

## BIOTECHNOLOGICAL POTENTIAL OF EFFECTIVE MICROORGANISMS IN RESTORING SOIL FERTILITY AND INCREASING THE RESISTANCE OF OILSEED RADISH (*RAPHANUS SATIVUS* VAR. *OLEIFORMIS*) PLANTS IN AGROECOSYSTEMS

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Soil microorganisms are a crucial element of agroecosystems, as they regulate soil functions, drive biogeochemical transformations, and maintain the stability of agricultural environments. This work considers the role of microbial fertilizers and effective microorganisms (EM) in improving soil fertility, adjusting physicochemical soil properties, and increasing plant tolerance to environmental stress.

Microbial fertilizers are widely regarded as a sustainable and environmentally friendly substitute for conventional mineral fertilizers. Their application contributes not only to increased crop yields and improved product quality but also to the gradual recovery and stabilization of soil structure, which is vital for long-term soil productivity. The microorganisms included in these preparations actively participate in the transformation and circulation of essential nutrients—primarily nitrogen, phosphorus, and potassium—thus reducing the need for high inputs of synthetic fertilizers.

An important aspect is the development and maintenance of balanced microbial populations within the plant rhizosphere. This process lowers the dependence on chemical pesticides and fungicides while strengthening the natural defense mechanisms of plants. As a result, agroecosystems treated with such biological products demonstrate higher adaptability to unfavorable conditions, including drought, pest pressure, and the spread of diseases.

Particular attention is paid to oilseed radish (*Raphanus sativus* var. *oleiformis*) as a biologically active element in agroecosystems. Owing to its well-developed root system and phytosanitary properties, it contributes to improving soil structure, increasing nutrient availability, and stimulating microbial processes in the soil. When combined with effective microorganisms, oilseed radish produces synergistic effects that support the growth of beneficial rhizosphere microorganisms and speed up soil recovery.

The analysis shows that effective microorganisms improve nutrient uptake by plants, promote growth and development, and activate systemic resistance responses. This leads to lower levels of pathogen occurrence and enhances the natural protective capacity of crops. In general, microbial fertilizers possess considerable biotechnological value, as they support both agricultural productivity and the preservation of ecological balance within agroecosystems. *Key words:* effective microorganisms, microbial fertilizers, soil fertility restoration, plant resilience, oilseed radish (*Raphanus sativus* var. *oleiformis*), rhizosphere microbiota, agroecosystems, sustainable agriculture.

### Біотехнологічний потенціал ефективних мікроорганізмів у відновленні родючості ґрунту та підвищенні стійкості рослин редьки олійної (*Raphanus sativus* var. *oleiformis*) в агроекосистемах. Ковка Н.С., Вергеліс В.І.

Мікроорганізми ґрунту є важливою складовою агроекосистем, оскільки вони регулюють функції ґрунту, забезпечують перебіг біогеохімічних процесів і підтримують стабільність сільськогосподарських угідь. У роботі розглянуто роль мікробних добрив та ефективних мікроорганізмів (ЕМ) у підвищенні родючості ґрунту, зміні його фізико-хімічних властивостей і посиленні стійкості рослин до стресових факторів.

Мікробні добрива широко розглядаються як стійка та екологічно безпечна альтернатива традиційним мінеральним добривам. Їх застосування сприяє не лише підвищенню врожайності та поліпшенню якості продукції, але й поступовому відновленню та стабілізації структури ґрунту, що є важливим для довготривалої продуктивності земель. Мікроорганізми, що входять до складу таких препаратів, активно беруть участь у трансформації та кругообігу основних елементів живлення – насамперед азоту, фосфору та калію, – що дозволяє зменшити потребу у внесенні значних обсягів синтетичних добрив.

Важливим аспектом є формування та підтримання збалансованих мікробних угруповань у ризосфері рослин. Це знижує залежність від хімічних пестицидів і фунгіцидів, одночасно підсилюючи природні захисні механізми рослин. У результаті агроекосистеми, оброблені такими біопрепаратами, демонструють вищу здатність адаптуватися до несприятливих умов, зокрема посухи, ураження шкідниками та поширення хвороб.



Окрема увага приділяється редьці олійній (*Raphanus sativus* var. *oleiformis*) як біологічно активному компоненту агроєкосистем. Завдяки добре розвиненій кореневій системі та фітосанітарним властивостям вона сприяє поліпшенню структури ґрунту, підвищенню доступності елементів живлення та активізації мікробіологічних процесів. У поєднанні з ефективними мікроорганізмами редька олійна забезпечує синергічний ефект, який сприяє розвитку корисної ризосферної мікрофлори та прискорює відновлення ґрунту.

Проведений аналіз показує, що ефективні мікроорганізми покращують засвоєння поживних речовин рослинами, стимулюють їх ріст і розвиток, а також активують механізми системної стійкості. Це призводить до зниження рівня ураження патогенами та підвищення природного захисту культур. Загалом мікробні добрива мають значний біотехнологічний потенціал, оскільки сприяють як підвищенню продуктивності агроценозів, так і збереженню екологічної рівноваги в агроєкосистемах. **Ключові слова:** ефективні мікроорганізми, мікробні добрива, відновлення родючості ґрунту, стійкість рослин, редька олійна (*Raphanus sativus* var. *oleiformis*), ризосферна мікробіота, агроєкосистеми, стале сільське господарство

**Problem statement.** Modern agriculture is confronted with a range of global challenges, including soil degradation, declining fertility, reduced diversity of soil microorganisms, as well as the adverse effects of excessive use of agrochemicals and climate change. Together, these factors lead to soil exhaustion, deterioration of soil structure, and a decrease in plant resistance to stress conditions. Effective microorganisms are considered a promising tool for improving the physicochemical properties of soil, enhancing nutrient availability, and strengthening the adaptive capacity of plants. At the same time, their large-scale application requires further scientific justification and evaluation of long-term impacts.

