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THE INFLUENCE OF METAL NANOCARBOXYLATES ON THE NITROGEN-FIXING ACTIVITY OF SYMBIOTIC SOYBEAN SYSTEMS GROWN UNDER FIELD CONDITIONS

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Background. Numerous scientific and industrial studies have proven the high effectiveness of using micronutrients in nanoscale form in agricultural crop cultivation technologies. Among them, special attention is drawn to soybeans, which hold a leading position in terms of sown areas among other leguminous crops in the country. They can provide up to 70 % of their own nitrogen needs through the fixation of its molecular form from the atmosphere in symbiosis with *Bradyrhizobium japonicum* nodulating bacteria. New methods of molecular biology, biotechnology, and genetic engineering, along with classical methods of microbiology, plant physiology, genetics, and agrochemistry, allow for addressing both fundamental questions regarding the characteristics of formation and functioning of legume-rhizobial systems, and practical approaches to correcting the interactions between symbiotic partners with the aim of creating highly effective symbioses. Therefore, research aimed at significant increasing the current level of biological nitrogen fixation and adapting symbiotic systems to negative environmental factors is currently relevant. The use of nanotechnology, in particular, the study of the effect of iron, germanium, and cobalt nanocarboxylates on the formation and functioning of the soybean-rhizobial symbiosis under field conditions in combination with seed inoculation with rhizobial bacteria may be promising.

Materials and Methods. The objects of the investigation were symbiotic systems created with the participation of the Almaz variety of soybean and the *Bradyrhizobium japonicum* B1-20 rhizobacteria, and with the introduction of nanocarboxylates of iron (Fe), germanium (Ge) and cobalt (Co) into their cultivation medium. Physiological, microbiological, biochemical, and statistical research methods were used.

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Results. It was found that under field conditions, before the pod formation stage, the vegetative mass of soybean plants inoculated with rhizobial bacteria with the introduction of nanoparticles of carboxylates of iron, germanium, or cobalt into their cultivation medium was at the level of control plants or slightly exceeded them. It has been shown that under the effects of chelated micronutrients, the number of root nodules increased compared to control plants during the flowering and pod formation stages, and their mass was greater from the three trifoliate leaf stage, which ensured efficient functioning of the legume-rhizobial symbiosis. It has been noted that the used metal nanocarboxylates promote active functioning of the symbiotic apparatus in soybean plants, as an increase in nitrogen-fixing activity was observed at the stages of three trifoliate leaf development and flowering, ranging from 26–70 % depending on the microelement used.

Conclusions. During field cultivation of soybeans, the effectiveness of pre-sowing seed inoculation with *Bradyrhizobium japonicum* B1-20 rhizobia was demonstrated through the introduction of iron, germanium, or cobalt nanocarboxylates into their cultivation medium. This opens up opportunities for increasing the efficiency of symbiotic systems of soybeans.

Keywords: soybean, *Bradyrhizobium japonicum,* nitrogen-fixing activity, nanocarboxylates of iron, germanium, cobalt

INTRODUCTION

In order to achieve high levels of plant productivity and maximum expression of their genetic potential, it is essential to implement techniques that make use of environmentally safe products. These products are capable of ensuring the efficient flow of physiological and biological processes within the plant organism (Lemishko *et al*., 2022). The biological fixation of atmospheric nitrogen by leguminous crops is a powerful factor in maintaining soil fertility, reducing the use of nitrogen fertilizers, and ensuring environmental safety (Raza *et al*., 2020). One of the most effective ways to create high-yielding agrocenoses in modern agriculture is through the use of intensification factors in the cultivation of leguminous plants. These factors include growth regulators, nitrogen-fixing bacteria preparations, organic biostimulants, and chelated micronutrient fertilizers (on a chelated basis). The use of nitrogen-fixing microorganisms allows for the biological binding of atmospheric molecular nitrogen through its conversion into available compounds, which improves plant nutrition and leads to increased grain productivity (Kots, 2021; Lemishko *et al*., 2022). For the normal growth and development of soybean plants, it is important to provide them with essential microelements that participate in the synthesis of proteins, carbohydrates, fats, vitamins, and promote an increase in the chlorophyll content in leaves, enhanced assimilation activity, and improved photosynthesis efficiency (Ahmed *et al*., 2020).

