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REVIEW

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Soil microbiomes and their potential for enhancing soil stability and carbon sequestration

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ABSTRACT

Soil microbiomes, composed of diverse microbial communities such as bacteria, fungi, and archaea, play a crucial role in enhancing soil stability and carbon sequestration. These microbes influence soil structure by producing extracellular polymeric substances (EPS), forming biofilms, and promoting soil aggregation. Their metabolic activities also regulate organic matter decomposition, stabilization, and carbon fluxes. Interactions between microbes and plant roots in the rhizosphere, along with microbial carbon fixation pathways, significantly contribute to long-term carbon storage. Recent biotechnological advances, including genetically engineered microbes, synthetic microbial consortia, and CRISPR-based gene editing, offer new strategies to enhance these soil functions. Case studies across agricultural ecosystems, restoration projects, bioremediation, and urban landscaping demonstrate practical applications of soil microbiomes in promoting environmental sustainability. However, challenges such as ecological risks, technical limitations, policy gaps, and socio-economic barriers remain. Future research must address these challenges and develop standardized tools, safe applications, and interdisciplinary collaborations to fully realize the potential of soil microbiomes in sustainable land and climate management.

KEYWORDS

Soil microbiomes; Carbon sequestration; Extracellular polymeric substances (EPS); Synthetic microbial consortia

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Introduction

Microbial life prevails in soils, which are dynamic ecosystems that are essential to preserving the health of the environment. The intricate communities of bacteria, fungus, archaea, and protozoa that make up soil microbiomes are essential to the mechanisms that support soil structure and carbon cycling. Their actions have an impact on soil stability and carbon sequestration by influencing soil aggregation, nutrient availability, and organic matter stabilization [1].

For plants to survive, water to be retained, and erosion to be avoided, soil stability is essential. Extracellular polymeric substances (EPS), one type of microbial exudate, help create soil aggregates and improve structural stability. These aggregates aid in the long-term storage of carbon by shielding organic matter from quick breakdown. An important part of the global carbon cycle is soil carbon sequestration. By breaking down organic waste and converting it into stable forms of soil organic carbon (SOC), microorganisms play a part. Necroplasm is one of the microbial leftovers that persists in soils for long periods of time and becomes an essential part of SOC. The mitigation of atmospheric CO_2 levels and the fight against climate change depend on this microbial mediation [2]. Opportunities to modify soil microbiomes for improved ecosystem services have been made possible by recent developments in biotechnology. The goal of strategies like genetic engineering and the creation of beneficial microbial consortia is to support microbial activities linked to soil stabilization and carbon storage. However, further research is essential for comprehending the effectiveness and ecological effects of these interventions [3].

This review analyzes the composition and roles of soil microbiomes, explaining how they influence soil stability and sequestration of carbon. In addition, case studies illustrating real-world applications are displayed, biotechnology approaches to enhance these microbial functions are examined, and future research objectives and difficulties in using soil microbiomes for environmental sustainability are discussed.

Soil Microbiomes: Composition and Ecological Functions

Microbial diversity and structure

Comprising bacteria, viruses, fungus, protozoa, and archaea, soil microbiomes include intricate communities. These microbes live in a variety of soil niches, such as bulk soil, the detritusphere (decomposing organic matter), and the rhizosphere (root-associated zone). A number of variables, including pH, moisture content, temperature, and nutrient availability, affect their dispersal. As shown in Table 1, certain microbial groups like Bacillus and Actinobacteria are crucial for soil aggregation and nutrient cycling, which contribute to soil stability [4].

Numerous bacterial phyla, including Proteobacteria, Actinobacteria, and Acidobacteria, are found in soils and each has a unique function in the decomposition of organic matter and the cycling of nutrients. Ascomycota and Basidiomycota are two examples of fungal communities that play a major role in the breakdown of lignocellulose and in symbiotic relationships with plants. Microbial hotspots, or regions with increased microbial activity as a result of higher concentrations of organic

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matter or root exudates, are created by the spatial variability of soils. These hotspots are essential for maintaining soil structure and transforming nutrients [5].

