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PRELIMINARY COMMUNICATION

Soil Microorganism: Key Drivers of Soil Fertility and Plant Health

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Summary

This paper highlights the importance of the biological component of soil and provides guidelines for achieving an optimal abundance of soil microorganisms through proper soil management. Microorganisms are an integral part of the soil's living phase, contributing to the decomposition of organic matter and driving biogeochemical cycles, including carbon, nitrogen, sulfur, phosphorus, and other elements. Additionally, they produce compounds that enhance nutrient availability, such as siderophores that facilitate iron uptake. Microorganisms also increase plant resistance to biotic and abiotic stresses, induce defense mechanisms against phytopathogens, and promote plant growth through the biosynthesis of growth regulators. Moreover, they play a key role in the degradation of xenobiotics, helping to reduce environmental pollutants. Their extracellular polymeric substances contribute to the formation of stable soil aggregates, improving soil aeration and water infiltration. As a fundamental biological component of soil fertility and crop productivity, microorganisms are essential for maintaining biological balance and ensuring overall ecosystem health.

Key words: soil health, nutrient cycling, PGPM, biopesticides, sustainable agriculture

Introduction

Soil is an ideal habitat for microscopic and macroscopic organisms, and its composition depends on physical, chemical and biological properties as well as environmental conditions. Microbial biomass in soil accounts for 1–5% of total organic matter, with fungi accounting for up to 90% of this biomass (Hopkins and Dungait, 2010). The highest concentration of microorganisms is found in the surface layers of the soil, where organic matter is most abundant. Soil microorganisms play a crucial role in maintaining the balance and health of the soil. In addition to decomposing organic matter, they are also involved in various biochemical processes and contribute to nutrient cycling and humus formation, which increses soil fertility. Understanding the microbial processes in soil and the interactions between abiotic and biotic factors is essential for maintaing soil fertility through sustainable agricultural practices.

Microorganisms in the element cycling and in soil aggregation

Microorganisms enhance the availability of nutrients by participating in the biogeochemical cycles of carbon, nitrogen, phosphorus, potassium, sulfur, iron and other microelements. Carbon cycling is essential for maintaining the natural carbon balance and has a significant impact on climate change and ecosystem health. Heterotrophic microorganisms contribute to carbon released into the atmosphere through organic material decomposition and respiration. Carbon is fixed in the soil by the assimilation of CO_2 through photosynthesis by photoautotrophs, phototrophic and chemoautotrophic bacteria. In anaerobic soil conditions, during the decomposition of organic matter, methanogenic bacteria produce methane, which volatilizes into the atmosphere and influences the negative effects of climate change. Aerobic and anaerobic microorganisms participate in the decomposition of organic matter in the process of ammonification. Various species of the genus *Nitrosomonas* and *Nitrobacter* oxidize ammonia to nitrite in the nitrification process, while nitrites formed during denitrification are reduced to elemental nitrogen by denitrifying bacteria. Free-living soil bacteria of the genus *Azotobacter*, *Clostridium*, *Bejirenckia*, *Azospirillum* and other diazotrophs, fix elemental nitrogen and reduce it to ammonia. Symbiotic nitrogen fixers such as bacteria of the genus *Azorhizobium*, *Bradyrhizobium*, *Rhizobium*, *Mesorhizobium*, *Frankia* and cyanobacteria *Anabeana* and *Nostoc*, which can also live freely, form a mutualistic community with higher plants and fix significant amounts of nitrogen. Microorganisms, especially bacteria and fungi, play a key role in phosphorus mineralization, the process in which organic phosphorus substances are broken down into inorganic phosphate forms through the catalytic action of phosphatase. Phosphorus is present in the soil in large quantities as poorly soluble inorganic phosphates such as $Ca_3(PO_4)_2$ or $FePO_4$, which are unavailable to plants. Phosphorus solubilization enables bacteria of the genus *Pseudomonas*, *Bacillus* and fungi *Penicillium*, *Aspergillus*, *Fusarium* and mycorrhizae to break down these compounds into plant-available forms with the help of organic acids.

Various species of the genus *Bacillus*, *Pseudomonas*, *Arthrobacter*, *Acidothiobacillus* and others participate in the potassium cycle and its availability to plants. Through processes such as mineral decomposition, mineralization of organic matter, production of organic acids and formation of complexes with potassium, microorganisms help release potassium from unavailable forms in the soil making it accessible for plant absorption. These microbiological processes are essential for soil health and crop productivity, providing plants with the potassium necessary for growth and development. Microorganisms play a key role in many stages of the sulfur cycle, facilitating the transformation of sulfur between different chemical forms. Microorganisms in soil and aquatic ecosystems can break down organic sulfur compounds, releasing sulfur in the H_2S form. Chemo- and photolithotrophs such as green sulfur and purple sulfur bacteria use H_2S as a source of electrons in the process of anaerobic photosynthesis. The oxidation of elemental sulfur to sulfate is carried out by photosynthetic and chemolithoautotrophic microorganisms, while the reduction of sulfate by sulfate-reducing bacteria of the genus *Desulfovibrio* and *Desulfomonas* results in the formation of hydrogen sulfide. Microorganisms are involved in the iron cycle in nature, which, although an essential element for many biological processes, is not always in an easily accessible form. Microorganisms influence the oxidation-reduction state of iron, primarily by producing siderophores that bind Fe^{3+} and reduce it to Fe^{2+}. In this way, siderophores help maintain the balance of iron in nature, making it available in forms that would otherwise be difficult for plants to use. Additionally, microorganisms influence the accessibility of other micronutrients such as zinc, copper, manganese, molybdenum, boron and cobalt. Bacteria play a significant role in forming stable soil aggregates, which help maintain soil quality, structure, and productivity. The stability of these aggregates improves aeration, water permeability, root growth and nutrient retention. Extracellular polymeric substances, especially polysaccharides are crucial for the stability of micro and macro aggregates, as they help retain water within the aggregates, reducing erosion. This creates better conditions for plants, making them more resilient to external factors such as rain, wind, or human activity. Furthermore, these substances reduce soil compaction by maintaining structural stability and increasing soil porosity, which improves air and water flow. The network of fungal hyphae also connects soil particles and forms stable macroaggregates that are more resistant to erosion and breakage.

