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PHYTOPATHOGENIC COMPONENT OF THE SOYBEAN ROOT MYCOBIOTA AND OPPORTUNITIES FOR THEIR BIOLOGICAL REGULATION

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Aim. To identify fungal phytopathogens from soybean roots and evaluate the antagonistic activity of *Trichoderma* spp. isolates alongside the antifungal efficacy of *Streptomyces*-based bioproducts against them.

Methods. Fungi were isolated on Czapek-Dox agar (HiMedia) and identified based on morphological and cultural features. The antagonistic potential of *Trichoderma* spp. was assessed via dual culture, while the antifungal efficacy of commercial bioproducts was determined using the agar diffusion method.

Results. Root mycobiota analysis revealed that Fusarium root rot is the dominant disease, caused by a complex of six species with *F. solani* prevailing (12.2–42.3%). In pesticide-free fields, natural regulation of *F. solani* by *Trichoderma* fungi was observed, whereas in commercial production, the presence of mycoparasites was negligible. Other pathogens (*C. cassiicola, Ph. sojae, S. sclerotiorum*) were harmful but localized. Efficient *Trichoderma* isolates and commercial bioproducts were screened for their ability to suppress pathogens.

Conclusions. Isolated *Trichoderma* strains exhibit significant antagonistic activity, particularly against *F. oxysporum* (70.9%). While Streptomyces-based bioproducts show limited antifungal efficacy against *F. solani*, they remain effective against other associated phytopathogens.

Keywords: phytopathogens, *Trichoderma* spp., *Streptomyces* spp., soybean root rot, *Fusarium solani*, microbial antagonism, biocontrol.

Fungal diseases of soybean in Ukraine are a key limiting factor for achieving high crop yields. Globally, approximately 50–80 specific fungal and fungus-like microorganisms are known to affect soybean, although only about 35 are considered economically significant for production [1, 2]. In Ukraine, between 15 and 25 phytopathogenic species are widespread on this crop. The most common diseases include fusarium wilt (*Fusarium* Link), ascochyta blight (*Ascochyta phaseolorum* Sacc.), septoria brown spot (*Septoria glycines* Hemmi), alternaria leaf spot (*Alternaria* Nees), downy mildew (*Peronospora manshurica* Sydow), stem canker (*Diaporthe* Nitschke), cercospora leaf blight (*Cercospora sojina* Hara), white mold (*Sclerotinia sclerotiorum* (Lib.) de Bary), and gray mold (*Botrytis cinerea* Pers.) [3].

Other species of the genus *Fusarium* were less frequent, including two unidentified species, *F. oxysporum*, *F. sporotrichioides*, and *F. verticillioides*. Additional phytopathogens included *Alternaria* spp., which are known to cause Alternaria leaf spot on soybean. However, these may also have originated as endophytes from the seeds, moving vertically to the roots during plant development.

In the Poltava and Ivano-Frankivsk regions, colonies of the dangerous pathogen *Phytophthora sojae* Kaufm. & Gerd. were

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isolated from soybean roots. This fungus-like organisms, which can infect both roots and stems, might have been introduced via the soil or infected seeds. Although *P. sojae* was previously a subject of external quarantine, it is no longer listed in the current Register of Regulated Pests (A-1) (Order No. 397, dated July 16, 2019). Additionally, plants infected with the white mold pathogen (*S. sclerotiorum*) were identified in the Chernihiv region.

The year 2014 was found to be the most favorable for pathogen development, with maximum disease incidence recorded across all types. Analysis of seed-borne infections from 2016 to 2022 indicates the dominance of *Fusarium* spp. (average 20.2%, maximum 50.0%). Seeds are also a frequent source of the ascochyta blight pathogen, *A. sojaecola* Abramov. Since 2019, phomopsis seed decay pathogens—fungi of the genus *Diaporthe* (including *D. longicolla*, *D. caulivora*, *D. sojae*, and *D. phaseolorum*)—have been isolated from seed samples [4, 5]. Studies of the phytopathogenic complex on soybean under irrigation in southern Ukraine identified the following species (by isolation frequency): *Fusarium* spp. (34%), *S. glycines* (25%), *S. sclerotiorum* (16%), and *P. manshurica* (13%) [6].

