

Review Article

Importance of Microbial Diversity in Soil Health and Ecological Function - A Review

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Abstract

Soil microbial diversity is a fundamental component of global biodiversity and plays an important role in sustainable agriculture, environmental protection, and human health. Soil microorganisms, including bacteria, fungi, and actinomycetes, contribute to soil health through organic matter decomposition, nutrient cycling, nitrogen fixation, and phosphorus solubilization. These microbial processes improve nutrient availability, support plant growth, suppress diseases, and maintain ecosystem stability. However, intensive agriculture, pollution, and land-use changes threaten soil microbial diversity and the ecosystem services it provides. This review synthesizes current knowledge on the ecological functions of soil microorganisms and evaluates their applications in sustainable agriculture and environmental monitoring. Recent scientific literature, case studies, and technological advances related to biofertilizers, plant growth-promoting microorganisms, and microbial biosensors were reviewed. Particular attention was given to beneficial microorganisms, especially nitrogen-fixing and phosphate-solubilizing bacteria, which can improve nutrient availability, reduce dependence on synthetic fertilizers, enhance soil fertility, and strengthen soil resilience. The potential of microbial biosensors as innovative tools for detecting environmental pollutants and supporting pollution assessment and waste management was also examined. The findings indicate that integrating beneficial microorganisms and microbial-based technologies can improve soil health, enhance agricultural productivity, reduce chemical inputs, and promote environmentally sustainable farming practices. Microbial biosensors also offer promising approaches for environmental monitoring and early pollutant detection. Overall, conserving and effectively utilizing soil microbial diversity is essential for sustainable agriculture, food security, and environmental conservation. Promoting beneficial microbial communities and advancing microbial biotechnology can contribute to resilient agricultural systems and help address growing global environmental challenges.

Keywords

Bio-fertilizer, Soil Health, Microbial Biosensor

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1. Introduction

One significant component of the total biological diversity of the world is microbial diversity. Recent technical developments in the study of microbial diversity have shown that many microorganisms remain unidentified and that little is known about their ecological roles. The key to creating new technologies for the efficient use of microorganisms for sustainable agriculture, environmental preservation, and human and animal health is careful microbe selection and clever test assay design [1].

Applications of microbes are becoming essential to solving significant environmental and agricultural problems. Microorganisms are used in agriculture to maintain soil health, safeguard plant health, and increase crop output. By fixing nitrogen, solubilizing phosphorus, and producing plant hormones, these bacteria can stimulate plant growth. Through processes including competition, antibiosis, and induced systemic resistance, they also aid in the defense of plants against diseases. Microbes are essential to the fertility and structure of soil because they facilitate the breakdown of organic materials and the cycling of nutrients [2]. The term "microbial diversity" refers to the variety of bacterial and fungal species in microbial communities; genetic diversity, or the quantity and distribution of genetic information within microbial species; and ecological diversity, or variation in community structure, complexity of interactions, number of trophic levels, and number of guilds [3]. Soil science, microbiology, and biodiversity have all recently been more interested in the freshly developing interdisciplinary field of soil microbial diversity. Research on soil microbial diversity is crucial for understanding natural biological processes, managing climate change, reducing different types of pollution, preserving ecological services, and encouraging the sustainable use of soil [4].

The area of soil surrounding plant roots where root activity affects soil qualities is known as the rhizosphere. Microbial diversity is crucial to the preservation of ecosystems and biological diversity. Microbial-plant interactions are crucial to the health of an ecosystem. The root system interacts closely with a variety of soil microbial populations in addition to aiding a plant's embedding in the ground, absorbing water and ions, and storing nutrients [5]. Negative nutrient balances in agriculture, poor soil health, and decreased productivity are the results of ongoing cropping without recycling enough crop or animal residues and nutrient imbalances brought on by inadequate nutrient application [6]. As a dynamic living system that provides a variety of ecosystem services, soil health is an essential part of terrestrial ecosystems. Water quality, plant production, nutrient cycling and decomposition, and the elimination of greenhouse gasses from the environment are some of these functions [7].

The biological, chemical, and physical characteristics of soil are directly related to its health and are impacted by the variety and activity of soil microorganisms [8]. Maintaining

soil health is crucial to sustainable agriculture because it guarantees ongoing food production without harming the environment [9]. By improving water use efficiency, nutrient availability, and plant resistance to environmental challenges, healthy soils boost agricultural output. By boosting the quantity, variety, and activity of soil microorganisms, agricultural techniques including conservation tillage and organic farming have been demonstrated to enhance soil health [10]. A variety of physical, chemical, and biological indicators that are reflective of crucial soil-based ecosystem services are frequently used to evaluate soil health, which is an integrated aspect of agroecosystem management. However, a number of recent studies have demonstrated that anthropogenic activities, including land use change, agricultural intensification, and climate change, are diminishing the soil's ability to carry out basic processes and functions [11]. This has raised worries that a decline in soil biodiversity could have a detrimental effect on a variety of ecosystem services and activities [12].

As the world's population continues to rise, healthy soils are essential for sustaining food supply. Nutrient cycle, disease resistance, and general crop health are all improved in soils that are rich in active microbial communities and exhibit synergistic interactions between plants, animals, and microorganisms. Long-term ecosystem stability is greatly aided by this dynamic interaction, especially in light of shifting global conditions [13]. Specifically, the primary organisms that maintain plant health and biomass production are soil microorganisms. Numerous research have shown that manipulating plant root and soil microbial communities directly or indirectly can be a potential method to increase food crop productivity, nutritional quality, and safety while also having positive benefits on the environment and human health [14, 15].