Oilseed radish (*Raphanus sativus* var. *oleiformis*) occupies an important place as a cover crop due to its ability to improve soil structure, reduce compaction, and increase the availability of nutrients through its well-developed root system. However, the combined effect of effective microorganisms and oilseed radish on soil fertility and plant resilience remains insufficiently investigated.

In this context, studying the interaction between effective microorganisms and oilseed radish, as well as their integrated impact on soil condition and crop productivity, is of considerable scientific and practical importance.

**Relevance of the study.** The relevance of this study is обусловлена the growing challenges faced by modern agriculture, particularly soil degradation, declining fertility, and the adverse environmental consequences associated with the intensive use of agrochemicals. In the context of climate change and the increasing demand for sustainable agricultural production, there is a clear need to adopt environmentally safe and resource-efficient approaches.

Effective microorganisms and microbial fertilizers are regarded as promising means for restoring soil fertility, improving its physicochemical characteristics, and strengthening plant tolerance to both biotic and abiotic stress factors. At the same time, considerable attention is given to the use of biologically active crops such as oilseed radish (*Raphanus sativus* var. *oleiformis*), which helps improve soil structure, stimulate microbial processes, and increase the availability of nutrients.

The combined use of effective microorganisms and oilseed radish can produce synergistic effects that

enhance soil recovery processes and contribute to greater stability of agroecosystems. In this regard, studying their biotechnological potential is highly relevant for supporting sustainable agricultural development and maintaining long-term soil health.

**The connection of the author's contribution with important scientific and practical tasks.** The author's work addresses a set of important scientific and applied issues within the framework of sustainable agriculture and environmental protection. The study focuses on advancing biotechnological solutions that help reduce reliance on synthetic fertilizers and pesticides, support more efficient nutrient cycling, and contribute to the recovery of soil microbial communities.

A key aspect of the research is the justification for the joint use of effective microorganisms and oilseed radish (*Raphanus sativus* var. *oleiformis*) as a complementary component within agroecosystems. This integrated approach makes it possible to better utilize natural soil recovery processes and to improve the adaptive capacity of plants when exposed to unfavorable environmental conditions.

From a practical standpoint, the findings may be applied in contemporary farming systems to increase crop yields, enhance soil condition, and improve resilience to various stress factors. In addition, the study aligns with the principles of integrated nutrient management, where biological methods are combined with limited use of chemical inputs. Such an approach helps maintain ecological balance while also contributing to improved economic performance and overall competitiveness of agricultural production.

**Analysis of recent studies and publications.** Over the past several decades, there has been a steady increase in scientific and practical interest in agricultural biotechnology, particularly in the application of effective microorganisms (EM) for improving soil condition and boosting plant productivity. Research findings indicate that EM can positively influence the composition of soil microbial communities, enhance nutrient availability, suppress harmful microorganisms, and improve plant tolerance to environmental stress.

For instance, Zhang et al. (2022) and Singh et al. (2021) demonstrated that consortia of beneficial microbes-including *Bacillus*, *Pseudomonas*, *Rhizobium*, and *Trichoderma*-support better soil aggregation, stimulate nitrogen fixation, and accelerate the

breakdown of organic matter [18]. Similarly, Kumar et al. (2023) reported that microbial formulations can reduce the need for mineral fertilizers without compromising yields, and in some cases even contribute to yield improvements [19].

Choudhary & Johri (2020) noted that many microorganisms synthesize biologically active compounds that enhance plant immune responses and increase resistance to both diseases and abiotic stressors such as salinity, drought, and temperature extremes. Experimental evidence presented by Gopalakrishnan et al. (2022) further confirms that microbial inoculants can raise soil organic matter levels and stimulate the activity of enzymes involved in nutrient transformations [7].

Alongside international research, recent studies conducted in Ukraine provide additional insights. Pavlo Pysarenko et al. (2024) examined the influence of probiotic treatments on the microbiological activity of typical chernozem soils and found that applying a 10% probiotic solution at a rate of 100 l/ha significantly increased the abundance of key microbial groups after 30 days, improving conditions for humus formation and the recovery of microbial communities [24]. Research by Olena Demyanyuk, Lyudmyla Symochko & Dmitry Shatsman (2020) analyzed the dynamics of soil microbiota across different ecosystems in Ukraine and showed that the combined use of mineral, organic, and biological fertilizers increased total microbial populations by approximately 1.3–4.1 times compared to unfertilized soils [25]. Iryna Bidnyha et al. (2025) investigated changes in soil organic matter under the combined influence of microbial preparations and tillage practices in southern Ukraine. Their results indicated that microbial agents accelerated straw decomposition by about 31% relative to the control and contributed to improved humus content, which in turn led to yield increases of 12.8–45.3% in grain sorghum [26].

A notable contribution to the advancement of sustainable agriculture in Ukraine has also been made by Tsytsiura Y.G. [27–28], whose work emphasizes the importance of crop rotation systems, green manure crops, and the biologization of farming practices in maintaining soil fertility. His studies highlight oilseed radish (*Raphanus sativus* var. *oleiformis*) as an effective cover crop that improves soil structure, supports nutrient cycling, and helps suppress soil-borne pathogens. Incorporating oilseed radish biomass into the soil has been shown to increase organic matter content, intensify microbial activity, and create favorable conditions for beneficial soil organisms. These findings support the idea of combining biologically active crops with microbial preparations in modern agroecosystems.