In Ukraine, soybean root system infections are caused by fungi of the genus *Fusarium*, *Thanatephorus cucumeris* Donk (*Rhizoctonia solani* Kuehn), *Thielaviopsis basicola* Ferr, fungi of the genus *Pythium* Pringsheim (*Pythium ultimum* Trow, *P. debaryanum* Hesse, etc.), *Athelia rolfsii* (Curzi) C.C. Tu and Kimbr (*Sclerotium rolfsii* Sacc.), and *Macrophomina phaseolina* (Tassi) Goid [7]. Globally, 64 species of fungal phytopathogens are known to cause soybean root rot, the most significant being species from the genera *Fusarium* and *Pythium*, as well as *R. solani*, *Helicobasidium mompa* Nobuj Tanaka, *Thielaviopsis basicola* Ferr, *and Stachybotrys chartarum* (Ehrenb.) S. Hughes, *S. rolfsii*, *Mycoleptodiscus terrestris* (Gerd.) Ostaz, and *Phymatotrichopsis omnivora* (Duggar) Hennebert [8].

Climate change in Ukraine, characterized by rising temperatures and low precipitation, exacerbates the negative impact of specific chemical treatments. Furthermore, increasing fertilizer and plant protection product prices reduces profitability in soybean production. Consequently, modern agricultural production shows a growing demand for expanding the spectrum of biological products in crop management. Bacteria (such as *Bacillus* spp. and *Streptomyces* spp.) and fungi (such as *Trichoderma* spp.) have demonstrated significant efficacy against soybean diseases. While numerous products derived from the genus *Trichoderma* are available on the Ukrainian market, their species diversity remains limited. Therefore, the search for biocontrol agents among soil-borne *Streptomyces* species, which synthesize a wide range of bioactive compounds, is highly promising.

Materials and Methods

Plant samples of the "Sculptor" soybean variety were obtained from the experimental fields of the Zabolotny Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine, as well as from commercial production sites across six regions of Ukraine: Kyiv, Cherkasy, Poltava, Chernihiv, Ivano-Frankivsk, and Mykolaiv. Fungal isolation from soybean roots was performed using Czapek-Dox agar. Root segments were washed under running water for one hour, surface-sterilized with 96% ethanol, rinsed with distilled water, and dried between layers of filter paper. The prepared material was placed in Petri dishes and incubated in a thermostat for seven days. Identification of the root mycobiota was conducted based on sporulation characteristics and morphological traits, as described [9, 10].

Antagonistic activity was evaluated using the dual culture method on Czapek-Dox agar supplemented with glucose. Seven-day-old fungal cultures were inoculated 30 mm from the edges of 90 mm Petri dishes. For control treatments (monocultures), fungi were placed in the center of the dish. Incubation was carried out for seven days in a thermostat at 22–25 °C [11]. The percentage of inhibition (I, %) was calculated using the formula:

$$I\,(\%) = R_1 - R_2 / R_1 \times 100\%,$$

where R_1 is the radial growth of the pathogen in the control, and R_2 is the radial growth in the presence of the antagonist [12].

The antifungal efficacy of biological products based on *Streptomyces* spp. (Department of General and Soil Microbiology, IMV) was investigated. The tested products included: "Phytovit" (liquid formulation), based on polyene antibiotics from *S. netropsis* (reidentified as *S. distallicus*) IMV Ac-5025, which also contains free amino acids, B-group vitamins, lipids, and phytohormones; and "Avercom®" (liquid formulation), based on natural major avermectins A1, A2, B1, and B2 (0.01%) from *S. avermitilis* IMV Ac-2179 (54). Seven-day-old fungal cultures were inoculated onto Czapek-Dox medium. The sensitivity of phytopathogens was determined using the agar well diffusion method [13]. Wells were cut with a sterile cork borer, and 5 µl of each product was added to each well. The dishes were incubated at 26 °C until the fungal colonies in the control treatment covered the entire surface. Subsequently, the zones of inhibition were measured for each treatment.

Statistical analysis of the results was performed using one-way Analysis of Variance (ANOVA) in STATISTICA 10. Additionally, the Least Significant Difference (LSD05) was calculated to determine the significance of differences between means.

