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Microbial Biomass and Soil Health in Sustainable Farming Systems

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This study examines the role of soil microbial biomass in improving soil health and supporting sustainable farming systems. The study is based on literature review and comparative analysis of sustainable practices such as organic amendments, cover cropping, crop rotation, and conservation tillage with conventional farming systems. Microbial biomass carbon (MBC) and nitrogen (MBN) were used as important indicators of soil health. Sustainable farming practices increased microbial activity by 25–40%, improving nutrient cycling, soil organic matter, and soil structure. Practices like reduced tillage and cover cropping enhanced microbial diversity and soil resilience. Biofertilizers such as Rhizobium and Azotobacter also improved nutrient availability while reducing dependence on chemical fertilizers. Microbial biomass is an important indicator of soil health and plays a key role in sustainable and climate-resilient agriculture. Promoting microbial-based farming practices can improve long-term soil fertility, environmental sustainability, and food security.

Keywords: Microbial biomass, soil health, sustainable agriculture, nutrient cycling, biofertilizers.

Introduction

Soil health refers to the ability of soil to continuously support biological productivity, environmental quality, and ecosystem sustainability through balanced physical, chemical, and biological functions that sustain plants, animals, and humans, thereby ensuring optimal productivity. Sustainable farming systems use integrated agricultural practices to meet present food demands. These systems conserve natural resources for future generations. Practices such as crop rotation, organic amendments, and reduced tillage help maintain ecological balance. According to Food and Agriculture Organization (2023), sustainable soil management practices are essential for maintaining soil productivity and environmental stability under changing climatic conditions. Soil microorganisms play a pivotal role in this ecosystem, driving nutrient cycling, organic matter decomposition, and soil structure formation—essential for fertility and resilience. Key indicators include microbial biomass carbon (MBC), the living carbon in soil microbes, and microbial biomass nitrogen (MBN), which reflect active microbial populations and nutrient availability.

In contrast, conventional agriculture relies on intensive chemical inputs and monocropping, often depleting soil organic matter, while sustainable systems enhance microbial activity for long-term productivity. However, soil degradation—through erosion, salinization, and compaction—affects over 33% of global soils, threatening food security.

Climate change exacerbates these issues via altered rainfall, temperature extremes, and elevated CO_2, undermining soil sustainability; yet, microbial biomass serves as a sensitive bioindicator for monitoring and restoring soil health in sustainable frameworks.

Concept of Soil Microbial Biomass and Soil Health in Sustainable Farming Systems

Soil microbial biomass represents the living component of soil organic matter and includes microorganisms such as bacteria, fungi, actinomycetes, algae, and protozoa. Although it constitutes only a small fraction of total soil organic matter, it plays a fundamental role in maintaining soil fertility, nutrient cycling, and sustainable agricultural productivity. In Indian farming systems, especially under integrated nutrient management and organic farming practices, soil microbial biomass is increasingly recognized as a sensitive indicator of soil health and ecosystem sustainability.

Microbial Biomass Carbon (MBC)

Microbial Biomass Carbon (MBC) refers to the total living carbon present in soil microorganisms. It usually constitutes about 1–5% of total soil organic carbon and represents the most active component of the soil ecosystem.

Importance

MBC is a sensitive indicator of soil health and quickly responds to changes in management practices, organic inputs, and environmental stress. It plays an important role in nutrient cycling, energy flow, and soil fertility. Therefore, MBC is widely used to assess soil quality and sustainability in farming systems. Higher MBC values (>200 µg g^{-1} soil) indicate healthy and biologically active soil with better nutrient availability and structure. Lower MBC levels suggest soil degradation caused by intensive tillage or excessive chemical use.

Estimation Methods

- **Fumigation–Extraction Method**

In this method, soil is fumigated with chloroform to break microbial cells and release soluble carbon. The extracted carbon is measured using 0.5 M K_2SO_4 solution and a TOC analyzer.

- **Substrate-Induced Respiration (SIR)** This method measures microbial activity by adding glucose to soil and estimating CO_2 released during respiration. It reflects active microbial biomass without destroying microbial cells.

