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Efficacy of the combined application of biological products in soybean cultivation under laboratory and field conditions

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Abstract. The aim of the study was to evaluate the efficacy of biological products through the soybean response across sowing, growth, phytosanitary, symbiotic, and productivity parameters under laboratory and field conditions. The study employed spectrophotometry, the Kjeldahl method, Soxhlet extraction, and analysis of variance. Under laboratory conditions, the combined seed treatment with Phytovit and Avercom yielded the highest germination energy of 88.7%, exceeding the control by 10.1 percentage points. Laboratory germination under this treatment was 94.3%, which was 7.9 percentage points higher than the control, whilst seedling infection by microflora decreased to 4.2%, representing a reduction of 7.6 percentage points. Under field conditions, the application of biological products had a positive effect on seedling emergence, plant stand density, development of the leaf apparatus, and root system. Under the combined application of the products, field germination was 87.1%, and the number of nodules at the V5 stage reached 20.6 per plant. The phytosanitary condition of the crop also shifted towards a reduction in disease incidence and pest damage: the incidence of root rot decreased to 6.3%, and the biological efficacy of protection was 59.6%. At the flowering stage, the combined treatment promoted the formation of a more developed assimilatory and symbiotic apparatus in the plants. The leaf area index reached 4.0 m^2/m^2, the number of active nodules was 25.9 per plant, and their mass was 0.58 g per plant, reflecting more active functioning of the leaf apparatus and root system during the transition of plants to reproductive development. The preservation of the leaf apparatus and nodule formation were accompanied by subsequent seed filling and accumulation of productive mass. Seed yield under the combined application of Phytovit

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and Avercom was 3.01 t/ha, the increase over the control was 24.4%, protein content was 39.1%, and oil content was 21.0%. The practical value of the study lies in the possibility of using its findings by agronomists, farmers, seed enterprises, and researchers to substantiate biological treatment of soybean, taking into account germination, phytosanitary condition, nodulation, yield, and seed quality

Keywords: phytosanitary condition; plant stand density; root system; number of nodules; reproductive organs

INTRODUCTION

The relevance of this study is determined by the need to clarify the factors that govern seed germination, seedling emergence, root system development, leaf apparatus development, and the formation of productive organs in soybean under both laboratory and field conditions. Soybean belongs to the group of crops in which ultimate productivity is formed through the successive passage of early, vegetative, and reproductive developmental phases. At these stages, the quality of the seed material, the phytosanitary condition of the crop, the activity of nodule formation, plant survival throughout the growing season, and the completeness of seed filling are all of significance. Therefore, studying the soybean response across a complex of laboratory, field, physiological, and productivity indicators makes it possible to detail the specific features of yield formation. The problem addressed by this study stems from the occurrence of non-uniform seed germination, seedling infection by microflora, thinning of plant stands following emergence, incidence of root and foliar diseases, pest damage to plants, and uneven development of the nodular apparatus. A separate challenge is the inadequate concordance between laboratory germination indicators and subsequent field growth and yield parameters. For this reason, evaluating soybean by a unified system of indicators – from laboratory germination through to seed quality – allows a more accurate description of the process of productivity formation in the crop.

With regard to the laboratory assessment of sowing quality, K. Kozhushko (2025) established that the effect of biostimulants on soybean seeds depended on the type of product and the concentration of the working solution. Some treatments increased germination and seedling development, whilst certain concentrations suppressed the initial formation of seed material. In an assessment of pre-sowing seed treatment, S. Berdin *et al*. (2024) demonstrated that the combination of biological products altered leaf area, nodule formation, and soybean yield. The most pronounced outcome was associated with combined seed preparation, which influenced not only initial development but also the subsequent formation of productivity. In the field of crop production research, S. Dymytrov & V. Sabluk (2023) established that seed treatment with biological products enhanced the development of the leaf apparatus, root system, and soybean yield. The results obtained demonstrated that the effect of biological treatment manifested through simultaneous changes in growth and productivity indicators. From the perspective of biological crop protection, A. Bueno *et al*. (2023) showed that biological control could constitute a component of protection against the principal phytophages of the crop. The results of their review demonstrated that biological agents are capable of reducing the dependence of crops on chemical pest control.

In the context of nutrition and physiological efficacy, C. Sible & F. Below (2023) established that the effect of biological products depended on product composition, crop, and the stage of application. The most pronounced effects were associated with improved uptake of nutrients, root system development, and the maintenance of productivity. In the area of combining biological and fungicidal protection, F. Santos *et al*. (2022) demonstrated that a Bacillus-based product in combination with fungicides reduced the development of foliar diseases in soybean. This approach also contributed to the preservation of productivity, since the protection of the leaf apparatus was associated with yield formation. In the context of combining bioformulations with mineral nutrition, A. Dass *et al*. (2025) established that the integration of bioformulations with fertilisers enhanced soybean productivity, nutrient use efficiency, and economic returns. The results showed that the biological components performed better not in isolation but within

a nutritional system, where they supported plant growth and nutrient utilisation. From the perspective of soil-physiological resilience of the agrocoenosis, J. Gonçalves e Silva *et al*. (2024) established that an integrated crop-livestock system improved soil condition and the physiological parameters of soybean. The positive changes manifested through better plant development, more active metabolism, and more stable functioning of the crop within the agroecosystem.

In the area of high-yield soybean cultivation, Y. Zhong & S. Zhong (2024) showed that crop yield was determined by the combination of sowing dates, plant stand density, nutrition, water regime, and crop protection. The summarised results confirmed that soybean productivity is formed not by a single technological factor but by their coordinated action throughout the growing season. When assessing soil microbiota and soil quality, Z. Wu *et al*. (2025) established that organic amendments combined with mineral fertilisers reduced microbial limitations in the soil and increased soybean yield. Changes in the microbial environment were associated with nutrient availability, soil quality, and the growth response of the crop.

From the perspective of plant growth-promoting rhizobacteria, D. Nagrale *et al*. (2023) showed that these microorganisms facilitated nutrient mobilisation, suppression of harmful organisms, and development of field crops. Their action manifested through support of nutrition, reduction of phytosanitary pressure, and improvement of growth processes. In the area of field testing of growth-promoting microorganisms, D. Neuhoff *et al*. (2024) substantiated the need for standardised evaluation of such products under actual field conditions. The proposed approaches demonstrated that reliable assessment must combine a controlled experimental design, clearly defined treatment variants, and comparison of laboratory and field indicators. The relationship between germination, nodulation, phytosanitary condition, and soybean productivity remains insufficiently studied, as these parameters have not previously been examined in a comprehensive manner within a single laboratory-field experiment. The aim of the study was to evaluate the efficacy of biological product application through the soybean response across indicators of germination, early development, phytosanitary condition, nodulation, yield, and seed quality. The objectives of the study included evaluating laboratory, field, and productivity indicators of soybean, comparing treatment variants, and determining changes in seed quality.