Results and Discussion

Soybean root mycobiota. Initially, the fungal complex of the roots of the "Sculptor" soybean variety, grown under experimental field conditions at the IMV without chemical treatments, was investigated. A total of nine fungal species were isolated. In addition to the fungal taxa, five bacterial colonies were also isolated (Fig. 1).

Two groups of fungi occupied a dominant position in the root mycobiota: phytopathogens belonging to the *Fusarium solani* species complex (FSSC) and their antagonists (hyperparasites) — fungi of the genus *Trichoderma*. The latter actively overgrew the *Fusarium* colonies, forming abundant sporulation and suppressing the phytopathogens. This indicates a state of equilibrium between the parasite and the host. However, such a balance is precarious for the plant. Under environmental stress, the chemical composition of root exudates changes; the phytopathogen tends to adapt more rapidly to these changes, leading to active disease progression. In contrast, *Trichoderma* species require more time to accumulate sufficient biomass to restrain *F. solani* development effectively.

Melanized fungi (*Cladosporium* sp., *Alternaria* sp., and *Alternaria botrytis*) accounted for 10% of the isolates. Fungi of the genus *Penicillium* sp. and various bacteria showed similar levels of abundance. *Aspergillus* sp. represented 7% of the soybean root mycobiota.

Thus, in the endophytic mycobiota of seeds grown without chemical treatments, the phytopathogenic species *F. solani* and its parasites *Trichoderma* sp. were dominant.

The study of soybean root microbiota was extended by analyzing plant material from various cultivation regions. Microorganisms were isolated from soybean roots collected in the Kyiv, Cherkasy, Poltava, Chernihiv, Ivano-Frankivsk, and Mykolaiv regions (Table 1).

From five to eight fungal taxa were isolated from soybean roots at each cultivation site: 8 isolates from the Cherkasy and Chernihiv regions, 7 from Kyiv and Mykolaiv, 6 from Ivano-Frankivsk, and 5 from the Poltava region. Numerous bacterial colonies were observed on Czapek-Dox medium, reaching their highest prevalence in the Poltava region. However, fungal colonies predominated in most samples, with *F. solani* being the most widespread species. Its maximum occurrence was recorded in the Ivano-Frankivsk and Chernihiv regions; this can be attributed to

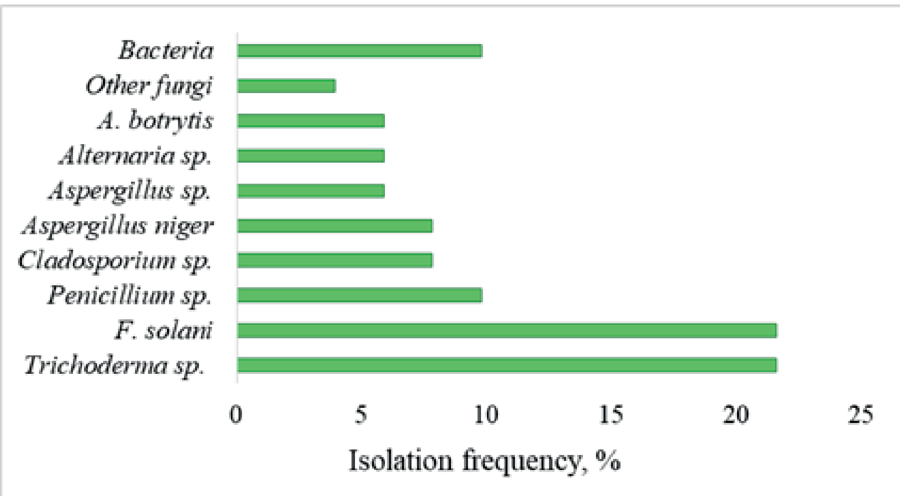

Fig. 1. **Microbiota of soybean roots during the flowering stage (experimental field of the IMV)**

Table 1. **Soybean root microbiota from different regions of Ukraine (budding-flowering stages)**

