the total mass of all nodules ranged from 0.29-0.95 g/plant, of which active ones – 0.19-0.70 g/plant. The lowest total mass of nodules and their active part was observed on the roots of plants from the control areas – 0.29-0.33 and 0.19-0.22 g/plant, depending on the variety. The most powerful symbiotic apparatus by weight with a total mass of nodules of 0.84-0.95 g/plant, including active 0.58-0.70 g/plant, was formed due to the interaction of inoculation factors and the application of a complete mineral fertiliser in normal $N_{30}P_{60}K_{60}$. The increase in the mass of nodule formations relative to the control was, respectively, 187.9-189.7 and 205.3-218.2%. An increase in the mass of root nodules, and their number, was observed before the onset of the phenological phase of seed filling, during which the total mass of nodules reached 0.61-1.84 g/plant, including active ones – up to 0.51-1.56 g/plant.

All the examined variants of technological techniques contributed to an increase in the mass of nodules. The interaction of inoculation factors and separate application of nitrogen fertilisers N_{30-45} had the most positive effect on the process of mass formation of the symbiotic apparatus against the background of $P_{60}K_{60}$. The maximum total mass of nodules – at the level of 1.45-1.84 g/plant and their active part – in the range of 1.26-1.56 g/plant was noted at the experiment site, where pre-sowing bacterisation of seeds was conducted with a bacterial preparation containing *Br. japonicum* and *B. Mucilaginosus* and with the application of $N_{30}P_{60}K_{60} + N_{15}$. The increase to control was 137.7-139.0 and 147.1-147.6%, respectively. Both in terms of the number and mass of all the bulbs of more powerful ones, the symbiotic apparatus formed a medium-ripening Suziriia variety.

An important indicator of the effectiveness of legume-rhizobial symbiosis is the active symbiotic potential, which lasts from the appearance to the destruction of leghemoglobin in root nodules (Patyka, 2015; Kobak, 2017; Furman, 2022). Seed inoculation with Phosphonitragine and mineral fertilisers had a positive effect on the efficiency of interaction between micro- and macrosymbionts (Table 3). The most effective symbiotic relationships were for seed bacterisation and, accordingly, more intensive colonisation of soybean plant roots with symbiotic bacteria. As a result, the increase in the active symbiotic potential in relation to control for the period from the budding phase to the onset of physiological ripeness of seeds in the Vilshanka variety was 4.81 thousand kg·days/ha, in the Suziriia variety – 5.46 thousand kg·days/ha or 47.8 and 46.7%, respectively.

Table 3. Efficiency of symbiotic nitrogen fixation of soybeans depending on the influence of organised factors (average for 2013-2015), kg/ha

Fertiliser	Inoculation	Vilshanka		Suziriia	
		active symbiotic potential, thousand kg·day/ha	amount of fixed nitrogen, kg/ha	active symbiotic potential, thousand kg·day/ha	amount of fixed nitrogen, kg/ha
Without fertilisers (control)	n/i	10.06	65.1 + 7.7**	11.69	70.9 + 10.6
	i	14.87	99.2 + 14.4	17.15	104.3 + 13.6
$P_{60}K_{60}$	n/i	11.21	68.0 + 9.4	13.04	74.2 + 9.4
	i	16.04	106.3 + 13.0	18.55	112.5 + 14.8
$N_{15}P_{60}K_{60}$	n/i	12.11	70.2 + 8.7	14.10	75.5 + 7.6
	i	16.63	108.4 + 14.0	19.75	118.2 + 18.2
$N_{30}P_{60}K_{60}$	n/i	13.06	73.9 + 8.7	15.15	76.5 + 10.8
	i	17.27	112.4 + 15.5	20.51	121.3 + 19.2
$N_{45}P_{60}K_{60}$	n/i	10.50	68.9 + 9.6	12.29	71.8 + 7.2
	i	12.87	103.8 + 15.4	14.40	107.1 + 18.5
$P_{60}K_{60} + N_{15}$	n/i	11.98	71.8 + 10.1	13.84	76.0 + 10.9
	i	16.43	110.8 + 15.7	19.43	120.9 + 20.5
$N_{15}P_{60}K_{60} + N_{15}$	n/i	13.31	78.2 + 10.8	15.75	78.8 + 9.8
	i	17.82	118.8 + 20.6	21.30	127.1 + 22.1
$N_{30}P_{60}K_{60} + N_{15}$	n/i	14.11	80.1 + 10.1	16.28	81.0 + 10.0
	i	18.40	124.2 + 19.9	22.23	130.3 + 21.2