Despite the progress achieved, several aspects still require further investigation, including the selection of optimal microbial consortia for specific soil and climatic conditions, the mechanisms underlying plant–microbe interactions in systems involving cover crops such as oilseed radish, and the long-term impacts of such practices.

Accordingly, future research should focus on clarifying these processes, improving microbial formulations, and integrating effective microorganisms into sustainable agricultural technologies.

**Identification of previously unresolved parts of the overall problem addressed in this article.** Despite the growing body of research on effective microorganisms and microbial fertilizers, several key aspects remain insufficiently explored. In particular, there is limited understanding of the optimal composition and compatibility of microbial consortia under different soil and climatic conditions, as well as their long-term effects on soil fertility, microbial community dynamics, and crop productivity. The mechanisms of interaction between introduced microorganisms and native soil microbiota, especially under stress conditions, also require further investigation. In addition, the combined use of microbial preparations with cover crops, particularly oilseed radish (*Raphanus sativus* var. *oleiformis*), has not been sufficiently studied, especially in terms of rhizosphere processes, nutrient cycling, and stimulation of beneficial microorganisms.

The novelty of the study lies in the integrated assessment of effective microorganisms for restoring soil fertility and enhancing plant resilience, with an emphasis on their synergistic interaction with oilseed radish. The research substantiates the role of microbial fertilizers in improving nutrient cycling, soil structure, and plant defense mechanisms, while highlighting the combined effect of effective microorganisms and oilseed radish in accelerating soil restoration and strengthening agroecosystem stability.

**Methodological or general scientific significance.** The methodological approach of the study is grounded in a combination of general scientific principles and applied research techniques, which together ensure the robustness and reliability of the obtained results.

To achieve the stated objectives, the research employed a range of theoretical, empirical, and analytical methods. Theoretical tools, including analysis, synthesis, induction, deduction, and comparison, were used to examine existing scientific literature, clarify core concepts, and develop the conceptual framework of the study. Empirical methods, such as observation, expert assessment, and statistical data processing, were applied to gather and evaluate information on the investigated processes and to identify the influence of key factors.

Quantitative methods, including correlation–regression analysis and economic-mathematical modeling, were used to determine relationships between variables and to assess the dynamics of the main indicators. At the same time, qualitative methods—such as content analysis and expert evaluation—were used to interpret the findings and provide a deeper understanding of the observed phenomena. The use of systemic and comparative approaches allowed the research object to be viewed as an integrated system and made it possible to compare the obtained results with analogous practices in related contexts.

Particular emphasis was placed on the comprehensive evaluation of agroecosystems involving the use of effective microorganisms in combination with oilseed radish (*Raphanus sativus* var. *oleiformis*) as a cover crop. This enabled the assessment of the contribution of oilseed radish to soil structure improvement, stimulation of microbial activity, and enhancement of nutrient cycling processes, as well as the identification of synergistic interactions within the system.

The information base of the study consists of scientific works by national and international researchers, along with statistical data and analytical materials from relevant sources.

**Presentation of the main material.** Microbial fertilizers are widely recognized as a key component of modern biologized agriculture, as they rely on living microorganisms to support plant nutrition, stimulate physiological processes, and improve overall crop performance. Their use is closely associated with the enhancement of soil quality, including improvements in structure, biological activity, and nutrient availability, which are essential prerequisites for maintaining long-term soil fertility and sustainable production systems.

The action of microbial fertilizers is determined by the metabolic activity of introduced microorganisms within the soil environment. In the course of their development, these organisms produce a range of biologically active compounds, including enzymes, organic acids, and secondary metabolites, which actively influence the composition and functioning of the soil microbiome. As a result, the abundance of beneficial microorganisms increases, soil structure becomes more stable, and the availability of essential macronutrients—particularly nitrogen, phosphorus, and potassium—is improved [3,10].

Microbial communities included in biofertilizers perform distinct but complementary functions in soil processes. Nitrogen-fixing bacteria such as *Azotobacter*, *Rhizobium*, and *Azospirillum* are capable of converting atmospheric nitrogen into plant-available forms. Phosphate-solubilizing and potassium-mobilizing microorganisms facilitate the transformation of nutrients from insoluble to accessible forms. In addition, beneficial microorganisms such as *Trichoderma* spp. and *Bacillus* spp. contribute to the suppression of phytopathogens and help plants better withstand environmental stress.

Another important feature of microbial fertilizers is their ability to stabilize and support the structure of soil microbial communities, ensuring more efficient nutrient cycling and reducing the need for chemical inputs. Their efficiency becomes even more pronounced when combined with oilseed radish (*Raphanus sativus* var. *oleiformis*), which acts as a cover crop improving soil physical properties, increasing organic matter content, and stimulating microbial activity in the rhizosphere.

The joint application of microbial fertilizers and oilseed radish enhances nutrient dynamics, restricts the development of harmful microorganisms, and supports

the formation of a more balanced and resilient agroecosystem. Such integrated use demonstrates clear synergistic effects and aligns with the principles of sustainable and biologically oriented farming systems (Table 1).

The application of microbial fertilizers results in a significant increase in both the abundance and functional diversity of soil microorganisms, particularly those that provide direct benefits to plants. This shift in the soil microbiome contributes to improved soil physical properties, including enhanced aggregation and reduced compaction, while simultaneously increasing the bioavailability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). In addition, microbial formulations play a protective role by limiting the proliferation of soil-borne pathogens and supporting overall plant health and vigor [3,10].