Representatives	Isolation frequency of the root microbiota, %					
	Kyiv region	Cherkasy region	Poltava region	Chernihiv region	Ivano-Frankivsk region	Mykolaiv region
Bacteria	44.8	46.4	63.3	29.7	42.8	45.8
Alternaria spp.	5.2	–	–	3.0	2.9	8.3
Aureobasidium pullulans	–	4.3	–	–	2.9	2.1
Aspergillus sp.	–	–	–	–	–	2.1
Backusella sp.	8.6	5.8	–	–	–	–
Corynespora cassiicola	–	4.3	–	–	1.4	–
Cladosporium sp.	–	2.9	8.2	–	–	–
Fusarium spp.	–	7.2 (1)	–	3.0 (2)	–	–
F. oxysporum	–	–	–	3.0	–	2.1
F. solani	22.4	21.7	12.2	40.3	42.8	25
F. sporotrichioides	–	–	–	3.0	–	–
F. verticillioides	–	–	2.0	–	–	–
Clonostachys rosea f. *rosea*	–	4.3	–	–	–	6.3
Mucor spp.	5.2	–	–	9.0	–	–
Penicillium spp.	–	2.9	6.1	6.0	–	8.3
Phytophthora sojae	–	–	8.2	–	2.9	–
Sclerotinia sclerotiorum	–	–	–	3.0	–	–
Trichoderma sp.	–	–	–	–	7.1	–
Other fungi	13.8	–	–	–	–	–
Total number of fungal species	7	8	5	8	6	7

higher precipitation levels in these areas, which favored root infection. The lowest infection rate was observed in the Poltava region, which may be due to the suppressive effect of active bacterial development.

Other species of the genus *Fusarium* were less frequent, including two unidentified species, *F. oxysporum*, *F. sporotrichioides*, and *F. verticillioides*. Additional phytopathogens included *Alternaria* spp., which cause Alternaria leaf spot on soybean. However, these may also have originated as endophytes from the seeds, moving vertically to the roots during plant development.

In the Poltava and Ivano-Frankivsk regions, colonies of the dangerous pathogen *Phytophthora sojae* Kaufm. & Gerd. were isolated from soybean roots. These fungus-like organisms, which can infect both roots and stems, might have beenintroduced via the soil or infected seeds. Although *P. sojae* was previously a subject of external quarantine, it is no longer listed in the current Register of Regulated Pests (A-1) (Order No. 397, dated July 16, 2019). Additionally, plants infected with the white mold pathogen (*S. sclerotiorum*) were identified in the Chernihiv region.

For the first time in Ukraine, the fungus *Corynespora cassiicola* (Berk. and Curt.) Wei C. was isolated from soybean roots. Brown colonies developed on Czapek-Dox agar supplemented with glucose. The species was identified by its characteristic elongated conidia of varying sizes; the number of septa (11 or more) correlated with conidial length (Fig. 2). In addition to causing target spot on soybean leaves, this pathogen can severely affect the plant's root system.

In addition to *Alternaria* spp., two other species of dark-pigmented (dematiaceous) fungi were isolated: *Aureobasidium pullulans* (de Bary & Löwenthal) and fungi of the genus *Cladosporium*. The former was prevalent in the Cherkasy, Ivano-Frankivsk, and Mykolaiv regions, while the latter was found in the Cherkasy and Poltava regions. Mucoralean fungi (genera *Backusella* and *Mucor*) were observed on the roots of soybean grown in the