Most microelements are active catalysts that accelerate biochemical reactions and influence their direction. They are involved in respiration, nutrition, reproduction of nodule bacteria, activate the synthesis of bacterial cell enzymes, accelerate a range of biochemical reactions, and increase the immunity of plants to pathogens of fungal and bacterial diseases, drought, and extreme temperatures (Fedoruk, 2020). Numerous scientific and industrial studies have demonstrated the high effectiveness of using chelated micronutrients in agricultural crop production technologies. Nanotechnology allows for increasing the efficiency of micronutrients by transforming them into a biologically active form – nanocarboxylates, which are the most accessible for agricultural crops.

Microelements obtained in the form of nanocarboxylates are colloidal solutions of ions of the corresponding chemical elements (particle size from 1 to 100 nm) bound to pure carboxylates of natural food acids (Awasthi *et al*., 2020). They are characterized by almost complete assimilation by the plant organism. They are integral participants in exchange processes occurring in plant and animal organisms, in particular, in the Krebs and Calvin cycles. When living cells come into contact with such chelated complexes, they perceive them as natural sources not only of necessary biogenic microelements, but also of additional energy. Nanoparticles of biogenic elements are characterized by extremely high reactivity and high penetrability into plant tissues, which leads to an increased efficiency of physiological and biochemical processes (Ahmad *et al*., 2022). These nanoparticles have been shown to have a significant impact on the overall productivity of photosynthesis, crop yield, and seed quality (Shovkova & Korotych, 2021). The use of certain biogenic element nanoparticles can enhance the activity of enzymes such as amylase, nitrate reductase, phosphatase, phytase, and others involved in metabolism and nutrient uptake. Through their effect on the components of the plant's antioxidant system, and thus on the photosynthetic activity of the leaf apparatus, they can provide plant resistance to diseases and other stressors in the environment (Landa, 2021).

New methods in molecular biology, biotechnology, and genetic engineering, along with classical methods in microbiology, plant physiology, genetics, and agrochemistry allow for addressing both fundamental questions related to the detection of features of the formation and functioning of plant-bacterial systems, as well as revealing practical ways to correct the interactions of symbiotic partners in order to create highly efficient symbioses.

S. F. Kozar *et al.* (2017) investigated the effectiveness of pre-sowing inoculation of winter wheat seeds with *Agrobacterium radiobacter* 204 bacteria, previously activated by metal nanocarboxylates, and the Avatar preparation (a complex of microelements–nanocarboxylates of metals) applied together and separately. The scientists have found an increase in the potential nitrogen-fixing activity of rhizosphere soil and a 24.4 % increase in wheat yield compared to the control variant (Kozar *et al*., 2017).

In vegetative conditions, scientists from the Symbiotic Nitrogen Fixation Department of the Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine found a positive effect of complex solutions of metal nanocarboxylates on the nitrogen-fixing activity of symbiotic systems of soybeans. The combination of a microbial preparation based on effective strains of rhizobia with carboxylates of microelements contributed to the increase in morphometric indicators of soybean plants and provided high yields of this crop. When using a combined preparation with compounds of germanium and molybdenum, nitrogenase activity indicators was increased by 23–63 %. When combining inoculum with germanium and iron nanocarboxylates, the increase was around 14–21 % depending on the phases of soybean plant organogenesis. In the experiment, soybean yield under the combination of *B. japonicum* with germanium and molybdenum nanocarboxylates increased by 10 %, and by 13 % – under the complex application of bacterial inoculum with germanium and ferrum carboxylate nanoparticles (Kots *et al*., 2019).

The morphological and functional properties of plants in agro-ecosystems are determined not only by the genetic characteristics of the organism itself, but also by a number of ecological factors that act in a complex way. Therefore, it is promising to study the growth and development of soybean plants and the functioning of the symbiotic apparatus in field conditions using microbial biopreparations and metal nanocarboxylates.