Because they are involved in important processes like the formation of soil structure, the breakdown of organic matter, the removal of toxins, and the cycling of carbon, nitrogen, phosphorus, and sulfur, microorganisms in soil are essential to the maintenance of soil function in both natural and managed agricultural soils [16]. Plant-microbe interactions are highly particular and characterized based on co-evolutionary pressures since the dynamics of microbial communities in the soil and rhizosphere can differ. The plant releases root exudates, which act as signaling molecules and serve as substrates for soil microorganisms [17]. Plant-microbe interactions in the rhizosphere support a variety of dynamic ecological processes, including nutrient cycling and carbon repossession. In addition to preserving the health of the soil, microbial variety is important for plant growth and development [18]. A wide variety of microorganisms, including bacteria, fungus, actinomycetes, algae, viruses, protozoans, and nematodes, can be found in the dynamic soil environment. These microbes are essential for preserving soil health and promoting nutrient cycling in the biosphere. They support biological changes, geo-

chemical processes, humus production, and the general sustainability of ecosystems. Furthermore, maintaining plant life and increasing plant productivity depend on these microbial populations [19].

The fundamentals of soil health are these biological indicators, which include microbial biomass, microbial diversity, soil respiration, and various enzyme activity [20]. Through their interactions with the vegetation above ground, soil biota have an impact on ecosystem functions. For instance, plant diversity and vegetation succession can be regulated by both soil microbes and wildlife. Mycorrhizal fungi and symbiotic N-fixing bacteria linked to plant roots facilitate the intake of nutrients, specifically N and P. More than 20,000 plant species rely on microbial symbionts for growth and survival, and symbiotic bacteria are thought to be responsible for ~5–20% of all N (up to 80% in boreal and temperate forests) and up to 75% of P that plants absorb each year [21, 22].

The process by which organic matter is broken down into simpler substances by microorganisms like bacteria, fungus, and actinomycetes is known as microbial decomposition. Because it converts complex organic compounds into forms that plants and other creatures can use, this process is essential for soil health and nutrient cycling. The initial breakdown of organic matter, the release of nutrients, and the creation of stable soil organic matter (SOM) are the stages of microbial decomposition [23, 24]. The microbiological diversity and structure of soil, particularly its functional diversity, are influenced by a variety of causes that can be broadly classified as either natural or manmade. Temperature, moisture, soil type, and agricultural vegetation type are examples of natural influences [25]. The use of pesticides, fertilizing, and soil tillage techniques are examples of human factors that have a significant impact on agriculture and the environment. Each of these methods, which are a part of how people manage agricultural land, has an effect on biodiversity, soil health, water quality, and the general sustainability of ecosystems [26].

Crop roots and soil bacteria, fungus, and actinomycetes form a symbiotic interaction that improves disease resistance, facilitates nutrient absorption, and aids in the breakdown of organic materials [27]. These microbes act as a natural buffer against environmental pressures by supporting crop nutrition as well as disease resistance and stress tolerance. Crop-soil-microbe cooperation enhances nutrient cycling and supports the stability of the soil ecosystem as a whole. The intricate process of organic matter decomposition in soil requires interactions between many microbial species. The effectiveness and result of the decomposition process are greatly influenced by these interactions, which can be neutral, hostile, or synergistic. For instance, some fungi and bacteria may cooperate to break down complex chemical substances more effectively than they could on their own. The quick breakdown of organic matter and the release of nutrients can result from this cooperative interaction [28, 29].

2. Importance of Microbial Diversity in Soil Health Management

I have seen how farmers know that healthy soil is key to plant growth and crop productivity. The look, smell, feel and taste of soil give clues about soil health. A dark rich soil usually shows organic matter. A pleasant earthy scent tells us that microbial activity is strong. Soft soil means moisture and good structure. Taste can sometimes hint at mineral presence. All these soil clues affect soil fertility and plant performance, which in turn change crop yields. Soil health can be disturbed by chemical or biological changes, in soil. Such disturbances hurt the habitats of soil microbes. Shrink the soil food network. When fewer microbes survive crop systems weaken, disease and pest risks rise and crop productivity falls [30].

Effective management of soil health is crucial for enhancing profitability and microbial diversity, which in turn improves soil function, reduces agricultural input costs, and boosts crop profitability [31]. Microbial diversity present in natural ecosystems has the following major functions.

2.1. Microbes as Biofertilizers

The use of many chemical and inorganic fertilizers in farming has caused many problems for the environment. These problems include things like eutrophication which's when water becomes too rich in nutrients. It also leads to soil health. The natural microflora in the soil is going down. These fertilizers also help cause the thinning of the ozone layer. In addition these methods are very bad, for peoples health [32]. To fix these problems I have found that using bio fertilizers works well and is a smart way to go. Many good tiny germs inside bio fertilizers do a job, at helping to stop the bad things that come from using chemical fertilizers and pesticide [33]. Microorganisms help make soil healthier. Microorganisms boost the amount of nutrients that plants can use. Microorganisms support farming ways that do not harm the planet. The result is crops that grow stronger and an ecosystem that feels more balanced. Microorganisms are now a staple in farming and, in organic agriculture [34].

Biofertilizers are an alternative to chemical fertilizers and biofertilizers help reduce ecological disruption. Biofertilizers are also cheap and good for the environment and biofertilizers can be made in amounts right, on the farm whenever farmers need biofertilizers [35]. Bio fertilizers not help to reduce the bad effects of chemical fertilizers on the soil but also help to build healthier soil ecosystems. By cutting down the use of chemicals, bio fertilizers are very important in a system that carefully manages nutrients making farming more sustainable and cheaper. The use of bio fertilizers is essential for encouraging energy sources for plants and for securing a more sustainable future, for agriculture [36].

