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ENVIRONMENTAL ASPECTS OF SOYBEAN GROWING IN CLIMATE CHANGE CONDITIONS

***JOLANTA PUCZEL**, dr. inż. International Academy of Applied Sciences in Łomża, Poland;*
***BRONISŁAW PUCZEL,** dr. inż. International Academy of Applied Sciences in Łomża, Poland*

Modern agricultural production takes place in conditions of global climate change, accompanied by an increase in average annual temperatures and prolonged periods of drought. In this regard, there is an urgent need to ecologize soybean cultivation technologies by integrating biological factors and selecting adaptive genotypes of European selection.

Field studies were conducted during 2023–2025 on gray forest medium loam soils in the middle zone of the European continent. In a two-factor experiment, the reaction of the early-ripening variety Aurelina and the mid-early variety Cordoba to pre-sowing seed inoculation with European biological products HighStick (BASF, Germany) and Rhizofix (France) was studied.

It was found that under temperature stress, the Cordoba variety showed a higher basic level of adaptability, providing a yield of 2.25 t/ha in the control (without treatment), which is 0.13 t/ha higher than the Aurelina variety. Pre-sowing inoculation of seeds with modern strains of nodule bacteria demonstrated high ecological efficiency, providing mathematically reliable yield increases that significantly exceeded the error of the NIP_{05} experiment of 0.14 t/ha. The maximum effect of biologization of nutrition was recorded when using the German preparation HighStik, where the yield increase was +0.42 t/ha for the Aurelina variety and +0.53 t/ha for the Cordoba variety. The French inoculant Rhizofix also provided a stable grain increase within 0.36–0.44 t/ha. The highest yield in the experiment, 2.78 t/ha, was formed by combining the Cordoba variety with the HighStick inoculant. The integration of European genetics and modern biological products in conditions of unstable moisture creates a high synergistic effect, allows you to optimize the work of the symbiotic apparatus, stabilize soybean yield, and reduce the anthropogenic load on agroecosystems.

***Keywords:** soybean, climate change, European varieties, inoculation, biological products, yield, symbiosis.*

Table 2, Ref. 14.

Problem statement. Soybean (*Glycine max* (L.) Merr.) is one of the leading agricultural crops in world and domestic crop production. It provides humanity with high-quality vegetable protein and oil. Due to its unique ability to symbiotic nitrogen fixation, soybean performs an important environment-forming function. It acts as a valuable precursor in crop rotation, contributes to the preservation of soil fertility and the reduction of the need for mineral nitrogen fertilizers. This makes it a basic element of environmentally safe farming systems [1, 2].

Modern agricultural production is carried out in conditions of global and regional climate changes. In Ukraine, this is manifested through: a rapid increase in average annual air temperatures, a shift of climatic zones to the north, a deficit of moisture in critical phases of plant development (flowering and bean filling), an increase in the frequency and duration of air and soil droughts and dry winds.

Traditional soybean cultivation technologies, which were developed for more stable hydrothermal conditions, are losing their effectiveness.

Farmers' attempts to compensate for climate stress through intensification (excessive use of pesticides, synthetic fertilizers, and aggressive tillage) create serious environmental risks. There is soil degradation, disruption of natural microbiocenoses, and a decrease in the efficiency of the nitrogen-fixing apparatus of soybeans. An acute scientific and practical contradiction arises: on the one hand, it is necessary to ensure stable soybean yields under severe climatic stress, and on the other hand, to minimize anthropogenic load on agroecosystems and preserve environmental quality [5, 6].

In this regard, there is an urgent need to substantiate environmentally safe, adaptive technologies for growing soybeans. They should combine the optimization of sowing dates, the selection of drought-resistant varieties, the minimization of soil cultivation and integrated plant protection using biological products. The development of such solutions will allow the agricultural sector to adapt to climate change. It will ensure the ecological stability of the environment and increase the competitiveness of the crop production industry [7, 8].

Analysis of recent research and publications. The issue of adaptation of agroecosystems to global climate challenges is in the focus of attention of many international and domestic researchers. Current global trends, highlighted in analytical reviews of FAO and leading scientific centers, confirm that the triple impact of climate change - a simultaneous increase in CO_2 concentration, prolonged droughts and temperature stresses - is radically changing the metabolism of leguminous crops. Global climate models (in particular, under the RCP4.5 and RCP8.5 scenarios) indicate a significant transformation of traditional soybean growing areas. They require immediate greening of technological approaches and protection of soil resources in accordance with the requirements of the European Green Deal [9, 10].