The aim of this study was to investigate the effect of nanocarboxylates of iron (Fe), germanium (Ge), and cobalt (Co) on the vegetative parameters of soybean plants development and the formation and functioning of soybean-rhizobial symbiosis under field conditions, using seed inoculation with an active strain of *B. japonicum* B1-20.

MATERIALS AND METHODS

The objects of the study were symbiotic systems created with the participation of the Almaz variety soybean and the *B. japonicum* B1-20 strain of nodular bacteria under the influence of nanocarboxylates of iron (Fe), germanium (Ge), and cobalt (Co). The rhizobium culture was grown at 26–28 °C on a mannitol-yeast medium with the following composition (g/L): KH_2PO_4 – 0.5, $MgSO_4$ – 0.2, NaCl – 0.1, yeast extract – 1.0, mannitol – 10.0.

The microelements used in our study were provided by LLC "Scientific and Production Company "Avatar" (Ukraine, Kyiv). Their production occurs in two stages: 1) obtaining an aqueous colloidal solution of microelement nanoparticles by dispersing highly purified granules of the corresponding metals in deionized water using electric current pulses; 2) obtaining metal carboxylates by direct interaction of the obtained nanoparticles with food-grade carboxylic acid.

The rhizobia were washed off the surface of agar medium with sterile water and inoculated with the obtained suspension into Erlenmeyer flasks (volume – 200 mL) containing a liquid medium, which in the corresponding variants contained chelated metals in a ratio of 1:1000. The concentration of the nanocarboxylates was Fe – 0.05 %; Ge – 0.001 %; Co – 0.001 %. The inoculum was introduced into the flasks at a concentration of 2 % of the volume of the nutrient medium. A freshly prepared suspension of rhizobia that contained nanometals was cultivated for 6 days at a temperature of +26...+28 °C on a microbiological shaker at a speed of 220 rpm, which provided constant aeration of the nutrient medium. In our previous research, we found that under pure culture conditions, the nanocarboxylates of Co, Fe, and Ge had the most stimulating effect on the growth dynamics of rhizobia. Their maximum impact was observed at a concentration of 1:1000. On the fourth day of cultivation, the growth of *B. japonicum* exceeded the control values by 21 % when Co was introduced, by 54 % when Fe was applied, and by 39 % when Ge was used (Kots *et al*., 2018). The purity of the bacterial culture was checked by seeding it on a nutrient agar medium, on which rhizobia do not grow. Bacterial inoculation with rhizobia (10^8 CFU/mL) was conducted for 1 hour according to the experimental scheme: seeds + *B.* japonicum B1-20 (control); seeds + (*B. japonicum* B1-20 + Fe nanocarboxylate); seeds + (*B. japonicum* B1-20 + Ge nanocarboxylate); seeds + (*B. japonicum* B1-20 + Co nanocarboxylate).

Field experiments were carried out on the territory of the Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine under optimal agroclimatic conditions. The plots were randomized and the area of each plot was 2.5 m^2. The experimental treatments were replicated four times. Soybean seeds were sown in the first decade of May at a depth of 3–5 cm, with a seeding rate of 40 seeds per meter of row, after the upper soil layer had warmed up to a temperature of 10–15 °C.

The vegetative mass of plants, the number and mass of root nodules, and the activity of nitrogen fixation were determined in such stages: the first trifoliate leaf, the third trifoliate leaf, flowering, and the pods formation in 6-10 repetitions. Nitrogen-fixing activity was studied by the acetylene method (Hardy, 1968) on an Agilent GC system 6850 chromatograph (USA).

The table and graphs present the arithmetic means and their standard errors (x ± SE). The significance of differences between samples was evaluated using one-way analysis of variance (ANOVA), where differences were considered significant at $P < 0.05$ using the Tukey test.

RESULTS AND DISCUSSION

It is known that the high effectiveness of metal nanoparticles, as well as growth stimulators, can promote growth processes and productivity of agricultural plants. Our research has revealed several differences in comparison with control plants regarding the formation of soybean plant biomass by inoculation with rhizobial bacteria and the introduction of metal nanoparticle containing carboxylates into the medium of their cultivation (see **Table**). At the stage of the first trifoliate leaf development, the aboveground mass of plants treated with an inoculant with iron (Fe) nanocarboxylates exceeded the plants of the control variant by 10 %, and the root mass – by 12 %.