Table 1. Key microbial groups and their roles in soil stability and carbon sequestration

Microbial Group	Function/Contribution
Bacteria	Decomposition of organic matter, nitrogen cycling
Fungi	Mycorrhizal networks, decomposition, carbon sequestration
Actinobacteria	Soil aggregation, nutrient cycling
Archaea	Methane cycling, nitrogen cycling

Role of soil microbes in ecosystems

Microorganisms in the soil play a crucial role in preserving ecosystem services. By breaking down organic materials and releasing nutrients like nitrogen, phosphorus, and sulfur that are necessary for plant growth, they propel biogeochemical cycles. Plants and some bacteria and fungus develop symbiotic interactions that improve nutrient uptake and offer defense against infections. Mycorrhizal fungi, for example, increase the root system's reach and make it easier for nutrients and water to be absorbed [6].

Additionally, by generating extracellular polymeric substances (EPS) that bind soil particles and enhance aggregation and porosity, microbial communities have an impact on soil structure. This structural improvement lowers the risk of erosion and helps retain water [6].

Methods for studying soil microbiomes

The study of soil microbiomes has been transformed by developments in molecular biology. Without the requirement for cultivation, high-throughput sequencing methods like Next-Generation Sequencing (NGS) enable thorough examination of microbial diversity and community composition [7].

Through the analysis of collective genetic material, metagenomics offers insights into the functional potential of microbial communities. This method aids in the identification of genes related to stress reactions, nutrient cycling, and other ecological processes. Another technique that connects microbial identification to function is Stable Isotope Probing (SIP). By inserting isotopically labeled substrates (such as ^13C or ^15N) into microbial DNA, scientists can identify the organisms that are actively engaged in particular metabolic activities [8].

Furthermore, DNA microarrays, also known as biochips, allow for the simultaneous analysis of gene expression levels across several genes, offering a glimpse of microbial activity in a variety of environmental settings.

Soil Stability: Concepts and Biological Drivers

The ability of soil to withstand erosion, preserve its structure, and promote plant development is referred to as soil stability. It has an impact on nitrogen cycling, water infiltration, and the avoidance of land deterioration, making it an essential part of soil health. Because stable soils promote healthy ecosystems and lessen the effects of extreme weather events, they are crucial for climate regulation, biodiversity protection, and sustainable agriculture [9].

Factors Affecting Soil Stability

A complex interaction between biological and environmental elements affects soil stability [10,11]:

Microbial activity

Extracellular polymeric substances (EPS) are produced by bacteria, fungus, and actinomycetes, among other soil microorganisms, and they bind soil particles to improve aggregate stability. By acting as organic "glues," these microbial exudates strengthen soil cohesiveness and lessen erosion vulnerability.

Root systems

By forming macropores that enhance water infiltration and physically connecting soil particles, plant roots help to stabilize the soil. The efficiency of root systems in stabilizing soil is influenced by their density and depth; plants with deeper roots provide better erosion resistance.

Soil organic matter (SOM)

By encouraging aggregation and water retention, organic matter improves soil structure. By providing food for soil organisms, it cultivates a robust microbial population that supports soil stability.

Soil fauna

Organisms such as earthworms and arthropods play a role in soil aeration and the formation of stable aggregates. Their burrowing activities create channels that facilitate root growth and water movement, indirectly supporting soil stability.

Environmental factors

Climate variables like precipitation, temperature, and wind can affect soil stability. For instance, heavy rainfall can lead to surface runoff, while high temperatures may reduce microbial activity, both impacting soil cohesion.

Understanding these factors is crucial for developing strategies to enhance soil stability, particularly in the face of challenges posed by climate change and land-use alterations.

