

# Soil Microorganisms' Role in Enhancing Soil Fertility and Plant Health

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## Abstract

Disrupting the ecological balance between soil, plants, and microorganisms certainly had major consequences as it was the indiscriminate use of different pesticides to increase agricultural productivity. Agricultural soil is mainly filled with soil microorganisms. The soil fertility and ability of plants growth is required by them. In addition, they boost the quality of the soil. They are a defense against diseases as well as insect infestations. The microbial strains promote plant growth and keep the soil healthy. Root interactions and soil texture are augmented by the bioavailability of microorganisms in soil rhizospheres. The pH of the soil is also changed by soil microorganisms. In this chapter, the significance of soil microorganisms to soil fertility, plant productivity, and plant health was stressed. This eco-friendly use of microorganisms helps boost the plant's growth and improves the vitality of the soil. This chapter highlight the key mechanisms by which soil microorganisms influence soil fertility and plant health.

**Keywords:** Soil fertility, Soil vigor, Plant vitality, Microorganism, Health

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## Introduction

Soil ecological functions and services have been considerably impacted by microorganisms in their diversity, which have continuously been vital components of the soil complex. The soil developed an eco-physiological setting for the interaction of microorganisms with other organisms such as the subterranean and aerial. Air, water, minerals, organic matter, and a wide range of macro- and microbes make up the soil ecosystem, a pretrial life support system (Deyn & Kooistra, 2021). Several soil types and pedogenesis have been recorded in which, bacteria, fungi, algae, actinomycetes, nematodes, and viruses show different compositions through the changes in biogeochemical cycling and plant productivity (Xiong et al., 2021). As a result, soil microorganisms can serve as a sensitive indicator of soil fertility, environmental changes, dysbiosis, and pollution, and may be a good metric to monitor the soil quality impacted by land use management practices over time (Wilhelm et al., 2022). There are a lot of microorganisms in soils and they make up about 75 percent of the Earth's global biomass. Together these account for up to 15% of living biomass, whereas fungi and archaea are present in less than 2% and 1% of total living biomass respectively (Banerjee & Heijden, 2023).

But soil is an essential and fragile natural resource on the Earth. Healthy crops are, of course, vital to the production of crops that increase yield, cleanse water, provide food for the animals and the human race, as well as a carbon sink, so contributing to climate regulation and therefore should be a priority for agricultural researchers and farmers. Sometimes 'quality' and 'health' are almost interchangeable phrases for a soil's ability to sustain a balanced ecosystem and provide nutrient for plants. Simply, soil quality is the soil ability to supply functions such as bioproduction support, plant and animal health promotion and environmental quality in relationship to ecosystem and land use criteria (Alori et al., 2024). The biological, chemical, and physical characteristics of soil essential for sustainable agricultural productivity with minimal environmental impact are known as soil quality. An ecosystem of interdependent components ensures healthy soil (Brevik et al., 2020). Good soil has a balance between the happiness of the inhabitants of its species, quality of its environment and its productivity (Khatoun et al., 2020).

Rhizosphere microorganisms are tightly linked to plants for nutrient acquisition, modification of soil physical and chemical properties, and plant hormone signaling. For such evaluation of plant health or such alleviating diseases due to biotic or abiotic stressors of plant diseases

using rhizodeposition, these parameters are essential (Dlamini et al., 2022). It is very important to note that soil microorganisms are very much affected by global climate change and this likewise impacts the soil with regard to the nutritional composition and structure of the soil (Vincze et al., 2024). Fertilizer application modifies the nutritional profile of the soil and change the activity of soil microorganisms (Jansson & Hofmockel, 2020). Microbial diversity around and inside plant roots is reduced by soil salinity stress (Seleiman et al., 2023; Alenazi et al., 2024). Heavy machinery and overgrazing lead to soil compaction, which reduces the pore space between soil particles, increases bulk density, and makes soil less porous and less permeable to water, air, or roots. This lowers soil fertility and productivity and compromises environmental quality; (Shaheb et al., 2021).