Plant growth promoting microbes

PGPM (Plant growth promoting microbes) represent various categories of microorganisms that positively influence plant growth through different mechanisms. These microbes improve plant health, enhance productivity, increase stress resistance and improve soil nutrient efficiency. The most common microorganisms in this category include bacteria from the genus *Azospirillum*, *Rhizobium*, *Pseudomonas*, *Bacillus*, *Enterobacter* and others, as well as fungi such as mycorrhiza and species from the genus *Trichoderma*. These microbes often exist in symbiosis with plants or reside in the rhizosphere where they directly influence plant growth. In addition to their role in nitrogen fixation, phosphorus solubilization and soil aggregation, these microorganisms produce plant hormones, such as auxins, cytokinins, and gibberellins, which stimulate plant growth (de Andarde et al., 2023). These hormones promotes root development, promote the formation of new shots and improve nutrient absorption. Microorganisms from the genus *Bacillus* and *Pseudomonas* synthesize secondary antimicrobial metabolites, including iturin, surfactin 2,4-diacetyl phloroglucinol (DAPG), and phenazines – compounds that inhibit pathogenic microorganisms, induce systemic resistance (ISR) in plants and improve plant disease resistance and can be used both preventively and curatively in the biological control of plant diseases (Dimkić et al., 2021). Furthermore, microorganisms help plants cope with environmental stress such as drought, by producing antioxidants that mitigate oxidative stress, enhancing water uptake, and lowering ethylene levels via ACC deaminase production. The use of PGPM in agriculture is becoming increasingly popular due to its environmental and economic benefits. However, a deeper understanding of the interactions between microbes, plants and soil is necessary to determine the conditions under which these microorganisms function most effectively (Moore et al., 2022).

Environmentally friendly and effective pesticides

The intensive use of agrochemicals, including plant protection products, to prevent and control plant diseases and to achieve high yields is common in agricultural production. However, their use can lead to several negative impacts, such as persistence, bioaccumulation, leaching into water resources, toxicity to non-target organisms, the development of resistance in pests and potential risks to human health. To minimize these adverse effects, it is crucial to research and develop safe, sustainable alternatives. One strategy includes optimizing the chemical structure of new plant protection products, such as heterocyclic compounds like imidazole. Heterocyclic compounds have potential advantages as next-generation pesticides due to their specific biological activity, faster environmental degradation, lower toxicity, greater selectivity, reduced risk of resistance development, and lower potential for bioaccumulation. They represent a safer alternative to traditional broad-spectrum chemical pesticides, by minimizing negative environmental and health impacts (Rastija et al., 2021). The design of new molecules with desirable properties involves optimizing their chemical structures to enhance biological activity and selectivity using the Computer-Aided Molecular Design (CAMD) approach. This includes methods such as Quantitative Structure-Activity Relationship (QSAR) analysis, which examines the relationship between the chemical structure and the biological activity.

How to increase the abundance of soil microorganisms?

The optimal abundance of beneficial microorganisms in the soil can be achieved through sustainable soil management, which improves soil fertility and structure while increasing plant resilience. Some important guidelines for maintaining healthy, microbiologically rich soil include supporting soil interactions by encouraging symbiotic relationships between plants and microorganisms, such as mycorrhiza and PGPM, which are essential for soil health. Plants that interact harmoniously with microorganisms create favorable conditions for their growth and reproduction. Regular application of organic material such as compost, and manure, which serves as a food source for microorganisms, stimulates microbial activity, maintaining their abundance and diversity. It is also important to maintain optimal soil moisture to support microbial life. Reducing the use of chemical pesticides and fertilizers, which can negatively impact beneficial microorganisms, is crucial; instead, integrated approaches to pest control and nutrient optimization should be pursued. Crop rotation and diversification help sustain soil health while minimizing excessive tillage to preserve microbial community dynamics. Sowing cover crops and using crop residues helps to conserve moisture, reduce nutrient leaching and prevent erosion and organic matter loss. Additionally, applying microbial inoculants such as biofertilizers and biopesticides containing beneficial microorganisms enhances microbial biodiversity. Implementing these guidelines will help maintain the balance of microbial communities in the soil, ensuring long-term fertility and sustainability in agricultural production.

Conclusions

Soil microorganisms are essential for maintaining soil fertility and promoting plant health by enhancing plant nutrient uptake and improving crop yields, while microbial diversity ensures ecosystem stability. However, the excessive use of chemical fertilizers and pesticides in agricultural practices can disrupt microbial communities, leading to soil degradation. Sustainable agricultural practices help preserve microbial diversity and boost soil productivity. Additionally, climate change and environmental factors significantly affect microbial composition, influencing their ability to sustain soil fertility. Understanding soil microbiomes has led to the biofertilizers and biopesticides development, reducing reliance on synthetic chemicals and promoting sustainable agriculture. Therefore, the conservation and restoration of microbial communities are vital for long-term soil health, agricultural productivity and global food security. Future research on soil microbiomes will offer innovative solutions for mitigating environmental challenges and ensuring a sustainable agricultural future.

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