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Review of exploring soil microbial ecology and its important in sustainable ecosystems.

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ABSTRACT

Soil is a dynamic and complex ecosystem that supports an enormous diversity of microorganisms essential for maintaining ecosystem functioning and sustainability. Soil microbial communities, including bacteria, fungi, archaea and protozoa, play pivotal roles in nutrient cycling, organic matter decomposition, soil structure formation, carbon sequestration and plant health. These microorganisms interact closely with plant roots in the rhizosphere, influencing nutrient availability, plant growth, and resistance to soil-borne pathogens. Increasing anthropogenic pressures, such as intensive agriculture, excessive chemical inputs, land-use change, and environmental pollution, have disrupted soil microbial diversity and ecological balance, threatening long-term agricultural productivity and environmental sustainability. This review critically examines the interrelationships between soil properties and microbial ecology, emphasizing the functional roles of soil microorganisms in sustaining ecosystem services and promoting sustainable agriculture. The review highlights recent advances in molecular and metagenomic approaches used to study soil microbial communities and discusses the potential of beneficial microorganisms, including plant growth-promoting rhizobacteria, mycorrhizal fungi, and disease-suppressive soils, as eco-friendly alternatives to chemical fertilizers and pesticides. Understanding soil–microbe–plant interactions is essential for developing sustainable soil management strategies that enhance soil health, improve crop productivity, and mitigate the impacts of climate change. Strengthening soil microbial ecology through conservation-based practices offers a promising pathway toward long-term environmental resilience and sustainable ecosystem management.

INTRODUCTION

Soil microbial ecology defines soil microorganisms including their roles and functions.It affects soil and plant life. Soil microbial ecology define microorganisms found in the soil ecosystem(Chinthala,Lakshmi Kalyani,2025).Soil hosts a diverse array of organisms that interact with one another and with an abiotic environment. Soil microbiomes are essential for sustaining soil ecosystem processes and respond to environmental alteration(Wang,Yijing et al.,2025).The soil micro-biome is an essential element of ecosystems regulating plant growth, nutrient cycling and providing resistance against soil-borne diseases(Zhou, Xing, et al.,2025).The microbiota in the soil for preserving sustainability and ecosystem productivity(Van der Heijden,2023).The rhizosphere is infection site of soil-borne diseases that form parasitic relationships with plants. It infects root tissue, and pathogens have to fight for available nutrients and microsites with members of the rhizosphere microbiome (Chapelle,Emilie, et al,2016).Soil microbial research is increasingly focused on harnessing our growing soil microbiome to better agricultural land management. Microbes are extremely abundant in soils, and together with plants, they account for the majority of global biomass in both the soil and deep surface.The most prevalent organisms are bacteria, fungi and archaea have much higher biomasses than animals (Banerjee,Samiran and Marcel GA Van Der Heijden,2023).The most significant way humans affect terrestrial ecosystems is through land use change, which is a major contributor to increased atmospheric carbon dioxide levels and a fundamental driver of global climate change (Shi, Jingwei, et al. 2023).The extensive microbial variety present in soils, together with their roles and resilience to fluctuating environments, render them valuable indicators for both investigative intelligence and prospective evidence. The colonization of biochar with soil microorganisms may significant for binding biochar to soil particles, thereby enhancing the soil structure. Biochars have a large surface area, have the ability to exchange cations, and are rich in nutrients(Muhammad et al.,2014).The significant contributors to nutrient cycling and release in soils influence enzyme function primarily through three mechanisms. Harmful metal ions are released, the morphological structure of enzymes or their corresponding substrate in soil is altered, and biological cells suffer impairment. The rhizosphere also known as the microbial storehouse region of soil, is immediately impacted by plant roots. The surface of roots and the tightly packed soil particles surrounding them are all part of this. The correlation between plant diversity and ecological functionality has been a continual emphasis in ecology.The significance of plant diversity in enhancing soil microbial activity, carbon sequestration, nutrient availability, soil fertility, and plant productivity (Furey and Tilman,2021).Nitrogen-fixing plants are acknowledged for promoting essential microbial species such as *Rhizobium spp. and Frankia spp.* The connection between plants and bacteria includes diverse belowground processes such as mutualism and pathogenicity. It strongly impacts the links between biodiversity and ecological functioning. Soil microbial diversity can autonomously augment plant nutrient absorption by promoting nutrient cycles (Trivedi, Pankaj, et al., 2020).The plant Growth-promoting Rhizobacteria (PGPR) are soil bacteria residing rhizosphere of plants.The ability to fix nitrogen, solubilize potassium, and solubilize phosphorus.The acidolysis, chelation, and exchange reactions can change soil's insoluble phosphorus and potassium compounds.The conversion of atmospheric N_2 into NH_3 by nitrogen-fixing microorganisms increases the availability of nutrients in the soil(Chowdhury ,Farhana,Tasnim, et al.,2020).PGPR releases antibiotics,secondary metabolites,hydrolases, HCN and cellulases to help plants stress.The biostimulant are low-carbon,natural,non-polluting,non-toxic.Plant Growth-Promoting Rhizobacteria (PGPR) biostimulant also referred to as microbial fertilizer or microbial agents has been developed to help address the issues with agricultural production. Rhizosphere bacteria synthesize auxins, gibberellins and cytokinins to enhance root growth, including those from *Azospirillum* and *Pseudomonas*. The iron more accessible to plants while limiting pathogen access. Suppress plant pathogens through competition, antibiotic production, or induced systemic resistance *Bacillus subtilis,Pseudomonas fluorescens.* Actinomycetes (*Streptomyce*s) produce antifungal and antibacterial compounds. Mycoparasitism competition and exclusion of beneficial bacteria outcome pathogens for resources and space(Zhang, Tongrui, et al.,2024).The green agenda emphasizing necessity of sustainable resource utilization, is rapidly gaining momentum.Plant pathology can contribute to this agenda by reducing estimated 20%–30% losses caused by pests,diseases,side effects of disease and pest control actions, as well as by improving agricultural efficiency.The goal is reduce inputs per unit of production, including watering, spraying pesticides and applying inorganic fertilizers. Effective disease resistance is frequently unavailable, regardless of whether it is introduced through conventional methods (plant breeding) or biotechnologically through genetic engineering, including new genomic technologies(Collinge and Sarrocco,2022).The most effective natural microbe-based plant defense are found in suppressive soils. Plant roots serve as the initial line of defense against soilborne pathogens by stimulating, enriching, and supporting soil microorganisms. Disease resistance is a critical tool for disease management. Soils have been observed to inhibit the transmission of diseases to the crops that are cultivated on them. Soils are source of microbes that are believed to assist plants in suppressing pathogens by enhancing the health of the plant, inducing natural plant defense producing antibiotics, and competing against pathogens. Soil that is disease-suppressive is defined as soil that suppresses crop disease as a result of the unique structure of its microbial community. Suppressive soil is appealing due to its potential for sustainability over multiple seasons in favorable conditions. It is classified into two categories. These conditions can be both general and specific.They contain biocontrol microorganisms that compete with or inhibit the pathogen, parasitize it, or cause plants to develop resistance to it. Plant defense against Fusarium diseases specifically implicates *Bacillus, Pseudomonas, Paenibacillus,* and *Streptomyces* species. Microbial community patterns vary by Fusarium patho system, host plant and soil origin (Todorovic, Irena, et al., 2023).