A significant contribution to the study of the response of soybeans to agroclimatic conditions of different regions was made by European scientists. Studies have shown that a critical moisture deficit in the generative phases (flowering - bean filling), when the optimal relative humidity should be 75–80%, leads to a sharp decrease in photosynthetic productivity. Under conditions of increasing air temperature above the optimal threshold of 30–32 °C, depression of growth processes, abortive flowers and deterioration of the technological quality of seeds are observed. The works of scientists prove that the shift of soybean cultivation areas to the north requires the introduction of new early-ripening and drought-resistant varieties of local selection. They are the ones that are adapted to local hydrothermal resources [11, 12].

The vector of modern scientific research is increasingly directed towards the development of environmentally safe elements of varietal agricultural technology. Recent publications are devoted to the optimization of sowing dates and seed sowing rates depending on the warming of the arable layer, which is a key tool for leveling spring and autumn frosts in vulnerable areas.

Particular attention is paid to the ecological aspects of preserving soil fertility: the effective functioning of the symbiotic apparatus of soybean under the conditions of seed inoculation with nodule bacteria strains, the integration of biological products to minimize chemical and pesticide loads on agrocenoses, the use of moisture- and soil-conserving methods of soil cultivation [13].

Despite the significant volume of scientific work, most of the available studies consider the impact of environmental factors or climate change in isolation - through the prism of only yield or individual agrotechnical techniques. At the same time, the complex relationship between modern hydrothermal anomalies of a particular region and the ecological stability of symbiotic soybean systems remains insufficiently studied. In particular, there is a lack of systematic data on the adaptive potential of new domestic soybean varieties with minimizing chemical load in conditions of unstable moisture. This determines the feasibility and relevance of our study [14].

The purpose of the research is to substantiate and experimentally evaluate environmentally safe, adaptive elements of soybean cultivation technology that ensure high stable crop productivity and minimize anthropogenic load on agroecosystems in the conditions of modern hydrothermal anomalies and climate change.

Materials and methods of research. Field research was carried out during 2023–2025. The soil cover of the experimental site is represented by gray forest medium loam soil. The humus horizon has the following agrochemical indicators: the humus content (according to Tyurin) is 2.4–2.6%, the content of mobile phosphorus and exchangeable potassium (according to Kirsanov) is increased, the pH of the salt extract is 5.6–5.8 (close to neutral), which is favorable for the development of both the soybean crop itself and nodule bacteria.

The experiment was set up using the split-plot method in four replications. The placement of variants was systematic. The total area of the sowing plot was 50 m^2, the accounting area was 30 m^2. The experimental design involved the study of two factors (two-factor complex experiment):

Factor A (European soybean variety): 1. Aurelina (early ripening variety, Saatbau, Austria); 2. Cordoba (medium early variety, Saatbau, Austria).

Factor B (Biological inoculant of European production): 1. Control (without seed treatment with biological preparations); 2. Biopreparation HighStick, based on Bradyrhizobium japonicum strains, BASF, Germany); 3. Biopreparation Rhizofix, based on Bradyrhizobium japonicum strains, Agro-Soya, France).

Pre-sowing inoculation of seeds was carried out directly on the day of sowing in a shaded place to prevent the negative impact of solar insolation on live bacterial strains. The technology of soybean cultivation in the experiment corresponded to generally accepted zonal recommendations, with the exception of the studied elements (refusal of applying starting doses of mineral nitrogen on variants with biological preparations for the purity of the assessment of symbiotic potential).

In the process of conducting research, the following generally accepted methods were used: field method - to study the interaction of varieties and biological products with hydrothermal environmental factors, monitoring phenological phases of growth and development; laboratory-field method - to determine the dynamics of the formation of leaf surface area (by the cutting method) and accounting for the number and mass of nodules on the root system (by the method of monoliths in the shiny bean phase); quantitative-weight method - to conduct structural analysis of the crop (determination of the number of beans on the plant, the mass of grain per plant and the mass of 1000 seeds) before harvesting; statistical method - mathematical and dispersion assessment of yield results (calculation of experimental error and least significant difference - NIP05) was carried out by the method of dispersion analysis using the computer software Statistica 10.

Presentation of the main material. The effectiveness of adaptive technologies for growing soybeans directly correlates with the level of moisture supply and temperature regime during the growing season. The agroclimatic observations we conducted confirmed the general trend towards warming. In particular, in the critical months for the crop (July–August), an excess of the average multi-year air temperature by 2 °C was recorded.

The effectiveness of adaptive soybean growing technologies directly correlates with the level of moisture supply and temperature regime during the growing season. According to meteorological observations, the growing season conditions in 2023–2025 were characterized by significant instability and clearly expressed temperature pressure during critical phases of crop development (Table 1).