Table 3, Continued

Fertiliser	Inoculation	Vilshanka		Suziriia	
		active symbiotic potential, thousand kg·day/ha	amount of fixed nitrogen, kg/ha	active symbiotic potential, thousand kg·day/ha	amount of fixed nitrogen, kg/ha
$HIP_{0.05}$ total $HIP_{0.05}$ variety $HIP_{0.05}$ fertiliser $HIP_{0.05}$ inoculation		1.05 0.52 0.87 0.52	–	–	1.05 0.52 0.87 0.52

Note: *n/i – seeds with no inoculation; i – inoculated seeds; ** M ± m – reliability interval of the arithmetic mean at the 5% substantiality level

The effectiveness of applying mineral fertilisers in the experiment was substantially determined by the norms and terms of applying nitrogen fertilisers against the background of $P_{60}K_{60}$. The least effective was a one-time application of N_{45} as a result, the increase in the active symbiotic potential relative to the control did not exceed 4.4-5.1%, depending on the variety. However, the introduction of the same nitrogen rate by retail method, on the contrary, provided maximum efficiency of legume-rhizobial symbiosis – the symbiotic potential increased by 39.2-40.3%.

According to this indicator, the best option in the experiment was the one where a combination of technological methods of inoculation and application was examined $N_{30}P_{60}K_{60} + N_{15}$ – the growth of active symbiotic potential reached 82.9-90.2%. The highest symbiotic activity is characteristic of the Suziriia variety.

The productivity of legume-rhizobial symbiosis is characterised by the amount of symbiotically fixed nitrogen, for calculations of the accumulation volumes of which data on the active symbiotic potential and specific active symbiosis were used (Posypanov, 1993). Soybean crops on control variants were the least symbiotically productive – 65.1-70.9 kg/ha, depending on the variety. Inoculation of seeds with a bacterial preparation provided an increase in the volume of biological nitrogen accumulation by 47.1-52.4% to the level of 99.2-104.3 kg/ha.

The application of mineral fertilisers, in comparison with bacterisation, affected the productivity of nitrogen fixation less effectively – in the Vilshanka variety, the increase was 4.5-23.0%, in the Suziriia variety – 4.7-14.2%. Of all the variants of the experiment, where the influence of the norms of complete mineral fertiliser on symbiotic productivity was examined, the lowest values were obtained for applying $N_{45}P_{60}K_{60}$ – 68.9-71.8 kg/ha, which almost did not differ from the values obtained on the variants where only phosphorus-potassium fertiliser was conducted – 68.0-74.2 kg/ha.

The most intense accumulation of symbiotically fixed nitrogen occurred due to the interaction of technological measures of seed bacterisation with Phosphonitragin and retail application of nitrogen fertilisers in the norm N_{30-45} against the background of $P_{60}K_{60}$ – 118.8-130.3 t/ha, which exceeded the control by 71.3-75.6%.

The intensity of development and the level of productivity of the soybean symbiotic apparatus are substantially determined by technological factors (Melnyk & Romanko, 2015; Petrychenko *et al.*, 2018; Didora *et al.*, 2019). Among the factors that most affect the formation and functioning of root nodules, most researchers distinguish inoculation and mineral fertilisers (Didora, 2018; Furman *et al.*, 2022). Thus, according to the results of the studies by Chynchyk (2017), before the onset of the seed filling phase, inoculation provided an increase in the raw mass of nodules with leghemoglobin at the level of 0.126-0.140 g/plant, depending on the variety, fertiliser application – 0.019-0.034 g/plant, while the difference between varieties in this indicator did not exceed 0.002 g/plant. According to V.F. Kaminsky (2006), pre-sowing bacterisation of seeds provided an increase in the mass of active nodules in the range of 0.15-0.35 g/plant and their number in the basal part of the root – 22-29 pcs./plant. Kots & Mamenko (2015) note that in plants inoculated 7 days before sowing, the mass of nodules in the stage of 3 real leaves exceeded the control by 1.5-2.0 times. In the experiments of O. Temriienko (2018), fertilisation and seed inoculation provided an increase in the number of active nodules by 14.7-18.3 pcs./plant or 76-77%, while the difference between the varieties on the control variants did not exceed 7.3 pcs./plant. The same pattern was observed in relation to the mass of active nodules. The results obtained in this study confirm the data of these researchers (Temriienko, 2018; Furman *et al*., 2022). It was established that in the budding phase due to inoculation, the increase in the number and mass of active nodules was 13.9-14.1 pcs./plant and 0.27-0.31 g/plant, due to mineral fertiliser – respectively, 3.6-13.0 pcs./plant and 0.04-0.24 g/plant, while the difference between the varieties in the control variants did not exceed 1.5 pcs./plant and 0.03 g/plant. Thus, the pattern was observed before the onset of the seed filling phase.