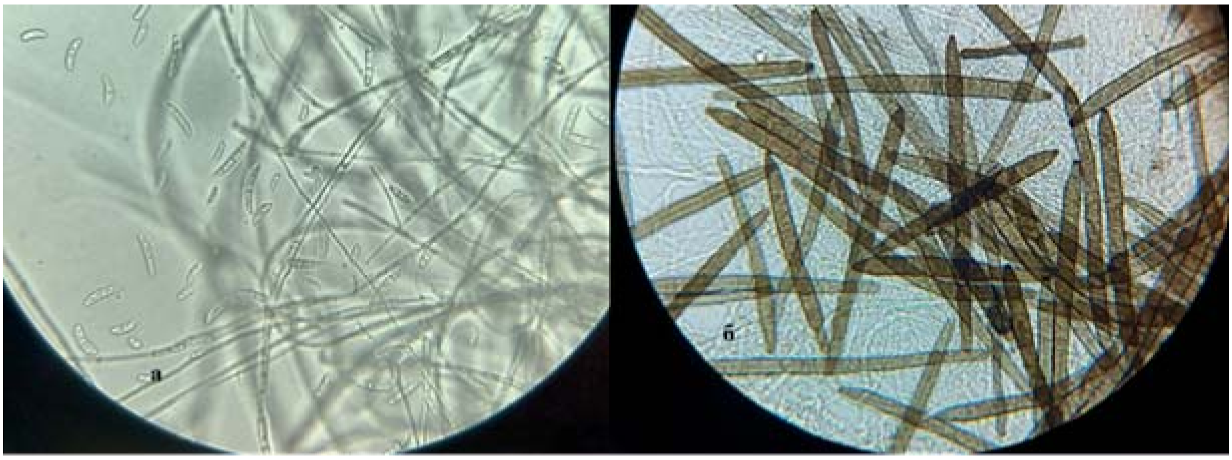

Fig. 2. **Conidial sporulation of phytopathogens isolated from soybean roots:** ***F. solani* (*a*) and *C. cassiicola* (*b*)** (magnification ×400)

central and northern parts of the country. Representatives of the genus *Aspergillus* showed the lowest prevalence, being isolated only from soybean samples in the south. In contrast, *Penicillium* spp. were found to be quite widespread, occurring in plant material from four different regions.

The prevalence of hyperparasites affecting *Fusarium* species was insignificant. *Trichoderma* sp. colonized soybean roots only in the Ivano-Frankivsk region, while *Clonostachys rosea* f. *rosea* (Link) Schroers was isolated from plants in the Cherkasy and Mykolaiv regions. Unlike the former, the latter species did not exert a strong inhibitory effect on *F. solani* development. Typically, solitary colonies formed on young fungal hyphae, thereby reducing conidial production. Later, the number of pink parasitic colonies increased, creating a circular pattern along the periphery of the *F. solani* colony.

Thus, the soybean root mycobiota is dominated by phytopathogenic species, primarily *Fusarium* spp., particularly *F. solani*. This species is the primary causal agent of *Fusarium* root rot. Other specialized pathogens are distributed across specific regions and have low isolation frequencies, namely *C. cassiicola*, *P. sojae*, and *S. sclerotiorum*. *Alternaria* spp., the causal agents of Alternaria leaf spot, generally do not infect the root system, although particular species are capable of affecting seedlings.

Antagonistic efficacy of *Trichoderma* spp. and antifungal properties of Streptomyces-based bioproducts. The efficacy of isolates of various origins belonging to the genera *Trichoderma* and *Gliocladium* (currently reclassified as *Trichoderma* spp.) against the development of *Fusarium* spp. was investigated (Table 2).

The isolate obtained during the study of soybean root mycobiota under chemical-free conditions proved to be the least effective. While it could effectively restrain *F. oxysporum*, its growth inhibition of *F. solani* was only 37.3%. This confirms the stable coexistence of *Trichoderma* fungi with the most dangerous *Fusarium* species. *Gliocladium* spp. Isolates obtained from wheat roots demonstrated better suppression of fungal development, though they were effective only against *F. oxysporum*. The most effective isolate for inhibiting *F. solani* growth on the medium was one isolated directly from a soil sample (Boryspil district, Kyiv region). All studied isolates exhibited higher efficacy against *F. oxysporum* than against *F. solani*.

The impact of Streptomyces-based biological products on the development of *F. solani*, *F. oxysporum*, *Alternaria* sp., and *S. sclerotiorum* was also investigated (Table 3).

Effective inhibition was observed against fungi of the genus *Alternaria* and *F. oxysporum*. However, the tested products did not inhibit the growth of *F. solani*. Avercom® exhibited superior efficacy against *Alternaria* sp. and *S. sclerotiorum* (Fig. 3). In contrast, Phytovit proved to be more effective in suppressing *F. oxysporum*.