MATERIALS AND METHODS

Conditions for establishing and conducting the laboratory-field experiment. The laboratory-field experiment was conducted in 2025 at the Uman National University of Horticulture: the laboratory phase was carried out in the educational and research seed analysis laboratory, and the field phase was conducted on the university's experimental field under the conditions of the Right-Bank Forest-Steppe of Ukraine. The methodological design of the experiment did not include an economic evaluation of biological product application or determination of their residual effects on soil microbiota in the following growing season. The experiment used seed material of soybean cultivar 'Annushka', obtained from a certified seed lot of the Uman National University of Horticulture. The cultivar belongs to the early-maturing group and was selected for its suitability to Forest-Steppe conditions, short growing season, and the possibility of evaluating the plant response to biological products within a complete development cycle. The laboratory phase involved germination of soybean seeds following treatment with biological products in four replications of 100 seeds per treatment. Germination was carried out in a Memmert IN55 thermostat (Germany) at a constant temperature of 24 ± 1°C on moistened Whatman Grade 1 filter paper (United Kingdom). The experiment was conducted in accordance with the provisions of ISTA (n.d.) and the Convention on Biological Diversity (2016).

The field experiment was established using a randomised block design with four replications per treatment. The area of each experimental plot was 48 m², of which the accounting area was 32 m². Within each treatment, 30 plants were analysed for phytosanitary and biometric determinations; 12 plants were selected for the study of nodulation; yield structure was determined from 20 representative plants; seed quality was assessed from three composite samples of 500 g each. No specific rhizobial inoculation of seed was carried out; nodules were formed from the natural population of nodule bacteria present in the soil, and

Phytovit and Avercom were evaluated as biological treatments without additional introduction of rhizobia. The experimental design comprised four treatments: untreated control; Phytovit – pre-sowing seed treatment at 0.05 L/t, applied by coating the seed with the working solution, mixing, and drying in the shade, followed by foliar application at 0.20 L/ha at the 3-4 trifoliate leaf stage; Avercom – pre-sowing seed treatment at 25 mL/t in 10 L of water, applied the day before sowing or on the day of sowing; foliar application at 0.30 L/ha was carried out at the 3-4 trifoliate leaf stage of soybean, upon the appearance of the first signs of pest damage, in the morning between 07:00 and 09:00 or in the evening between 18:00 and 20:00 at an air temperature not exceeding 24°C. Phytovit + Avercom – a combination of the same pre-sowing and foliar application rates in a tank mixture. Phytovit was selected as a metabolic biological product based on biologically active substances of the soil streptomycete *Streptomyces netropsis*, without viable cells of the producer organism; its mode of action is associated with bioprotective, growth-stimulating, and anti-stress effects on plants. Avercom was used as a biological insecto-acaronematicide based on a complex of natural avermectins produced by *Streptomyces avermitilis*; its action is associated with contact-intestinal effects on pests and nematodes, as well as additional growth-stimulating and adaptogenic properties. The experiment was established in early-maturing soybean crops with a row spacing of 45 cm and a seeding rate of 620 thousand viable seeds per hectare. The previous crop was winter wheat cultivar 'Podolianka'. The soil of the experimental plot was typical chernozem of light loamy texture. In the plough layer of 0-30 cm, humus content was 3.18%, pH of the salt extract was 6.7, nitrate nitrogen content was 21.4 mg/kg, mobile phosphorus content was 74.6 mg/kg, and exchangeable potassium content was 108.3 mg/kg. Primary tillage comprised stubble cultivation to a depth of 7-9 cm and ploughing to 23-25 cm. Prior to sowing, cultivation to a depth of 4-5 cm with levelling of the seedbed was carried out.

Fertilisation in all experimental treatments was uniform and provided for the application of a mineral background of $N_{30}P_{60}K_{60}$. Phosphorus and potassium fertilisers were applied during primary tillage, whilst nitrogen fertilisers were applied prior to pre-sowing cultivation. Sowing was carried out in the first decade of May, when the soil temperature at seed placement depth reached 10-12°C. Sowing depth was 4-5 cm. For weed control, an identical crop management system was applied across all treatments so that the effect of the biological products could be evaluated without the influence of differing agronomic backgrounds. The growing season was characterised by moderately dry conditions: the mean air temperature for May-September was 19.1°C, total precipitation was 286.4 mm, and the greatest moisture deficit was observed in the second half of June and in July, i.e. during the periods of budding, flowering, and early seed filling. Foliar applications of biological products were carried out at the 3-4 trifoliate leaf stage and at the onset of budding using a Marolex Profession 12 Plus knapsack sprayer (Poland); the working solution volume was 250 L/ha. Spraying was performed in the morning, approximately between 07:00 and 09:00, at an air temperature not exceeding 24°C, in the absence of precipitation, and with wind speed below 3 m/s. All other elements of soybean cultivation technology were identical across the control and experimental treatments.

Sowing properties of soybean seeds following biological treatment. Germination energy (%) was determined under laboratory conditions on the fourth day of germination by counting the number of seeds that had formed normally developed seedlings. Seeds were placed in Petri dishes or germination containers on moistened Whatman Grade 1 filter paper (United Kingdom) in a Memmert IN55 thermostat (Germany) at a constant temperature of 25°C. Laboratory germination (%) was determined following completion of the standard germination period by counting normally formed seedlings. Normally developed seedlings were defined as those with an intact primary root, a formed shoot, and no signs of pronounced growth suppression. The calculation was performed using formula (1):

$$G_l = \frac{n_g}{N} \times 100, \quad (1)$$

where G_l is laboratory germination (%); n_g is the number of normally germinated seeds (units); N is the total number of seeds in the sample (units). Primary root length (cm) was measured from the base of the seedling to the tip of the primary

root using a Topex 30 cm laboratory ruler (Poland). Shoot length (cm) was determined from the point of transition of the root into the hypocotyl to the uppermost point of the seedling using a Mitutoyo 500-196-30 Absolute Digimatic Caliper digital calliper (Japan). Seedling dry weight (mg) was determined after drying of the plant material to constant weight in a Binder ED 56 drying oven (Germany) at 65°C. Following drying, samples were weighed on a Radwag AS 220.R2 analytical balance (Poland) to an accuracy of 0.0001 g. Seedling vigour index (conventional units) was calculated as the sum of root length and shoot length, taking into account laboratory germination:

$$I_s = G_l \times (L_r + L_s), \quad (2)$$

where I_s is seedling vigour index; G_l is laboratory germination (%); L_r is mean primary root length (cm); L_s is mean seedling shoot length (cm). Seedling infection by microflora (%) was determined as the proportion of seedlings exhibiting mould, tissue darkening, root or cotyledon necrosis. A Levenhuk Zeno Handy ZH7 5×/16 mm hand lens (USA) was used to clarify the condition of surface tissues.