Table 1

Meteorological indicators for the soybean growing season (May – September) in central Europe

Vegetation month	Average air temperature, °C	Total precipitation, mm	GTC (Selyaninov hydrothermal coefficient)
May (*sowing - seedlings*)			
Average long-term rate	15,2	52	1,11
Average for 2023–2025	16,8	41	0,79
June (*vegetative growth*)			
Average long-term rate	18,4	76	1,38
Average for 2023–2025	20,1	62	1,02
July (*flowering – bean formation*)			
Average long-term rate	20,2	81	1,29
Average for 2023–2025	23,4	34	0,47
August (*grain loading*)			
Average long-term rate	19,4	58	0,96
Average for 2023–2025	22,9	29	0,41
September (*ripening – harvesting*)			
Average long-term rate	14,3	49	1,14
Average for 2023–2025	16,1	35	0,72
Total for the growing season	19,9	201	0,69
Norm	17,5	316	-

Source: generated by the author

In the initial phases of soybean growth (May–June), the temperature regime was 1.6–1.7 °C above normal, which, against the background of a slight deficit of precipitation, provided good conditions for the emergence of seedlings. However, in July and August, during the critical period for soybeans of flowering, formation and filling of beans, a sharp increase in average monthly air temperatures was recorded by 3.2 °C and 3.5 °C, respectively. At the same time, a deep moisture deficit was observed: in July, only 42.0% of the precipitation rate fell, and in August - 50.0%. The hydrothermal coefficient during this period decreased to critical levels of 0.47 and 0.41, which indicates the onset of severe air and soil drought. It was these conditions that allowed us to objectively assess the adaptive capacity of the studied European varieties and the effectiveness of the use of inoculants as factors in reducing climatic stress in plants. The distribution of precipitation over the years of research had a clearly expressed uneven character. Periods of air drought coincided with the most important stages of soybean organogenesis - flowering and the beginning of bean formation. This allowed a comprehensive assessment of the ecological plasticity of the studied varieties and the identification of the most resistant genotypes under severe temperature pressure.

Since soybean is the basic crop of ecological agriculture, special attention was paid to monitoring the activity of nodule bacteria (*Bradyrhizobium japonicum*). It was found that elevated soil temperatures and moisture deficit in the arable layer at the initial stages of growth caused environmental stress, which inhibited the processes of root system infection and primary nodule formation. However, the use of environmentally safe agricultural measures (inoculation with modern biological preparations, optimization of sowing dates) allowed to significantly reduce this negative impact. In the bean filling phase, the variants with the introduction of the biological preparation formed the maximum mass of nodules on one plant. This ensured high nitrogenase activity and allowed to reduce the anthropogenic load by refusing high doses of mineral nitrogen.

The main criterion for the environmental and technological efficiency of the studied options was the actual yield of soybean grain (Table 2).

Table 2

Soybean yield depending on the studied factors under climate change conditions, t/ha (average over the years of research)

Factor A: Soybean variety	Factor B: Biological product	Yield, t/ha	Deviation from control, +/-
Aurelina (early ripening)	Control (no treatment)	2,12	-
	HiStik	2,54	+0,42
	Rhizofix	2,48	+0,36
Cordoba (middle early)	Control (no treatment)	2,25	-
	HiStik	2,78	+0,53
	Rhizofix	2,69	+0,44
NIR_{05}, t/ha	Factor A: 0,11	Factor B: 0,14	Interaction of factors A+B: 0,19

Source: own research

According to the data of variance analysis presented in Table 1, both studied factors had a significant impact on the formation of the productivity of soybean agrocenosis. Among the studied genotypes, the highest basic adaptability potential under temperature stress was revealed by the Cordoba variety, providing a yield of 2.25 t/ha in the control, which is 0.13 t/ha higher than the Aurelina variety.

The maximum effect of biologization of nutrition was recorded in variants using the German inoculant HighStik. The use of this drug allowed to obtain a significant increase in yield for both varieties: +0.42 t/ha for the Aurelina variety and +0.53 t/ha for the Cordoba variety, which significantly exceeds the experimental error limit (NIP_{05} 0.14 t/ha). The French drug Rhizofix also showed high ecological efficiency, providing a mathematically probable grain increase within the range of 0.36-0.44 t/ha.

The highest yield in the experiment (2.78 t/ha) was formed by combining the Cordoba variety with seed inoculation with the HighStik preparation. This proves the high synergistic interaction of European genetics and modern strains of nodule bacteria in conditions of unstable moisture.