Microbial Contributions to Soil Stability

Microbial EPS & soil biofilms

High-molecular-weight substances known as extracellular polymeric substances (EPS) are released by bacteria, fungus, and algae, among other soil microorganisms. Polysaccharides, proteins, lipids, and nucleic acids make up the majority of these compounds. EPS facilitates microbial adherence to soil particles and plant roots by acting as a matrix for biofilm development in soil settings. By binding soil particles together, EPS synthesis improves soil aggregation and, consequently, soil stability and structure. This aggregation improves water retention and lessens soil erosion, both of which improve soil health overall [12].

In soil ecosystems, biofilms structured populations of bacteria wrapped in extracellular polysaccharides are essential.

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They mediate nutrient cycling and pollutant degradation and serve as barriers to defend against environmental stresses including desiccation and nutrient variations. Environmental circumstances, nutritional availability, and the species composition of microorganisms all affect the production of biofilms. Utilizing microbial capacities to improve soil stability requires an understanding of the dynamics of EPS generation and biofilm development [13].

Soil aggregation processes

The term soil aggregation describes how soil particles group together to form aggregates, which is essential for preserving soil fertility and structure. Microorganisms use a variety of methods to aid in the aggregation of soil [14,15]:

EPS production

As previously indicated, EPS function as natural binders, encouraging the cohesiveness of soil particles and aggregate formation.

Fungal hyphae

These hyphae, which are produced by fungi, link soil particles to create a network that stabilizes aggregates.

Bacterial activity

Some bacteria generate EPS, which improves aggregate stability by facilitating soil particle attachment.

Root exudates

Exudates from plant roots promote microbial activity, which raises the generation of EPS and enhances aggregation.

In addition to improving soil structure, these microbial activities also increase porosity, water infiltration, and nutrient retention all of which are essential for managing soil sustainably.

Impact on erosion and land degradation

The productivity and health of soil are threatened by land degradation and soil erosion, two serious environmental issues. Microorganisms are essential for reducing these problems [16,17]:

Biofilm formation

Microbial biofilms serve as shields on soil surfaces, lessening the force of precipitation and halting soil separation.

Soil consolidation

Microorganisms that produce EPS cause soil particles to bind together to create aggregates that are less prone to erosion.

Restoration of damaged lands

By increasing microbial variety and activity, microbial inoculants have been utilized to restore damaged soils, improving soil fertility and structure.

Formation of biocrusts

Microbial communities in dry and semi-arid areas create biocrusts that shield soil surfaces from water and wind erosion, encourage water infiltration, and aid in the cycling of nutrients.

In order to counteract soil deterioration and promote soil health, sustainable techniques for erosion control and land restoration can be developed by utilizing these microbial processes.

Carbon Sequestration in Soils: Principles and Importance

Function in carbon cycle

As a source and a sink of carbon, soils play a crucial role in the global carbon cycle. According to estimates, soils store over 2,400 gigatons of carbon down to a depth of two meters, which is more than the atmosphere and terrestrial vegetation combined. The main way that carbon enters soils is through photosynthesis in plants, which is then carried to the soil by decomposing plant matter and root exudates. This organic matter is then broken down by microorganisms, which stabilize the remaining carbon in soil organic matter (SOM) and release some carbon back into the atmosphere as CO_2 through respiration [18].

Soil carbon pools and fluxes

There are several pools of soil carbon, and each has a different turnover rate [19,20]:

Active pool

Consisting of quickly decomposing labile organic materials that contributes to instantaneous carbon fluxes.

Slow pool

Made up of organic materials that has partially decomposed and has a slower turnover rate.

Passive pool

Helps store carbon over time by containing deeply degraded organic matter that is resistant to breakdown.

These pools are dynamic, with microbial activity, temperature, moisture, and land management techniques all having an impact on carbon flows. In order to evaluate soil carbon dynamics and their function in climate regulation, it is imperative to comprehend these pools and fluxes [20].