Early field development of soybean following biological treatment. Field germination (%) was determined by counting the number of plants that had emerged on fixed row segments, with subsequent recalculation relative to the number of viable seeds sown. Counts were carried out at the stage of full emergence on permanently marked plots. The calculation was performed using formula (3):

$$G_f = \frac{n_s}{N_s} \times 100, \quad (3)$$

where G_f is field germination (%); n_s is the number of seedlings that emerged (units); N_s is the number of viable seeds sown (units). Plant height at the V3 stage (i.e. the stage of three fully developed trifoliate leaves) (cm) was measured from the soil surface to the uppermost point of the plant using a Stanley 2 m measuring rod (USA). Plant stand density at the V3 stage (plants/m²) was determined by direct counting of plants on the accounting area, with subsequent recalculation per square metre. The calculation was performed using formula (4):

$$D = \frac{N_p}{A}, \quad (4)$$

where D is plant stand density (plants/m²); N_p is the number of plants on the accounting area (units); A is the accounting area (m²). Leaf area (cm²/plant) was determined from the length and maximum width of leaf blades using a Topex 30 cm measuring ruler (Poland). Chlorophyll content (SPAD units) was determined using a Konica Minolta SPAD-502Plus portable chlorophyll meter (Japan) on fully expanded leaves of the middle tier. Root dry weight (g/plant) was determined after washing the root system free of soil, drying to constant weight in a Binder ED 56 drying oven (Germany) at 65°C, and weighing on a Radwag PS 1000.R2 laboratory balance (Poland). The number of nodules at the V5 stage (i.e. the stage of five fully developed trifoliate leaves) (nodules/plant) was established by direct counting of nodular formations on the main and lateral roots following washing of the root system in running water. Counting was carried out using an Eschenbach mobilux 6× hand lens (Germany).

Assessment of diseases and pest damage in soybean plants. The incidence of root rot (%) was determined as the proportion of plants exhibiting darkening of the root zone, necrosis of the root collar, or damage to the primary roots. Assessments were made using a Levenhuk Zeno Handy ZH7 5×/16 mm hand lens (USA). The development of foliar diseases (%) was determined as the proportion of the affected leaf area on the accounting plants. A Carson LED Lighted LinenTest LT-30 11.5× hand lens (USA) was used to detail the symptoms. The proportion of plants with pest damage (%) was determined as the number of plants exhibiting disruption of leaf blade integrity, tissue punctures, leaf edge feeding, or other characteristic signs of phytophage feeding activity. The calculation was performed using formula (5):

$$P_d = \frac{n_d}{N} \times 100, \quad (5)$$

where P_d is the proportion of plants with pest damage (%); n_d is the number of damaged plants (units); N is the total number of plants examined (units). The density of sucking pests (individuals/plant) was determined by direct counting of individuals on the leaves and stems of accounting plants. A BioQuip Plastic Vial Set entomological container (USA) was used to facilitate counting.

Plant survival to the flowering stage (%) was calculated as the ratio of the number of plants at the flowering stage to the number of plants at the full emergence stage:

$$S_f = \left(1 - \frac{N_s - N_f}{N_s}\right) \times 100, \quad (6)$$

where S_f is plant survival to the flowering stage (%); N_s is the number of plants at the full emergence stage (units); N_f is the number of plants at the flowering stage (units). Assessments were conducted by two specialists with higher agronomic education, one of whom held the degree of PhD in Agricultural Sciences. The calculation was performed using formula (7):

$$I_d = \frac{\sum(a_i \times n_i)}{N}, \quad (7)$$

where I_d is the plant disease/damage index (score); a_i is the disease or damage score; n_i is the number of plants with the corresponding score (units); N is the total number of plants examined (units). The biological efficacy of protection (%) was calculated from the reduction in root rot incidence in the experimental treatments compared with the control:

$$E_b = \frac{R_k - R_d}{R_k} \times 100, \quad (8)$$

where E_b is the biological efficacy of protection (%); R_k is disease or damage development in the control (%); R_d is disease or damage development in the experimental treatment (%). The plant disease/damage index (score) was determined as the weighted mean score of disease incidence and pest damage on a 5-point scale, where 0 = no symptoms; 1 = slight damage; 2 = moderate; 3 = medium; 4 = severe; 5 = very severe damage or pest injury.

Physiological characterisation of soybean plants during flowering. The leaf area index (m^2/m^2) was determined on the basis of the leaf area of a single plant and the plant stand density per unit area. The calculation was performed using formula (9):

$$LAI = \frac{S_l \times D}{10{,}000}, \quad (9)$$

where LAI is the leaf area index (m^2/m^2); S_l is the leaf area of a single plant (cm^2); D is plant stand density (plants/m^2). Total chlorophyll content (mg/g fresh weight) was determined by spectrophotometry following extraction of pigments with 80% acetone. A fresh leaf tissue sample was ground in a porcelain mortar, the extract was filtered, and the optical density was measured on a Shimadzu UV-1800 spectrophotometer (Japan) at wavelengths of 645 and 663 nm. Photosynthetic potential (million $m^2 \cdot$ days/ha) was determined from the mean value of the leaf area index between two recording dates and the duration of the inter-recording period. The calculation was performed using formula (10):

$$FP = \frac{LAI_1 + LAI_2}{2} \times T \times 0.01, \quad (10)$$

where FP is photosynthetic potential (million $m^2 \cdot$ days/ha, after conversion); LAI_1 is the leaf area index at the first recording date (m^2/m^2); LAI_2 is the leaf area index at the second recording date (m^2/m^2); T is the duration of the inter-recording period (days); 0.01 is the conversion factor from $m^2 \cdot$ days/m^2 to million $m^2 \cdot$ days/ha. For presentation in million $m^2 \cdot$ days/ha, the values obtained were recalculated with reference to the crop area. The number of active nodules (nodules/plant) was determined following washing of the root system and sectioning of the nodules. Nodules with pink or reddish colouration of the internal tissue were classified as active. The proportion of active nodules (%) was calculated using formula (11):

$$A_n = \frac{N_a}{N_t} \times 100, \quad (11)$$

where A_n is the proportion of active nodules (%); N_a is the number of active nodules (units); N_t is the total number of nodules on the plant (units). Nodule mass (g/plant) was determined following separation of nodular formations from the roots and weighing on a Radwag AS 220.R2 analytical balance (Poland). Leaf canopy temperature (°C) was measured using a Testo 835-H1 infrared thermometer (Germany) between 12:00 and 14:00 under clear or partly cloudy conditions, with no shading of plants at the time of measurement.

Yield structure of soybean following application of biological products. The number of pods and seeds (units/plant) was determined by direct counting of all formed pods on representative plants prior to harvest, after which the mean value for each treatment was calculated using the arithmetic mean in Microsoft Excel 2019 (USA). The weight of 1,000 seeds (g) was determined using the

standard method by selecting two sub-samples of 500 seeds each and weighing on a Radwag PS 1000. R2 laboratory balance (Poland). Seed yield (t/ha) was determined following harvest, cleaning, and weighing of the seed mass from the accounting area. Recalculation was performed to the standard soybean seed moisture content of 14%. The calculation was performed using formula (12):

$$Y = \frac{M \times 10{,}000}{A \times 1{,}000} \times \frac{100 - W}{100 - W_s}, \quad (12)$$

where Y is seed yield (t/ha); M is the seed mass from the accounting area (kg); A is the accounting area of the plot (m^2); W is actual seed moisture content (%); W_s is standard seed moisture content (%). The yield increase over the control (%) was calculated as the ratio of yield in the experimental treatment to the yield in the control:

$$Y_i = \frac{Y_d - Y_k}{Y_k} \times 100, \quad (13)$$

where Y_i is the yield increase over the control (%); Y_d is yield in the experimental treatment (t/ha); Y_k is yield in the control treatment (t/ha). Protein content in the seed (%) was determined by the Kjeldahl method following mineralisation of samples and determination of total nitrogen on a Velp Scientifica UDK 159 automatic analyser (Italy). Oil content in the seed (%) was determined by extraction in a Gerhardt Soxtherm SOX 412 apparatus (Germany) using petroleum ether as the extractant. Following completion of extraction, the residual solvent was removed, and the mass of extracted oil was determined gravimetrically. Statistical analysis of the results was performed by analysis of variance using Statistica 13.3 software (USA).

