



Soil Microbial Biodiversity: The Secret Force behind Climate Control, Food Security, and Ecosystem Sustainability

**Kolte Akshay Balasaheb¹,
Sujata L. Bankar²,
Arpita Sharma^{3*},
Shiv Singh Tomar⁴, Jyoti⁵**

^{1&2}Ph.D. Scholar, School of
Agricultural Sciences,

^{3*}Associate Professor, School of
Agricultural Sciences,

⁴Professor and Dean, School of
Agricultural Sciences,

⁵Assistant Professor II, School of
Engineering and Sciences,
GD Goenka University Sohna,
Haryana, India



Open Access

*Corresponding Author
Arpita Sharma*

Article History

Received: 1. 1.2026

Revised: 5. 1.2026

Accepted: 10. 1.2026

This article is published under the
terms of the [Creative Commons
Attribution License 4.0](https://creativecommons.org/licenses/by/4.0/).

INTRODUCTION

When thinking about life on Earth, observable ecosystems like forests, oceans, or coral reefs are frequently the emphasis. However, the earth beneath our feet is home to one of the most important and varied ecosystems. A living system teeming with microorganisms that build complex ecological networks, soil is not inert substance. The coexistence of billions of microorganisms representing thousands of species in a single gram of healthy soil drives processes that support ecosystem health, climate management, and food production. As a key component of sustainable development, soil microbial biodiversity—the range of microbial species and their genetic and functional characteristics—is becoming more widely acknowledged. These microscopic organisms supply nutrients, regulate the climate, and serve as the planet's natural recycling system. Addressing global issues like food shortages, climate change, and ecological degradation requires an understanding of and commitment to protecting this hidden biodiversity (FAO, 2020). There are more living things in a teaspoon of healthy soil than there are people on the planet. Due to their difficulty in observing and studying, soil microorganisms were disregarded for many years. These microscopic organisms are now understood to be the foundation of terrestrial ecosystems because of developments in molecular biology and DNA sequencing. Without them, life on land would cease to exist as we know it, plants would have difficulty growing, and nutrients would remain trapped. Bacteria, fungus, archaea, protozoa, and microscopic invertebrates like nematodes make up the majority of soil microbial communities.

Through intricate food webs, these species interact to control energy flow, nutrient turnover, and decomposition in the soil environment. The productivity of terrestrial ecosystems is directly impacted by their combined activity, which establishes soil fertility, structure, and biological stability. Functional redundancy provided by microbial variety guarantees that vital functions continue even in the face of changing environmental conditions. The stability of ecosystems under growing anthropogenic and climatic stress depends on this resilience.

3. The Production of Food and Soil Microbial Biodiversity

3.1 Cycling and Availability of Nutrients

The biogeochemical cycle of vital nutrients, including nitrogen (N), phosphorus (P), carbon (C), and sulfur (S), which are necessary for plant growth, is fueled by soil microbes. By breaking down organic matter, microorganisms transform complicated chemicals into nutrients that plants may use. Despite being widely available in the environment, these nutrients are frequently in forms that are inaccessible to plants. Through a

variety of metabolic processes, soil bacteria convert these nutrients into forms that plants can use. While phosphate-solubilizing bacteria (*Bacillus*, *Pseudomonas*) liberate phosphorus from insoluble mineral complexes, nitrogen-fixing bacteria (e.g., *Rhizobium* spp.) transform atmospheric nitrogen into forms that may be used. These methods maintain soil fertility over time and lessen reliance on artificial fertilizers.

3.1.1. Cycling of Nitrogen

For plants to synthesize proteins, nucleic acids, and chlorophyll, nitrogen is an essential nutrient. But plants cannot directly use atmospheric nitrogen (N₂) since it is inert. Leguminous plants develop symbiotic partnerships with nitrogen-fixing bacteria like *Rhizobium* spp., which transform atmospheric nitrogen into ammonia (NH₃), which plants may easily absorb [Li & Li, 2023]. Soybeans and alfalfa, for example, can provide up to 70% of the nitrogen needed by these crops through symbiotic nitrogen fixation, according to research. This greatly reduces the requirement for synthetic fertilizers and increases agricultural output (Table 1).

