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Microbial Soil Amendments for Climate Change Mitigation

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The use of microbial soil amendments has emerged as a promising strategy for climate change mitigation through enhanced soil carbon sequestration and reduced greenhouse gas (GHG) emissions. Beneficial microorganisms, including arbuscular mycorrhizal fungi (AMF), nitrogen-fixing bacteria and plant growth-promoting rhizobacteria (PGPR), can significantly influence soil-plant-microbe interactions, improving soil health and agricultural sustainability. These microbes contribute to carbon sequestration by promoting root biomass development, increasing rhizodeposition and enhancing the formation and stabilization of soil aggregates, which physically protect soil organic carbon (SOC) from microbial degradation. Mycorrhizal fungi, in particular, extend the absorptive capacity of plant roots and deposit recalcitrant carbon in the form of glomalin-related soil proteins. In addition to carbon storage, microbial amendments can reduce emissions of potent GHGs such as nitrous oxide (N_2O) and methane (CH_4) by altering nitrogen cycling and stimulating methane-oxidizing microbial populations. For example, some PGPR strains can inhibit nitrification or enhance nitrogen-use efficiency, reducing N_2O emissions from fertilized soils. Furthermore, microbial inoculants can improve nutrient uptake, decrease reliance on synthetic fertilizers and increase plant resilience to abiotic stresses, thereby supporting ecosystem stability under climate variability. The effectiveness of microbial amendments is influenced by soil characteristics, climate conditions, crop type and compatibility between microbial strains and host plants. Therefore, site-specific application strategies and long-term monitoring are essential for maximizing benefits. Despite these challenges, integrating microbial soil amendments into regenerative and precision agriculture offers a scalable, nature-based approach to climate mitigation. This article reviews the current state of knowledge on microbial amendments for climate mitigation, their mechanisms of action and their potential role in transforming soil management practices toward sustainability and resilience in the face of global climate change.

Keywords: Climate Change, Carbon sequestration, Microbial, Soil health, Sustainable agriculture.

Introduction

Climate change poses a significant threat to global food security, ecosystem stability and human well-being, largely driven by rising concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Agriculture is both a victim and a contributor to climate change, responsible for approximately 10-12 per cent of global GHG emissions, primarily through soil management practices, fertilizer use and livestock production. To address these challenges, there is an urgent need for sustainable, science-driven strategies that can reduce emissions, enhance soil carbon sequestration and build climate-resilient agricultural systems. Microbial soil amendments, comprising beneficial microorganisms such as arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR) and nitrogen-fixing bacteria, have gained attention as a nature-based

solution with multifaceted environmental benefits. These microbial inputs interact with plants and soil in complex ways, influencing nutrient cycling, root development and soil organic matter (SOM) dynamics. Through mechanisms such as enhanced rhizodeposition, improved soil aggregation and microbial carbon stabilization, microbial amendments can significantly increase soil organic carbon (SOC) stocks. Additionally, certain microbes can mitigate GHG emissions by suppressing nitrification, enhancing nitrogen-use efficiency or promoting methane oxidation in aerobic soil environments. The application of microbial amendments aligns with principles of regenerative agriculture, promoting biodiversity, reducing dependence on synthetic agrochemicals and enhancing the resilience of agroecosystems under climatic stress. However, their performance is context-dependent, influenced by biotic and abiotic factors including soil type, climate, crop species and microbial compatibility. Despite promising results in controlled studies, large-scale field adoption remains limited due to variability in outcomes, regulatory constraints and knowledge gaps regarding long-term effects. This article explores the role of microbial soil amendments in mitigating climate change, focusing on their biogeochemical mechanisms, agronomic benefits and the challenges and opportunities for integrating them into sustainable land management practices.

Mechanisms of Climate Change Mitigation

Microbial soil amendments contribute to climate change mitigation through two primary mechanisms: enhancing soil carbon sequestration and reducing greenhouse gas (GHG) emissions. These processes are driven by complex interactions among soil microbial communities, plant roots and soil physical and chemical properties.

➢ **Soil Carbon Sequestration**

Microbial inoculants enhance soil organic carbon (SOC) storage through various synergistic pathways:

✓ **Rhizodeposition and Root Biomass Enhancement**: Beneficial microbes such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) stimulate root growth and increase rhizodeposition, the release of organic compounds from roots into the soil. These exudates serve as substrates for microbial metabolism and are precursors to stable forms of organic carbon.

✓ **Soil Aggregation and Organic Matter Stabilization**: Microbial exudates, particularly glomalin-related soil proteins produced by AMF, promote the formation of soil aggregates. Aggregation physically protects organic matter from microbial decomposition and enhances carbon residence time in soil.

✓ **Microbial Necromass Contribution**: Microbial cell residues (necromass) are increasingly recognized as a major source of stable SOC. The turnover of microbial biomass results in the accumulation of microbial-derived carbon compounds that bind to soil minerals, forming persistent carbon pools.