RESULTS

The combined application of Phytovit and Avercom produced the most pronounced seed response at the laboratory stage: germination energy was 88.7%, exceeding the control by 10.1 percentage points. The separate application of Phytovit and Avercom also increased this indicator; however, their combination yielded more uniform seedling formation during the early recording period. This outcome was associated with a simultaneous enhancement of initial growth processes and a reduction in the proportion of seeds that were delayed at the swelling or primary root emergence stage. Seeds subjected to the combined treatment transitioned more rapidly to active growth, and the seedlings formed were more uniform in outward condition. Laboratory germination under this treatment reached 94.3%, whilst in the control it was 86.4%. Accordingly, the increase in germination was associated not only with a greater number of germinated seeds but also with the formation of normally developed seedlings with a distinct primary root, an initial shoot, and intact cotyledons. In the treatments with biological products, the proportion of weak and developmentally delayed seedlings was lower; however, it was precisely the combined treatment that united the growth-stimulating action of Phytovit with the bioprotective action of Avercom, thereby ensuring more complete completion of early morphogenesis. Seedlings subjected to this treatment were characterised by preservation of tissue integrity, absence of widespread growth suppression, and formation of more uniform plant material by the time of the final laboratory assessment.

Development of the root portion was also greatest under the combined treatment: primary root length reached 9.4 cm, exceeding the control by 2.2 cm. Separate application of the products yielded intermediate values, with Phytovit having a stronger effect on root elongation and Avercom on the reduction of signs of microbial damage. Under the combined treatment, the primary root formed without widespread shortening, darkening of the apical portion, or disruption of the growth direction, indicating that early growth proceeded without noticeable tissue suppression. In some seedlings, the initiation of lateral rootlets was observed, so the root system had a more fully formed appearance by the time the laboratory assessment was completed. Seedling infection by microflora under the combined treatment decreased to 4.2%, which was 7.6 percentage points lower than the control. Of the individual products, a lower level of infection was provided by Avercom, consistent with its bioprotective orientation, whilst Phytovit more effectively supported the growth activity of seedlings. In the combined treatment, these effects were united: mould, darkening, necrosis of individual sections, and tissue softening manifested less frequently on the seed surface and seedling tissues. Symptoms of infection remained localised and did not cause widespread loss of seedlings from the general sample (Table 1).

Table 1. Laboratory germination indicators of soybean seeds depending on treatment scheme

Indicator	Control	Phytovit	Avercom	Phytovit + Avercom
Germination energy, %	78.6	84.8	82.9	88.7
Laboratory germination, %	86.4	91.2	89.6	94.3
Primary root length, cm	7.2	8.5	8.1	9.4
Shoot length, cm	5.9	6.8	6.5	7.4
Seedling dry weight, mg	74.5	82.1	79.8	87.6
Seedling vigour index, conventional units	1,132	1,395	1,308	1,584
Seedling infection by microflora (fungal-bacterial infection), %	11.8	7.1	6.4	4.2

Note: statistical analysis was performed by one-way analysis of variance (ANOVA); differences between the biological treatment variants and the control are statistically significant at $p \leq 0.05$ for all indicators presented
Source: developed by the author on the basis of formulae (1-2)

Based on the results of the laboratory phase, it was established that pre-sowing treatment with biological products was accompanied by changes in the passage of the initial developmental phases of soybean seeds. In the combined application variant of Phytovit and Avercom, uniform germination was observed, along with formation of a greater proportion of normally developed seedlings, active elongation of the primary root, and lower expression of microflora on seedlings. The results of the laboratory assessment demonstrated that the treated seed material passed through early developmental stages with a lower proportion of visually suppressed, infected, or underdeveloped seedlings. The data obtained served as the basis for the subsequent field evaluation of the effect of biological products on germination, plant stand density, early growth, and soybean productivity formation.

In the control, field germination was 78.9%, whilst the combined treatment yielded an increase of +8.2 percentage points. Separate application of Phytovit and Avercom also improved seedling emergence, though less markedly. This difference between treatments was associated with the combined treatment uniting stimulation of early seed growth with a reduction in losses at the initial stage of field development. In the control, lower germination manifested through thinning of individual row sections and non-uniform emergence, whilst in the treatments with biological products the crop stand had better coverage and a smaller proportion of plants that were delayed in transitioning to the next developmental phase. Plant stand density was also higher under biological treatment, confirming better realisation of field germination following emergence. Under the combined application of Phytovit and Avercom, it reached 43.6 plants/m^2, whilst in the control it was 39.5 plants/m^2. Phytovit applied separately yielded slightly higher plant stand density than Avercom, consistent with its growth-stimulating action. At the same time, the combined treatment exceeded both individual treatments, as it united support of growth processes with lower biotic pressure on young plants. This reduced plant loss following emergence and contributed to more uniform formation of the early plant canopy.

Early development of the shoot was most active under the combined treatment, manifesting through greater plant height and leaf area. At the V3 stage, plant height under the Phytovit + Avercom combination was 18.3 cm, and leaf area was 151 cm^2/plant. Separate application of Phytovit produced a stronger growth response than Avercom; however, the combined treatment yielded the higher overall result. The increase in leaf area was associated not with the visual appearance of the leaves but with the quantitative accumulation of the assimilatory apparatus. Description of the physical appearance of the leaf blades has been omitted, as no deviations indicative of widespread leaf tissue suppression were established within this assessment. The chlorophyll indicator confirmed the advantage of the combined treatment over the separate application of products. Under Avercom, chlorophyll content was 38.1 SPAD units; under Phytovit it was higher, and the maximum value was obtained in the Phytovit + Avercom treatment. This sequence demonstrated that Phytovit had a stronger influence on the formation of the leaf apparatus, whilst Avercom acted primarily through a reduction

of phytosanitary pressure. In the combined treatment, these effects were united, so plants had a higher chlorophyll status at the early stage of the growing season (Table 2).