Role of Microbial Biomass in Sustainable Farming

Funtion	Role
Nutrient Cycling	Drives N, P, S mineralization, converting organic forms to plant available ions through microbial metabolism.
Organic Matter Decomposition	Breaks down plant residues into stable humus, improving soil fertility and water retention.
Soil Aggregation	Fungal hyphae and bacterial polysaccharides bind particles, creating stable structure for better aeration and root growth.
Carbon Sequestration	Stores atmospheric CO_2 in soil organic matter, mitigating climate change while sustaining long-term productivity.
Disease Suppression	Produces antibiotics and competes with pathogens, protecting plant roots from diseases.
Rhizosphere Interaction	Enhances nutrient and water uptake through symbiotic relationships like mycorrhizae and PGPR

Major Components of Soil Microbial Biomass

The soil microbial community is composed of several groups of microorganisms, each performing specific ecological and biochemical functions.

Bacteria

Bacteria are the most abundant microorganisms present in soil. They rapidly decompose simple organic materials and convert nutrients into plant-available forms. Nitrogen-fixing bacteria such as Rhizobium and Azotobacter enrich soil nitrogen, while phosphate-solubilizing bacteria improve phosphorus availability. In Indian pulse- and soybean-based cropping systems, the nitrogen-fixing ability of associated bacteria play a crucial role in improving nutrient cycling, enhancing nitrogen availability, and increasing crop productivity under integrated nutrient management practices

Fungi

Fungi form long filamentous structures called mycelia, which bind soil particles together and improve aggregate stability. They are highly efficient in decomposing complex organic compounds such as cellulose and lignin. Mycorrhizal fungi establish symbiotic associations with plant roots and enhance water and nutrient uptake, particularly phosphorus and micronutrients. Conservation agriculture practices widely adopted in rainfed regions of India encourage fungal proliferation and improve soil structure. Research findings indicate that mycorrhizal fungi improve phosphorus uptake, soil aggregation, and drought tolerance in sustainable farming systems.

Actinomycetes

Actinomycetes are filamentous microorganisms that possess characteristics intermediate between bacteria and fungi. They are important decomposers of resistant organic materials and produce several antibiotics that suppress soil-borne pathogens. Several studies reported that actinomycetes contribute to disease suppression and organic residue decomposition in organically managed soils. Their presence is commonly associated with well-aerated and organically managed soils.

Algae

Soil algae are microscopic photosynthetic organisms that contribute organic carbon to the soil ecosystem. In flooded rice ecosystems and moist soils, blue-green algae play a major role in biological nitrogen fixation and soil fertility enhancement. Indian rice cultivation systems often utilize algal biofertilization as an eco-friendly nutrient source.

Protozoa

Protozoa regulate microbial balance by feeding on bacteria and releasing nutrients, especially nitrogen, in forms readily available to plants. Their grazing activity stimulates microbial turnover and contributes to nutrient mineralization processes.

Soil Health and Its Indicators

Soil health refers to the ability of soil to function as a living ecosystem capable of sustaining plants, animals, and humans while maintaining environmental quality. A healthy soil possesses balanced physical, chemical, and biological properties that support sustainable agricultural production.

1. Biological Indicators of Soil Health

Biological indicators provide direct information about microbial activity and nutrient transformations occurring in soil.

- **Microbial Biomass Carbon (MBC)** MBC represents the total living microbial carbon present in soil. It serves as an early and sensitive indicator of changes in soil organic matter and management practices. Higher MBC values are generally observed in soils receiving organic amendments, crop residues, and biofertilizers.
- **Microbial Biomass Nitrogen (MBN)** MBN measures the nitrogen contained within living microbial tissues and reflects the soil's nitrogen cycling potential. Increased microbial biomass nitrogen indicates active nutrient turnover and improved soil fertility.
- **Soil Respiration:** Soil respiration measures carbon dioxide (CO_2) released during microbial decomposition of organic matter. Greater respiration rates indicate higher biological activity and active decomposition processes.
- **Enzyme Activity :** Soil enzymes such as dehydrogenase, urease, phosphatase, and catalase participate in nutrient transformation reactions. Enhanced enzyme activity reflects improved microbial functioning and efficient nutrient cycling in sustainable farming systems.

Dehydrogenase → microbial oxidative activity
Urease → nitrogen mineralization
Phosphatase → phosphorus availability

2. **Physical Indicators of Soil Health** Physical properties influence root growth, water movement, aeration, and resistance to erosion.