Strong ecological principles that optimize the benefits of organisms in the ecosystem, sustainable agriculture seeks to meet the needs of the present generation while maintaining the use of resources for future generations. Typically, this implies a long-term specific application particular to a location in which plant and animal life have developed as a unified system. Cropping patterns that involve the use of resources as well as available technology are part of the cropping system, such as intercropping, mixed cropping, and sequential cropping. In these systems improved management strategy and agricultural productivity require consideration of the spatial distributions of microorganisms (El-Ramady et al., 2024). Continuous farming may lower the bacterial population in the soil, increase the relative number of fungi. Such a decrease in buffering capacity against selective biotic and abiotic stress may facilitate disease load. Preserving agricultural residues through methods of crop management that retain residues can enhance mineralization of soil organic matter and microbial activity as well as decrease soil erosion. The reduced tillage can enhance the soil microbial activity and continue to protect the quality of the soil, water and air (Raimi et al., 2017). The process of crop rotation regulates soil fertility, and microbial communities (Benitez, et al., 2017). In dryland farming systems with low biomass production under limited rainfall and elevated temperature conditions, therefore, little is known about soil microbial community enhancement in semiarid settings (Liebig et al., 2006).

Soil microbial communities may directly and indirectly respond to climatic changes such as increased atmospheric CO<sub>2</sub>, global warming and altered precipitation patterns (Raimi et al., 2017). Unfortunately, carbon and nitrogen pools have been inadequately studied in many studies in microbial ecology, because it is challenging to precisely quantify them (Kong et al., 2011). Human activities such as increased greenhouse gas emissions (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O) and various forms of environment degradation, agricultural practices and increase in population may contribute to the starting and proceed climate change and, accordingly, have impact on soil microbial population (Cavicchioli et al., 2019; Nisbet et al., 2019).

## 1. Things which Determine the Soil Health

Soil structure deterioration, elevated bulk density, depletion of soil organic matter and vital nutrients along with changes in soil pH have negative effect on soil biota abundance, species richness and diversity (Topa et al., 2021). Extraction that is removed from organic matter and mineral fertilizers without restoration decreases, and eventually eliminates, soil fertility and productivity. Nutritional shortness may be a result of erosion. Deforestation and bush burning, unregulated, adversely affect microbial communities, which then contribute to greenhouse gas release to the atmosphere. Industrial activities or chemical spill may render it unable to perform ecosystem functions severely when it is exposed to soil to dangerous substances (Alori et. al., 2024). High salt concentration in the irrigation water resulted in the bulk density and porosity decrease, due to collapse of the tiny aggregates and deposits in between the interstices to finally form semi compressed layers (Hassan et al., 2019).

## 2. Soil Microorganisms and their Functions

The principal living reservoirs of the soil ecosystem are soil microorganisms. They carry out a wide range of ecosystem functions such as biogeochemical cycles, decomposition of organic matter, removal of toxins, promotion of plant growth and maintenance of ecological economy and soil health (Wang et al., 2024). . As a result, soil microorganisms are routinely used as bioindicators of soil quality. Terrestrial ecosystems depend heavily on soil microorganisms, including autotrophic and heterotrophic bacteria; fungi; nitrogen fixing bacteria; nitrifiers; denitrifiers; and phosphorus solubilizers for transformation and processing of C, N, and P (Aralappanavar et al., 2014). But extracellular hyphae can mitigate soil compaction from soil microorganisms, including fungi. By increasing soil porosity and aeration risks associated with waterlogging and soil erosion are reduced. Their extracellular hyphae and the secreted polysaccharides promote soil aggregate formation and improve health of soil (Wei et al., 2024). Most soil bacteria help decompose organic matter, yet are essential to many nutrient cycling processes. Indeed, some specific bacteria, *Azotobacter vinelandii*, *Bacillus megaterium*, *Chlamydomonas sajabo*, and *Rhizobium sp.*, have been shown to produce extracellular compounds, such as polysaccharides and amino acids, that enhance adhesion of soil particles and form aggregates to increase the soil structure (Mengual et al., 2014).

Soil bacteria and plant produces extracellular enzymes that help breakdown organic matter and nutrient cycling in soil (Brevik et al., 2020; Coonan et al., 2020). Soil enzymes participate in the metabolic activities of the carbon and nitrogen cycles as well (Yan et al., 2021). extracellular enzymes that help breakdown organic matter and nutrient cycling in soil (Brevik et al., 2020; Coonan et al., 2020). Soil enzymes participate in the metabolic activities of the carbon and nitrogen cycles as well (Yan et al., 2021).

Bacteria, fungi, actinomycetes, protozoa, and algae are the primary microbial groups for agriculture and for the soil ecosystem (Javed et al., 2021). Plant diseases, insect and weed pest life cycles, as well as the dynamics of beneficial symbiotic relationships with plant roots (often nitrogen fixing bacteria and mycorrhizal fungi), are affected by highly varied microbial populations. A considerable influence of edaphic properties and their parameter fluctuations on biogeochemical cycles, plant nutrition, soil structure, particle attributes and the retention capacity for water and nutrients (Skorobogatov et al., 2020). They work with living plants and decomposed organic matter to keep and rejuvenate the best soil functionality (Alori et al., 2020).