An increase in root mass by 26 % was observed when using an inoculant with cobalt (Co) nanocarboxylate. It is known that cobalt activates plant growth processes through its influence on metabolism, protein synthesis, and carbohydrate assimilation (Hu *et al*., 2021).

During the developmental stage of the three trifoliate leaves and flowering, the vegetative mass of the investigated plants was at the same level as the control, regardless of the added metal (see **Table**). The only exception was the aboveground mass of plants under the influence of germanium (Ge) nanocarboxylate, which exceeded the control plants by 21 %. During the flowering stage, the pre-sowing use of iron (Fe) nanocarboxylate as an additional component of the nutrient medium led to a decrease in the aboveground mass by 19 %, while the root mass increased by 33 % compared to control plants. During the pods formation stage, in all variants where inoculants with metal nanocarboxylates were used, we observed a decrease in the soybean vegetative mass from 17 % to 25 % (see **Table**). The root mass under the treatment of metal nanocarboxylates was at the same level as that of control plants only under the influence of germanium (Ge).

Thus, before the stage of pods formation, the vegetative mass of soybean plants with the introduction of nanocarboxylates of iron (Fe), germanium (Ge), cobalt (Co) into the rhizobia cultivation medium was at the level of plants in the control, or slightly exceeded them (as an example, in the development stage of the first trifoliate leaf under the action of iron (Fe) and growth of the mass of the root system under treatment with cobalt (Co)).

Treatment of legume seeds with microbial preparations is the most effective way of providing plants with the necessary substances during the initial period of their growth and development (Raza *et al*., 2020). For soybeans, a powerful root system is one of the important factors in the formation of an effective legume-rhizobia symbiosis. On the roots, due to the symbiosis of plants with rhizobia, nodules are formed, in which the process of nitrogen fixation takes place due to the functioning of the nitrogenase enzyme complex. The intensity of nitrogen fixation depends on the number and mass of root nodules (Kots, 2021).

A study of the process of formation of the symbiotic apparatus by introducing nanocarboxylates of metals into the culture medium of rhizobia showed that the number of nodules on soybean roots was at the level of control plants in the development stage of the first and third trifoliate leaves (**Fig. 1**).

Vegetative mass of soybean plants under inoculation of *Bradyrhizobium japonicum* B1-20 seeds and addition of metal nanocarboxylates to the rhizobia cultivation medium

Variant	Aboveground mass, g	Root mass, g
The stage of development of the first trifoliate leaf		
B1-20 (control)	2.12±0.11[a]	0.57±0.02[a]
B1-20+Fe	2.33±0.10[b]	0.64±0.03[b]
B1-20+Ge	2.01±0.13[a]	0.47±0.03[c]
B1-20+Co	2.09±0.09[a]	0.72±0.04[d]
The stage of development of three trifoliate leaves		
B1-20 (control)	3.54±0.22[a]	0.91±0.07[a]
B1-20+Fe	3.95±0.26[ab]	0.98±0.05[a]
B1-20+Ge	4.29±0.27[b]	0.97±0.04[a]
B1-20+Co	3.96±0.34[ab]	0.95±0.06[a]
Flowering stage		
B1-20 (control)	12.83±1.61[a]	1.82±0.17[a]
B1-20+Fe	10.34±1.36[b]	2.42±0.32[b]
B1-20+Ge	12.22±1.13[ab]	1.81±0.14[a]
B1-20+Co	13.42±1.25[a]	1.89±0.21[ab]
Pods formation stage		
B1-20 (control)	24.16±1.29[a]	2.89±0.03[a]
B1-20+Fe	17.99±3.71[b]	1.88±0.37[b]
B1-20+Ge	19.93±2.24[b]	2.81±0.30[a]
B1-20+Co	18.96±1.46[b]	2.31±0.10[c]