Table 1: Soil microorganisms' availability and cycling of nutrients.

Microbe Group	Examples	Main Functions in Soil
Bacteria	Nitrosomonas, Rhizobium	Nutrient cycling, nitrogen fixation
Fungi	Mycorrhizal fungi	Nutrient uptake, soil aggregation
Archaea	Methanogens	Carbon cycling, methane production
Protozoa	Amoebae, ciliates	Control bacterial populations
Viruses	Bacteriophages	Regulate microbial communities

The processes of nitrification and denitrification, in addition to nitrogen fixation, are essential for controlling the availability of nitrogen in soils [Chen et al., 2023]. microorganisms that nitrate, like *Nitrosomonas* species. The preferred forms of nitrogen for plant uptake are nitrites (NO₂⁻) and nitrates (NO₃⁻), which are produced by *Nitrobacter* spp. and ammonia. The nitrogen cycle is subsequently completed by denitrifying bacteria, like *Pseudomonas* species, which transform nitrates back into gaseous nitrogen (N₂) or nitrous oxide (N₂O) [Lazcano et al., 2021]. According to research, a varied population of nitrifying and denitrifying bacteria can increase crop yield stability and

environmental sustainability by stabilizing nitrogen cycling in agricultural soils and lowering the risk of nitrogen loss through gas emissions and leaching (Table 1).

3.1.2. Phosphorus Dissolution

Another vital mineral for plants is phosphorus, which is important for root growth, energy transfer, and general plant health [Djuuna et al., 2022]. But phosphorus is frequently found in soil in insoluble forms that plants cannot directly access. Phosphorus can be liberated from these insoluble substances by phosphate-solubilizing microorganisms (PSMs), which include a variety of bacteria and fungi, and made available to plants [Kaur et al., 2024; Khan et al., 2024;

Sarmah et al., 2023]. For instance, studies have shown that organic acids secreted by species like *Bacillus* and *Pseudomonas* greatly boost the solubilization of phosphate in soils, improving phosphorus availability and, ultimately, plant development (Table 1). Additional research has demonstrated that, particularly in situations when phosphorus availability is low, inoculating crops like maize with phosphate-solubilizing fungi like *Aspergillus* spp. can increase phosphorus intake and boost yields (Table 1). This illustrates how important microbial diversity is for controlling soil phosphorus levels and promoting plant nutrition.

3.1.3. Organic Matter Decomposition

Because it returns nutrients that have been held in plant leftovers and animal manures to the soil, the microbial breakdown of organic matter is essential to nutrient cycling [Fang et al., 2023]. A wide variety of microorganisms, including bacteria, fungus, and actinomycetes, are responsible for this process. They convert complicated organic molecules into simpler substances that plants can absorb. According to research, for example, microbial diversity and the rate at which organic matter decomposes are intimately related; greater diversity results in quicker nutrient release and better soil health [Fang et al., 2023]. Fungi, especially those belonging to the phyla Ascomycota and Basidiomycota, are essential for the breakdown of complex organic compounds like cellulose and lignin, which promotes the production of humus and increases soil fertility (Table 1). A varied microbial community speeds up the breakdown process and guarantees that nutrients are effectively cycled and made available to crops.

3.1.4. The Solubility of Potassium

Although potassium is typically found in large quantities in soils, it is frequently found in forms that are difficult for plants to absorb. Potassium from these inaccessible forms can be dissolved by specific soil bacteria, allowing plants to absorb it. For instance, it has been demonstrated that potassium-solubilizing bacteria (KSB), such as *Bacillus* and *Frateriia* spp., increase the

bioavailability of potassium in soils, hence promoting plant development and production under conditions of potassium deficiency (Table 1). According to field research, applying KSBs to crops like rice greatly boosts the plants' absorption of potassium, improving yield and stress tolerance [Johnson et al., 2022]. This demonstrates how vital microbial variety is to preserving soil potassium availability, which is essential for plant growth and stress tolerance.