Rhizobium forms a partnership with the roots of legume plants. These Rhizobium live either on the surface of the roots or in the soil nearby. Some bio fertilizers work for different

types of plants and use things like Blue-Green Algae (BGA) Rhizobium and Azolla. Other bioinoculants are made for crops. These specific bioinoculants include Azospirillum, Azotobacter, phosphorus-solubilizing bacteria (PSB) arbuscular mycorrhiza (VAM) and nitrogen-fixing cyanobacteria, like

Anabaena [36, 37]. These tiny living things are all called bio-fertilizers. Also called plant growth-promoting rhizobacteria and plant growth-promoting rhizobacteria (Figure 1 and Table 1).

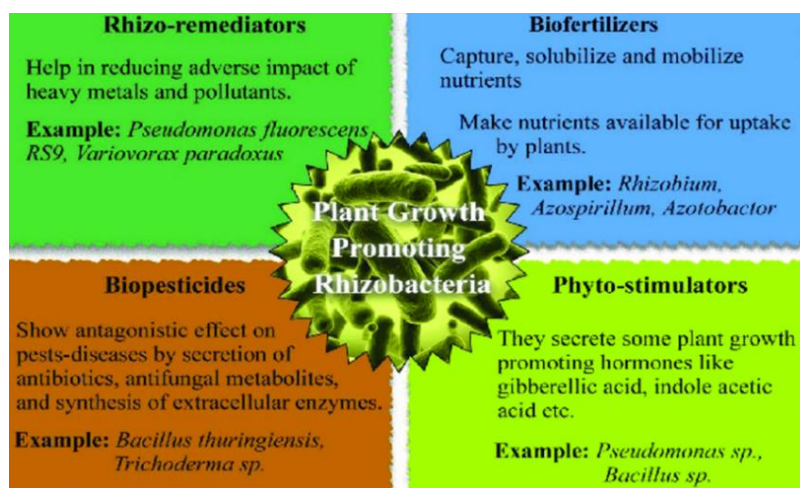


Figure 1. PGPR classification and involving microorganisms.

Table 1. Microbial inoculants used as bio fertilizers, Plant Growth Promoting Rhizobacteria.

Bio fertilizer	Plant Growth Promoting Rhizobacteria	References
Rhizobium, Azotobacter,	Acetobacter, Aeromonas hydrophila, Azotobacter,	
Azospirillum brasilense,	Achromobacter, Alcaligenes, Anabaena,	
Azospirillum lipoferum,	Arthrobacter, Azoarcus, Azospirillum brasilense,	
Azotobacter chroococcum,	A. irakense, A. lipoferum, Azotobacter,	
Acetobacter diazotrophicus,	Acinetobacter calcoaceticus, A. baumannii,	
Bacillus licheniformis, B. megaterium, B. mucilaginosus,	Bacillus polymyxa, Beijerinckia, Burkholderia gladioli, Burkholderia cepacia, Clostridium,	
B. edaphicus, B. subtilis	Derrxia, Enterobacter, Erwinia spp., Ewingella americana, Escherichia vulneris, Flavobacterium,	[35, 38]
Actinomyces, Streptomyces	Frankia, Gluconacetobacter, Klebsiella,	
Herbaspirillum seropedicae	Mycobacterium phlei, Proteus penneri,	
Rhizobium phaseoli, Thiobacillus thiooxidans, Glomus fasciculatum	Pseudomonas fluorescens, P. luteola, P. alcaligenes, P. putida, Rhizobium leguminosarum,	
Blue Green Algae (BGA), and Azolla	Rahnella aquatilis, Serratia plymuthica, S. ficaria, Sinorhizobium, Shigella spp., Vibrio fluvialis, and Zoogloea	

2.1.1. Nutrient Acquisition

Nutrient acquisition is an important function of beneficial soil microorganisms that contributes to plant growth and soil fertility. Soil microorganisms can improve the availability and

uptake of essential nutrients through several mechanisms, including biological nitrogen fixation, phosphate solubilization and mineralization, and siderophore production, which can enhance the availability of micronutrients such as iron. These microbial activities contribute to nutrient cycling and can increase the availability of nutrients in the rhizosphere, thereby

facilitating their uptake by plants [39, 40]. Among the important microbial groups involved in nutrient acquisition are nitrogen-fixing bacteria and phosphate-solubilizing microorganisms, which are discussed in the following sections.

2.1.2. Nitrogen-Fixing Bacteria

Legume plants that have root nodules can fix nitrogen when they work with bacteria from the genera *Rhizobium*, *Bradyrhizobium*, *Sinorhizobium*, *Azorhizobium* and *Mesorhizobium*. These bacteria together are called rhizobia [41]. Within the genus *Rhizobium* species such as *Rhizobium trifolii*, *Rhizobium giardinii*, *Rhizobium leguminosarum* and another *Rhizobium* species have been found to form nodules and create a relationship with various common bean varieties, in tropical regions [42]. Nitrogen-fixing bacteria turn nitrogen into ammonia. The enzyme that does this is called nitrogenase. It is made by the *nif* gene. This reaction changes nitrogen into a form that plants can use. I notice that most of the nitrogen that plants get comes from microbes that live with their roots. In fact eighty percent of the biologically fixed organic nitrogen comes from those helpful microbes. Non-symbiotic nitrogen fixers are also important, in the buildup of nitrogen. The nitrogen moves into the hosts cytoplasm because of concentration differences. There it is turned into biological nitrogen inside the bacterial cytoplasm [43].