✓ **Biochemical Transformation of Organic Inputs**: Microbial enzymes catalyze the transformation of plant residues into humified organic matter, increasing its stability and integration into long-term carbon pools.

➢ **Reduction of Greenhouse Gas Emissions**

Microbial soil amendments can also influence the emission dynamics of key GHGs; nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2):

✓ **Nitrous Oxide (N_2O) Mitigation**: Certain PGPR strains possess the ability to modulate nitrogen cycling by promoting biological nitrogen fixation, suppressing nitrification, or enhancing plant nitrogen uptake. These actions reduce the accumulation of excess nitrate in soils, limiting denitrification and subsequent N_2O emissions.

✓ **Methane (CH_4) Oxidation**: In well-aerated soils, methanotrophic bacteria oxidize methane before it escapes to the atmosphere. Microbial amendments that improve soil aeration or stimulate methanotroph activity can reduce CH_4 emissions, particularly in rice paddies and wetland systems.

- ✓ **Reduction in CO_2 Emissions from Fertilizer Use**: By improving nutrient-use efficiency, microbial amendments can decrease the demand for synthetic fertilizers, whose production and application are significant sources of CO_2 emissions. Moreover, reduced tillage and improved soil structure associated with microbial activity contribute to lower respiration rates and CO_2 fluxes.

Modern Techniques Supporting Microbial Soil Amendments

- ➢ **Soil Metagenomics and Microbiome Profiling:** Advances in high-throughput DNA sequencing and metagenomics allow researchers to analyze the diversity and function of soil microbial communities with unprecedented precision. By identifying beneficial microbial strains and their ecological roles, scientists can design targeted amendments tailored to specific soil and crop conditions. Metatranscriptomics and metaproteomics further reveal gene expression patterns and microbial metabolic activity under different environmental conditions.
- ➢ **Synthetic Microbial Consortia:** Rather than relying on single-strain inoculants, researchers are now developing synthetic microbial consortia i.e. engineered combinations of complementary microbial species that interact synergistically. These consortia are designed to perform multiple functions simultaneously, such as nitrogen fixation, phosphorus solubilization and pathogen suppression, while enhancing soil carbon stabilization and reducing GHG emissions.
- ➢ **Formulation and Delivery Technologies** Advancements in carrier materials (e.g., biochar, alginate beads, nanomaterials etc.) and encapsulation techniques improve the shelf-life, stability and field performance of microbial inoculants. Precision application methods, including seed coatings, root dipping, foliar sprays and drip irrigation delivery systems, ensure better microbial establishment and interaction with plant roots.
- ➢ **Remote Sensing and Precision Agriculture:** Remote sensing technologies, GIS mapping and drone-based monitoring systems allow farmers to assess soil health, carbon levels and microbial activity across large fields. Combined with AI and machine learning, these tools can optimize the timing and placement of microbial amendments for maximum impact.
- ➢ **CRISPR and Genetic Engineering of Microbes:** Emerging gene-editing tools like CRISPR-Cas9 are being explored to enhance microbial traits relevant to climate mitigation, such as increased carbon fixation potential, stress tolerance or targeted inhibition of GHG-producing pathways. While still in early stages, these approaches hold promise for next-generation microbial biofertilizers.

Case Studies: Real-World Applications of Microbial Soil Amendments

Loam Bio – Microbial Fungal Treatments for Enhanced Carbon Sequestration (Australia & USA)

- **Company**: Loam Bio, an agri-tech startup founded in 2019.
- **Innovation**: Developed a microbial fungal treatment to enhance soil's carbon storage capacity.
- **Effectiveness**: Field trials show treated soils can store more than double the carbon compared to conventional regenerative agriculture practices.
- **Environmental Impact**: Supports carbon sequestration efforts, addressing climate change challenges.
- **Agricultural Benefits**: Improves soil health by retaining more water and nutrients, resulting in increased crop productivity.
- **Funding**: Secured over $100 million in investments.
- **Expansion**: Expanding field trials to the United States.

Methane-Derived Microbial Biostimulant for Rice Cultivation (India)

- **Study Area**: Vellore, Tamil Nadu, India.
- **Focus of Experiment**: Methane-derived microbial biostimulant used to address greenhouse gas emissions and improve agricultural practices

- **Duration of Study**: Conducted over three crop seasons, spanning 2021 to 2023.
- **Environmental Impact**: Significant reduction in methane emissions, contributing to mitigating climate change effects
- **Agricultural Benefits**: Enhanced rice yield, providing a sustainable boost to rice production.
- **Broader Implications**: Demonstrates a promising and eco-friendly approach to balancing productivity with environmental responsibility

Bacillus Consortium for Soil Bioaugmentation (West Bengal, India)

- **Research Location**: West Bengal, India.
- **Innovation**: Developed a multi-strain consortium of plant growth-promoting *Bacillus* species.
- **Objective**: To bioaugment over-exploited agricultural soils for improved soil health and productivity.
- **Combination Used**: Consortium applied with vermicompost.
- **Impact on Soil**:

✓ Significantly improved soil microbial diversity.
✓ Increased abundance of functional genera and metabolic pathways, as revealed by metagenomic analyses.