Conclusions and prospects for further research. As a result of the conducted research on the ecological aspects of soybean cultivation in conditions of climate change and the assessment of the adaptive potential of European varieties using modern biological products, the following patterns were established. Under conditions of temperature pressure and unstable moisture, the highest basic level of adaptability was revealed by the medium-early variety of European selection Cordoba, which in the control variant (without seed treatment) formed a grain yield of 2.25 t/ha, which is 0.13 t/ha higher compared to the early-ripening variety Aurelina.

Pre-sowing inoculation of seeds with modern European biological preparations is an effective tool for ecological nutrition, which allows to level hydrothermal stress and provides mathematically probable yield increases that significantly exceed the experimental error (NIP_{05} 0.14 t/ha). The maximum effect of biologization was recorded when using the German preparation HighStik. Its integration provided a significant increase in yield: +0.42 t/ha for the Aurelina variety and +0.53 t/ha for the Cordoba variety. The French biological preparation Rhizofix also demonstrated high efficiency with a productivity increase within 0.36-0.44 t/ha.

The most stable and productive agrocenosis under climate change conditions was the combination of the Cordoba variety with the HighStic inoculant, where the maximum yield in the experiment was achieved - 2.78 t/ha. This confirms the presence of a high synergistic effect between European genetics and active strains of nodule bacteria, which allows optimizing the nitrogen balance of the soil and reducing the chemical load on the environment.

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АНОТАЦІЯ
ЕКОЛОГІЧНІ АСПЕКТИ ВИРОЩУВАННЯ СОЇ В УМОВАХ ЗМІНИ КЛІМАТУ

Сучасне сільськогосподарське виробництво здійснюється в умовах глобальних змін клімату, що супроводжуються підвищенням середньорічних температур і тривалими періодами посухи. У зв'язку з цим виникає нагальна потреба в екологізації технологій вирощування сої шляхом інтеграції біологічних чинників та добору адаптивних генотипів європейської селекції.

Польові дослідження проводили протягом 2023–2025 років на сірих лісових середньосуглинкових ґрунтах у середній смузі Європи. У двофакторному досліді вивчали реакцію ранньостиглого сорту Aurelina та середньораннього сорту Cordoba на передпосівну інокуляцію насіння європейськими біопрепаратами HighStick (BASF, Німеччина) та Rhizofix (Франція). Встановлено, що в умовах температурного стресу сорт Cordoba продемонстрував вищий базовий рівень адаптивності, забезпечивши врожайність 2,25 т/га на контролі (без обробки), що на 0,13 т/га перевищує показник сорту Aurelina. Передпосівна інокуляція насіння сучасними штамами бульбочкових бактерій виявилася високоефективною з екологічного погляду, забезпечивши статистично достовірні прирости врожайності, які суттєво перевищували величину $НІР_{05}$ (0,14 т/га). Найвищий ефект від біологізації живлення було зафіксовано при застосуванні німецького препарату HighStik: приріст урожайності становив +0,42 т/га для сорту Aurelina та +0,53 т/га для сорту Cordoba. Французький інокулянт Rhizofix також забезпечив стабільний приріст урожаю зерна в межах 0,36–0,44 т/га. Найвищу врожайність у досліді – 2,78 т/га – отримано завдяки поєднанню сорту Cordoba з інокулянтом HighStik. Поєднання європейської генетики та сучасних біопрепаратів в умовах нестійкого зволоження забезпечує високий синергічний ефект, дозволяє оптимізувати роботу симбіотичного апарату, стабілізувати врожайність сої та зменшити антропогенне навантаження на агроекосистеми.

Ключові слова: *соя, зміна клімату, європейські сорти, інокуляція, біологічні препарати, врожайність, симбіоз.*
Табл. 2, Літ. 14.

Інформація про автора

Jolanta Puczel, dr inż. International Academy of Applied Sciences in Łomża, Poland, jolanta.puczel@wp.pl; ORCID: https://orcid.org/0009-0009-1713-7058.

Bronisław Puczel, dr inż. International Academy of Applied Sciences in Łomża, Poland, bronekpuczel@gmail.com ORCID: https://orcid.org/0009-0008-5097-9639.

Йоланта Пуцель, доктор інж. Міжнародна академія прикладних наук у Ломжі, Польща, bronekpuczel@gmail.com; ORCID: https://orcid.org/0009-0009-1713-7058.

Броніслав Пуцель, доктор інж. Міжнародна академія прикладних наук у Ломжі, Польща, bronekpuczel@gmail.com ORCID: https://orcid.org/0009-0008-5097-9639.

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