Table 2. Effect of biological products on field germination and early soybean growth

Indicator	Control	Phytovit	Avercom	Phytovit + Avercom
Field germination, %	78.9	83.6	82.4	87.1
Plant stand density at V3 stage, plants/m²	39.5	41.8	41.2	43.6
Plant height at V3 stage, cm	14.6	16.8	16.1	18.3
Leaf area, cm²/plant	118	134	129	151
Chlorophyll content, SPAD units	36.4	39.2	38.1	41.6
Root dry weight, g/plant	0.48	0.57	0.54	0.64
Number of nodules at V5 stage, nodules/plant	14.2	17.8	16.9	20.6

Note: statistical analysis was performed by one-way analysis of variance (ANOVA); differences between the biological treatment variants and the control are statistically significant at $p \leq 0.05$ for all indicators presented
Source: developed by the author on the basis of formulae (3-4)

Thus, all three biological treatment schemes improved the early development of soybean compared with the control; however, the combined application of Phytovit and Avercom yielded the highest values for field germination, plant stand density, leaf area, and nodulation. The data obtained confirmed that the initial changes recorded at the laboratory stage were realised in better field development of plants and formed the basis for the subsequent assessment of the phytosanitary condition of the crop. Biological treatment reduced the phytosanitary pressure on soybean crops, with the most pronounced limitation of diseases and pest damage obtained under the combination of Phytovit and Avercom. In the control treatment, the incidence of root rot was 15.6%, manifesting through infection of the root zone, weakening of some plants, and non-uniform resumption of growth following the initial vegetative phases. In the treatments with biological products, the proportion of such plants was lower, as treatment reduced the pressure of soil microflora on young roots and the root collar. In practical terms, this meant less thinning of the plant stand, better plant survival, and more uniform formation of the above-ground mass during the early growth period. Foliar diseases also manifested with less intensity following application of biological products, but the mode of action of the products differed. Under Phytovit treatment, development of foliar diseases was 8.6%, meaning that infection remained predominantly localised and did not progress to widespread destruction of the assimilatory surface. Avercom manifested more prominently through limitation of pest damage: the proportion of damaged plants in this treatment was 10.5%. This difference between the products demonstrated that Phytovit more effectively maintained the condition of the leaf apparatus, whilst Avercom had a stronger effect on the entomological pressure. Under combined application, these directions of action were united, so disease incidence and phytophage damage did not form extensive foci of plant suppression.

The plant disease/damage index most effectively summarised the phytosanitary differences between treatments, as it accounted not only for the presence of symptoms but also for the degree of their expression. In the control it was 3.1 score, corresponding to a medium level of damage with a noticeable effect on plant condition. Under the combined treatment, the index decreased to 1.3 score, meaning symptoms remained predominantly slight and localised. In practical terms, this meant less loss of functional leaf area, a lower level of root system suppression, and better plant survival within the crop stand. The disease/damage index thus reflected the overall phytosanitary risk for subsequent crop development. The combined application of Phytovit and Avercom provided the highest biological efficacy of protection – 59.6%. This result was associated with the simultaneous reduction of root zone infection, localisation of foliar symptoms, and a lower proportion of plants with pest damage. In this treatment, the phytosanitary condition of the crop was not limited to a single protective

direction but encompassed several levels: the root system, the leaf apparatus, and plant survival through to subsequent developmental stages. This created more favourable conditions for the further formation of the assimilatory surface, the nodular apparatus, and the reproductive organs (Table 3).

Table 3. Disease incidence and pest damage in soybean plants

Indicator	Control	Phytovit	Avercom	Phytovit + Avercom
Incidence of root rot, %	15.6	10.8	9.7	6.3
Development of foliar diseases, %	12.4	8.6	7.8	5.1
Proportion of plants with pest damage, %	18.2	14.7	10.5	7.8
Density of sucking pests, individuals/plant	4.6	3.8	2.5	1.9
Plant survival to flowering stage, %	87.5	91.6	92.2	94.8
Plant disease/damage index, score	3.1	2.2	1.9	1.3
Biological efficacy of protection, %	0.0	30.8	37.8	59.6

Note: statistical analysis was performed by one-way analysis of variance (ANOVA); differences between the biological treatment variants and the control are statistically significant at $p \leqslant 0.05$ for all indicators presented
Source: developed by the author on the basis of formulae (5-8)

The phytosanitary condition of soybean crops under different biological product application schemes was associated with the expression of root rot, foliar diseases, pest damage, and the overall efficacy of the protective action. In the control treatment, symptoms of root zone infection were most prominent. Under Phytovit treatment, attention was directed to the condition of the leaf apparatus, where diseases manifested locally. In the Avercom treatment, assessment was focused on plant pest damage during the early growth phase. The combined treatment encompassed the overall phytosanitary condition of the crop through the total reduction in disease and damage expression. The data obtained were used for the subsequent analysis of physiological plant indicators and the formation of soybean productivity.

The combined biological treatment provided more pronounced development of the assimilatory apparatus at the flowering stage compared with the control and separate application of the products. The leaf area index under the Phytovit + Avercom combination was 4.0 m^2/m^2, whilst in the control it was 3.2 m^2/m^2. The increase in this indicator reflected a greater area of functional leaf surface per unit of crop stand, which was associated with better plant survival, more active accumulation of vegetative mass, and lower phytosanitary pressure during the preceding developmental period. Separate application of Phytovit and Avercom also contributed to an increase in the leaf area index; however, the combined treatment ensured more complete canopy closure and more uniform formation of the assimilatory area. Photosynthetic potential also increased under biological treatment, with the highest level obtained in the Phytovit + Avercom treatment. In the combined treatment it was 2.03 million $m^2 \cdot$ days/ha, whilst in the control it was 1.64 million $m^2 \cdot$ days/ha. This difference demonstrated that plants not only formed a greater leaf area but also maintained its functional contribution to organic matter accumulation for a longer period. In practical terms, this meant a higher capacity of the crop stand to sustain photosynthetic activity during the flowering stage, when the basis for subsequent seed filling is formed. The individual products produced an intermediate effect; however, their combined application provided a more complete integration of leaf development, pigment status, and the duration of assimilatory apparatus activity. Leaf canopy temperature decreased under the combined treatment compared with the control: in the control it was 30.6°C, whilst in the Phytovit + Avercom treatment it was 29.1°C. The lower leaf surface temperature indicated reduced thermal loading on the plants and a more stable water-physiological status during the period of active vegetation. This indicator complemented the results regarding the leaf area index and photosynthetic potential, since greater assimilatory area was of significance only provided its functional activity was preserved. Accordingly, at the flowering stage, the combined treatment ensured not an isolated improvement of a single parameter but simultaneous changes in the leaf

apparatus, pigment status, symbiotic activity, and the thermal regime of the plants. Symbiotic activity of soybean also intensified following application of biological products, manifesting in a greater number of active nodules and a higher proportion thereof. Following Avercom application, 21.8 active nodules per plant were formed on the root system, whilst under the combined treatment this indicator was higher. The proportion of active nodules under the Phytovit + Avercom combination exceeded the Avercom treatment by 6.6 percentage points. This response was associated with better root system development and a lower level of plant infection during the early vegetative phases. Phytovit promoted more active growth of the root portion, whilst Avercom reduced the action of factors that could limit the formation of the symbiotic apparatus. In the combined treatment, these directions of action were united, so nodulation was part of the overall physiological condition of the plants during the flowering stage (Table 4).