The presented results of the study also show a positive effect on the formation of the symbiotic apparatus of phosphorus-potassium fertilisers, the introduction of which in a dose of $P_{60}K_{60}$ against the background of inoculation, provided an increase in the number and mass of active nodules in the seed filling phase in the range of 1.8-4.5 pcs./plant and 0.05-0.11 g/plant relative to variants where only inoculation was performed. The obtained data are confirmed in the experiments of Gamaiunova & Nazarchuk (2013), who note that the application of phosphorus-potassium fertilisers in the norm of $P_{45}K_{60}$ in combination with bacterisation of soybean seeds, compared only with bacterisation, provided an increase in the number of active nodules on plant roots by 40-81.8%.

More substantial increases in both the mass of active root nodules and their number were noted for the combination of inoculation and full mineral fertiliser application. Moreover, the size of the symbiotic apparatus was most influenced by the norms and timing of nitrogen fertilisers, the importance of which in soybean cultivation is the most controversial agrotechnical measure (Faridula *et al*., 2015; Chynchyk, 2017). According to the results presented in the study, the smallest increase in the number and mass of active nodules both on non-inoculated plants and during pre-sowing seed inoculation was observed with a separate application of nitrogen fertilisers in a dose of N_{45} against the background of $P_{45}K_{60}$. The symbiotic apparatus was most developed under the condition of the interaction of seed bacterisation factors and the introduction of low doses of nitrogen fertilisers – $N_{15–30}$ against the background of $P_{60}K_{60}$. These data confirm the scientific statement of many researchers (Li, 2020) on the positive effect of low doses of nitrogen fertilisers on the formation of root nodules on soybean roots.

A valuable result of this study is the confirmed positive effect of separate application of nitrogen fertilisers on the formation of the soybean symbiotic apparatus. It is established that nitrogen fertilisers applied in the norm N_{45} during pre-sowing cultivation and in the budding phase of plants in combination with technological measures of seed bacterisation ensures the formation of the most developed symbiotic apparatus. The increase in the number and mass of active nodules from the use of such a technological model, compared with a single application of the same nitrogen rate, is 16.3-17.2 pcs./plant and 0.48-0.58 g/plant. The results obtained in th study are confirmed by F.R. Bender *et al*. (2022) and V. Didora *et al*. (2019).

It is established that the technological model that contributes to the formation of the most developed symbiotic apparatus ensures the accumulation of the maximum amount of biological nitrogen. The higher efficiency of legume-rhizobial symbiosis is determined by fertilisation and inoculation than the varietal characteristics of soybeans, which is confirmed by the results of the studies by other researchers who have examined the influence of technological techniques on the effectiveness of soybean symbiosis (Bender *et al*., 2022). The presented study states that the difference between the examined soybean varieties in terms of the level of biological nitrogen accumulation was insubstantial and did not exceed 5.8 kg/ha. Inoculation of seeds of the early-ripening Vilshanka variety and the medium-ripening Suziriia variety provided an increase in biological nitrogen at the level of 33.4-34.1 kg/ha. The addition of a complete mineral fertiliser against the background of seed bacterisation increased the increase in accumulated atmospheric nitrogen by 43.3-59.4 kg/ha. Other researchers also note a more substantial positive effect of applying a complete mineral fertiliser compared to inoculation on the process of atmospheric nitrogen accumulation. According to V.F. Didora *et al*. (2019) when growing soybeans in the absence of mineral fertiliser, seed inoculation contributed to the accumulation of 82.3 kg/ha, the introduction of $N_{60}P_{60}K_{60}$ increased this volume of biological nitrogen by 46.1 kg/ha. Thus, bacterial and mineral nutrition is an important factor influencing the formation and productivity of the soybean symbiotic apparatus, which is a substantial factor in enriching the soil with biological nitrogen.