Diversity of soil microbiome

Soil microbial communities are essential for numerous ecosystem processes, serving as principle agents of nutrient cycling, organic matter decomposition, and greenhouse emissions. Their composition and diversity are intrinsically connected to their functional capacity. Several methodologies, including experimental manipulations and extensive meta-analyses, have investigated complex interactions among microbial diversity, abundance, and ecosystem services (Fields, Bryden, and Ville-Petri,Friman,2022).The soil microbes are important in sustainable crop production and soil health. Microbes play essential roles in nutrient cycling, organic matter decomposition and disease suppression.The anthropogenic activities such as nitrogen fertilizers are negatively impact microbial diversity and soil health (Pattnaik, Swati, Balram Mohapatra, and Abhishek Gupta,2021).The global increase in nitrogen had a detrimental effect on soil microbial diversity, according to a meta-analysis conducted (Kumar, Vinay et al,2023).These obstacles and organismal interactions support soil health and the decomposition of dangerous pollutants. Some soil microbe interactions benefit one or both populations, while others harm one party. The mechanisms that determine the composition of the microbiome are still unclear, and soil contains a wide variety of microbial populations(Barton, Larry L. and Diana E. Northup, 2011).Nucleic acid-based molecular techniques are increasingly employed to characterize diversity, abundance and activities of soil biota. DNA and RNA are frequently isolated from soil or amplified using polymerase chain reaction (PCR). The amplified fragments are using several approaches. Accelerated technological progress in nucleic acid sequencing, microscopy ,mass spectrometry and genes(metagenome),gene transcripts (metatranscriptome), and proteins (metaproteome) derived from soil communities. The structure and function of soil biotic communities can be comprehensively understood by combining molecular methods with other techniques, which are referred to as a polyphasic or multiphasic approach (Thies, Janice E., Matthias C. Rillig, and Ellen R. Graber, 2015).The impact varied based on characteristics including land use, nitrogen fertility, and duration of nitrogen application.The comparative significance of microbial richness and composition in influencing multifuntionality is an area of active investigation.The impact varied based on characteristics including land use, nitrogen fertility type, and the duration of nitrogen application.The comparative significance of microbial richness and composition in influencing multifunctionality is an area of active investigation. Soil multifunctionality was shown to be separately contributed to by microbial richness and composition (Wicaksono,Wisnu, Adi, et al.,2021).Demonstrating the necessity to evaluate both factors of soil health. Microbiological phyla differ in their functional roles and reactions to environmental changes (Fracchia, F. et al. 2022). Actinobacteria were found to be sensitive indicators for soil health in agricultural soils that were polluted (Cirillo, Valerio et al. 2023).Biocontrol microorganisms have been demonstrated to significantly change the organization and diversity of soil bacterial communities(Liu,Hang,et al,2022).