Table 4. Physiological condition of soybean plants at the flowering stage

Indicator	Control	Phytovit	Avercom	Phytovit + Avercom
Leaf area index, m^2/m^2	3.2	3.6	3.5	4.0
Total chlorophyll content, mg/g fresh weight	1.82	2.04	1.98	2.21
Photosynthetic potential, million m^2·days/ha	1.64	1.82	1.78	2.03
Active nodules, nodules/plant	18.4	22.6	21.8	25.9
Proportion of active nodules, %	62.1	68.4	66.9	73.5
Nodule mass, g/plant	0.42	0.51	0.49	0.58
Leaf canopy temperature, °C	30.6	29.8	29.9	29.1

Note: statistical analysis was performed by one-way analysis of variance (ANOVA); differences between the biological treatment variants and the control are statistically significant at $p \leq 0.05$ for all indicators presented
Source: developed by the author on the basis of formulae (9-11)

Thus, at the flowering stage, the combined treatment simultaneously improved four interrelated parameters: a greater assimilatory surface (LAI 4.0 m^2/m^2), higher photosynthetic potential (2.03 million $m^2 \cdot$ days/ha), more active symbiotic apparatus (25.9 active nodules/plant), and lower thermal loading on the leaves (29.1°C). It was precisely this combination of changes that formed the physiological basis for subsequent seed filling and accumulation of productive mass. The combined application of Phytovit and Avercom ensured the greatest formation of reproductive organs, manifesting in an increase in the number of pods per plant. In the control, this indicator was 31.4 pods/plant, whilst under the combined application of the products it reached 40.5 pods/plant. Separate application of Phytovit and Avercom also increased the number of pods, but less markedly. This difference was associated with the better condition of plants during the preceding stages: higher field germination, more developed leaf area, lower phytosanitary pressure, and more active root system formation. As a result, a greater proportion of flower buds progressed to formed pods, and the reproductive portion of the plant was denser compared with the control. Seed filling of the pods was also most fully realised under the combined treatment. Under Phytovit application, 78.6 seeds per plant were recorded, whilst in the Phytovit + Avercom treatment this indicator was higher, at 89.4 seeds/plant. The increase relative to Phytovit alone was 10.8 seeds/plant, demonstrating the additional effect of combining the products. Phytovit more effectively supported growth and physiological processes, whilst Avercom reduced losses associated with plant damage and phytosanitary pressure. In the combined treatment, these effects were united, so the productive portion of the plant formed more completely.

Seed weight increased in all treated variants, but the maximum value was obtained under the combined application of the products. Under Avercom, the weight of 1,000 seeds was 157.1 g, and under the combined treatment it was 164.6 g. The increase in this indicator was associated with more favourable passage of the filling period, preservation of the assimilatory surface, and translocation of photosynthates to the seed. The individual products yielded an intermediate result, whilst their combined application produced

a higher level of seed filling. The weight of 1,000 seeds in this case reflected the completeness of dry matter accumulation in the seed. Seed yield most clearly reflected the cumulative effect of the preceding growth, phytosanitary, and physiological changes. Under the Phytovit + Avercom combination, it was 3.01 t/ha, corresponding to an increase over the control of 24.4%. Separate application of Phytovit yielded a higher yield increase than Avercom; however, the combined treatment provided the highest result. This was explained by the simultaneous increase in the number of pods, better seed filling, greater seed weight, and plant survival through to the ripening period. That is, yield was formed not through a single structural element but through the accumulation of effects at several stages of soybean development. Qualitative seed indicators changed less sharply than the yield structure components; however, the combined treatment provided the highest protein and oil values among all treatments. Protein content under the Phytovit + Avercom combination was 39.1%, which was 1.3 percentage points higher than the control, and oil content reached 21.0%. The changes obtained demonstrated that biological products exerted their primary influence on yield formation and seed filling, whilst qualitative parameters responded more moderately. In the combined treatment, the increase in protein and oil content was accompanied by greater seed weight and higher yield; therefore, the final outcome was characterised not only by an increase in the quantity of produce but also by the preservation of its qualitative properties (Table 5). Analysis of variance confirmed the statistical significance of differences between treatments for yield, field germination, and the number of active nodules ($p \leq 0.05$). The least pronounced, though nonetheless significant, differences were recorded for protein and oil content in the seed.

Table 5. Soybean productivity depending on biological product application

Indicator	Control	Phytovit	Avercom	Phytovit + Avercom
Number of pods, pods/plant	31.4	36.2	35.1	40.5
Number of seeds, seeds/plant	67.2	78.6	75.9	89.4
Weight of 1,000 seeds, g	151.8	158.9	157.1	164.6
Seed yield, t/ha	2.42	2.72	2.66	3.01
Yield increase over control, %	0.0	12.4	9.9	24.4
Protein content in seed, %	37.8	38.5	38.3	39.1
Oil content in seed, %	20.3	20.7	20.6	21.0

Note: statistical analysis was performed by one-way analysis of variance (ANOVA); differences between the biological treatment variants and the control are statistically significant at $p \leq 0.05$ for all indicators presented
Source: developed by the author on the basis of formulae (12-13)

The yield structure of soybean in the experiment encompassed the number of pods, seed filling, seed weight, and the overall output of produce per unit area. These indicators were formed successively throughout the growing season and reflected the transition of plants from vegetative growth to reproductive development. Following emergence, the basis of future productivity was constituted by plant survival within the crop stand, as it was this that determined the number of individuals capable of progressing to flowering, flower bud formation, and pod ripening. Subsequent development of the leaf area ensured the accumulation of photosynthates, which were translocated to the stem, root system, and reproductive organs. The condition of the root system influenced the uptake of water and nutrients, whilst nodule formation supported nitrogen nutrition of the plants during the period of active growth and seed filling. The phytosanitary condition of the crop determined the preservation of functional tissues of leaves, stems, and roots, so the level of disease incidence or pest damage was reflected in the completeness of formation of the productive portion of the plants. The number of pods indicated the result of the initiation and survival of reproductive organs; the number of seeds indicated pod filling; the weight of 1,000 seeds indicated the completion of filling and dry matter accumulation; and yield indicated the total seed mass output following harvest. In this sequence, the early condition of the crop stand, development of the assimilatory apparatus, functioning of the

roots, and preservation of reproductive organs translated into the quantitative and qualitative parameters of the harvest.

DISCUSSION

The results obtained demonstrated that the application of biological products influenced the successive developmental stages of soybean – from seed germination through to yield formation. At the laboratory stage, the combined application of Phytovit and Avercom was associated with more uniform seedling formation, preservation of tissue integrity, and lower expression of microflora. This response created the preconditions for a greater proportion of the seed material to transition to subsequent developmental phases without pronounced suppression. Under field conditions, the effect of the products manifested through the condition of seedlings, development of the leaf apparatus, formation of the root system, and nodular formations. Plant survival following emergence was accompanied by more active accumulation of above-ground mass and better functioning of the assimilatory surface. The phytosanitary condition of the crop also changed: disease incidence and pest damage did not attain widespread distribution, which supported further plant development throughout the growing season. Yield formation reflected the preceding growth stages, as the number of reproductive organs, seed filling, and seed quality depended on plant condition throughout the growing season. The combined application of biological products ensured a successive connection between germination, field development, phytosanitary condition, symbiotic activity, and soybean productivity.