### 3.1 Microorganisms Role in Improving Soil Health and Fertility

Fundamental to lucrative, efficient, and ecologically sustainable agricultural systems, are robust soils with optimal soil structure, resistance to compaction, advantageous soil chemical properties, significant organic matter, enhanced biological activity, effective plant nutrient recycling, and availability, minimized weed and disease pressures as shown in Table 1 (Wieme et al., 2020; Melakeberhan et al., 2021).

This then leads to an increase in soil organic matter which subsequently increases soil organic matter to improve the cohesiveness of soil particles and hence improving soil health (Alori et al., 2024). Predation and other means by which soil microorganisms control pests like insects, nematodes and soil borne diseases increase soil health. Other nematodes and soil dwelling insects are preyed on by predatory nematodes and mites, reducing populations of nematodes and soil dwelling insects in the soil (Alori et al., 2020). The healthy formation of healthy soils requires the presence of soil microorganisms (Bender & Heijden, 2022). For soil development and soil fertility the organic and inorganic materials decomposition and nutrient cycling is essential (Odelade & Babalola, 2019; Krasilnikov et al., 2022). They accomplish 80-90% of all biological geochemical processes in the soil (Gobler et al., 2021). Soil microbial composition has already been used as a biological indicator of soil health (Pérez-Guzmán et al., 2021). Microbial diversity and community structures are good bio indicators of soil and environmental health. Pristine land has proved to be a lost contact; what was found there was subjected to intensive tillage and agricultural practices, and poor soil management and land use regulations have blackmailed its soil ecosystems, reduced diversity and altering microbial communities in the vast majority of agricultural soils (Trivedi et al., 2016). Furthermore, the soil microbial community composition is important to determine the health status of the soil. The ratio of fungi to bacteria. The ratio is a crucial indicator of soil health and fertility, believed to enhance soil organic carbon mineralization and improve microbial stability and persistence (Naylor et al., 2022). In particular, soil enzyme activities and the microbiome function they depend on are critical indicators of soil health, providing an indication of soil nutrient cycling, particularly of carbon (Li et al., 2016). Soil microbes are important for keeping soil healthy (Table 1). Soil microorganisms are important in soil mixing and form micro pores and are very sensitive, thereby vital in determining soil disturbances, microbial community structure, microbial respiration, biomass and agricultural economies (Brevik et al., 2020).

**Table 1:** Role of Microorganisms in Improving Soil Health and Fertility (Pang et al., 2021)

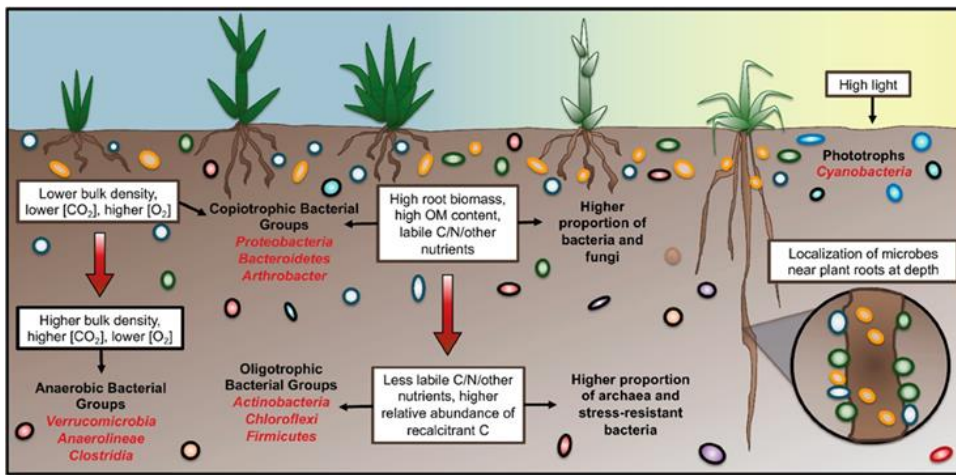
Microorganism	Role in Soil Health and Fertility	Impact on Soil	References
Nitrogen-Fixing Bacteria	Convert atmospheric nitrogen into forms that plants can use (e.g., ammonium or nitrates).	Increases soil nitrogen content, enhancing plant growth.	(Wang et al., 2021)
Mycorrhizal Fungi	Form symbiotic relationships with plant roots to improve nutrient absorption, especially phosphorus.	Enhances nutrient uptake, improves root health, and aids in water retention.	(Salnikova & Makarenko, 2021)
Decomposers (e.g., bacteria, fungi)	Break down organic matter, recycling nutrients back into the soil.	Increases organic matter, enhances soil structure, and recycles nutrients.	(Raina et al., 2021)
Actinomycetes	Produce antibiotics that suppress soil-borne pathogens, enhancing plant health.	Reduces harmful pathogens, leading to healthier plants.	(Wang et al., 2021)
<i>Rhizobium</i> Bacteria	Specialized nitrogen-fixing bacteria in legume root nodules.	Increases nitrogen availability in soil, beneficial for crop rotation.	(Muthukumar, 2021)
Azotobacter	Free-living nitrogen-fixing bacteria that do not require a plant host.	Improves nitrogen fixation in soil, promoting healthier plant growth.	(Sharma & Kaur, 2021)
<i>Trichoderma</i> spp.	Fungi that help in controlling root pathogens and stimulating plant growth.	Enhances plant immunity and reduces damage from root diseases.	(Jian et al., 2021)
Lactic Acid Bacteria	Help in fermenting organic matter, contributing to the breakdown of organic material and making it available for plants.	Improves soil microbial diversity and nutrient cycling.	(Omirin et al., 2021)
Vermicomposting Worms	Decompose organic waste into nutrient-rich humus, improving soil texture and nutrient content.	Increases soil fertility, enhances moisture retention, and improves aeration.	(Mao et al., 2021)