2.1.3. Phosphate-Solubilizing Bacteria

Phosphorus (P) is a nutrient. Phosphorus (P) is needed for

metabolic processes. Phosphorus (P) allows energy transfer. It enables signal transduction. Phosphorus (P) supports -molecular biosynthesis. Phosphorus (P) fuels photosynthesis. Phosphorus (P) drives respiration, in plants. However Phosphorus (P) is one of the nutrients that limits plant growth [44]. Phosphate-solubilizing bacteria are living things that can break down inorganic phosphate. This helps plants get the phosphate they need. These bacteria are very important for making soil more fertile. They change phosphate that plants cannot use into a form that plants can use. Some of the ways that phosphate-solubilizing bacteria do this include making acids, like citric acid and lactic acid. They also release substances called phosphatases [45].

Many bacterial species can break down phosphates, which's very important, for making soil more fertile and helping plants grow. Using phosphate-solubilizing bacteria or PSB as inoculants can improve the way plants take in phosphorus. When plants absorb phosphorus they can produce higher crop yields. The effective phosphates solubilizers are often found among the genera *Pseudomonas*, *Bacillus* and *Rhizobium* [46]. (Figure 2, Table 2).

Siderophores are compounds produced by various microorganisms in soil that utilize chelation to enhance their biological activity. These extracellular fluorescent pigments have a strong affinity for iron (III), are water-soluble, and possess a low molecular weight.

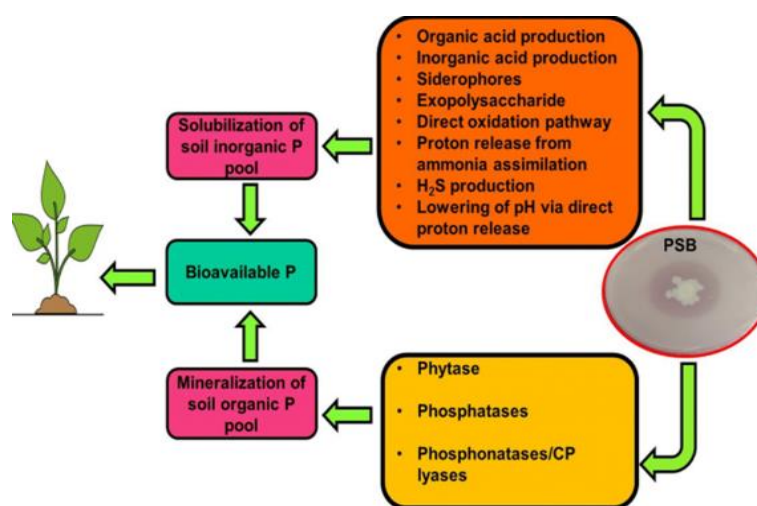


Figure 2. Mechanisms of P solubilisation by phosphate solubilizing bacteria.

2.1.4. Plant Growth Promoting Bacteria (PGPB)

We usually call plant bacteria that help plants grow and develop PGPB. PGPB can work as biocontrol agents. These PGPB help plant growth and development in a way by fighting

off harmful plant pathogens. In another way PGPB can help plant growth and development. PGPB do this by making more mineral nutrients available or by helping to balance phytohormone levels [43]. Endophytic or free-living helpful microscopic bacteria stimulate plant growth and development by direct and indirect methods. (Figure 3).

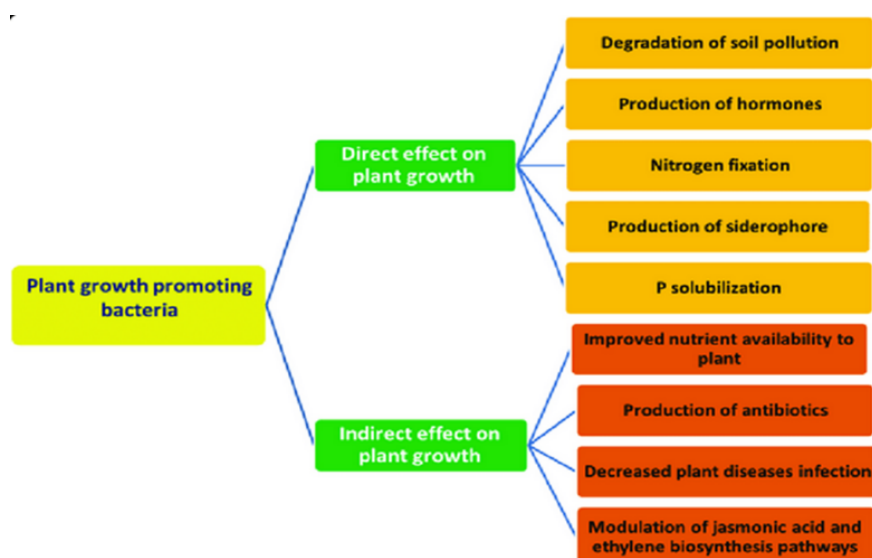


Figure 3. An illustration of the plant growth promoting activities by PGPR.

