

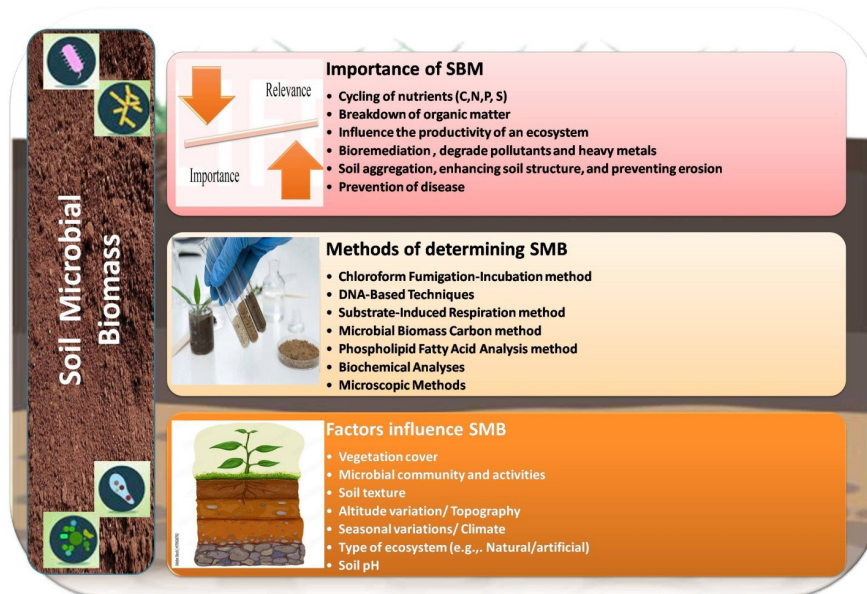
## Soil Microbial Biomass: A Crucial Indicator of Soil Health

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Soil health is fundamental to the sustainability and productivity of agricultural systems, forest ecosystems, and the environment at large.<sup>1,2</sup> A number of characteristics need to be evaluated in order to fully comprehend the complex equilibrium present in soil ecosystems. Soil microbial biomass is one important indicator of these parameters.<sup>3</sup> The significance of soil microbial biomass and its function as a major indicator of soil

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health, are underlined in this article. This comprehensive examination also emphasizes the complex roles that microbial biomass plays in maintaining the health and functionality of ecosystems.<sup>4</sup>

The term "soil microbial biomass" describes the living elements of soil, which include bacteria, fungus, protozoa, and other microscopic organisms. Even though their microscopic size, microorganisms collectively form a sizeable amount of the Earth's biomass.<sup>5</sup> Their importance emerges from their versatility, ubiquity and vital roles in ecosystem functioning. These microorganisms are essential for the cycling of nutrients, breakdown of organic matter, prevention of disease and the maintenance of soil structure.<sup>6</sup> Microbial activities contribute to soil aggregation, enhancing soil structure, and preventing erosion, therefore, may be considered as the indicator of soil health. A diverse and abundant microbial community confers resilience to soil against environmental stresses.

Microbes are principal agents in the decomposition of organic matter through enzymatic breakdown. They help to release nutrients by breaking down complicated substances into simpler forms, facilitating nutrient release from the dead and decaying matters.<sup>7-9</sup> This process is pivotal for the cycling of elements like carbon, nitrogen, phosphorus, and sulphur, making these nutrients available for plant uptake and subsequent trophic levels.<sup>10,11</sup> As a major component of nitrogen cycle, some microbial species are able to fix atmospheric nitrogen that plants can utilise. Through symbiotic partnerships with leguminous plants, nitrogen-fixing bacteria like *Rhizobium* improve soil fertility. Moreover, microbes also engaged in symbiotic relationships with plants (mycorrhizal fungi), animals (gut microbiota) and other organisms. Mutual benefits from these interactions frequently include improved resilience to environmental stressors, pathogen defence, and nutrient exchange.<sup>12,13</sup> In ecosystems, microbes exist at different trophic levels. In certain circumstances, they act as primary producers by using either photosynthesis or chemosynthesis to synthesise organic chemicals. Furthermore, they serve as the foundation of food webs, supporting higher trophic levels by providing food for macro- and microfauna.<sup>5</sup> Microbial predation regulates population sizes and controls the proliferation of other microorganisms. Soil microbes also play a crucial role in the bioremediation too. Microbes possess remarkable abilities to degrade pollutants, such as hydrocarbons, pesticides, and heavy metals. Bioremediation techniques leverage microbial metabolic processes to mitigate the environmental contamination, offering a sustainable approach to ecosystem restoration.<sup>14</sup> Microbial activities influence greenhouse gas emissions, including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). Understanding microbial roles in these processes is crucial for assessing their impact on global climate dynamics.