3.1.5. Water Regulation and Soil Structure

Soil particles are bound together into stable aggregates by microbial secretions, such as fungal hyphae and extracellular polymeric compounds. Better aggregation decreases erosion while increasing soil porosity, aeration, and water-holding capacity. These outward enhancements promote root growth and increase crop resistance to abiotic stressors like drought.

3.1.6. Plant Health and Disease Suppression

Through competitive exclusion, the synthesis of antimicrobial chemicals, and the promotion of plant defense mechanisms including induced systemic resistance (ISR), a diversified soil microbiome reduces soil-borne pathogens. Biological disease suppression promotes healthier agroecosystems and lessens the need for chemical pesticides.

3.1.7. Promotion of Plant Growth

Numerous soil microbes generate phytohormones that promote root elongation and branching, including auxins, gibberellins, and cytokinins. Improved root systems increase the uptake of nutrients and water, which boosts plant vigor and production stability.

4. Soil Microbes' Function in Climate Regulation

4.1 Sequestering Carbon

About three times as much carbon is stored in soils than in the atmosphere and vegetation put together. By breaking down organic materials and converting it into stable soil organic carbon (SOC), soil bacteria control carbon storage. Soil biodiversity is an important ally in mitigating climate change because microbial biomass and necromass play a major role in long-term carbon stabilization.

4.2 Dynamics of Greenhouse Gases

Major greenhouse gas production and consumption are regulated by microbial activities. Methanotrophs reduce emissions by oxidizing methane, whereas methanogenic archaea create methane in anaerobic soils. A greenhouse gas that is far more potent than CO₂, nitrous oxide fluxes, are controlled by nitrifying and denitrifying bacteria. Whether soils behave as sources or sinks of greenhouse gases depends on the balance between these microbial species.

4.3 Mechanisms of Climate Feedback

The composition and function of microbial communities are impacted by climate change, which also modifies soil temperature and moisture regimes. Decreased microbial diversity can hasten the loss of carbon, resulting in positive feedback loops that exacerbate the effects of climate change.

4.4. Multifunctionality of Ecosystems and Soil Microbial Biodiversity

Ecosystem multifunctionality, or the concurrent provision of several ecosystem functions like carbon storage, nitrogen cycling, water management, and plant productivity, is supported by soil microbial diversity. Research shows that decreases in microbial diversity have a substantial negative impact on ecosystem resilience and function. The distinct contributions made by various microbial communities highlight the significance of preserving overall diversity as opposed to concentrating on specific functional taxa.

4.5. Dangers to Microbial Biodiversity in Soils

Microbial diversity can be significantly decreased by contemporary farming methods

such as excessive tillage, extensive pesticide usage, monocropping, and soil contamination. These delicate subterranean ecosystems are further threatened by land deterioration, soil erosion, and climate change (Heijden et al., 2008). Ecosystems lose resilience, crops become more susceptible, and soil becomes less fertile when microbial diversity decreases.

5. Soil microbial biodiversity is threatened despite its significance:

- 1) Intensive agriculture: Microbial habitats are disturbed by excessive tillage, monoculture systems, and the misuse of synthetic fertilizers and pesticides.
- 2) Land-use change: Microbial niches and soil structure are weakened by urbanization, deforestation, and soil erosion.
- 3) Climate change: Soil processes are disrupted and microbial richness is decreased due to warming and changed precipitation patterns. Crop productivity, soil fertility, nutrient cycling, and ecosystem resilience are all jeopardized when microbial diversity is lost.

6. Techniques for Sustainable Management and Conservation

Microbial biodiversity can be preserved and restored through sustainable soil management techniques as conservation or reduced tillage, crop diversification and rotation, using cover crops, applying compost and organic amendments, utilizing microbial inoculants and biofertilizers, new agricultural technologies based on microbiomes present viable approaches to increase crop yields while reducing environmental effects (Table 2).