The effectiveness of microbial fertilizers is associated with several key biological mechanisms. These include atmospheric nitrogen fixation, solubilization of phosphorus compounds, and mobilization of potassium from mineral sources, all of which convert nutrients into plant-accessible forms. Furthermore, many beneficial microorganisms synthesize phytoactive compounds that stimulate root growth, improve nutrient uptake efficiency, and enhance plant resilience to abiotic stresses such as drought, salinity, and heavy metal contamination. The establishment of symbiotic associations—particularly with nitrogen-fixing bacteria and mycorrhizal fungi—further strengthens nutrient acquisition and contributes to stable and sustainable crop performance while reducing reliance on synthetic fertilizers.

Empirical studies confirm the positive impact of microbial inoculants on plant development and productivity. In particular, microbial combinations involving *Azospirillum brasilense*, *Bacillus subtilis*, and related strains have demonstrated improvements in vegetative growth, reproductive traits, and overall yield parameters in various agricultural crops [20]. These outcomes are largely attributed to enhanced nutrient cycling processes and the synthesis of phytohormones that regulate plant physiological functions.

Nitrogen is a fundamental element for plant growth; however, atmospheric nitrogen (N<sub>2</sub>) is not directly accessible to plants. Through the process of biological nitrogen fixation, microorganisms such as *Rhizobium* spp. and free-living diazotrophs like *Azotobacter* convert atmospheric nitrogen into ammonia via the nitrogenase enzyme system, thereby enriching soil nitrogen content. Similarly, potassium-mobilizing microorganisms, including *Bacillus circulans*, *Bacillus mucilaginosus*, and *Bacillus edaphicus*, release potassium from insoluble mineral forms through the production of organic acids and mineral weathering processes, increasing its availability to plants.

Phosphorus availability in soils is often limited due to its presence in insoluble or strongly bound forms. Phosphate-solubilizing microorganisms, particularly species of *Bacillus* and *Pseudomonas*, secrete organic

Table 1

## Microorganisms commonly present in microbial fertilizers and their functional roles

Type of microbial fertilizer	Main microorganisms	Function
Bacterial fertilizers (nitrogen-fixing)	<i>Azotobacter chroococcum</i> , <i>Azospirillum brasilense</i> , <i>Rhizobium spp.</i> , <i>Klebsiella spp.</i>	Convert atmospheric nitrogen (N <sub>2</sub> ) into plant-available forms (ammonia, nitrates), thereby enhancing plant growth and improving soil nitrogen balance.
Phosphate-solubilizing bacteria	<i>Bacillus spp.</i> ( <i>B. megaterium</i> , <i>B. cereus</i> , <i>B. mucilaginosus</i> ), <i>Pseudomonas spp.</i> , <i>Rhodopseudomonas spp.</i> , <i>Klebsiella pneumoniae</i> , <i>Alcaligenes spp.</i> , <i>Serratia spp.</i> , <i>Thiobacillus spp.</i> ( <i>Acidithiobacillus thiooxidans</i> , <i>Thiobacillus thioparus</i> )	Solubilize insoluble phosphorus compounds through the production of organic acids and enzymes, increasing phosphorus availability for plant uptake.
Potassium-mobilizing bacteria	<i>Bacillus edaphicus</i> , <i>Bacillus mucilaginosus</i>	Release potassium from mineral structures (silicates) via mineralization processes, increasing the pool of plant-available potassium in soil.
Lactic acid bacteria	Lactic acid bacteria (various genera)	Produce organic acids and antimicrobial substances that suppress soil pathogens, stimulate root development, and improve nutrient absorption.
Fungal fertilizers (mycorrhizal fungi)	Mycorrhizal fungi (Ascomycota and related groups)	Enhance nutrient and water uptake through symbiosis with plant roots, secrete enzymes and organic acids, improve soil aggregation and structure.
Actinomycete fertilizers	<i>Streptomyces spp.</i> ( <i>S. jingyangensis</i> , <i>S. pactum</i> , etc.)	Produce bioactive compounds with antimicrobial properties, suppress phytopathogens, decompose organic matter, reduce soil bulk density, and improve soil physical characteristics.

acids and chelating agents that lower soil pH and facilitate the transformation of phosphorus into forms that can be readily absorbed by plants.

A promising approach in modern agroecosystem management involves the integrated use of microbial fertilizers with cover crops such as oilseed radish (*Raphanus sativus* var. *oleiformis*). Due to its extensive and well-developed root system, oilseed radish improves soil structure, alleviates compaction, and enhances the redistribution of nutrients within the soil profile. Its biomass contributes to organic matter accumulation and stimulates microbial activity in the rhizosphere. When combined with microbial fertilizers, oilseed radish intensifies rhizosphere interactions, promotes nutrient cycling, and supports the development of a stable and functionally active soil microbiome. This integrated strategy ultimately leads to improved soil fertility, increased crop productivity, and greater sustainability of agroecosystems.

Fig. 1 illustrates the interaction of *Pseudomonas* spp. with soil phosphorus minerals, demonstrating the secretion of organic acids that facilitate the dissolution of insoluble phosphate compounds.

Soil microorganisms constitute an essential part of the soil system, determining its biological activity, stability, and overall ecological functioning. Their importance becomes particularly evident in agroecosystems where oilseed radish (*Raphanus sativus* var. *oleiformis*) is grown, as this crop is highly sensitive to the condi-

tion of the soil microbiome. A well-balanced and active microbial community is therefore a critical prerequisite for its normal growth and development.