Studies of soybean root endophytes conducted by Ukrainian scientists corroborate our findings regarding the dominance of *Fusarium* spp within the root mycobiota. In the mycobiota of the “Lehenda” variety, the following fungal genera were identified:

Table 2. **Antagonistic activity of *Trichoderma* spp. against *Fusarium* spp. under *in vitro* conditions**

Fungal isolates	Source of isolates	Fungal growth inhibition, %	
		F. solani	*F. oxysporum*
Trichoderma sp. SR	Soybean roots	37.3	69.1
Gliocladium sp. 4	Wheat roots	53.3	70.6
Gliocladium sp. 6	Wheat roots	45.2	72.7
Trichoderma sp. S	Soil from Kyiv region	54.7	71.2
LSD_{05}		3.94	–*

Note: $P = 0.418$ — the analysis revealed no statistically significant differences between the studied isolates regarding inhibition of *F. oxysporum.*

Table 3. **Antifungal properties of Streptomyces-based bioproducts**

Biological product	*F. solani*	*F. oxysporum*	*Alternaria* sp.	*S. sclerotiorum*
	growth inhibition zones, mm			
Phytovit	0	8.5±0.7*	9.5±0.7	0
Avercom®	0	6.7±0.4	11±0.8	3±0.8
HIP_{05}	–	1.28	1.29	–

Note: Values within each row represent means (±SD, $n = 3$).

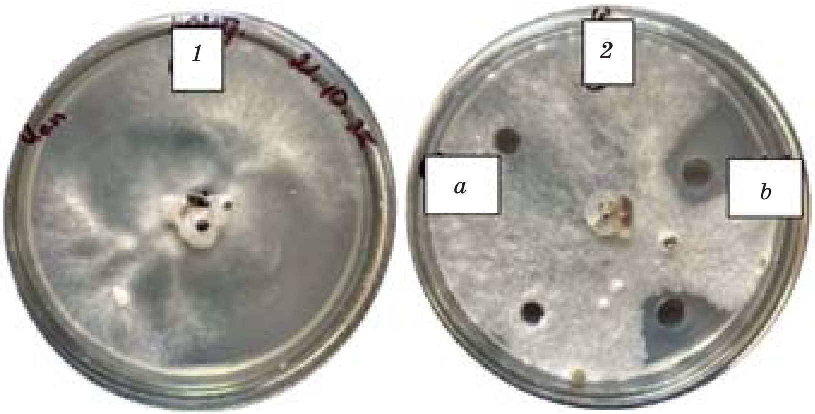

Fig. 3. **Antifungal activity of bioproducts:**
1 — control (left) and *2* — treatment — the effect of Phytovit (*a*) and Avercom® (*b*)

Fusarium, Gliocladium, Penicillium, Rhizopus, Verticillium, other fungi, and *Trichoderma*. In our study, the highest isolation frequency was observed for *F. solani* and *Trichoderma* sp. under the aforementioned conditions; representatives of the genus *Gliocladium* also developed actively alongside *Fusarium* fungi. A comparison of the mycobiota from soil, rhizosphere, and rhizoplane provided insights into *Fusarium* spp.'s capacity to infect soybean plants. The species composition was most diverse in the soil mycobiota, whereas the fewest taxa were isolated from soybean roots. The highest fungal concentration was observed in the root rhizosphere, with a nearly 40-fold increase in phytopathogenic *Fusarium* spp. Consequently, fungal spores in the moist soil converged from all directions into the rhizosphere zone under the influence of root exudates, awaiting infection. Ultimately, only about 5% of these microorganisms were able to overcome the immune barrier and enter the internal root tissues. In some cases, this percentage might even be lower, as specific pathogens could have been transmitted vertically from seeds to roots [14].

In another study by Ukrainian researchers, 16 isolates causing root system damage (*Fusarium* Link: Fr, *Alternaria* (Fr.) Keissler, and *Verticillium* Nees) were obtained from soybean plants. The genus *Fusarium* was represented by *F. oxysporum*, *F. solani*, *F. moniliforme* var. lactis, and *F. gibbosum*, the latter of which proved to be the most pathogenic. Additionally, the phytopathogenic species *Alternaria consortialis* was identified; it initially infected seedlings, then spread to roots, stems, and leaves, where dark brown spots were observed [15]. In our studies across various regions of Ukraine, however, only *F. solani* maintained a dominant position.