Table 2: Major Functional Roles of Soil Microbial Biodiversity in Sustainable Agriculture and Ecosystem Health

S.No.	Microbial Function	Key Microbial Groups	Primary Processes	Impact on Food Security & Ecosystems
1.	Nutrient cycling	Bacteria (<i>Rhizobium</i> , <i>Bacillus</i> , <i>Pseudomonas</i>), Fungi	Nitrogen fixation, phosphorus solubilization, organic matter decomposition	Enhances nutrient availability, reduces fertilizer dependency
2.	Soil structure formation	Fungi (mycorrhizae), bacteria	Aggregate formation via hyphae and exopolysaccharides	Improves soil aeration, water retention, erosion control
3.	Plant growth promotion	Plant growth-promoting bacteria (PGPB)	Production of phytohormones (auxins, gibberellins)	Stimulates root growth, improves nutrient and water uptake

4.	Disease suppression	Actinomycetes, <i>Trichoderma</i> , <i>Pseudomonas</i>	Antibiotic production, competition, ISR induction	Reduces soil-borne pathogens, lowers pesticide use
5.	Stress tolerance	Rhizobacteria, mycorrhizal fungi	Osmoprotection, enhanced nutrient uptake	Improves crop resilience to drought, salinity, heat
6.	Carbon sequestration	Bacteria, fungi, archaea	SOC formation, microbial necromass accumulation	Climate change mitigation, long-term soil fertility
7.	Greenhouse gas regulation	Methanotrophs, nitrifiers, denitrifiers	CH ₄ oxidation, N ₂ O regulation	Controls greenhouse

7. AI Tools for Soil Microbial Biodiversity, Climate Control & Sustainable Agriculture

Artificial intelligence (AI) is increasingly emerging as a powerful approach for advancing soil microbial biodiversity research and supporting sustainable agriculture and climate resilience. Machine learning and deep learning models enable the analysis of complex, high-dimensional soil and microbiome datasets to predict nutrient cycling efficiency, crop productivity, carbon sequestration potential, and greenhouse gas emissions. AI-assisted metagenomics platforms facilitate rapid identification and functional profiling of soil microbial communities, improving understanding of nitrogen fixation, phosphorus solubilization, organic matter decomposition, and plant–microbe interactions. In precision agriculture, AI integrates real-time soil data with remote sensing to optimize fertilizer application, irrigation, and crop management, thereby reducing chemical inputs while enhancing soil health. AI-based decision support systems further assist farmers and policymakers in selecting conservation practices, crop rotations, and microbial inoculants tailored to local conditions. Additionally, AI-powered bioinformatics tools integrate microbial, plant, and climate datasets to reveal ecosystem multifunctionality and resilience under environmental stress. Collectively, these AI-driven approaches provide predictive insights and practical solutions for conserving soil microbial diversity, improving food security, regulating greenhouse gases, and strengthening ecosystem sustainability in the face of climate change.

CONCLUSION

The hidden yet essential basis of life on Earth is made up of soil bacteria. They maintain

ecosystem stability, control nutrient cycles, promote plant development, and affect the climate. Even though they are minuscule, their combined influence is tremendous. The future of agriculture, climate resilience, and human life all depend on the recognition and preservation of soil biodiversity. We take care of life itself when we take care of the soil. Despite being invisible, soil bacteria have a huge impact. They safeguard crops, maintain the health of ecosystems that support all terrestrial life, including humans, sustain plant life, and control Earth's climate. Sustainable agriculture and environmental preservation depend on soil being understood as a living system rather than an inert resource. Enhancing soils is only one benefit of preserving and promoting soil microbial diversity; another is safeguarding the continuation of life on Earth.