Organic carbon for climate regulation

An essential component of climate change mitigation is soil organic carbon, or SOC. Soils aid in lowering atmospheric CO_2 concentrations, a significant greenhouse gas that contributes to global warming, by storing carbon. Carbon storage capacity can be increased by raising SOC levels through techniques including cover crops, organic amendments, and reduced tillage. Additionally, SOC increases soil fertility and tolerance to climate-related pressures by improving soil structure, water retention, and nutrient availability [21].

Microbial Contributions to Soil Carbon Sequestration

Decomposition and stabilization of organic matter

Bacteria and fungus are among the soil microorganisms that are essential to the breakdown of organic matter, which is a basic carbon cycle process. These microorganisms convert complex organic compounds into simpler ones from soil fauna, plant wastes, and root exudates. Microbial respiration releases carbon as carbon dioxide (CO_2) throughout this process. Not all carbon is lost, though; a sizable amount is kept in the soil as soil organic carbon (SOC) [22].

Microbial activities that encourage the production of microaggregates have an impact on the stabilization of SOC. By encasing organic matter in soil particles, these microaggregates

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physically prevent it from decomposing further. Additionally, by expanding the pool of stable organic matter, microbial necromass the leftovers of dead microorganisms contribute to SOC. The net carbon storage in soils is determined by the equilibrium between microbial stabilization and breakdown processes, underscoring the vital role that microbial communities play in carbon sequestration [23].

Interactions in carbon capture

The area of soil affected by plant roots, known as the rhizosphere, is a hotspot for carbon cycling and microbial activity. Numerous organic substances, such as sugars, amino acids, and organic acids, are released into the rhizosphere by plants. By providing soil microorganisms with a carbon source, these exudates promote a dynamic plant–microbe interaction that affects soil carbon dynamics [24].

In order to improve the plant's intake of nutrients and water, arbuscular mycorrhizal fungi (AMF) develop symbiotic associations with plant roots by spreading their hyphae into the soil. AMF receives carbon from the plant in exchange. In addition to improving plant nutrition, this relationship helps sequester carbon. SOC levels can be raised by stabilizing the carbon that is delivered to AMF and integrating it into their biomass [22,25].

Moreover, the rhizosphere's microbial populations' richness and makeup can affect how well carbon is captured. When processing organic matter, diverse microbial communities are frequently more robust and effective, which improves carbon sequestration. Therefore, maximizing soil carbon storage requires an understanding of the ability to manage plant–microbe interactions [25,26].

Microbial carbon fixation pathways

In addition to breaking down organic materials, some soil microorganisms have the ability to fix CO_2 from the atmosphere and transform it into organic carbon via a variety of biochemical processes. To incorporate CO_2 into their biomass, these autotrophic microbes use a variety of carbon fixation mechanisms, including the 3-hydroxypropionate (3-HP) pathway, the reductive tricarboxylic acid (rTCA) cycle, and the Calvin-Benson-Bassham (CBB) cycle [27].

By directly integrating atmospheric CO_2 into the soil microbial biomass, the action of these carbon-fixing microorganisms aids in the sequestration of carbon in the soil. By raising the amount of organic carbon in the soil, this technique improves soil fertility in addition to lowering atmospheric CO_2 levels. Environmental elements including soil pH, temperature, moisture, and nutrient availability affect how well microorganisms fix carbon [28].

Soil microbes play a major role in carbon sequestration by fixing atmospheric CO_2 directly, facilitating plant–microbe interactions in the rhizosphere, and breaking down and stabilizing organic materials. Developing methods to improve soil carbon storage and slow down climate change requires an understanding of these microbial processes [29].