2.2. Environmental Monitoring

Microbial biosensors are very important for monitoring. Microbial biosensors use living microorganisms to find and measure pollutants, in different ecosystems helping environmental monitoring [47]. Pollutants in the environment pose significant risks to human health, leading to a variety of diseases and health complications. Research has been carried out on the extraction of metals from waste materials using different microorganisms, tailored to the specific type of waste (Ta-

ble 4 and Figure 4). This includes waste containing base metals, precious metals, and hazardous substances. Electronic scrap represents a particularly intriguing category of waste, as it consists of a blend of various metals primarily copper (Cu), aluminum (Al), iron (Fe), and nickel (Ni) along with their alloys [48]. Additionally, microorganisms play a crucial role in the treatment of these wastes, offering potential solutions to mitigate their harmful effects [49]. Industrial wastes have profound effects on ecological functions, disrupting air, water, soil health and ultimately impacting biodiversity and ecosystem health.

Table 2. Examples of industrial waste treated with bacterial leaching.

Types of Waste	Leached metal	Used microorganisms	References
Sewage sludge	Cu, Ni, Zn, Cr	Iron-oxidizing bacteria	
Tannery	Cr	Acidithiobacillus thiooxidans	
Electronic scrap	Cu, Ni, Al, Zn	Acidithiobacillus ferrooxidans Thermo-plasma acidophilum & Sulfobacillus thermosulfi dooxidans	[47, 48, 50]
Fly ashes	Zn, Al, Cd, Cu, Ni, Cr, Pb, Mn, Fe	Thiobacillus thiooxidans + Thiobacillus ferrooxidans, Aspergillus niger	
Jewellery waste, Automobile catalytic converter, electronic scrap	Ag, Au, Pt	Chromobacterium violaceum, Pseudomonas fluorescens, Pseudomonas. Plecoglossida	

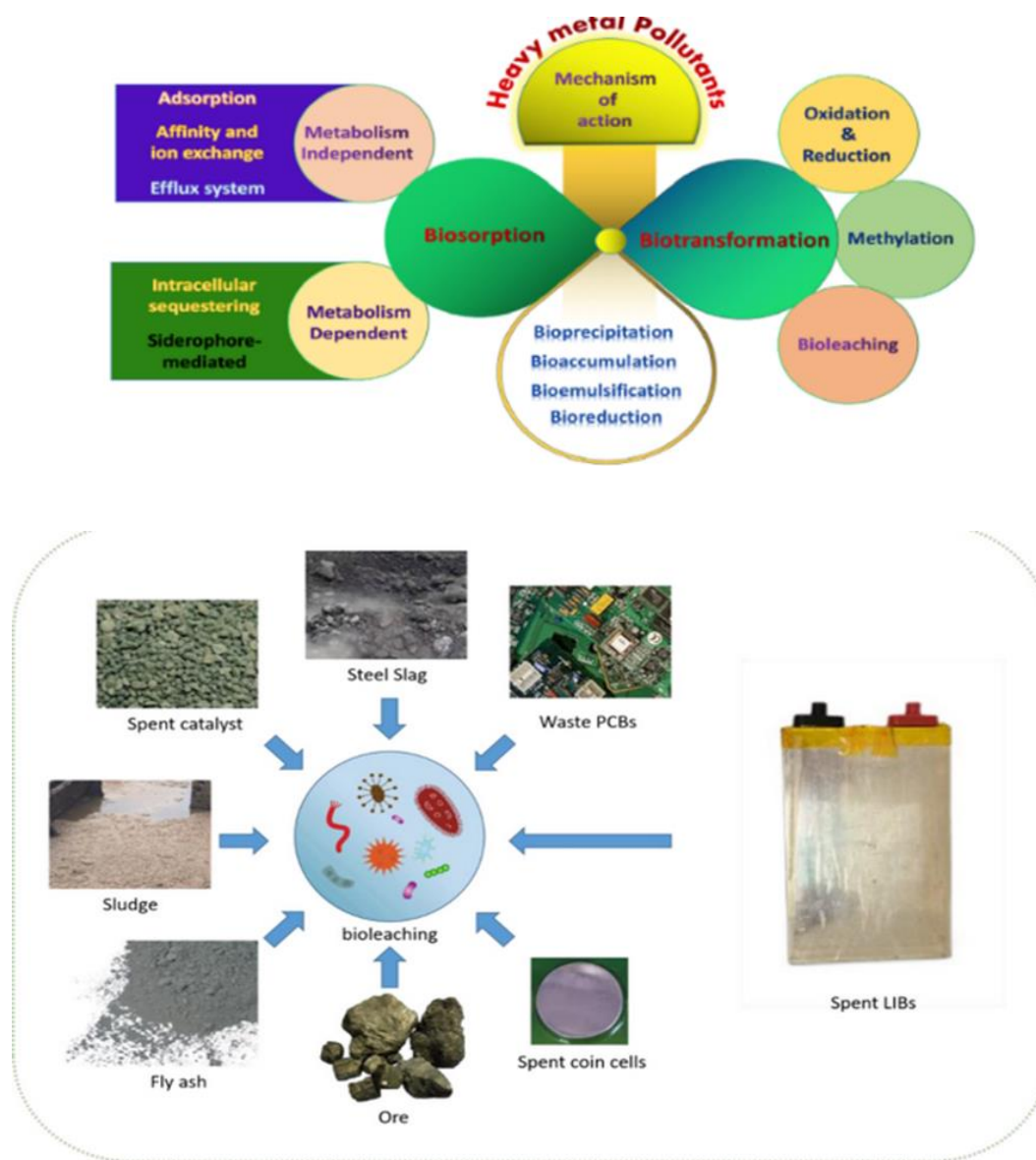


Figure 4. Industrial waste treated with bacterial leaching.