CONCLUSIONS

As a result of the study, it was established that growing soybeans based on reasonable bacterial and mineral nutrition in the conditions of the right-bank Forest-Steppe of Ukraine on typical low-humus chernozem allows forming a highly productive soy-rhizobial symbiosis. The effectiveness of the symbiotic system was largely determined by the norms and timing of nitrogen fertiliser application against the background of phosphorus-potassium fertiliser and inoculation. The application of only phosphorous-potash fertilisers, although had a positive effect on the formation of the number and mass of root nodules, the size and efficiency of the symbiotic apparatus with the addition of a complete mineral fertiliser were substantially higher both inoculation and in its absence. With the application of $P_{60}K_{60}$, the number of active nodules in the budding phase increased – by 3.6-4.3 pcs./plant, depending on the variety, for applying full mineral fertiliser – by 1.8-13.4 pcs./plant. With a separate application of nitrogen fertilisers, small starting doses of nitrogen were more effective – within the limits of N_{15-30}, which provided an increase in the number of active bulbs by 89.3-164.2%, with the application of N_{45} against the background of $P_{60}K_{60}$, the number of active bulbs increased only by 24.7-27.3%. Inoculation with a complex preparation, containing *Br. japonicum* and *B. Mucilaginosus* strains provided an increase in the number of active nodules by 174.1-210.1%. The interaction of fertiliser and inoculation factors increased the increase in the number of active root nodules by 271.2-275.3%. The most favourable conditions for the formation of a well-developed symbiotic apparatus on the root systems of soybean plants of Vilshanka and Suziriia are obtained according to the technological model of their cultivation, which provided for inoculation of seeds with a bacterial preparation containing nodule bacteria and fosformobilising microorganisms and the introduction of $N_{30}P_{60}K_{60} + N_{15}$ in the budding phase. The interaction of these technological techniques provided an increase in the number of active root nodules in an early-ripening variety by 198.6%, and in a medium-ripening variety – by 146.9%. Similar patterns were observed in the mass of active root nodules, the increase in control on this variant was 147.0-147.6%, and the level of active symbiotic potential, the increase of which reached 82.9-90.2%. In all variants of the experiment, the highest symbiotic activity is characteristic of the variety Suziriia. Application of full mineral fertiliser in the norm of $N_{30}P_{60}K_{60} + N_{15}$ and conducting pre-sowing seed bacterisation with the preparation based on strains of nodule bacteria and fosformobilising microorganisms provided the highest productivity of symbiotic systems in terms of the volume of accumulation of symbiotically fixed nitrogen – in the early-ripening soybean variety Vilshanka – 124.2 kg/ha, in the medium-ripening variety Suziriia – 130.3 kg/ha. Further research will be aimed at investigating the effect of bacterial and mineral fertiliser on the formation of highly productive soybean crops.

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CONFLICT OF INTERESTS

None.

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Симбіотична продуктивність сої залежно від інокуляції та удобрення в умовах Правобережного Лісостепу

Анотація. Враховуючи високу цінність біохімічного складу насіння сої та універсальність використання цієї культури, потреби в ній і надалі зростатимуть, що обумовлює необхідність удосконалення існуючих та розробку нових технологій її вирощування з урахуванням місцевих агрокліматичних ресурсів. Тому, на сьогодні дослідження, спрямовані на вивчення агроекологічних основ використання хімічних та біологічних прийомів у сучасних технологіях вирощування сої є актуальними. Метою досліджень було виявити особливості формування симбіотичної продуктивності сої під впливом бактеріально-мінерального удобрення в умовах правобережного Лісостепу України. Для досягнення мети було закладено польовий метод за розробленою схемою. Встановлено позитивний вплив мінерального удобрення та інокуляції на формування симбіотичного апарату сої та його продуктивність. Найменший приріст кількості кореневих бульбочок відмічали за внесення $N_{45}P_{60}K_{60}$ – 24,7-27,3 % залежно від сорту. Більш ефективними були невеликі стартові дози азоту – у межах $N_{15\text{-}30}$ – вони забезпечували приріст кількості активних бульбочок на 51,2-106,9 %. Бактеризація насіння комплексним бактеріальним препаратом Фосфонітрагін збільшувала кількість активних бульбочок на коренях сої на 106,8-138,6 % залежно від сорту. Взаємодія технологічних прийомів мінерального удобрення та інокуляції сприяла зростанню як кількості бульбочок з леггемоглобіном – на 128,5-198,6 %, так і їх маси – на 111,1-147,6 %. Максимального розвитку симбіотичний апарат сої досягав при взаємодії факторів інокуляції насіння бактеріальним препаратом, що містить штами містить штами Br. japonicum і B. Mucilaginosus та внесення $N_{30}P_{60}K_{60}+N_{15}$ у фазі бутонізації. Така технологічна модель вирощування культури забезпечила найвищу продуктивність бобово-ризобіального симбіозу рослин сої за обсягами накопичення симбіотично фіксованого азоту – у скоростиглого сорту сої Вільшанка – 124,2 кг/га, у середньостиглого сорту Сузір'я – 130,3 кг/га. Практичне значення одержаних результатів досліджень полягає в удосконаленні сортових технологій вирощування сої на основі комплексного застосування інокуляції насіння бактеріальним препаратом та внесення азотних добрив в роздрібний спосіб на фоні фосфорно-калійного удобрення

Ключові слова: мінеральне добриво; сорт; симбіотичний апарат; активний симбіотичний потенціал; біологічний азот