We report the first isolation of *C. cassiicola* from soybean roots in Ukraine. This fungus causes target spot, a late-onset disease that infects stems, leaves, pods, and seeds. The leaves develop characteristic concentric target-like spots with chlorotic halos due to the accumulation of the toxin cassiicolin. *C. cassiicola* spreads upward from the stem and lower leaves to the upper tiers. Severely affected leaves wither and drop. Furthermore, the pathogen causes soybean root rot, which begins as a red spot that turns purple and eventually black. The fungus is a polyphagous pathogen found on 400 plant species across 70 countries [16–18].

Fusarium-type root rot in soybean is typically caused not by a single species but by a complex, largely determined by geographical factors. In Hubei Province, China, *F. proliferatum* was the most virulent, while in Sichuan, the most aggressive species were *F. oxysporum*, *F. equiseti*, and *F. graminearum* [19, 20]. A pathogenicity study of six *Fusarium* species in Canada showed that *F. avenaceum* caused the greatest average reduction in seed germination (94.1%), *F. oxysporum* had the maximum negative impact on plant development, and *F. graminearum*, *F. acuminatum*, and *F. redolens* caused significant disease progression. In contrast to these highly virulent species, *F. solani* was found to be the least virulent in that region [21]. However, in Heilongjiang Province (PRC), among nine *Fusarium* species isolated from 485 root samples, *F. oxysporum* and *F. solani* were the most prevalent and aggressive, causing the most severe root rot symptoms [22]. Our findings align with the latter, as soybean root rot was caused by a Fusarium complex comprising 6 species, with *F. solani* dominant.

Our study of the antifungal activity of *Streptomyces*-based products demonstrated inhibition of *Alternaria* sp. and *F. oxysporum*, but no efficacy against *F. solani*. Nevertheless, their high efficacy against soybeans is well known when used in combination with other agents under field conditions (unpublished but reported industrial trial results). An analysis of 38 studies on the effectiveness of streptomycetes against Fusarium diseases showed that 16 reported disease control levels above 50%, with seven of those exceeding 70% [23]. In Indonesia, an *S. sasae* strain was isolated whose primary secondary metabolite, 2-methyl-1,3-dioxolane, effectively inhibits the growth of *F. solani* and *F. oxysporum* [24]. *Streptomyces* sp. CACIS-1.16CA and *S. lydicus* WYEC 108 suppressed *Alternaria* spp. from tomatoes by 65% and 50%, respectively, compared to 47% and 37% for *F. solani* [25]. The species *S. griseocarneus* R132 inhibited *F. solani* from passion fruit within a range of 23–56% [26].

Fungi of the genus *Trichoderma* act against *Fusarium* spp. as antagonists and mycoparasites, while also enhancing systemic plant resistance. Eight *Trichoderma* species identified from 37 strains in soybean rhizosphere soil demonstrated inhibitory effects of 47.6–72.9% against *F. oxysporum*. Greenhouse trials using strain 223H16 reduced disease development by 83.8% compared to the control. Field application of *Trichoderma* improved soybean growth parameters, including pod number and plant height, and increased rhizosphere fungal diversity, resulting in a 50% reduction in *Fusarium* spp. population [27].

The *Trichoderma* strains isolated in our study showed effective reduction of *F. oxysporum* (69.1–72.7%) but low antagonistic activity against *F. solani* (37.3–54.7%). Ukrainian researchers have previously noted the limited efficacy of local *Trichoderma* strains against *F. solani*. In an antagonism study of 100 strains, 26 inhibited *F. solani* growth by 60% or more, while only six exceeded 70%. This limited efficacy was attributed to the rapid growth of the phytopathogen and its ability to synthesize trichothecenes [11].

The efficacy of two *T. longibrachiatum* isolates (TL6 and TL13) from Gansu Province was studied against winter pea root rot in China, caused by *F. solani* and F. *avenaceum*. By the seventh day, efficacy reached 54.6% (TL6) and 59.1% (TL13). Seed treatment with these isolates enhanced plant growth, reduced root rot incidence, increased antioxidant enzyme activity, and activated plant defense mechanisms [28].

In warmer climates, higher antagonistic activity of *Trichoderma* has been reported.