- **Bulk Density:** Bulk density indicates the degree of soil compaction. Excessive compaction restricts root penetration, water infiltration, and microbial activity. Organic matter additions generally reduce bulk density and improve soil porosity.
- **Aggregate Stability:** Aggregate stability refers to the resistance of soil aggregates against disintegration by water. Stable aggregates improve aeration, infiltration, and resistance to erosion.
- **Organic Carbon**: Soil organic carbon serves as an important energy source for microorganisms and is considered a key indicator of soil fertility. Sustainable farming practices such as compost application, residue retention, and cover cropping help maintain higher organic carbon levels. Organic matter and microbial products improve soil structure and enhance moisture retention, which is particularly important under dryland farming conditions in India

3. **Chemical Indicators of Soil Health**

Soil pH: Soil pH influences nutrient solubility and microbial activity, thereby affecting crop productivity. Most agricultural crops perform best in slightly acidic to neutral soils (pH 6.0–7.5), whereas extreme acidity or alkalinity can reduce nutrient availability. Balanced nutrient management through the integrated use of fertilizers and organic inputs improves nutrient availability and minimizes environmental losses

Effect of Sustainable Practices on Microbial Biomass

Practice	Effect on Microbial Biomass
Organic Farming	Increases MBC and MBN by 20-50% through regular organic amendments that serve as energy sources for microbes.
Conservation Tillage	Maintains higher microbial populations by preserving soil structure and residue cover, reducing disruption to fungal networks.
Crop Rotation	Boosts diversity and biomass by alternating root exudates and residue inputs, enhancing nutrient cycling microbes.
Green Manuring	Rapidly elevates MBC through fresh biomass incorporation, stimulating decomposition and N-fixing bacteria.
Biofertilizers	Directly introduces beneficial microbes (Rhizobium, Azotobacter), increasing active biomass and enzyme activity.
Cover Crops	Provides continuous root exudates and biomass, sustaining microbial activity during off-seasons and improving C:N ratios.
Residue Management	Retains crop residues on surface, promoting fungal growth and humus formation for stable microbial pools.
Integrated Nutrient Management (INM)	Combines organics with minerals, optimizing microbial growth without overload, achieving balanced nutrient release.

Future prospects

Precision Agriculture: The use of soil sensors and GPS-guided technologies enables precise application of organic amendments and bioinputs, improving nutrient-use efficiency and enhancing microbial biomass through targeted nutrient delivery.

Biofertilizers: Advanced multi-strain biofertilizer formulations, such as combinations of *Rhizobium* and plant growth-promoting rhizobacteria (PGPR), can provide consistent nitrogen fixation and phosphorus solubilization, thereby reducing dependence on synthetic fertilizers while improving microbial biomass carbon (MBC).

Carbon Farming: Practices such as cover cropping and reduced tillage enhance soil microbial biomass and promote carbon sequestration, contributing to improved soil health, reduced atmospheric CO_2, and increased long-term farm profitability.

Microbial Consortia: Tailored consortia of beneficial fungi, bacteria, and actinomycetes can create synergistic interactions that improve nutrient cycling, soil fertility, and disease resistance in different cropping systems.

Climate-Smart Agriculture: The integration of microbial inoculants with drought-tolerant crop varieties and water-efficient irrigation practices helps sustain microbial activity and crop productivity under changing climatic conditions and irregular rainfall patterns.

AI and Soil Biology Research: Artificial intelligence and machine learning approaches are increasingly being used to analyze microbial DNA sequencing data, predict microbial biomass responses under different climate scenarios, and support proactive farm management through customized microbial solutions.

Conclusion

Soil microbial biomass is a sensitive indicator of soil health and plays a vital role in nutrient cycling, organic matter decomposition, and maintenance of soil fertility. Sustainable farming practices such as organic amendments, crop rotation, residue retention, and conservation tillage significantly improve microbial activity, leading to healthier and more resilient soil ecosystems. The use of biofertilizers like Rhizobium, Azotobacter, PSB, and mycorrhizae helps reduce dependence on chemical fertilizers while enhancing nutrient availability and crop productivity. Moreover, active microbial communities improve soil carbon sequestration, water-holding capacity, and tolerance to climate stress, making them important for climate-resilient agriculture. Future research should focus on region specific microbial management and advanced studies on microbial diversity under changing climatic conditions. At the policy level, promoting biofertilizers, organic inputs, and soil biological indicators in soil health programs will support sustainable agriculture and long-term food security in India.

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