2.3. Microbiological as Decomposer of Organic Matter

When plant residues are returned to the soil many organic compounds begin to break down. This breakdown is mainly caused by activity. I see that heterotrophic microorganisms, such, as bacteria, fungi, actinomycetes and protozoa are the ones that drive this process [51]. (Figure 5 and Table 5). Unlike autotrophs, which can produce their own food from simple substances, heterotrophs obtain both energy and carbon exclusively from organic compounds. In addition to the microflora and microfauna, various mesofauna species, such as earthworms, also play a crucial role in the initial breakdown of organic residues. Decomposition is a way that dead things

break down. This decomposition process works by tearing apart organic material and using tiny organisms to turn complex organic molecules into much simpler parts. Through decomposition dead organic material eventually becomes organic and inorganic compounds [52].

Soil enzymes released by soil microbes are crucial for the processes of nutrient mineralization and the decomposition of organic matter. Their activities significantly influence the availability of nutrients for plants, acting as "sensors" of soil organic matter (SOM) decomposition, microbial health and the physico-chemical conditions of the soil [53]. Organic matter decomposition serves three functions for the microflora: providing energy for growth, supplying carbon for the formation of cell material, and providing other nutrient, elements needed for cell growth.

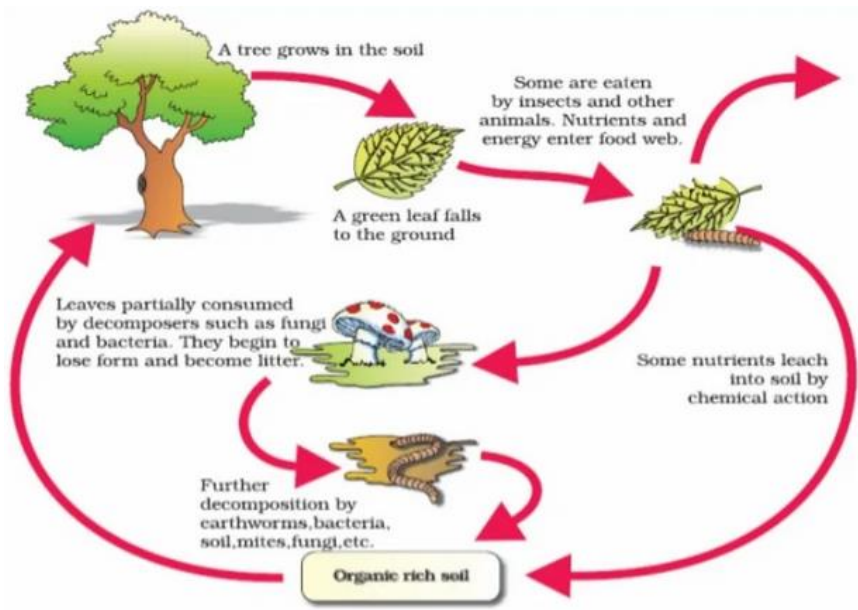


Figure 3. Role of various microorganisms in decomposition of organic matter.

Table 5. Role of microorganisms in decomposition of organic matter.

Microbial Group	Enzymes Produced	Organic Matter Decomposed	Reference
Bacteria	Cellulases, Proteases, Lipases	Cellulose, proteins, lipids	[54]
Fungi	Cellulases, Lignin-degrading enzymes	Cellulose, lignin	[55]
Actinomycetes	Chitinases, Hemicellulases	Chitin, hemicellulose	[56, 57]
Protozoa	Proteases	Proteins	

3. Conclusion

Microbial diversity is an important part of the worlds living things. Many tiny living things are still not known. Their jobs in nature are not fully understood. New discoveries in studying these creatures show how important they are for farming keeping the environment safe and helping people stay healthy. Soil creatures help plants grow fight diseases and keep the soil healthy. They help with nitrogen make phosphorus easier to use make plant hormones and help nutrients move around.

Soil health is very important for the whole environment to work well. It depends on the variety of life in the soil. This variety helps with nutrients helps plants grow and makes the soil stronger. Things people do, like farming a lot and changes in the weather can hurt this tiny life. This makes the soil less able to do its job. Ways of farming that are kinder to the land like growing without chemicals and not digging much help the tiny life and the soil. Tiny creatures also act like fertilizers. They are a choice instead of chemicals. They make nutrients easier for plants to use make crops healthier and help the soil stay strong. Bacteria that fix nitrogen, bacteria that help with

phosphorus and bacteria that help plants grow are very important. They help farming longer and make more food. Tiny sensors made from living things are tools, for checking the environment. They help find pollution and see how well waste is handled.

Abbreviations

- BGA Blue-Green Algae
- PGPB Plant Growth Promoting Bacteria
- PGPR Plant Growth Promoting Rhizobacteria
- PSB Phosphorus-Solubilizing Bacteria
- SOM Soil Organic Matter
- VAM Arbuscular Mycorrhiza

Author Contributions

Tesfaye Tadesse Gebre: Conceptualization, Data curation, Supervision, Writing – review & editing