Note: Various letters of upper indices a, b, c, in the table indicate values that vary one from another within one column in the corresponding phase of soybean development (first trifoliate leaft, three trifoliate leaves, flowering stage, pods formation stage) as a result of comparison using the Tukey test (P <0.05)

During the flowering stage, it was established that under the pre-sowing treatment of seeds inoculated with iron (Fe) nanocarboxylate, the number of root nodules increased significantly (by 56.7 %) compared to control plants, and under the action of cobalt (Co) the number of nodules was 9.6 % lower. At the stage of pods formation, it was shown that soybean plants formed 37 % more root nodules under the action of germanium (Ge) nanocarboxylate, and 18 % – under the action of cobalt (Co) nanocarboxylate compared to control plants. When soybean seeds were treated with rhizobia cultivated with iron nanocarboxylate (Fe), the number of root nodules was lower by 19.8 % compared to plants of the control variant.

The mass of root nodules under the action of inoculants with metal nanocarboxylates was at the level of control plants in the stage of the development of the first trifoliate leaf in all variants of the experiment (**Fig. 2**).

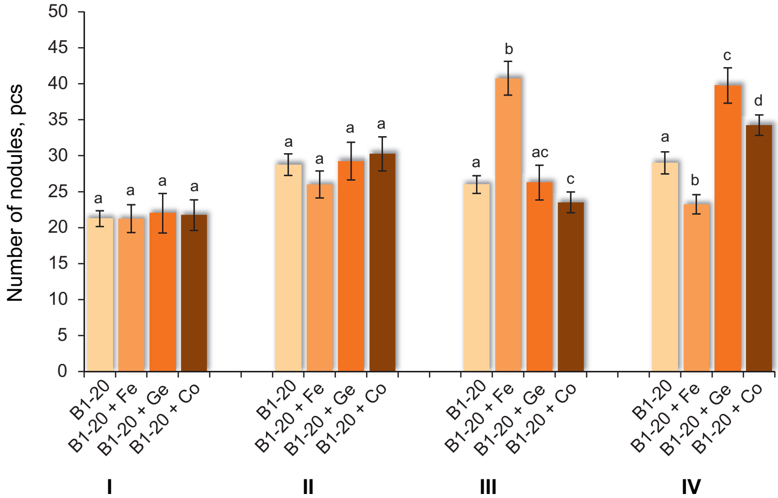

Fig. 1. The number of nodules on soybean roots after inoculation of *B. japonicum* B1-20 seeds and the addition of metal nanocarboxylates to the rhizobia cultivation medium

Note: I – the stage of development of the first trifoliate leaf; II – the stage of development of three trifoliate leaves; III – flowering stage; IV – pods formation stage. The different letters of the upper indices a, b, c, d indicate a significant difference between the variants regarding the number of nodules on soybean roots within the single development stage (I, II, III, IV) as a result of comparison using the Tukey test (P <0.05)

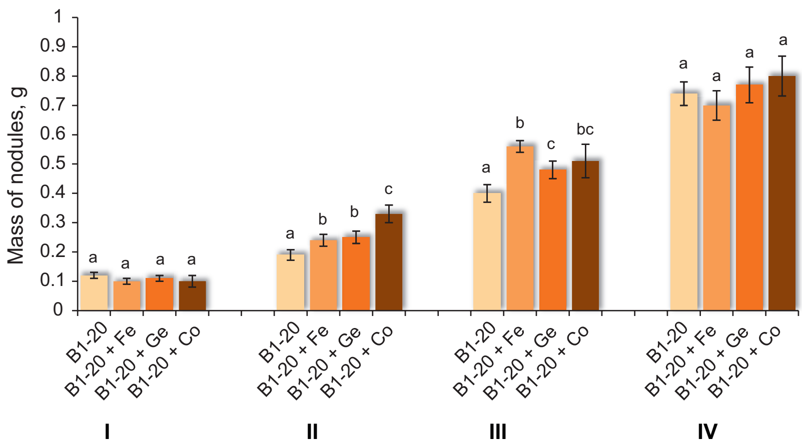

Fig. 2. The mass of root nodules after inoculation of seeds with *B. japonicum* B1-20 and addition of metal nanocarboxylates to rhizobia culture medium