### 3.2 Soil Architecture and Moisture Retention under Microbial Influence

Some of the soil health augmentations come from soil organisms delivering such soil structure and water retention capacity. Improving soil structure through decompaction soil and stabilizing soil aggregate is so greatly dependent upon soil microorganisms (Gupta & Germida, 2015). The management of aquatic ecosystem is dependent on the services provided by bacteria in improving soil structure, facilitating nutrient aggregation and recycling of water, thereby sustaining soil health and productivity (Enagbonma & Babalola, 2019).

This image shows how microorganisms can work to shape the soil and retain moisture. According to Figure 1, the drawing depicts a plant with roots penetrating layers of the soil in which 35, 36 microbial activities (including those mediated by mycorrhizal fungi and nitrogen-fixing bacteria) influence 37 soil structure. Soil Microbes help to Soil structure and aggregate formation Soils aggregate, allowing water to be retained within soil micropores. The symbiotic relationship between plant roots, microorganism, and soil particles is essential for maintaining the health, fertility, and moisture balance of the soil (Aponte et al., 2021).

Actinomycetes are crucial for producing stable humus and improving soil structure, nutrient hold and water holding. Unicellular or multicellular fungi may live and help breakdown and nitrogen cycling in soil. Arbuscular Mycorrhizal fungi and others fungi formed hyphae and mycelium, which have a large surface, dig inside the soil, catch soil particles, and stick them together (Begum et al., 2019). Several soil microorganisms play pivotal roles in a diversity of soil ecological processes, such as pedogenesis, sustainable soil nutrient heterogeneity, soil respiration, microbial activity, and water infiltration and storage (Aponte et al., 2021). Positive correlations were between soil organic matter (SOM) and the connectivity of soil macropores. Which prohibited the accumulation of SOM significantly improved the soil pore architecture, promoted the development of the soil microbial community, enhanced the soil water retention capacity and decreased the occurrence of preferential flow (Hu & Pan, 2024).



**Fig. 1:** Trends in Microbial Community Composition and Function by Soil Depth (Retrieved from Biorender)

### 3.3 Effects of Soil Microorganisms on Plant Health

Rhizosphere microorganisms are often referred to as the second genome of the plants that play a key role for plant-microbe-soil interactions, which are important for plant health and productivity (Zhang et al., 2017; Xun et al., 2021; Kumawat et al., 2022). Plant growth promoting bacteria can help plants by fixing nitrogen and increasing solubilization of phosphate and potassium of soil (Bai et al., 2022; Lin et al., 2022). Furthermore, the species filled a number of functions within the ecosystem, some being beneficial such as nutrient recycling, decomposition of organic matter, or participation in mutualistic or symbiotic associations with plants, together with harmful roles as potential pathogenic microbes causing and spreading plant diseases, which resulted in impaired plant growth and considerable crop losses (Jacoby et al., 2017). This function plays the role of diminishing stress ethylene levels by promoting plant growth under biotic and abiotic stress through plant associated microorganisms (Adedayo et al., 2022). Despite being referred to as biological control agents for insect pests, entomopathogenic ‘nematodes are also responsible for maintaining ecological balance and as important soil health markers, they require free living nematodes. Nematodes are widely distributed, inhabit many habitats, and serve as indicators of soil functionality & condition in response to environmental and human perturbations (Zhang et al., 2020; Preez et al., 2022).