In the context of biological seed treatment and integrated control of harmful organisms, J. Lamichhane *et al*. (2022) and W. Zhou *et al*. (2024) examined how biological and combined approaches altered the initial development of crops, phytosanitary condition, and yield. In a meta-analysis of 396 studies, J. Lamichhane *et al*. demonstrated that biological seed treatment increased seedling emergence, plant biomass, disease control, and yield; for yield, the mean increase was 21 ± 2% compared with untreated seed. In the present study, yield under the combined treatment increased by 24.4%, which was close to the generalised effect established in the meta-analysis. This indicates that the action of Phytovit and Avercom was realised not only through germination but also through subsequent plant survival, reduced root rot incidence, development of the nodular apparatus, and seed filling. W. Zhou *et al*. considered integrated protection as a system combining biological control, monitoring, and several protective measures, rather than as the action of a single agent. This is consistent with the result obtained: the Phytovit + Avercom combination yielded a higher effect than the individual products, as Phytovit supported initial growth and the assimilatory apparatus whilst Avercom reduced biotic pressure; together, these actions translated into a lower disease/damage index, more active nodulation, and higher seed productivity.

In the context of microbial nutrition, rhizosphere activity, and plant biostimulation, H. Khosravi *et al*. (2024) and R. Johnson *et al*. (2024) focused on the role of PGPR biofertilisers and biostimulants in crop growth, nutrition, and stress tolerance. H. Khosravi *et al*. described the action of rhizobacteria through nitrogen fixation, hormone production, and solubilisation of nutrient compounds, though with greater emphasis on the general prospects of application. R. Johnson *et al*. considered biostimulants as agents influencing plant metabolism, productivity, and resistance to adverse factors. In the present study, the microbial-physiological aspect was revealed through the relationship between the leaf apparatus, chlorophyll status, nodulation, and subsequent seed formation. In particular, the increase in chlorophyll content to 2.21 mg/g fresh weight and the rise in the proportion of active nodules to 73.5% in the combined treatment is consistent with the mechanisms of PGPR action described by H. Khosravi *et al*. through hormonal stimulation and nutrient mobilisation, whilst R. Johnson *et al*. associated similar changes in pigment status with a reduction in abiotic stress loading on plants.

In the area of biocontrol mechanisms and the practical application of biological agents, A. Tyagi *et al*. (2024) and M. Villavicencio-Vásquez *et al*. (2025) analysed the mechanisms of action, selection, formulations, and limitations of biocontrol agents in plant protection. M. Villavicencio-Vásquez *et al*. examined *Trichoderma* and *Bacillus* through the mechanisms of mycoparasitism, competition, antibiosis, enzymatic activity, and

induced resistance. A. Tyagi *et al*. reviewed the role of bacterial, fungal, and viral agents in the control of crop diseases, drawing attention to the factors that alter their efficacy in the field. In the present study, the biocontrol component was not limited to a phytopathological description alone, as the phytosanitary condition was linked to plant development, preservation of the leaf surface, and formation of yield structure. The reduction of the plant disease/damage index from 3.1 to 1.3 score and the biological efficacy of protection of 59.6% are consistent with the mechanisms described by M. Villavicencio-Vásquez *et al*.: Avercom, based on *S. avermitilis*, exerted contact-intestinal action on phytophages, whilst Phytovit, acting through metabolites of *S. netropsis*, could induce systemic plant resistance to pathogens – which explains the different directions of action of the two products when used in combination. This made it possible to demonstrate that the action of the biological products manifested not in isolation but through the interrelationship of protective, physiological, and productivity-related changes in soybean crops.

To characterise the relationship between nutrition, symbiotic activity, and yield, A. Mirriam *et al*. (2022) and V. Paramesh *et al*. (2023) demonstrated that the combination of several agronomic factors yielded a higher result than the action of a single component. V. Paramesh *et al*. summarised that integrated nutrient management increased crop yield across a broad range – from 1.3 to 66.5% – whilst simultaneously improving soil properties and soil microbiological activity. A. Mirriam *et al*. established that *Bradyrhizobium* inoculation combined with phosphorus nutrition provided a soybean yield increase of up to 30%, with the best result obtained at an application rate of 15 kg P/ha. In the present study, the yield increase under the combined application of Phytovit and Avercom was 24.4%, which was lower than the maximum reported by A. Mirriam *et al*. but higher than some of the effects summarised by V. Paramesh *et al*. The difference lay in the fact that here the result was formed not through a mineral nutrition system or Bradyrhizobium inoculation but through the combination of the growth-stimulating and bioprotective action of the products. It was precisely for this reason that the combined treatment yielded a better result than the separate application of Phytovit or Avercom: the former product supported early growth and the leaf apparatus, the latter reduced phytosanitary pressure, and their combined action translated into higher nodulation, better seed filling, and greater yield.

With regard to production constraints of soybean and the role of microbial bioformulations, A. Khan *et al*. (2023) and P. Majidian *et al*. (2024) analysed different levels of the problem: from production dependence on external factors to the technological stability of microbial products. P. Majidian *et al*. noted that Iran covers more than 90% of its soybean requirements through imports, and attributed the production decline to biotic and abiotic stresses, a narrow cultivar base, and technological limitations. A. Khan *et al*. considered microbial bioformulations as a system in which efficacy depends on the viability of the microorganisms, the carrier, the delivery method, and the capacity to support plant nutrition, growth, and protection; for a stable crop response, a sufficient number of viable cells was indicated as necessary, specifically not below 10^6-10^7. In the present study, these principles were tested not at the level of general technological prospects but through specific soybean indicators: the combined treatment provided a yield of 3.01 t/ha, an increase over the control of 24.4%, and lower seedling infection by microflora. The superior result of the combined treatment was explained by the combination of two actions: Phytovit supported early growth and leaf apparatus formation, whilst Avercom reduced biotic pressure, so the effect progressed from germination through to nodulation, seed filling, and increased productivity.

In the analysis of organic nutrient sources and the plant microbiome, M. Khan *et al*. (2024) and S. Compant *et al*. (2025) focused on soil organic matter, microbial activity, rhizosphere processes, and the role of microorganisms in crop growth. M. Khan *et al*. considered organic fertilisers and cover crops as factors improving the soil environment and microbial biomass, whilst S. Compant *et al*. reviewed the functions of the plant microbiome in nutrition, stress tolerance, and protection from pathogens. In the present study, this area was made specific through the soybean response to biological treatment: seedling infection by microflora decreased to 4.2%, the incidence of root rot decreased to 6.3%, and the number of nodules at the V5 stage reached 20.6 per plant. In contrast to

studies where the emphasis is placed on the general functions of soil microbiota, the present study demonstrates the transition from lower microbial infection to more active nodulation, more stable plant development, and yield formation. The Phytovit + Avercom combination yielded a higher result than the individual products through the combination of growth support and reduction of biotic pressure.