Note: I – the stage of development of the first trifoliate leaf; II – the stage of development of three trifoliate leaves; III – flowering stage; IV – pods formation stage. The different letters of the upper indices a, b, c, d indicate a significant difference between the variants regarding the mass of root nodules on soybean roots within the single development stage (I, II, III, IV) as a result of comparison using the Tukey test (P <0.05)

At the stage of the development of the third trifoliate leaf and flowering, the parameters of the nodule mass of all studied plants exceeded the control ones: under the action of iron nanocarboxylate (Fe) by 26.3 and 40 %; germanium (Ge) by 31.5 and 20 %; cobalt (Co) by 73.6 and 27.5 %, respectively. It was noted that at the stage of pods formation, the mass of root nodules formed with the participation of rhizobia cultivated with metal nanocarboxylates was at the level of control plants (**Fig. 2**).

The introduction of iron (Fe), germanium (Ge) and cobalt (Co) nanocarboxylates into the culture medium of *B. japonicum* B1-20 contributed to the formation of a powerful symbiotic apparatus in soybeans compared to plants inoculated without the use of chelated microelements. Under the action of metal nanocarboxylates, the number of nodules increased compared to control plants at the stage of flowering and pods formation, and the mass was greater already in the period of active functioning of the symbiosis (at the stage of the development of three trifoliate leaves and flowering).

It was established that at the stage of the development of the first trifoliate leaf, the nitrogen-fixing activity (NFA) of plants with the application of nanocarboxylates of iron (Fe) and germanium (Ge) was at the level of control plants, and under the action of nanocarboxylate of cobalt (Co) it was lower by 29.8 % (**Fig. 3**). It was established that at the stage of three trifoliate leaves development, the nitrogen-fixing activity of soybean seeds treated with an inoculant with germanium (Ge) nanocarboxylate was 70.9 % higher than that of control plants, and with the application of cobalt (Co) nanocarboxylate, it was 27.6 % higher.

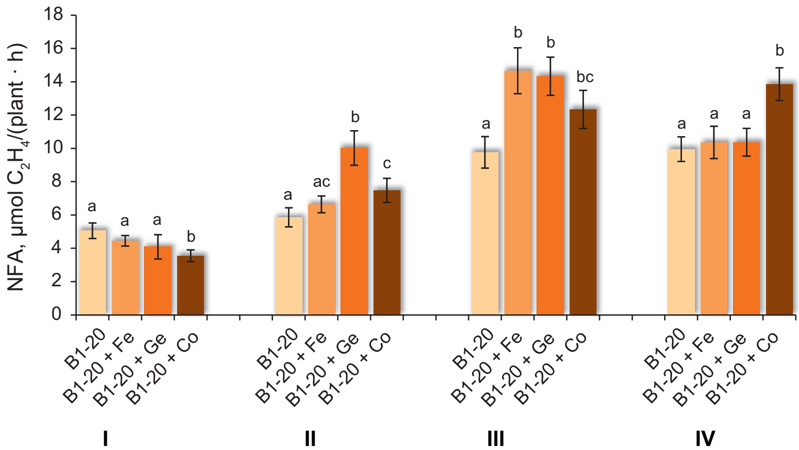

Fig. 3. The nitrogen-fixing activity of soybean root nodules after inoculation of *B. japonicum* B1-20 seeds and addition of metal nanocarboxylates to rhizobia culture medium

Note: I – the stage of development of the first trifoliate leaf; II – the stage of development of three trifoliate leaves; III – flowering stage; IV – pods formation stage. The different letters of the upper indices a, b, c, d indicate a significant difference between the variants regarding the nitrogen-fixing activity of soybean root nodules within the single development stage (I, II, III, IV) as a result of comparison using the Tukey test ($P < 0.05$)

At the flowering stage of plants of all variants, where inoculant with nanocarboxylates of iron (Fe), germanium (Ge) and cobalt (Co) was used, NFA was higher by 50.2; 46.8; 26.4 %, respectively, compared to plants inoculated with nodule bacteria without an additional application of microelements. A significant increase in the mass of root nodules in plants of all variants was also noted at this stage (**Fig. 2**). At the pods formation stage, soybean nitrogen-fixing activity was at the level of control plants, except for the treatment where cobalt (Co) nanocarboxylate was added to the medium of cultivation of rhizobia, which promoted an increase in NFA by 39.2 %.