Any disturbances in the composition or activity of soil microorganisms can negatively affect oilseed radish. A decline in beneficial microbial populations disrupts soil processes, creates conditions favorable for the development of phytopathogens, and ultimately degrades the growing environment. Under such conditions, plants experience increased stress and are less able to realize their genetic productivity potential. At the same time, beneficial microorganisms contribute to plant protection by producing microbe-associated molecular signals (MAMPs), which are recognized by plants and trigger appropriate defense mechanisms, allowing them to respond effectively to both harmful and neutral microorganisms.

The diversity and abundance of beneficial soil microbes serve as important indicators of soil fertility and directly influence the performance of oilseed radish. A rich and active microbial community supports better root development, promotes biomass accumulation, and improves seed formation. The use of microbial fertilizers plays a significant role in this context, as it helps establish a more favorable rhizosphere environment around the root system of oilseed radish, increasing microbial diversity and overall biological activity. In addition, such fertilizers stimulate native soil microbiota and, together with organic amendments, create conditions

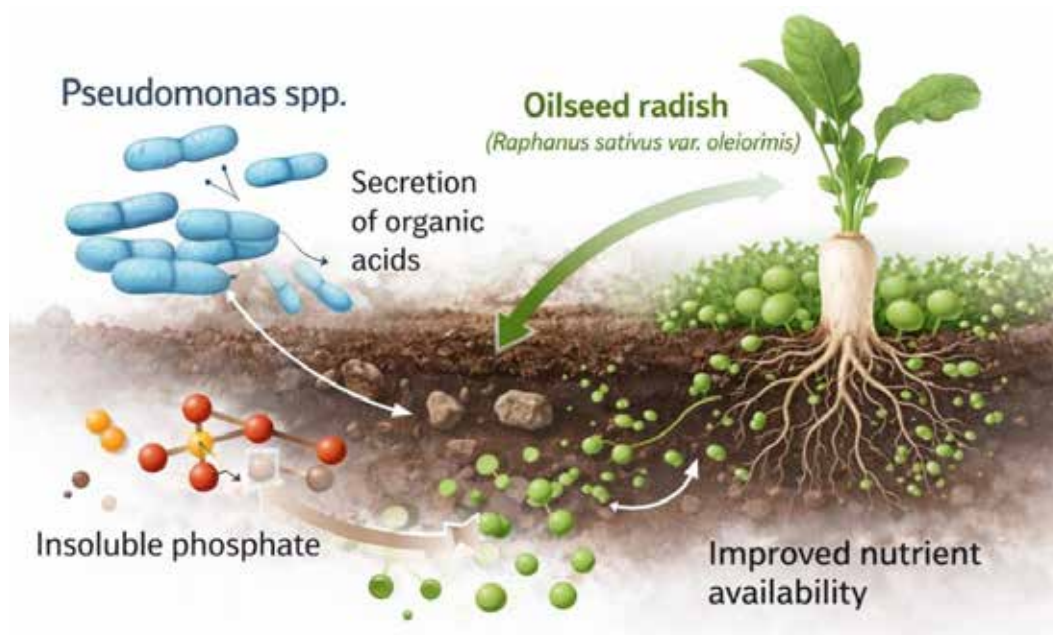


Fig.1. Interaction of *pseudomonas spp.* and oilseed radish (*Raphanus sativus var. oleiformis*) with soil phosphorus minerals

that better align with the physiological requirements of the crop. This contributes to improved nutrient availability, enhanced soil structure, and more effective plant establishment.

As shown in Fig. 2, these microbial communities also limit pathogen development through competitive interactions, improve soil aggregation, and increase the availability of key nutrients (N, P, K), thereby creating more favorable conditions for plant growth.

High-throughput sequencing of soil microbial communities following the application of microbial fertilizers enables a more comprehensive evaluation of the mechanisms that regulate microbial population dynamics in agroecosystems. This methodology is particularly relevant for oilseed radish (*Raphanus sativus var. oleiformis*), since its growth performance, root architecture, and yield formation are closely associated with the structure and functional activity of the soil microbiome. The introduction of microbial fertilizers promotes the proliferation of beneficial microorganisms, increases microbial diversity, enhances soil fertility, and helps maintain more stable and favorable conditions for oilseed radish cultivation [11,15,19].

In oilseed radish production systems, the prolonged and intensive use of mineral fertilizers may result in soil degradation processes, including compaction, decreased porosity, reduced aeration, and impaired water infiltration. These changes negatively affect root penetration and overall plant development. The application of microbial fertilizers mitigates these adverse effects by stimulating microbial activity, supporting biodiversity within the soil microbiome, and facilitating the formation of stable soil aggregates. Consequently, soil phys-

ical properties are improved, aeration is enhanced, and the root zone environment becomes more conducive to proper root growth. Moreover, microbial formulations that include halotolerant strains can help reduce the negative impact of soil salinity, further contributing to the optimization of growth conditions for oilseed radish.

Soil microorganisms, particularly bacteria and fungi, are essential for the formation and stabilization of soil aggregates, thereby improving soil structure and enhancing nutrient availability and uptake. This is especially relevant for oilseed radish (*Raphanus sativus var. oleiformis*), which requires accessible forms of nitrogen (N), phosphorus (P), and potassium (K) to support biomass accumulation and yield formation.

Oilseed radish is susceptible to a wide range of pathogens; therefore, microbial fertilizers enriched with antagonistic microorganisms such as *Trichoderma* spp., *Pseudomonas aureofaciens*, and *Streptomyces* spp. are effectively used for biological disease control. These microorganisms suppress pathogens through competitive exclusion, production of antimicrobial metabolites, and inhibition of pathogen development. For instance, *Bacillus amyloliquefaciens* DH-4 produces thermostable compounds that disrupt pathogen cell structures, reducing infection pressure.