Bacteria

Bacteria are the most prevalent organisms in soil. Bacteria play primary role in soil processes, contributing to biogeochemical cycles and preserving soil health, despite their tiny size and relative simplicity. Bacteria's capacity to flourish in soil is a result of their exceptional metabolic adaptability and phenotypic plasticity. The phylogenetic and physiological diversity of soil bacteria, as well as certain aspects of their survival and functionality in soils (Semenov, Mikhail V., et al.,2025). Rhizospheric bacteria are group of different types of microorganisms that dwell in the soil around plant roots is called the rhizosphere.The rhizospheric microbiome can have advantageous,adverse or neutral effects on the plant.Bacteria dominate soil microbial communities,contributing to nitrogen fixation ,pathogen suppression and organic matter decomposition.Genera like *Rhizobium spp.,pseudomonas spp.and Bacillus spp.*play an important role in nutrient cycling and planth health.The rhizosphere is a living area full of different kinds of bacteria(Ling,Ning,Tingting Wang and Yakov Kuzyakov,2022).The bulk soil acts as a seed bank for microbes and plants specifically recruit advantageous bacteria through root exudates.This distinction makes the rhizosphere microenvironment very different from the bulk soil community. Some microbes move into the root endosphere and form close mutual relationships with the host plant in this zone (Compant, Stephane, et al. 2021). Plants change the microbiota in their rhizosphere by secreting substances from their roots and making immune reactions(Ali, Shimaila, and Bernard R. Glick,2024) .

List of soil Bacteria roles and characteristics

Bacteria characteristics	**Functions**	**Bacterial spp.**	**Ecological importance**	**References**
Soil bacteria	Cause disease in plants	*Ralstonia solanacearum,Agrobacterium tumefaciense*	Regulate plant populations and lead to crop losses	Mansfield,John et al(2012)
Soil bacteria	Suppress plant pathogen	*Bacillus subtilis, Pseudomonas fluorescens*	Protect plants, sustainable agriculture	Raaijmakers, Jos M. and Mark Mazzola(2016)
Role in decomposition	Break down organic matter	*Bacillus spp.*, *Actinobacteria*, *Clostridium spp.*	Release nutrients	Chen, Huaihai et al.(2022)
Nutrient cycling	Roles in nitrogen, phosphorus, sulfur and carbon cycling	*Rhizobium spp.*, *Thiobacillus spp.*, *Pseudomonas spp.*	Increase soil fertility	Van Der Heijden, et al(2008)
Soil structure formation	Produce extracellular polysaccharides and soil aggregation	*Bacillus spp.*, *Pseudomonas spp.*	Stable soil structure	Chenu et al(2011)
Bioremediation	Degrade hydrocarbons pesticides and heavy metals	*Pseudomonas putida*, *Acinetobacter spp.*, *Bacillus spp.*	detoxify polluted soils and promote	Azubuike, Christopher et al (2016)

			ecosystem	
Plant growth promotion	Produce phytohormones, solubilize nutrients, and enhance stress tolerance	*Pseudomonas putida*, *Acinetobacte spp.*, *Bacillus spp.*	polluted soils and promote ecosystem	Azubuike et al. (2016)
Antibiotic production	Produce secondary metabolites to suppress soil pathogens	*Streptomyces spp..Bacillu spp.*, *Pseudomonas spp.*	Control diseases and balance in soils	Raaijmakers, Jos M., Maria Vlami, and Jorge T. De Souza(2002)