Yitagesu Girma Legesse: Data curation, Investigation, Software, Supervision, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Dar, Z. A., et al., Microbial diversity and their role in plant and soil health under stress conditions, in *In vitro plant breeding towards novel agronomic traits: Biotic and abiotic stress tolerance*. 2019, Springer. p. 149–166.
- [2] Aslam, K., et al., Role of Microorganisms in Bioremediation. *Pakistan Journal of Biochemistry and Biotechnology*, 2021. 2: p. 140–176.
- [3] Joos, L. and C. De Tender, Soil under stress: The importance of soil life and how it is influenced by (micro) plastic pollution. 2022.
- [4] Lavergne, C., et al., Rising awareness to improve conservation of microorganisms in terrestrial ecosystems: advances and future directions in soil microbial diversity from Chile and the Antarctic Peninsula. *Frontiers in Environmental Science*, 2024. 12: p. 1326158.
- [5] Thepbandit, W. and D. Athinuwat, Rhizosphere microorganisms supply availability of soil nutrients and induce plant defense. *Microorganisms*, 2024. 12(3): p. 558.
- [6] Spohn, M., S. Braun, and C. A. Sierra, Continuous decrease in soil organic matter despite increased plant productivity in an 80-years-old phosphorus-addition experiment. *Communications earth & environment*, 2023. 4(1): p. 251.
- [7] M. Tahat, M., et al., Soil health and sustainable agriculture. *Sustainability*, 2020. 12(12): p. 4859.
- [8] Sahu, P. K., et al., Connecting microbial capabilities with the soil and plant health: Options for agricultural sustainability. *Ecological Indicators*, 2019. 105: p. 601–612.
- [9] Xing, Y., X. Wang, and A. Mustafa, Exploring the link between soil health and crop productivity. *Ecotoxicology and environmental safety*, 2025. 289: p. 117703.
- [10] Cárceles Rodríguez, B., et al., Conservation agriculture as a sustainable system for soil health: A review. *Soil Systems*, 2022. 6(4): p. 87.
- [11] Bertola, M., A. Ferrarini, and G. Visioli, Improvement of soil microbial diversity through sustainable agricultural practices and its evaluation by-omics approaches: A perspective for the environment, food quality and human safety. *Microorganisms*, 2021. 9(7): p. 1400.
- [12] Wagg, C., et al., Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proceedings of the National Academy of Sciences*, 2014. 111(14): p. 5266–5270.
- [13] Bender, S. F., C. Wagg, and M. G. van der Heijden, An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. *Trends in ecology & evolution*, 2016. 31(6): p. 440–452.
- [14] Hirt, H., Healthy soils for healthy plants for healthy humans. *The EMBO Reports*, 2020. 21(8): p. EMBR202051069.
- [15] Martínez-Hidalgo, P., et al., Engineering root microbiomes for healthier crops and soils using beneficial, environmentally safe bacteria. *Canadian journal of microbiology*, 2019. 65(2): p. 91–104.
- [16] Garbeva, P. v., J. A. Van Veen, and J. D. Van Elsas, Microbial diversity in soil: selection of microbial populations by plant and soil type and implications for disease suppressiveness. *Annu. Rev. Phytopathol.*, 2004. 42(1): p. 243–270.
- [17] Huang, X.-F., et al., Rhizosphere interactions: root exudates, microbes, and microbial communities. *Botany*, 2014. 92(4): p. 267–275.
- [18] Yang, L., et al., Mechanisms of rhizosphere plant-microbe interactions: molecular insights into microbial colonization. *Frontiers in Plant Science*, 2024. 15: p. 1491495.
- [19] Zhang, H., et al., Soil bacterial diversity and its relationship with soil CO₂ and mineral composition: a case study of the Laiwu experimental site. *International journal of environmental research and public health*, 2020. 17(16): p. 5699.
- [20] Maharjan, M., et al., Effect of land use and management practices on microbial biomass and enzyme activities in subtropical top-and sub-soils. *Applied Soil Ecology*, 2017. 113: p. 22–28.
- [21] Dellagi, A., I. Quillere, and B. Hirel, Beneficial soil-borne bacteria and fungi: a promising way to improve plant nitrogen acquisition. *Journal of Experimental Botany*, 2020. 71(15): p. 4469–4479.
- [22] Alquichire-Rojas, S., et al., Root symbiotic fungi improve nitrogen transfer and morpho-physiological performance in Chenopodium quinoa. *Frontiers in Plant Science*, 2024. 15: p. 1386234.
- [23] Cotrufo, M. F., et al., The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global change biology*, 2013. 19(4): p. 988–995.
- [24] Hicks, L. C., K. Lajtha, and J. Rousk, Nutrient limitation may induce microbial mining for resources from persistent soil organic matter. *Ecology*, 2021. 102(6): p. e03328.
- [25] Javed, A., et al., Soil fertility: Factors affecting soil fertility, and biodiversity responsible for soil fertility. *International Journal of Plant, Animal and Environmental Sciences*, 2022. 12(1): p. 21–33.
- [26] Ni, B., et al., Increasing pesticide diversity impairs soil microbial functions. *Proceedings of the National Academy of Sciences*, 2025. 122(2): p. e2419917122.
- [27] Harman, G. E. and N. Uphoff, Symbiotic root-endophytic soil microbes improve crop productivity and provide environmental benefits. *Scientifica*, 2019. 2019(1): p. 9106395.
- [28] Metcalf, J. L., et al., Microbial community assembly and metabolic function during mammalian corpse decomposition. *Science*, 2016. 351(6269): p. 158–162.