An essential component of food systems, climate regulation, and ecological stability is soil microbial biodiversity. These microscopic creatures function as buffers against environmental stress, regulators of greenhouse gas dynamics, and engineers of soil fertility. Long-term ecosystem conservation, climate resilience, and sustainable agriculture all depend on maintaining and improving soil microbial diversity. The silent, invisible communities beneath our feet are crucial to the vibrancy of life above ground, including food security, healthy landscapes, and a stable climate. A key factor supporting food systems, propelling climate-critical processes, and preserving ecosystem functionality is soil microbial biodiversity. Diverse microbial communities enable and facilitate life on land, from carbon sequestration and resilience to environmental change to nutrient cycling and plant health. In order to address the issues of climate change, sustainable agriculture, and ecosystem protection in the

twenty-first century, it is imperative that this hidden biodiversity be preserved and enhanced. The quiet, microscopic communities in the soil are essential to the vitality of life above ground, including the food on our plates, the forests in our landscapes, and the temperature that makes our planet habitable. These creatures are not merely inhabitants of the ground beneath our feet; they are ecosystem stewards, climate controllers, and life engineers. A sustainable future depends on preserving and enhancing soil microbial biodiversity, which goes beyond simple scientific objectives.

REFERENCES

- FAO (2020). State of Knowledge of Soil Biodiversity, Food and Agriculture Organization of the United Nations.
- Van der Heijden, M. G. A., Bardgett, R. D., & Van Straalen, N. M. (2008). The unseen majority: Soil microbes as drivers of plant diversity and productivity. *Ecology Letters*, 11(3), 296–310.
- Li, X.; Li, Z. What determines symbiotic nitrogen fixation efficiency in rhizobium: Recent insights into *Rhizobium leguminosarum*. *Arch. Microbiol.* **2023**, *205*, 300. [Google Scholar] [CrossRef] [PubMed]
- Chen, Q.; Long, C.; Chang, K.; Cheng, X. Various seasonal patterns and potential mechanisms of soil nitrogen transformation along an elevational gradient in the Hengduan Mountains. *Funct. Ecol.* **2023**, *37*, 1962–1973. [Google Scholar] [CrossRef]
- Lazcano, C.; Zhu-Barker, X.; Decock, C. Effects of Organic Fertilizers on the Soil Microorganisms Responsible for N₂O Emissions: A Review. *Microorganisms* **2021**, *9*, 983. [Google Scholar] [CrossRef]
- Djuuna, I.A.F.; Prabawardani, S.; Massora, M. Population Distribution of Phosphate-solubilizing Microorganisms in Agricultural Soil. *Microbes Environ.* **2022**, *37*, ME21041. [Google Scholar] [CrossRef] [PubMed]
- Kaur, H.; Mir, R.A.; Hussain, S.J.; Prasad, B.; Kumar, P.; Aloo, B.N.; Sharma, C.M.; Dubey, R.C. Prospects of phosphate solubilizing microorganisms in sustainable agriculture. *World J. Microbiol. Biotechnol.* **2024**, *40*, 291. [Google Scholar] [CrossRef] [PubMed]
- Khan, N.; Siddiqui, M.H.; Ahmad, S.; Ahmad, M.M.; Siddiqui, S. New Insights in Enhancing the Phosphorus Use Efficiency using Phosphate-Solubilizing Microorganisms and Their Role in Cropping System. *Geomicrobiol. J.* **2024**, *41*, 485–495. [Google Scholar] [CrossRef]
- Sarmah, R.; Sarma, A.K. Phosphate Solubilizing Microorganisms: A Review. *Commun. Soil Sci. Plant Anal.* **2023**, *54*, 1306–1315. [Google Scholar] [CrossRef]
- Fang, Q.; Lu, A.; Hong, H.; Kuzyakov, Y.; Algeo, T.J.J.; Zhao, L.; Olshansky, Y.; Moravec, B.; Barrientes, D.M.M.; Chorover, J. Mineral weathering is linked to microbial priming in the critical zone. *Nat. Commun.* **2023**, *14*, 345. [Google Scholar] [CrossRef] [PubMed].
- Johnson, R.; Vishwakarma, K.; Hossen, Md. S.; Kumar, V.; Shackira, A.M.; Puthur, Jos T. ; Abdi, G.; Sarraf, M.; Hasanuzzaman, M. Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiology and Biochemistry.* **2022**, *172*, 56-69.