In India, a comparison of three *Trichoderma* isolates and 24 *Pseudomonas* strains against 11 *F. solani* isolates showed that the fungi performed better. *Trichoderma* inhibited mycelial growth by 65.15–84.40%, whereas bacteria inhibited mycelial growth by only 6.85–59.13% [29]. In Mexico, four *Trichoderma* species were effective against *F. solani* causing strawberry root rot: *T. hamatum* (66.95%), *T. asperellum* (66.91%), *T. konigiopsis* (64.3%), and *T. harzianum* (71.1%) [30]. In Saudi Arabia, out of 30 *Trichoderma* isolates, only four (*T. atroviride*, *T. harzianum*, *T. asperellum*, and *T. viride*) were effective against tomato root rot pathogens *F. solani* and *R. solani*. Among these, *T. asperellum* AATri56 emerged as a promising isolate for suppressing root rot and promoting plant growth [31].

Based on the research of other scientists, the search for biocontrol agents effective against *F. solani* remains a priority, requiring the identification of new isolates and strains from local *Trichoderma* and *Streptomyces* species.

Conclusions

In the root mycobiota of soybean grown without chemical treatments, two dominant microorganisms were identified: the phytopathogen *F. solani* and a Trichoderma species, which restrained the pathogen's development. Under commercial production conditions, *F. solani* remained the most prevalent species within the fungal complex, with isolation frequencies ranging from 12.2% to 42.3% across cultivation sites. The diversity of other phytopathogenic species included various *Fusarium* spp., *Alternaria* spp., *C. cassiicola*, *Ph. sojae*, and *S. sclerotiorum*. Notably, the species *C. cassiicola* was isolated from soybean roots in Ukraine for the first time.

Evaluation of the antagonistic activity of *Trichoderma* isolates from various substrates revealed effective inhibition of *F. oxysporum* (69.1–72.7%) but low efficacy against *F. solani* (37.3–54.7%). Bioproducts based on *Streptomyces* spp. did not restrict the growth of *F. solani in vitro* but effectively suppressed the development of *Alternaria* sp. and *F. oxysporum*. Avercom® demonstrated broader antifungal activity by inhibiting three pathogens, whereas Phytovit was effective against two.

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Author contributions

N. M. Serhiichuk — conducting the study, analysis of the results, and writing the article, T. O. Rozhkova — development of the research concept, planning the experiment, investigation, data curation; Yu. V. Kolomiets — final editing of the article, arrangement of literary sources. All authors agree with the final version of the manuscript.

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ФІТОПАТОГЕННА СКЛАДОВА МІКОБІОТИ КОРЕНІВ СОЇ ТА МОЖЛИВОСТІ ЇЇ БІОЛОГІЧНОГО РЕГУЛЮВАННЯ

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Мета. Ідентифікувати фітопатогенні гриби з коренів сої та оцінити антагоністичну активність ізолятів *Trichoderma* spp. поряд з антифунгальною ефективністю біопрепаратів на основі *Streptomyces* проти них.

Методи. Гриби виділяли на агарі Чапека-Докса (HiMedia) та ідентифікували за морфолого-культуральними ознаками. Антагоністичний потенціал *Trichoderma* spp. оцінювали методом дуальних культур, тоді як антифунгальну ефективність комерційних біопрепаратів визначали методом дифузії в агар.

Результати. Аналіз мікобіоти коренів показав, що домінуючим захворюванням є фузаріозна коренева гниль, спричинена комплексом із шести видів із переважанням *F. solani* (12,2–42,3%). На полях без застосування пестицидів спостерігалося природне регулювання *F. solani* грибами роду *Trichoderma*, тоді як у промисловому виробництві присутність мікопаразитів була незначною. Інші патогени (*C. cassiicola*, *Ph. sojae*, *S. sclerotiorum*) були шкідливими, але мали локальне поширення. Було проведено скринінг ефективних ізолятів *Trichoderma* та комерційних біопрепаратів для пригнічення патогенів.

Висновки. Виділені штами *Trichoderma* виявляли значну антагоністичну активність, зокрема проти *F. oxysporum* (70,9%). Хоча біопрепарати на основі *Streptomyces* демонстрували обмежену антифунгальну ефективність проти *F. solani*, вони залишалися дієвими проти інших супутніх фітопатогенів.

Ключові слова: фітопатогени, *Trichoderma* spp., *Streptomyces* spp., коренева гниль сої, *Fusarium solani*, мікробний антагонізм, біоконтроль.

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