Fungi

Fungi play a crucial role in soil and microbial ecology, contributing to nutrient cycling, organic matter decomposition, plant health, and soil structure. They interact with other microbes, influence plant growth, and contribute to ecosystem stability. This is because rhizosphere fungi are very close to the roots of most plants, making them grow much faster. The fungi, and especially mycorrhizae help plants connect with microbes. Soil bacteria dominate rhizosphere region immediately around the root network. Fungi appear to dominate the biomass due to their large size. Fungi prefer soils that are relatively stable, with organic wastes with high carbon-to-nitrogen ratios and slower nutrient recycling rates. The host plant can act as a bridge between them and the other insect or plant. Fungi are significant components of soil's microbial ecosystem. The bulk of fungal species decompose lignin and soil organic materials.The fungi use simple sugars to fuel their metabolism. Fungi prefer low pH or mildly acidic soils that are relatively undisturbed (Lavelle, Patrick, et al. 2016). Fungi degrade complex organic molecules into simple sugars, making them available to various types of microbes.They also degrade dead organic substances, converting the remains into useable products (Khan, Atif, and Toleti Subba Rao, 2019).These fungal plant associations have a positive effect on food plants, which can be seen in the nutritional aspects for plants and managed by adding a mix of microbes that work well together and have positive effects on each other (Suyal, Deep Chandra, et al.,2021).Fungus are particularly rhizospheric and commonly present in soil and improves crop yields. Rhizospheric fungi can protect plants from biotic and abiotic stresses and are used in many agricultural products to keep nematodes and pathogens at bay. The epiphytic *Trichoderma spp*. and rhizospheric fungus are both used as biocontrol agents (Vosatka, Miroslav, et al., 2012).*Penicillium bilaiae* is able to acquire phosphate. Mycorrhizal soil is primarily composed of the fungus *Trichoderma viride* and *Trichoderma harzianum* (Pirttila, Anna Maria, et al. 2021). Microorganisms such as *Sclerotium spp.,Pythium spp.,Rhizoctonia spp.,Botrytis spp., Sclerosis spp., Gaeumannomyces spp., and Fusarium spp*. are eradicated by their actions.

List of soil fungi roles and characteristics

Fungi characteristics	Functions	Fungal spp.	Ecological importance	References
Role in decomposition	Break complex organic compounds simpler compounds	*Aspergillus spp. Basidiomycota*	Contribute to soil organic matter formation and carbon cycling	Boer, Wietse de et al,(2005)
Nutrient cycling	nitrogen, carbon, and phosphorus cycles	*Glomus spp.*, *Fusarium spp.*	Improve soil fertility and nutrient availability	Van Der Heijden et al(2008)
Soil structure formation	Produce hyphal networks and exude polysaccharides, enhancing soil aggregate	*Trichoderma spp.*, *Aspergillus spp.*	Stabilize soil, reduce erosion, and increase water infiltration	Harman, Gary E., et al.(2004)
Symbiotic relationships	Form mutualistic associations with plants	*Glomus spp.*, *Rhizophagus spp.*, *Ectomycorrhizal fungi*	Enhance nutrient uptake, drought resistance and pathogen resistance	Smith, Sally E., and David J. Read.(2010)
Degradation	Degrade toxic substances like hydrocarbons,	*Aspergillus spp.*,	Bioremediation of contaminated soils	Arslan, Muhammad, et al.(2017)

	pesticides and heavy metal			

Archaea

Archaea are a significant component of Earth's biosphere. They constitute the microbiota of all creatures.The morphological, metabolic, and geographical diversity enables various ecological functions such as carbon fixation, nitrogen cycling, organic compound, maintenance of microbial symbiotic and syntrophic communities.Soil archaea (*Thaumarchaeota*) are dominant ammonia oxidizers, often outcompeting bacteria in nutrient-poor environments. Facilitate carbon cycling and greenhouse gas regulation. Archaea contribute to microbial diversity in extreme conditions like salinity, temperature, and pH. Participate in nitrogen, sulfur, and carbon cycles essential for ecosystem balance. Archaea can degrade complex pollutants, making them valuable for restoring contaminated soils.Archaea are a diverse, prolific, and extensively distributed category of microbes within the biosphere. Archaea significantly influence biogeochemical cycling. These microbes significantly impact global geochemical cycles and greenhouse gas emissions due to their evolution of diverse energy metabolisms.The organic and inorganic electron donors and acceptors including fixation of carbon from inorganic sources (Offre et al., 2013).The functions of archaeal communities in agricultural soils, freshwater biofilms and estuary surface waters using 16S amplicon high-throughput sequencing. The diverse proportions of archaeal phyla and taxa found from soils. to estuaries and major impact of environmental differences on archaeal abundance(Wang, Hualong, et al.,2020).