Biotechnological Interventions in Soil Microbiomes

GEMs for soil stability

In the context of recovering soil health, genetically modified microbes (GEMs) have become effective instruments for improving soil stability. In order to improve soil fertility and quality, these bioengineered microbes are made to have improved capacities for breaking down contaminants like hydrocarbons, pesticides, and heavy metals. In contrast to native bacteria alone, GEMs can be designed to hyperexcrete biomolecules that support bioremediation processes, speeding up the breakdown of pollutants and improving soil health [30]. Additionally, GEMs can be modified to generate extracellular polymeric substances (EPS), which encourage soil aggregation and improve the stability and structure of the soil. These microorganisms aid in the development of stable soil aggregates, which improves water retention, decreases erosion, and increases nutrient availability all of which are essential for preserving soil health and promoting plant growth [26,30].

SMCs in carbon sequestration

Since soil ecosystems are so complicated, using synthetic microbial consortia (SMCs) is frequently necessary to achieve the needed carbon sequestration results. SMCs are specifically designed groups of microorganisms that complement one another to improve soil processes including pollution degradation and carbon capture. In order to improve soil fertility and stability, these consortia can be made to contain bacteria with complementary skills, such as nitrogen fixation, EPS generation, and pollutant degradation [31].

For instance, a group of mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR) can increase soil aggregation, facilitate nutrient uptake, and boost plant growth, all of which increase carbon sequestration. SMCs can also be designed to break down complex organic contaminants, which will lessen their negative effects on soil health and help store more carbon [32].

CRISPR-based microbial engineering

Soil microbiome engineering has been transformed by developments in gene editing technologies, especially CRISPR-Cas systems. By precisely altering microbial genomes, CRISPR-based techniques make it possible to introduce particular features that improve soil stability and carbon sequestration [33].

For example, CRISPR can be used to add genes that allow microorganisms to create EPS, fix nitrogen in the atmosphere, or digest particular contaminants. These changes have the potential to improve soil health and boost carbon storage by improving the functional abilities of soil microbes. Furthermore, it is possible to create CRISPR-based systems that dynamically manage microbial activities in the soil by modifying gene expression in response to environmental stimuli [34].

Risk and regulation in microbial applications

There are significant ecological and regulatory issues with the use of genetically modified microorganisms in soil ecosystems. Potential hazards, such as unforeseen consequences on native microbial communities, horizontal gene transfer, and long-term ecological repercussions, must be carefully considered before introducing GEMs into soil ecosystems [35].

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Studies on the mobility and permanence of GEMs in soil, their interactions with native organisms, and their effects on soil biodiversity and ecosystem functioning should all be part of thorough risk assessments. In order to guarantee the safe, efficient, and environmentally sustainable use of GEMs in soil contexts, regulatory frameworks must also be put in place to control their release and use [36].

To create policies and standards that strike a balance between the advantages of GEM applications and the requirement to preserve biodiversity and safeguard soil ecosystems, cooperation between researchers, legislators, and stakeholders is crucial [35,36].

Case Studies: Soil Microbiomes in Practice

Soil microbes in ecosystem recovery

The effectiveness of reforestation and ecosystem restoration initiatives is greatly influenced by soil microbiomes. It has been demonstrated that adding certain soil microbes, including mycorrhizal fungus, to tree planting increases plant growth by an average of 64%, underscoring the significance of microbial communities in ecosystem restoration [37].

Furthermore, it has been discovered that using grass and shrub species in restoration initiatives increases microbial diversity and stability in degraded grasslands as well as ecosystem multifunctionality. These methods highlight how important it is to take soil microbiomes into account when developing restoration plans in order to produce long-lasting and successful results [38].

Microbial bioremediation of soils

An ecologically safe substitute for conventional remediation techniques, bioremediation uses soil microbiomes to break down or change pollutants in contaminated soils. The potential of microbial communities in soil detoxification has been highlighted by the ability of some bacterial strains, such as Pseudomonas mendocina and Brevundimonas olei, to digest more than 60% of the polycyclic aromatic hydrocarbons (PAHs) in contaminated soils [33,34].