### 4. Microorganisms and Plant Productivity

Improving plant output and relieving stress requires beneficial microbes. This includes diverse microbial biomass, including bacteria, nematodes, fungi, and viruses in the rhizosphere soil environment, which have stress tolerance-enhancing properties. In addition to these plant- microbial relationships, plants also have symbiotic relationships with rhizosphere bacteria, which are recognized as the phenomenon of plant-microbial interaction (Shaffique et al., 2023). Plant-microbial interactions are starting points for environmental cleaning and reducing pollution. This is a compelling, well-supported approach for tackling the degradation of organic pollutants and the accumulation and stabilization of metal contaminants via the use of natural processes. In effect, these bacteria have become effective filters or traps (Raklami et al., 2022). PGPR are extremely essential beneficial microorganisms that aid in the growth and development of plants, they contain heavy metal stress resistance (Manoj et al., 2020).

### 5. Challenges and Prospects in Augmenting Soil Fertility by Microbial Applications

Soil microorganisms' importance in increasing soil fertility and plant health is well established; however, several hindrances exist which limit their optimal usage. The variability of microbial effectiveness under field conditions is a major issue. In laboratory studies, microbial inoculants frequently show great benefits, but their effectiveness in varied agroecosystems may vary with environmental factors including soil composition, moisture levels, pH, and temperature. However, the survival of these microbes and their colonization and interactions with plant roots make it nontrivial to achieve consistent results with these factors (Zhang, 2021).

A major obstacle is the compatibility between imported microbial strains and native soil microbial communities. This may allow competing indigenous bacteria to outcompete foreign strains for resources, thus attenuating bioinoculant efficacy. The introduction of bacteria may cause ecological problems, by disrupting existent soil ecosystems. It is a big challenge to find the balance between soil fertility improvement and the maintenance of indigenous biodiversity. The widespread adoption of microbial technology is further retarded by economic and logistical factors. Microbial products are less easily accessible for smallholder farmers because of limited shelf life and increased production costs combined with the requirement for special storage conditions. The failure of the use of these products to be effective is attributable to the lack of comprehension or technical skills in farmers regarding how to use them properly (Melakeberhan et al., 2021).

Two possible approaches to address these issues are presented, based on future developments in biotechnology and microbial ecology. Genomic and metagenomic techniques can identify resilient microbial strains with improved adaptation in different environmental conditions. Synthetic biology methods are capable of engineering microorganisms with engineered functions such as improved nutrient solubilization and enhanced tolerance to environmental stressors (Cavicchioli et al., 2019).

Combining microbial technology with precision agriculture methods will improve this. One way to improve the use of microbial inoculants is to incorporate site-specific soil analysis and data driven application methods. At the same time, interdisciplinary interaction between microbiologists, agronomists, and soil scientists will be a vital step in dealing with this complex problem space (Preez et al., 2022). Advancement

of microbiological solutions requires policy endorsement and educational programmers. Facilitating its adoption can include subsidies for microbial product, research expenditures and training for farmers programs. By facilitating public-private collaborations, vital bridge that exists between scientific research and practical application, discoveries can make it to the end user (Lin et al., 2022).

## Conclusion

Crop health depends on the quality of soil. So, during the previous years, farmers focused on soil quality improvement through artificial fertilizers and pesticides. However, some concern has arisen around chemicals in that they are ongoing sources of environmental pollution and create health risks. With consumer's shifting preference towards organic food and concerns of the food safety, the emergence of the organic food has caused the farmer to adopt the sustainable agricultural practice. It seems to be the principal rationalization that the adoption of more environmentally sound methods has been made, including biofertilizers, biopesticides and so on. Ecological soil management aims to achieve high agricultural productivity while minimizing pollution by creating a resilient underground ecosystem, represented by ideal soil structure, thriving and diverse soil organisms, and enough nutrient supply. This results in plants being fed with their best environments to grow and to protect against pests. These ecological tactics can be classified into the following strategies: defensive resilient plants and beneficial species, reduced insect populations, and growing resilient plants. Many different types of beneficial microorganisms can be used to increase crop quality and crop output. In sustainable agriculture beneficial microorganisms are very important since they improve plant growth and combat illnesses in an environmentally friendly way. This chapter showed the important roles of beneficial bacteria in agriculture in utilization they have in increasing soil fertility and raising plant productivity and health. Research on the benefits of microbial products in agriculture is extensive though problems associated with the utilization of microbial biofertilizers and microbial biopesticides need to be addressed and solved.

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