- **Agricultural Benefits**: Enhanced vegetative growth and soybean yield.
- **Sustainability**: Provides an eco-friendly solution for rejuvenating degraded soils and boosting agricultural productivity.

It's an exciting example of harnessing microbial technology for sustainable agriculture!

Biochar and Organic Waste Amendments for Soil Health (Global)

- **Study Published**: 2024.
- **Focus**: Investigated the combined use of biochar, farmyard manure, and pressmud (a sugarcane byproduct) to improve saline soil health.
- **Soil Enhancements**:

✓ Increased soil organic carbon levels.
✓ Improved available nitrogen content.
✓ Enhanced microbial enzyme activities, promoting nutrient cycling.

- **Role of Biochar**:

✓ Retains nutrients and moisture due to its porous structure.
✓ Creates a favorable environment for microbial growth.
✓ Improves soil structure and overall fertility.

- **Sustainability**: Provides an effective and eco-friendly method to restore degraded, salt-affected soils.

Meta-Analysis on Biochar's Impact on Soil Microbial Biomass Carbon (Global)

- **Year of Study**: 2023.
- **Focus**: Examined the impact of biochar amendment on soil microbial biomass carbon (SMBC).
- **Scope**: Covered various climates and land-use types.
- **Key Findings**:

✓ Biochar significantly enhances SMBC across all mean annual temperature (MAT) and mean annual precipitation (MAP) conditions.
✓ The most substantial increase in SMBC was observed in regions with low MAT and MAP.

- **Mechanism**:

✓ Biochar helps mitigate the adverse effects of low temperatures on soil microbial activity.
✓ Its porous structure improves soil water holding capacity, fostering a better environment for microbial growth.

- **Environmental and Agricultural Benefits**: Highlights the potential of biochar to enhance soil health in diverse climates, particularly in challenging conditions.

Potential Risks and Concerns

1. **Ecological Disruption**
✓ Introduced microbes may disturb native soil microbial communities or biodiversity.
✓ Risk of unintended effects on non-target organisms or nutrient cycles.
2. **Performance Variability**
✓ Effectiveness is inconsistent across different soils, climates and crops.
✓ Some microbes fail to establish or survive long-term in the field.
3. **Over-Reliance & Misuse**
✓ May be wrongly used as a substitute for good soil management practices.
✓ Excessive application can cause imbalances or unintended outcomes.
4. **Quality and Regulation Issues**
✓ Commercial products may vary in quality and microbial content.
✓ Lack of clear regulatory frameworks in many regions.
5. **Ethical and Access Concerns**
✓ Patented strains may limit access for smallholders.
✓ Uneven benefits between industrial and subsistence farming systems.

Future Prospects

1. Integration with Regenerative and Climate-Smart Agriculture: Microbial technologies are expected to play a central role in regenerative farming systems by enhancing soil health, reducing input dependency and sequestering carbon. Their integration with crop diversification, organic inputs and conservation tillage will be critical for long-term sustainability.

2. Advances in Microbial Ecology and Engineering: Breakthroughs in metagenomics, metabolomics and synthetic biology are enabling the design of customized microbial consortia tailored to specific soils and crops. Genetically optimized microbes with enhanced carbon-fixing, stress-resistance or greenhouse gas-reducing traits may revolutionize soil management.

3. Climate Policy and Carbon Markets: As global carbon credit markets expand, verified microbial-based carbon sequestration could offer farmers new revenue streams. Standardized monitoring tools and data-backed verification systems will be key to scaling this opportunity.

4. Digital Agriculture and Precision Application: The convergence of microbial amendments with AI, remote sensing and soil health monitoring tools will enable precise, data-driven applications for maximizing effectiveness while minimizing risks.

5. Global Adoption and Capacity Building: International collaboration and policy support can facilitate technology transfer to developing countries. Capacity building, farmer education and inclusive access models will be essential to ensure equitable benefits across diverse farming systems.

Conclusion

Microbial soil amendments offer a powerful, nature-based solution for climate change mitigation by enhancing soil carbon sequestration and reducing greenhouse gas emissions. With advances in science and technology, their role in sustainable and regenerative agriculture is expanding. However, to fully realize their potential, challenges such as ecological risks, inconsistent performance and regulatory gaps must be addressed. With proper management and policy support, microbial amendments can become a key tool for building climate-resilient and productive agricultural systems.