Roles of soil Archaea in soil microbial ecology

Characteristics	Functions	Archaea	Ecological importance	References
Soil structure stability	Single-celled, prokaryotic organisms with unique lipid membranes and	*Crenarchaeota spp., Euryarchaeota spp., Thaumarchaeota spp.*	contributing to ecosystem stability	Schleper, Christa, German Jurgens, and Melanie

	genetic features			Jonuscheit(2005)
Ammonia Oxidation	Convert ammonia to nitrite	*Nitrososphaera spp.*, *Nitrosopumilus spp.*	Major contributors to global nitrification	Schleper et al(2005)
Methanogenesis	Produce methane under anaerobic conditions	*Methanobacterium spp.*, *Methanosarcina spp.*	carbon cycling and greenhouse gas emissions	Thauer, Rudolf K., et al.(2008)
Methane oxidation	Oxidize methane	*Methanotrophic archaea*	Reduce methane emissions and mitigate greenhouse gas effects	Knittel, Katrin, et al(2009)
Salt and PH tolerance	Survive in saline and highly alkaline soils	*Halobacterium spp.*, *Natronococcus spp.*	Contribute to soil stabilization and microbial diversity in extreme environments	Ventosa, Antonio, Joaquín J. Nieto, and Aharon Oren(1998)
Nutrient cycling	sulfur and nitrogen cycling	*Sulfolobus spp.*, *Nitrosopumilus spp.*	facilitating sulfur oxidation and nitrogen availability	Offre, Pierre, Anja Spang, et al(2013)
Carbon fixation	Fix carbon	*Thaumarchaeota spp.*, *Crenarchaeota spp.*,	Support carbon cycling,	Bates, Scott T., et al. (2011)
Stress adaptation	Extreme conditions like high	*Thermoplasma spp.*, *Sulfolobus spp.*	microbial resilience and	Ricardo Cavicchioli,

	temperatures, salinity, or acidity		diversity	Khawar S et al(2002)
Symbiotic relationships	interactions with other microbes and plants	*Thaumarchaeota spp.*	Enhance nutrient cycling and plant-microbe interactions	Offre et al. (2013)31
Bioremediation	Degrade hydrocarbons	*Archaeoglobus spp.*, *Methanosarcina spp.*	Contribute to remediation of contaminated environments	Gadd, Geoffrey Michael(2010)

Role of soil microbiomes in environmental resilience and pollution degradation

Soil contamination presents a significant risk to global ecological integrity and human health (Singh, B.R., 2020). Human activities bring many organic contaminants into forest soil, upsetting the biological equilibrium of forest ecosystems (Chen,Zhikun et al., 2023).Industrial zones and locations with high human activity frequently surpass safety thresholds for contamination in soil, endangering and stability of these ecosystems(Sui, chuntian et al,2018).These pollutants adversely affects microbial diversity and activity,potentially contaminating ground water and entering food chain,resulting in extensive damage.The microbial breakdown of organic contaminants in soils,persistent organic pollutants(POPs),petroleum hydrocarbons, medicines and volatiles organic compounds(VOCs).Environmental adaptability of microbial communities, the influence of soil and ecosystem variables on degrading efficiency organic contaminants in soils(Liu, Pengfei, et al., 2025).

Conclusion

Soil and microbial ecology are essential for ecosystem sustainability, supporting nutrient cycling, plant development and environmental resistance. Enhancing our comprehension of microbial processes and their applications helps tackle global issues, including food security and climate change mitigation. Future research must emphasize transdisciplinary strategies to fully use the potential of soil microbial communities for sustainability. Soil and microbial ecology are fundamental to ecosystem sustainability, supporting critical processes such as the nitrogen cycle. Soil functions as a dynamic home for various microbial populations that govern nutrient conversions, improve soil fertility, and facilitate plant development. Microorganisms including bacteria, fungi, archaea and protozoa are essential for nutrient cycling, organic matter breakdown, and soil structure. The complex interactions among soil microorganisms and plants necessitate the preservation of healthy soils. These interactions affect nutrient availability, water retention, and plant tolerance to stress, preserving stability and productivity of terrestrial ecosystems. Soil microbial ecology is crucial for tackling global issues, including food security, climate change, and environmental degradation. Enhancing soil health and encouraging beneficial microbial activity. It develops sustainable agriculture, diminishes dependence on chemical fertilizers, alleviates greenhouse gas emissions, and builds a more resilient, balanced ecosystem.

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