Through mechanisms including antibiosis and induced systemic resistance, microbial fertilizers enhance plant tolerance to biotic stress and improve overall plant health. In contrast, excessive use of chemical fertilizers and pesticides leads to soil degradation, compaction, and reduced biological activity, negatively affecting root development and nutrient uptake in oilseed radish systems.

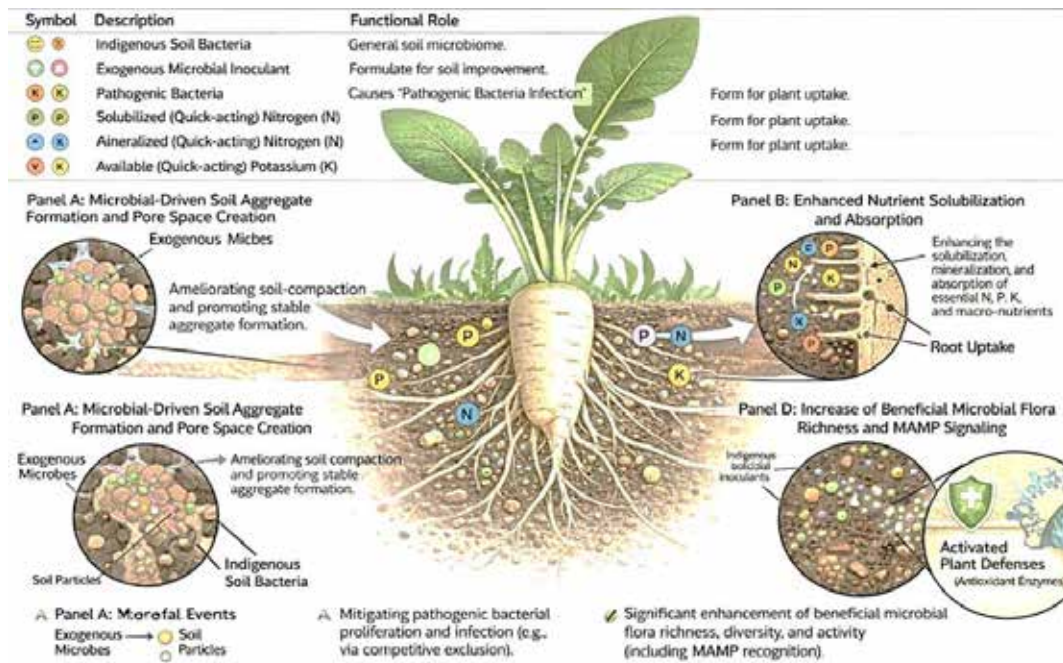


Fig. 2. The role of established microorganisms in shaping the productivity of oilseed radish (*Raphanus sativus* var. *oleiformis*)

Microbial fertilizers help mitigate these negative effects by stimulating microbial activity, decomposing pesticide residues, improving soil aeration, and restoring favorable conditions for root growth. Certain strains, such as *Pseudomonas pseudoalcaligenes* PS-5, are capable of degrading toxic compounds like ethyl parathion, contributing to soil detoxification. As a result, microbial inoculants enhance microbial diversity, improve soil physicochemical properties, and increase enzymatic activity, supporting plant resilience and soil functionality.

In addition, microbial fertilizers contribute to nutrient cycling and long-term soil health by promoting the decomposition of organic matter, the formation of stable soil aggregates, and the maintenance of a balanced microbial community. They also induce systemic resistance in plants, strengthening their defense mechanisms against various stress factors [13,19].

Recent studies highlight the effectiveness of microbial consortia in improving growth and stress tolerance of oilseed radish. In particular, inoculation with *Azospirillum brasilense*, *Bacillus subtilis*, and *Trichoderma harzianum* has been shown to increase biomass, enhance chlorophyll content, and improve resistance to drought and salinity stress [20,21]. These effects are particularly important for oilseed radish used in crop rotations and as a cover crop. Overall, microbial fertilizers enhance both plant productivity and resilience by activating multiple beneficial mechanisms, including induced systemic resistance (ISR), ensuring stable development under varying environmental conditions [22].

For instance, inoculation with *Trichoderma harzianum* has been shown to increase the activity of plant antioxidant enzymes by approximately 35–40%, thereby mitigating oxidative stress under drought and salinity conditions [23]. Similarly, *Bacillus subtilis* and *Azospirillum brasilense* stimulate root system development by promoting elongation and lateral branching, which enhances water and nutrient uptake; in treated plants, root length may increase by 20–25% compared to untreated controls [24].

Numerous studies confirm the beneficial effects of microbial fertilizers on crop performance under stress conditions. In sunflower, a microbial consortium consisting of *Azospirillum brasilense*, *Bacillus subtilis*, and *Mucilaginibacter polysaccharea* increased plant height by 15–18%, the number of flower heads by 12–15%, and seed yield by 20–22% [20]. In maize, inoculation with *Bacillus amyloliquefaciens* enhanced drought tolerance, leading to increases in biomass (18–20%) and grain yield (15–17%) compared to the control [25]. In wheat, phosphate- and potassium-solubilizing bacteria improved nutrient uptake by 10–12%, reduced disease incidence by about 30%, and contributed to more stable yield and grain quality [26,25].

In oilseed radish (*Raphanus sativus* var. *oleiferus*), the combined application of *Trichoderma harzianum* and *Bacillus subtilis* resulted in a ~25% increase in root biomass, a ~20% increase in shoot dry mass, and an 8–10% rise in seed oil content under moderate drought conditions.