Therefore, the bacteriization of soybean seeds with nodule bacteria *B. japonicum* B1-20 with the addition of iron (Fe), germanium (Ge) and cobalt (Co) nanocarboxylates to the medium of rhizobia cultivation contributed to the active functioning of the symbiotic system with a positive effect on nitrogen-fixing activity at the stage of three trifoliate leaves and flowering – when plants have a special need for nitrogen for the formation of generative organs and harvest. This can also be explained by the fact that the plants were sufficiently provided with microelements which are necessary for during the period of active functioning of symbiosis.

The literature reports that iron is an important element for plants due to its role as a cofactor for many proteins. It is necessary for the synthesis of chlorophyll and for the maintenance of the structure and functions of chloroplasts, and it is actively involved in metabolic processes. It participates in enzyme systems associated with oxidative-reductive reactions in the cell. Its ions, as components of nitrate reductase and nitrogenase, contribute to the reduction of nitrates and biological nitrogen fixation (Kumar *et al*., 2021).

Germanium in plants is believed to activate the breakdown of water into hydrogen and oxygen, enhance oxygen utilization, and also affect hydrogen ions, mitigating their harmful effects on cells by facilitating their interaction with oxygen through transport to all parts of the organism (Liu *et al*., 2016).

Cobalt has a positive effect on the formation of nitrogen-fixing root nodules. This trace element is a component of vitamin B12 and enhances plant growth and development through the interaction of cell hormones in auxin exchange; it participates in oxidative-reductive reactions, photosynthesis (increases the amount of chlorophyll), nucleic acid synthesis, and intensifies respiration processes in plants, leading to the formation of carbohydrates, fats, sugars, vitamins, and enzyme activation (including nitrate reductase). Cobalt accelerates the development of vegetative organs, promotes flowering, increases resistance to stress factors, improves yield, and helps to better absorb nitrogen, potassium, phosphorus, and magnesium from the soil. It is mostly concentrated in generative organs, as well as in root nodules (Hu *et al*., 2021).

Thus, the obtained research results can be used in the development of new and improvement of the existing elements of soybean cultivation technology. Because it was found that the treatment of seeds with nodule bacteria with the introduction in the medium of their cultivation of metal nanocarboxylates as an additional source of microelements contributes to the effective functioning of leguminous-rhizobial symbiosis.

CONCLUSION

During field studies of the formation and functioning of the legume-rhizobial symbiosis under the influence of seed inoculation and the addition of metal carboxylate nanoparticles of iron, germanium, or cobalt to the inoculation suspension, it was found that prior to the pod formation stage, the vegetative mass of soybean plants was at the level of or slightly exceeded that of the control plants. It was shown that under the action of microfertilizers on a chelate basis, the number of root nodules increased compared to control plants at the stage of flowering and pod formation, and the mass was greater starting from the stage of the development of three trifoliate leaves, which ensured the effective functioning of legume-rhizobial symbiosis. To increase the nitrogen-fixing activity, it is advisable to use nanocarboxylates of germanium and cobalt. These elements provide an increase in the researched indicator compared to the control, in the most critical period for soybean productivity: from three trifoliate leaves to flowering, while cobalt nanocarboxylate provides a high level of nitrogen-fixing activity even in the stage of pods formation, when a decrease in the level of the nitrogen-fixing activity is usually observed due to the redistribution of metabolites.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Human Rights: This article does not contain any studies with human subjects performed by any of the authors.

Animal Studies: This article does not include animal studies.