- [29] Geisen, S., et al., Protists as catalyzers of microbial litter breakdown and carbon cycling at different temperature regimes. *The ISME Journal*, 2021. 15(2): p. 618–621.
- [30] Gupta, A., et al., Linking soil microbial diversity to modern agriculture practices: a review. *International journal of environmental research and public health*, 2022. 19(5): p. 3141.
- [31] Srivastava, R. K., et al., Advancements in soil management: Optimizing crop production through interdisciplinary approaches. *Journal of Agriculture and Food Research*, 2024. 18: p. 101528.
- [32] Khan, M., et al., Fertilizers and their contaminants in soils, surface and groundwater. *Encyclopedia of the Anthropocene*, 2018. 5: p. 225–240.
- [33] Bhatti, A. A., S. Haq, and R. A. Bhat, Actinomycetes benefaction role in soil and plant health. *Microbial pathogenesis*, 2017. 111: p. 458–467.
- [34] Reganold, J. P. and J. M. Wachter, Organic agriculture in the twenty-first century. *Nature plants*, 2016. 2(2): p. 15221.
- [35] Seenivasagan, R. and O. O. Babalola, Utilization of microbial consortia as biofertilizers and biopesticides for the production of feasible agricultural product. *Biology*, 2021. 10(11): p. 1111.
- [36] Ramasamy, M., T. Geetha, and M. Yuvaraj, Role of biofertilizers in plant growth and soil health, in *Nitrogen fixation*. 2020, IntechOpen.
- [37] Mohammadi, K. and Y. Sohrabi, Bacterial biofertilizers for sustainable crop production: a review. 2012.
- [38] Lacey, L. A. and L. G. Neven, The potential of the fungus, *Muscodor albus*, as a microbial control agent of potato tuber moth (Lepidoptera: Gelechiidae) in stored potatoes. *Journal of Invertebrate Pathology*, 2006. 91(3): p. 195–198.
- [39] Timofeeva, A. M., M. R. Galyamova, and S. E. Sedykh, Plant Growth-Promoting Soil Bacteria: Nitrogen Fixation, Phosphate Solubilization, Siderophore Production, and Other Biological Activities. *Plants (Basel)*, 2023. 12(24).
- [40] Pang, F., et al., Soil phosphorus transformation and plant uptake driven by phosphate-solubilizing microorganisms. *Frontiers in Microbiology*, 2024. Volume 15 - 2024.
- [41] Shamseldin, A., A. Abdelkhalek, and M. J. Sadowsky, Recent changes to the classification of symbiotic, nitrogen-fixing, legume-associating bacteria: a review: A. Shamseldin et al. *Symbiosis*, 2017. 71(2): p. 91–109.
- [42] Koskey, G., et al., Potential of native rhizobia in enhancing nitrogen fixation and yields of climbing beans (*Phaseolus vulgaris* L.) in contrasting environments of Eastern Kenya. *Frontiers in plant science*, 2017. 8: p. 443.
- [43] Ramakrishna, W., R. Yadav, and K. Li, Plant growth promoting bacteria in agriculture: Two sides of a coin. *Applied Soil Ecology*, 2019. 138: p. 10–18.
- [44] Fernández, L. A., et al., Phosphate-solubilization activity of bacterial strains in soil and their effect on soybean growth under greenhouse conditions. *Biology and Fertility of Soils*, 2007. 43(6): p. 805–809.
- [45] Timofeeva, A., M. Galyamova, and S. Sedykh, Prospects for using phosphate-solubilizing microorganisms as natural fertilizers in agriculture. *Plants*, 2022. 11(16): p. 2119.
- [46] Zaidi, A., et al., Plant growth promotion by phosphate solubilizing bacteria. *Acta microbiologica et immunologica Hungarica*, 2009. 56(3): p. 263–284.
- [47] Mishra, D. and Y. H. Rhee, Microbial leaching of metals from solid industrial wastes. *Journal of Microbiology*, 2014. 52(1): p. 1–7.
- [48] Willner, J. and A. Fornalczyk, Extraction of metals from electronic waste by bacterial leaching. *Environment protection engineering*, 2013. 39(1): p. 197–208.
- [49] Thirumalaivasan, N., et al., Utilization of fungal and bacterial bioremediation techniques for the treatment of toxic waste and biowaste. *Frontiers in Materials*, 2024. 11: p. 1416445.
- [50] Chi, T. D., et al., Bioleaching of gold and copper from waste mobile phone PCBs by using a cyanogenic bacterium. *Minerals Engineering*, 2011. 24(11): p. 1219–1222.
- [51] Khatoon, H., et al., Role of microbes in organic carbon decomposition and maintenance of soil ecosystem. *International Journal of Chemical Studies*, 2017. 5(6): p. 1648–1656.
- [52] Fang, C., et al., Incorporating microorganisms as decomposers into models to simulate soil organic matter decomposition. *Geoderma*, 2005. 129(3–4): p. 139–146.
- [53] Kotroczo, Z., et al., Soil enzyme activity in response to long-term organic matter manipulation. *Soil Biology and Biochemistry*, 2014. 70: p. 237–243.
- [54] Inan Bektas, K., et al., Isolation and characterization of detergent-compatible amylase-, protease-, lipase-, and cellulase-producing bacteria. *Brazilian Journal of Microbiology*, 2023. 54(2): p. 725–737.
- [55] Kantharaj, P., et al., Lignocellulose degrading enzymes from fungi and their industrial applications. *Int. J. Curr. Res. Rev*, 2017. 9(21): p. 1–12.
- [56] Das, P., R. Solanki, and M. Khanna, Isolation and screening of cellulolytic actinomycetes from diverse habitats. *International Journal of Advanced Biotechnology and Research*, 2014. 5(3): p. 438–451.
- [57] Khan, A. and T. S. Rao, Molecular evolution of xenobiotic degrading genes and mobile DNA elements in soil bacteria, in *Microbial diversity in the genomic era*. 2019, Elsevier. p. 657–678.