Table 4 summarizes the principal microbial agents and their functional roles in enhancing plant stress tol-

Table 2

**Major plant pathogens relevant to oil radish (*Raphanus sativus* var. *oleiformis*) and their suppression by beneficial microorganisms**

Crop/Disease Context (including oil radish)	Main pathogenic microorganisms	Suppression by beneficial microorganisms
Fungal leaf and root diseases (incl. oil radish)	<i>Magnaporthe oryzae</i>	<i>Fusarium</i> spp., <i>Armillaria novae-zelandiae</i> , <i>Falciphora oryzae</i>
Grey mold (relevant to oil radish under влажні умови)	<i>Botrytis cinerea</i>	<i>Bacillus subtilis</i> , <i>Bacillus amyloliquefaciens</i>
Rust diseases (analogous risks in oil radish systems)	<i>Puccinia</i> spp.	<i>Doru luteipes</i>
Root rot and wilt diseases affecting oil radish	<i>Fusarium graminearum</i>	<i>Bacillus cereus</i> , <i>Azotobacter nigricans</i>
Vascular wilts (including potential threats to oil radish)	<i>Fusarium oxysporum</i>	<i>Bacillus amyloliquefaciens</i>
Anthraco-like diseases in Brassicaceae (incl. oil radish)	<i>Colletotrichum sublineolum</i>	<i>Trichoderma harzianum</i> , <i>Fusarium oxysporum</i> , beneficial protozoa

Table 3

**Multifunctional EM fertilizers on soil and plant health with emphasis on oil radish (*Raphanus sativus* var. *oleiferus*)**

Function	Mechanism	Outcome for Oil Radish ( <i>Raphanus sativus</i> var. <i>oleiferus</i> )
Nitrogen fixation	Symbiotic (Rhizobia, Frankia) and free-living bacteria ( <i>Azotobacter</i> , <i>Azospirillum</i> ) convert atmospheric N <sub>2</sub> to ammonia	Enhanced nitrogen availability supports rapid vegetative growth and biomass accumulation, important for root development and green mass of oil radish
Phosphate solubilization	Phosphate-solubilizing bacteria ( <i>Bacillus</i> , <i>Pseudomonas</i> , <i>Escherichia</i> ) release organic acids	Promotes stronger root system development, improves nutrient and water uptake, increases seed yield and oil content
Potassium mobilization	Potassium-solubilizing bacteria ( <i>Bacillus circulans</i> , <i>B. mucilaginosus</i> ) mineralize insoluble K	Enhances stress tolerance (drought, cold), ensures optimal accumulation of dry matter and oil in seeds
Biocontrol of pathogens	Antagonistic microorganisms ( <i>Trichoderma</i> , <i>Bacillus</i> , <i>Pseudomonas</i> ) compete with pathogens and produce antibiotics	Reduces incidence of root and foliar diseases, improves overall plant health and seed quality
Soil structure improvement	Microbial metabolites and fungal hyphae stabilize soil aggregates	Increases aeration and water retention, enhancing root growth and nutrient absorption, crucial for oil radish root development
Degradation of pollutants	Microbes such as <i>Pseudomonas pseudoalcaligenes</i> degrade pesticide residues	Detoxifies soil, supports microbial diversity, and improves the environmental safety of oil radish cultivation

erance and productivity, with particular emphasis on oil-seed radish. As presented, the effects of different microorganisms are mediated through mechanisms such as nutrient solubilization, biological nitrogen fixation, exopolysaccharide production, and induction of systemic resistance. In oilseed radish, these processes are especially pronounced, where inoculation with *Trichoderma harzianum*, *Bacillus subtilis*, and *Azospirillum brasilense* improves root elongation and branching by 20–25%, increases root and shoot biomass by 20–25%, and enhances seed oil content by 8–10% under moderate drought stress.

The cumulative effects of these microorganisms result in enhanced root development, improved nutrient uptake, and greater resilience against both biotic and abiotic stresses. By simultaneously influencing soil biological activity and plant physiological responses, microbial inoculants contribute to the establishment of a more stable and efficient plant–soil system. This integrated action supports balanced growth, optimizes resource utilization, and ultimately leads to improved crop performance under variable environmental conditions.

Figure 3 illustrates the relative contribution of various microbial groups to crop yield and stress tolerance.

Table 4

**Microbial agents enhancing stress tolerance and productivity in oil radish and other crops**

Microbial Agent	Type of Stress Mitigated	Mechanism	Observed Outcome for Oil Radish ( <i>Raphanus sativus</i> var. <i>oleiferus</i> )
<i>Trichoderma harzianum</i>	Drought, salinity	Enhances antioxidant enzyme activity, induces systemic resistance	Antioxidant enzyme activity increased by 35–40%, reduced oxidative damage, higher root and shoot biomass (25% and 20% increase, respectively)
<i>Bacillus subtilis</i>	Drought, pathogen infection	Root growth stimulation, ISR activation, antibiotic production	Improved root elongation and branching (20–25% increase), reduced disease incidence, higher seed yield
<i>Azospirillum brasilense</i>	Nutrient limitation, drought	Nitrogen fixation, phytohormone production	Increased nutrient uptake (10–12%), enhanced vegetative growth, higher seed yield (8–10% increase in oil content)
<i>Mucilaginibacter polysaccharea</i>	Salinity, soil compaction	Production of exopolysaccharides, soil aggregation	Improved soil structure, better water retention, enhanced stress resilience for roots and shoots
<i>Bacillus amyloliquefaciens</i>	Pathogens, drought	Antimicrobial compound production, ISR activation	Reduced disease incidence, improved drought tolerance, increased productivity and biomass accumulation

Nitrogen-fixing bacteria predominantly enhance yield by supplying assimilable nitrogen, whereas *Trichoderma* spp. and *Bacillus* spp. primarily strengthen plant resistance to pathogens and environmental stresses.