AUTHOR CONTRIBUTIONS

Conceptualization, [A.Kh.; L.R.]; methodology, [A.Kh.; L.R.; P.P.]; validation, [A.Kh.; S.K.]; formal analysis, [P.P.; L.R.; S.K.].; investigation, [A.Kh.; L.R.; S.K.]; resources, [P.P.; S.K.]; data curation, [A.Kh.; L.R.; S.K.]; writing – original draft preparation, [A.Kh.; L.R]; writing – review and editing, [P.P.; S.K.]; visualization, [P.P.; A.Kh.; S.K.]; supervision, [S.K.]. All authors have read and agreed to the published version of the manuscript.

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ВПЛИВ НАНОКАРБОКСИЛАТІВ МЕТАЛІВ НА АЗОТФІКСУВАЛЬНУ АКТИВНІСТЬ СИМБІОТИЧНИХ СИСТЕМ СОЇ, ВИРОЩЕНОЇ У ПОЛЬОВИХ УМОВАХ

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Вступ. Численними науковими та виробничими дослідженнями доведено високу ефективність застосування мікродобрив у наноформі в технологіях вирощу-

вання сільськогосподарських культур. Серед них особливу увагу привертає до себе соя, що займає серед інших зернобобових культур у нашій країні лідерські позиції за посівними площами і здатна у симбіозі з бульбочковими бактеріями *Bradyrhizobium japonicum* забезпечувати до 70 % власної потреби в азоті завдяки фіксації його молекулярної форми з атмосфери. Нові методи молекулярної біології, біотехнології та генної інженерії, поряд із класичними методами мікробіології, фізіології рослин, генетики й агрохімії, дають змогу як вирішувати фундаментальні питання, що стосуються виявлення особливостей формування та функціонування бобово-ризобіальних систем, так і розкривати практичні способи корекції взаємин симбіотичних партнерів з метою створення високоефективних симбіозів. Тому актуальними на сьогодні є дослідження, спрямовані на суттєве підвищення наявного рівня біологічного перетворення азоту атмосфери й адаптації симбіотичних систем до негативних факторів навколишнього середовища. Перспективним у такому аспекті може бути залучення нанотехнологій, зокрема, вивчення впливу нанокарбоксилатів феруму, германію та кобальту на формування і функціонування бобово-ризобіального симбіозу рослин сої, вирощеної у польових умовах, на тлі інокуляції насіння бульбочковими бактеріями.

Матеріали й методи. Об'єктами дослідження були симбіотичні системи, створені за участю сої сорту Алмаз і бульбочкових бактерій *Bradyrhizobium japonicum* B1-20 після внесення в середовище їхнього культивування нанокарбоксилатів феруму (Fe), германію (Ge) та кобальту (Co). Використовували фізіологічні, мікробіологічні, біохімічні та статистичні методи дослідження.

Результати. Встановлено, що у польових умовах до фази утворення бобів вегетативна маса рослин сої за інокуляції насіння бульбочковими бактеріями і внесення в середовище їхнього культивування наночастинок карбоксилатів феруму, германію або кобальту була на рівні контрольних рослин або трохи перевищувала їх. З'ясовано, що за дії мікродобрив на хелатній основі кількість кореневих бульбочок зростала, порівняно з контрольними рослинами у фази цвітіння й утворення бобів, а їхня маса була більшою вже починаючи з фази розвитку трьох трійчастих листків, що забезпечило ефективне функціонування бобово-ризобіального симбіозу. Відзначено, що використані нами нанокарбоксилати металів сприяють активному функціонуванню симбіотичного апарату у рослин сої, оскільки у фази розвитку трьох трійчастих листків і цвітіння спостерігали зростання азотфіксувальної активності на 26–70 % залежно від застосованого мікроелемента.

Висновки. Під час вирощування сої у польових умовах доведено перспективність передпосівної бактеризації насіння сої бульбочковими бактеріями *Bradyrhizobium japonicum* B1-20 за додавання до середовища їхнього культивування нанокарбоксилатів феруму, германію або кобальту. Це відкриває можливість підвищити ефективність симбіотичних систем сої.

Ключові слова: соя, *Bradyrhizobium japonicum*, азотфіксувальна активність, нанокарбоксилати феруму, германію, кобальту

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