The removal of dangerous materials like lead and arsenic from contaminated locations has showed promise when using native plants and fungus in bioremediation projects. Initial findings from a study headed by the University of California, Riverside, showed that using native California plants and fungus to clean up contaminated brownfields especially in Los Angeles could significantly lower the levels of heavy metals [21].

Soil microbiomes in urban landscaping

Soil management in urban settings is particularly difficult because of things like pollution, compaction, and space constraints. On the other hand, incorporating sustainable landscaping techniques and green infrastructure can increase urban soil microbiomes, which will improve ecosystem services. Diverse bacterial populations that aid in pollutant degradation and nutrient cycling are supported by engineered soils, or Technosols, which are utilized in urban green infrastructure projects like vegetated swales and bioswales, according to studies [29,33].

It has been discovered that organic additions made from nearby municipal waste products dramatically change urban soil microbiomes, enhancing soil health and plant development. By recycling waste materials, these supplements not only increase microbial diversity but also support environmentally friendly urban landscaping technique [17,27].

Discussion

Numerous technical obstacles stand in the way of soil microbiome research. Finding reliable and repeatable results is challenging due to the complexity and variation of soil ecosystems. The composition and function of microbial communities can be greatly influenced by soil physicochemical characteristics, including pH, moisture level, and nutrient content, which makes data interpretation more difficult. Furthermore, investigations may become confused by the presence of relic DNA from deceased microorganisms, which could result in an overestimation of microbial diversity and activity [37].

Despite their strength, current sequencing technologies are typically inaccessible to many researchers due to their high computational resource and skill requirements. Furthermore, the comparability of research conducted in various locations and under various conditions is hampered by the absence of defined protocols and databases [19,31].

Environmental and ecological concerns

Because of the potential for unintended consequences, such as the disruption of native microbial communities and the possibility of horizontal gene transfer, which could result in the spread of undesirable traits, as well as the uncertainty surrounding the long-term stability and persistence of introduced microbes in soil environments, interventions that aim to modify soil microbiomes such as the introduction of genetically engineered microbes or synthetic microbial consortia raise ecological concerns. Without careful risk assessments and monitoring, these interventions could unintentionally harm biodiversity and soil health. There are socioeconomic and policy-related obstacles to the use of soil microbiome technologies. Policymakers and the general public frequently lack knowledge and comprehension of the significance of soil microbiomes, which can hinder the creation and application of supportive policies [30].

Additionally, concerns about equality, intellectual property, and regulation are brought up by the commercialization of products based on microbiomes. Strong regulatory frameworks and international collaboration are necessary to guarantee that benefits are shared equitably and that goods are safe and efficient [39].

Future research and innovations

To facilitate cross-study comparability, future research should concentrate on creating standardized procedures and datasets. Potentially addressing some of the drawbacks of existing sequencing techniques, developments in biosensing technology offer exciting opportunities for in-situ, real-time monitoring of soil microbiomes. By combining research on soil microbiomes with other fields like agronomy and climate science, a more comprehensive knowledge of their involvement in ecosystem functioning will be possible. To ensure that soil microbiome research results in workable solutions for sustainable land

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management, it is also crucial to promote cooperation between scientists, decision-makers, and people in general [40].

Conclusion

In addition to providing creative options for sustainable land management, soil microbiomes are essential for preserving soil stability and encouraging carbon sequestration. These bacteria improve the structure, fertility, and resilience of soil by contributing extracellular polymeric compounds, biofilm formation, and organic matter decomposition. Even though there are still obstacles to overcome, such as ecological hazards and technical constraints, developments in biotechnological interventions and synthetic consortia have bright futures. In order to ensure the sustainable use of soil resources for future generations, future research should focus on addressing these issues and investigating novel approaches to harness soil microbiomes for ecosystem restoration and climate change mitigation.

Disclosure statement

No potential conflict of interest was reported by the authors.

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