The role of microbial biomass in soil fertility is a critical and multifaceted aspect of the intricate web that sustains life on our planet. Soil, often regarded as a complex living system, harbours an astonishingly diverse community of microorganisms, including bacteria, fungi, archaea, protozoa, and algae.<sup>15</sup> These tiny life forms are essential to the maintenance of soil fertility, facilitation of nutrient cycling, improvement of plant and soil health, and eventually supporting global food production.<sup>16</sup> The process of decomposition is orchestrated by various microorganisms, results in the release of essential nutrients such as nitrogen, phosphorus, potassium, and other micronutrients. These nutrients are crucial for the growth and development of plants, thereby directly influencing soil fertility. Microbial biomass plays an important part in the cycling of nutrients, which is one of its most notable contributions. Plants and microbes coexist in a symbiotic relationship, for instance, mycorrhizal fungi associated with plant roots. The spreading of the root system's reach and supporting the uptake of nutrients and water, especially phosphorus and nitrogen, which are frequently present in organic materials in the forms that are not immediately available to plants. Furthermore, certain microbial communities, such as nitrogen-fixing bacteria like *Rhizobium* and *Azotobacter*, have the remarkable ability to convert atmospheric nitrogen into a form usable by plants - a process crucial for maintaining soil fertility and reducing dependence on external nitrogen sources like synthetic fertilizers.<sup>17</sup> The stability and structure of the soil are greatly enhanced by the activity of these microorganisms.<sup>18</sup> Extracellular polymeric substances (EPS) derived by microbial secretions aid in the binding of soil particles, hence enhancing soil aggregation and porosity. This enhances water infiltration, aeration, and root penetration, creating a

conducive environment for plant growth.<sup>19,20</sup> Microbial biomass not only improves soil structure and cycles nutrients, but it is also essential for suppressing plant diseases. Certain soil microbes exhibit antagonistic behaviour towards plant pathogens by producing antibiotics or competing for resources, thereby reducing the incidence of diseases and promoting overall plant health.

Assessing soil microbial biomass is crucial for understanding soil health, nutrient cycling, and ecosystem functioning. Various methods are employed to quantify and characterize these microbial communities, each offering unique insights into the abundance, diversity, and activity of soil microbes. Some frequently used common methods for assessing soil microbial biomass are.

1. *Chloroform Fumigation-Incubation method* (CFI): This method involves fumigating soil samples with chloroform to kill soil microbes.<sup>21,22</sup> The difference in carbon dioxide (CO<sub>2</sub>) released from fumigated versus non-fumigated samples during incubation allows estimation of microbial biomass carbon. This technique estimates both the microbial biomass carbon and the microbial metabolic quotient.

2. *Substrate-Induced Respiration method* (SIR): It involves measuring the increase in CO<sub>2</sub> emissions after adding a substrate (like glucose) to the soil. The additional CO<sub>2</sub> released indicates microbial activity and can be used to estimate microbial biomass and metabolic potential.

3. *Phospholipid Fatty Acid Analysis method* (PLFA): PLFA analysis identifies and quantifies phospholipid fatty acids present in microbial cell membranes. Different microbes have distinct fatty acid profiles, enabling estimation of microbial biomass, community structure, and changes in microbial composition based on the types and amounts of fatty acids present.