Additionally, the synergistic interaction between different functional groups of microorganisms further amplifies their overall effectiveness. When combined within microbial consortia, nitrogen-fixing, phosphate-solubilizing, and biocontrol microorganisms can simultaneously improve nutrient availability, stimulate plant growth regulators, and suppress pathogenic populations. This integrated functionality leads to more efficient colonization of the rhizosphere, enhanced microbial stability, and a more robust response of plants to environmental fluctuations, which is particularly important for maintaining consistent productivity in agroecosystems.

As illustrated in Fig. 3, different microbial groups contribute variably to the productivity and stress tolerance of oil radish (*Raphanus sativus* var. *oleiferus*) under moderate drought. *Trichoderma harzianum* shows the highest impact on enhancing stress tolerance, largely through improved antioxidant activity and biomass increase. Species within the *Bacillus* genus offer a balanced approach: *B. subtilis* significantly supports root growth, while *B. amyloliquefaciens* excels in increasing overall productivity through systemic resistance (ISR). *Azospirillum brasilense* also provides considerable benefits, with an 8–10% increase in seed oil content being notable.

Overall, the synergistic use of these diverse microbial groups in biofertilizers can maximize oil radish produc-

tivity and improve plant resistance to abiotic stressors like drought, highlighting the importance of integrating microbial-based solutions into sustainable agricultural practices for this crop.

**Main conclusions.** The study demonstrates that microbial fertilizers significantly enhance the diversity of beneficial microorganisms, which is critical for maintaining microecological balance and improving soil and plant health. Through the production of secondary metabolites, proteins, enzymes, and plant hormones, these fertilizers stimulate plant growth and enhance the uptake of essential nutrients such as nitrogen, phosphorus, and potassium.

These findings confirm the potential of microbial fertilizers as an effective and sustainable alternative to chemical fertilizers, promoting environmentally friendly agricultural practices. Further research should focus on: investigating the long-term effects of microbial fertilizers on soil microbial communities and crop productivity; optimizing formulations to target specific crops and environmental conditions; exploring the synergistic effects of combined microbial consortia to maximize nutrient availability and stress tolerance in plants; assessing the economic feasibility and scalability of microbial fertilizer applications in different agricultural systems.

**Prospects for using the research results.** The results of this study open new perspectives for the transition to sustainable and ecologically oriented agricultural technologies. Theoretical and practical conclusions can be used for: developing integrated crop protection and nutrition programs that combine

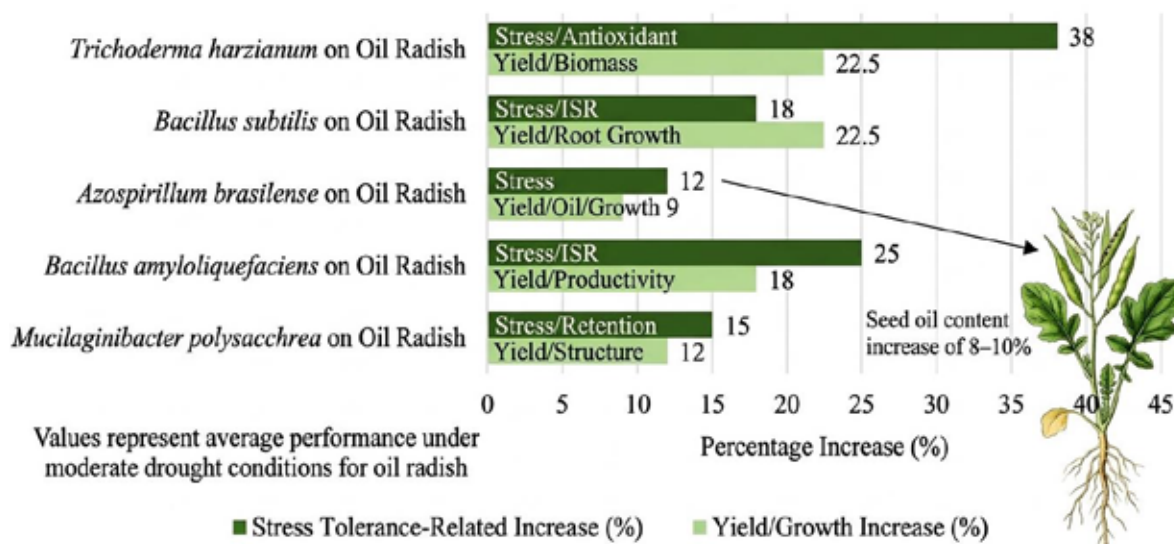


Fig. 3. Microbial effects on oil radish (*Raphanus sativus* var. *oleiferus*) under moderate drought

minimal required amounts of mineral fertilizers and pesticides with highly effective microbial preparations, aimed at achieving stable yields while minimizing environmental pressure; creating new targeted complex microbial consortia tailored to specific soil and climatic conditions of Ukraine and various crop rotation systems, ensuring maximum efficiency of biofertilizer application; substantiating strategies for restoring degraded and exhausted soils by identify-

ing key microbial groups capable of revitalizing the natural fertility of chernozems and other soil types; enhancing the competitiveness of Ukrainian agricultural production on the international market by implementing green technologies and reducing dependence on expensive chemical inputs.

Overall, integrating microbial fertilizers into modern agricultural practices offers promising prospects for sustainable crop production and soil health management.

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