In terms of biotic pressure and long-term agronomic background, A. Afzal & T. Mukhtar (2024) and S. Panday *et al*. (2024) examined different sources of productivity constraints: phytoparasitic nematodes and long-term fertilisation systems in crop rotations. A. Afzal & T. Mukhtar reviewed approaches to nematode management as a factor of yield loss, focusing on protective strategies and food security. S. Panday *et al*. demonstrated that long-term fertilisation schemes altered productivity, profitability, and water use in a soybean-wheat system. In the present study, the biotic and production components were linked through the condition of the root system, the phytosanitary background, and the subsequent formation of seeds. In contrast to studies where harmful organisms or long-term nutrition are analysed separately, the present study traces how early reduction of seedling infection and more stable root development translated into more active nodulation and formation of the reproductive portion of soybean.

For the assessment of agroecosystem resilience to climatic and biodiversity-related factors, N.-F. Wan *et al*. (2024) and A. Raza *et al*. (2025) directed attention to broader mechanisms of agricultural adaptation. A. Raza *et al*. considered strategies for developing climate-smart crops oriented towards the preservation of productivity under stress conditions. N.-F. Wan *et al*. analysed the cascading socio-ecological benefits of biodiversity for agricultural production, including pest regulation and the maintenance of agroecosystem functions. In the present study, resilience was examined not through breeding or landscape-level approaches but through the soybean response to biological treatment under laboratory and field conditions. The results obtained detailed how the condition of seedlings, the leaf apparatus, the root system, and the phytosanitary background formed the foundation for yield structure. This approach narrowed the scale of analysis to a specific crop but more deeply revealed the internal sequence of growth and productivity changes.

In the examination of initial seed quality and the role of beneficial bacteria, L. Reed & B. Glick (2023) and D. Patyal *et al*. (2025) analysed technologies that influence the initial development of plants. D. Patyal *et al*. described seed coating as a method of improving seed quality, protecting seedlings, and enhancing the field realisation of crop potential. L. Reed & B. Glick reviewed the application of plant growth-promoting bacteria to support agricultural crop development. In the present study, this area was made specific through the soybean response to biological treatment from the moment of germination through to seed ripening. Whereas in the cited works the main emphasis fell on coating technology or the general role of bacteria, the present study demonstrated the subsequent transition of initial changes into field germination, symbiotic activity, preservation of the leaf apparatus, and formation of seed mass. The present study thus detailed the action of biological treatment of soybean through the successive connection between germination, field development, phytosanitary condition, symbiotic activity, and yield formation.

CONCLUSIONS

The study involved a laboratory-field assessment of the effect of Phytovit, Avercom, and their combination on the sowing, growth, phytosanitary, physiological, and productivity indicators of soybean. The laboratory phase demonstrated that the combined seed treatment most markedly affected the initial seedling development: germination energy was 88.7%, laboratory germination was 94.3%, root length was 9.4 cm, and seedling infection by microflora decreased to 4.2%. The data indicated more uniform seedling formation, preservation of tissue integrity, and lower expression of microbial infection during the laboratory germination period. Under field conditions, the application of biological products was reflected in seedling emergence, plant stand density, development of the leaf apparatus, and formation of the root system. Under the Phytovit + Avercom combination, field germination reached 87.1%, leaf area was 151 cm^2/plant, and the number of nodules at the V5 stage was 20.6 per plant. This plant response demonstrated the successive transition

of laboratory changes into field development, as the treated plants formed more uniform crop stands, accumulated above-ground mass more actively, and possessed a formed nodular apparatus at the early stage of the growing season. The phytosanitary condition of the crop also changed depending on the treatment scheme. Under the combined application of the products, the incidence of root rot decreased to 6.3%, the development of foliar diseases decreased to 5.1%, and the biological efficacy of protection was 59.6%. This demonstrated a reduction in disease expression, a lower level of plant pest damage, and better crop survival through to the flowering stage. The reduction in phytosanitary pressure created conditions for the further development of the leaf apparatus, root system, and reproductive portion of the plants. At the flowering stage, the combined treatment promoted the formation of a more developed assimilatory and symbiotic apparatus in the plants. The leaf area index was 4.0 m^2/m^2, the number of active nodules was 25.9 per plant, and their mass was 0.58 g per plant. Nodule formation and preservation of the leaf apparatus were associated with subsequent seed filling and accumulation of productive mass. Soybean productivity confirmed the succession of changes recorded at the preceding stages of the study. Under the combined application of Phytovit and Avercom, seed yield was 3.01 t/ha, the increase over the control was 24.4%, the weight of 1,000 seeds was 164.6 g, protein content was 39.1%, and oil content was 21.0%. The combination of the products thus ensured the coordinated formation of the sowing, phytosanitary, symbiotic, and productivity parameters of soybean, which manifested in better plant condition throughout the growing season and higher quality of the seed formed. A limitation of the study was that it did not encompass an economic evaluation of biological product application or their residual effects on soil microbiota in the following growing season. Further research should be conducted for other cultivars, regions, and growing years, and with consideration of economic efficiency.

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Ефективність комплексного застосування біопрепаратів при вирощуванні сої в лабораторних та польових умовах

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Анотація. Метою дослідження було оцінити ефективність біопрепаратів через реакцію сої за посівними, ростовими, фітосанітарними, симбіотичними та продуктивними параметрами в лабораторних і польових умовах. У дослідженні використовували спектрофотометрію, метод К'єльдаля, екстракцію Сокслета та дисперсійний аналіз. У лабораторних умовах комплексна обробка насіння Фітовітом і Аверкомом забезпечувала найвищу енергію проростання – 88,7 %, що перевищувало контроль на 10,1 в. п. Лабораторна схожість за цієї схеми становила 94,3 % і була вищою за контроль на 7,9 в. п., тоді як ураженість проростків мікрофлорою знижувалася до 4,2 %, тобто була меншою на 7,6 в. п. У польових умовах застосування біопрепаратів позитивно позначалося на формуванні сходів, густоті рослин, розвитку листкового апарату та кореневої системи. За комплексного використання препаратів польова схожість становила 87,1 %, а кількість бульбочок у фазі V5 досягала 20,6 шт./рослину. Фітосанітарний стан посівів також змінювався в напрямі зменшення ураження хворобами й пошкодження шкідниками: поширення кореневих гнилей знижувалося до 6,3 %, а біологічна ефективність захисту становила 59,6 %. У фазі цвітіння комплексна обробка сприяла формуванню більш розвиненого асиміляційного та симбіотичного апарату рослин. Індекс листкової поверхні досягав 4,0 м²/м², кількість активних бульбочок – 25,9 шт./рослину, а їхня маса – 0,58 г/рослину, що відображало активніше функціонування листкової поверхні та кореневої системи в період переходу рослин до генеративного розвитку. Збереження листкового апарату й формування бульбочок поєднувалися з подальшим наливом насіння та накопиченням продуктивної маси. Урожайність насіння за поєднання Фітовіту й Аверкому становила 3,01 т/га, приріст до контролю – 24,4 %, вміст білка – 39,1 %, а олії – 21,0 %. Практична цінність дослідження полягає в можливості використання його результатів агрономами, фермерами, насіннєвими господарствами та дослідниками для обґрунтування біологічної обробки сої з урахуванням проростання, фітосанітарного стану, бульбочкоутворення, урожайності та якості насіння

Ключові слова: фітосанітарний стан; густота рослин; коренева система; кількість бульбочок; генеративні органи