4. *Microbial Biomass Carbon method* (MBC) Measurement: Direct measurement of microbial biomass carbon involves extracting and quantifying the carbon content of soil microbial cells. This can be done using techniques like substrate-induced respiration, fumigation-extraction, or the use of isotopic labelling.

5. *DNA-Based Techniques*: Molecular techniques such as quantitative polymerase chain reaction (qPCR) and high-throughput sequencing (e.g., amplicon sequencing of 16S rRNA genes or ITS regions) allow for assessing microbial biomass indirectly by quantifying microbial DNA. These methods provide insights into microbial diversity, richness, and community composition.

6. *Biochemical Analyses*: Enzyme assays targeting specific microbial activities (e.g., dehydrogenase, β-glucosidase, urease) provide information on the functional potential of microbial communities, indicating microbial biomass and activity indirectly through the rates of substrate transformation.

7. *Microscopic Methods*: Microscopic techniques like microscopy (using stains like DAPI) or electron microscopy can directly visualize and count microbial cells, providing qualitative and quantitative information about microbial biomass and morphology.

When assessing soil microbial biomass, it is essential to consider the limitations and advantages of each method. Combining multiple techniques often provides a more comprehensive understanding of soil microbial communities, their biomass, diversity, and functional potential. Additionally, accounting for factors like soil type, environmental conditions, and sampling strategies are crucial for accurate and meaningful interpretations of microbial biomass data.

The microbial biomass in soil is an indispensable component of soil fertility. Its myriad functions, including nutrient cycling, soil structure improvement, disease suppression, and symbiotic relationships with plants, highlight the critical importance of preserving and nurturing soil microbial communities. Sustainable land

management practices that prioritize the conservation of soil biodiversity and minimize disruptions to microbial ecosystems are essential for ensuring long-term soil fertility and global food security. However, it is important to note that the balance and diversity of microbial communities are susceptible to various factors, including land management practices, chemical inputs, climate change, and pollution. Anthropogenic activities, such as the excessive use of pesticides, fertilizers, and land degradation, can disrupt these delicate ecosystems, leading to a decline in soil fertility and overall ecosystem health.<sup>23,24</sup>

In essence, soil microbial biomass conservation and enhancement are integral to sustainable land management. By fostering healthy microbial communities, agriculture can become more resilient, productive, and environmentally friendly, ensuring the long-term health of both soil and ecosystems. Practices like reduced tillage, crop rotation, organic amendments, adding compost, manure, or crop residues, using microbial inoculants and composts, techniques like afforestation, cover cropping, restoration of degraded soils, minimizing the soil disturbance, activity by providing varied root exudates and organic matter, application of specific microbial species or biofertilizers etc. can enhance nutrient availability and soil health.<sup>25-27</sup> All these practices along with or individually may promote microbial diversity and abundance.

Balancing practices including finding a balance between conservation practices and agricultural productivity is essential. Therefore, adapting to local conditions (microbial communities vary based on geography and soil types, requiring site-specific strategies) and long-term commitment (conserving and enhancing soil microbial biomass is a continuous process that requires long-term commitment and consistent practices) can sustain the fertility of soil as well as the soil microbial population.

Understanding the role of soil microbial biomass as a crucial indicator of soil health opens avenues for further research. Advances in technology and comprehensive studies will aid in developing more precise methods to evaluate and enhance soil microbial communities. Microbial biomass serves as the foundation of ecosystem functioning, exerting profound influences on nutrient cycling, energy flow, environmental resilience, and ecological stability. Advances in microbiology and biotechnology continue to unveil the intricate relationships between microbial communities and ecosystems, providing opportunities for innovative solutions in fields like agriculture, wasteland management, and conservation.

As we delve deeper into the complexities of microbial interactions within ecosystems, further research and interdisciplinary collaborations will be pivotal in harnessing their potential for sustainable environmental management and preserving the delicate balance of Earth's ecosystems.

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