

Microbiological Indicator of Soil Heath

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Soil health refers to the ability of soil to function as a living ecosystem that supports plants, animals, and humans. It depends on the interactions among soil organisms, minerals, and organic matter, which play important roles in nutrient cycling, water infiltration, and the natural suppression of soil-borne diseases [1].

Soil microorganisms are essential for maintaining soil health because they contribute to several biological and biochemical processes. Microbial indicators are measurable characteristics, such as microbial biomass, abundance, diversity, activity, and functional capacity, that help assess the biological condition of soil. These indicators also provide useful information on nutrient cycling, organic matter decomposition, and the effects of different agricultural management practices on soil health. The major roles of microbial indicators are discussed below.

Major Roles of Microbial Indicators in Soil Health Assessment

Early detection of soil degradation and recovery: Soil microorganisms are highly sensitive to changes in their surrounding environment. Their abundance and activity can change rapidly in response to agricultural practices, nutrient availability, soil moisture, salinity, and contamination. These changes can provide early signs of soil degradation or improvement, even before visible changes appear in soil properties. Thus, microbial indicators are useful for monitoring soil health and assessing its recovery under different management practices [2].

Quantification of nutrient cycling and soil enzyme activity: Soil microorganisms play an important role in breaking down organic residues and converting nutrients into forms that plants can absorb. This process is largely supported by microbial enzymes, which help decompose complex organic compounds and regulate the cycling of carbon, nitrogen, phosphorus, and sulphur. Measuring the activity of these enzymes provides valuable information about nutrient availability and the biological functioning of soil [3]. Some important soil enzymes and their functions include:

- **β -Glucosidase:** Involved in the decomposition of organic carbon compounds and carbon cycling.
- **N-Acetyl- β -glucosaminidase:** Contributes to the breakdown of nitrogen-containing organic compounds and is associated with carbon and nitrogen cycling.
- **Phosphatase:** Helps release phosphorus from organic compounds, making it available for plant uptake.
- **Arylsulfatase:** Participates in the mineralization of organic sulphur compounds and contributes to sulphur cycling [3].

Assessment of soil organic matter and carbon sequestration: Soil microorganisms are actively involved in the formation, decomposition, transformation, and stabilization of soil organic matter. During these processes, they influence how organic carbon is released, recycled, or retained in the soil. Therefore, studying microbial biomass and activity helps in understanding soil organic matter dynamics and the role of microorganisms in soil carbon sequestration [3].

Assessment of soil biological resilience: Soil biological resilience is the ability of soil microorganisms and their associated biological processes to withstand environmental disturbances and recover after stressful conditions. Soils with diverse and active microbial communities are generally better able to maintain essential functions such as organic matter decomposition, nutrient cycling, beneficial plant–microbe interactions, and the suppression of soil-borne pathogens. Therefore, microbial diversity and activity are useful indicators for understanding the resilience and long-term functioning of soil ecosystems [4].

Types of Soil Microbiome

- **Bacteria:** Bacteria are the most abundant prokaryotes in the soil rhizosphere and contribute to plant growth promotion, biological nitrogen fixation, and nutrient solubilization. Examples: *Bacillus* spp., *Pseudomonas* spp., and *Rhizobium* spp. [5].
- **Fungi:** Soil fungi support organic matter decomposition, soil aggregation, and plant nutrient uptake through saprophytic and mycorrhizal associations. Examples: *Trichoderma* spp., *Aspergillus* spp., *Penicillium* spp., and *Glomus* spp. [6].
- **Actinomycetes:** Actinomycetes are Gram-positive bacteria with high G+C content that form branching, filamentous structures. They are commonly found in well-aerated, dry, and alkaline soils. Examples: *Streptomyces* spp., *Micromonospora* spp., and *Nocardia* spp. [7].
- **Archaea:** Archaea are single-celled prokaryotes found in diverse soil environments, including extreme and moderate conditions. Examples: *Nitrososphaera* spp. and *Methanosarcina* spp. [8].

Major Soil Microbial Indicators

Microbial Biomass Carbon: Represents the carbon present in living soil microorganisms, including bacteria, fungi, and actinomycetes, and generally accounts for 1–5% of total soil organic carbon [9].

Soil Respiration: Measures carbon dioxide released from soil through microbial decomposition of organic matter and root respiration.

Soil Enzyme Activity: Soil enzymes facilitate organic matter decomposition and nutrient cycling. Important enzymes include:

- **Dehydrogenase:** Indicates overall microbial metabolic activity.
- **Phosphatase:** Reflects phosphorus mineralization potential and biological phosphorus demand.
- **Urease:** Catalyses the breakdown of urea into ammonia and carbon dioxide [10].

Microbial Diversity and Richness: Reflect the variety and number of microbial taxa present in soil, providing insights into microbial community structure and soil biological health.

Nitrogen-Fixing Microorganisms: These microorganisms contain nitrogenase enzymes that convert atmospheric nitrogen into ammonia. They include:

- **Symbiotic diazotrophs:** *Rhizobium*, *Bradyrhizobium*, and *Sinorhizobium* in legumes, and *Frankia* in actinorhizal plants.
- **Free-living and associative diazotrophs:** *Azotobacter*, *Azospirillum*, and *Beijerinckia*.

Microbial Colonization: Refers to the establishment of beneficial microorganisms in the rhizosphere, on root surfaces, or within plant tissues. The main processes include:

- **Chemotaxis:** Movement of microorganisms towards root exudates containing sugars, amino acids, and organic acids.
- **Attachment:** Adhesion to root surfaces through exopolysaccharide production and biofilm formation.
- **Symbiotic integration:** Formation of arbuscules by arbuscular mycorrhizal fungi or root nodules by rhizobia [11].

Microbial Indicators Under Different Agricultural Practices

Soil microorganisms contribute to nutrient cycling, organic matter decomposition, soil aggregation, and disease suppression. Changes in their abundance, diversity, and activity help assess the effects of agricultural practices on soil health.

Organic Farming: Uses organic inputs such as compost, farmyard manure, green manure, and crop residues to maintain soil fertility while limiting synthetic fertilizers and pesticides according to organic farming standards [12].

Conventional Farming: Generally involves mineral fertilizers, chemical pesticides, intensive tillage, and improved crop varieties. Its effects on soil microorganisms depend on input levels, tillage, crop rotation, and residue management [13].

Conservation Agriculture: Emphasizes minimum soil disturbance, continuous soil cover, and crop diversification. These practices help maintain soil structure, organic matter, and favourable conditions for microbial activity [13].

Integrated Nutrient Management: Combines organic manures, mineral fertilizers, and biofertilizers to improve nutrient-use efficiency, maintain soil fertility, and support beneficial microorganisms [13].

Impact of Environmental Stress on Soil Microorganisms

Environmental stresses such as climate change, drought, salinity, heavy metals, and pesticides can alter microbial diversity, activity, and soil biological processes. Their effects vary with stress intensity, duration, soil conditions, and microbial tolerance.

Climate Change: Rising temperatures, altered rainfall patterns, drought, and flooding influence soil moisture, carbon availability, and microbial community composition [14].

Drought and Salinity: Water scarcity restricts microbial activity, while salinity causes osmotic stress and ion toxicity, affecting microbial growth and biochemical processes [14, 15].

Heavy Metal Contamination: Accumulation of cadmium, lead, chromium, copper, nickel, and mercury from industrial, agricultural, and environmental sources can affect microbial biomass, enzyme activity, and community structure [16].

Pesticide Application: Pesticides may influence non-target soil microorganisms, depending on their chemical properties, application rates, persistence, and soil conditions. These effects can be assessed through changes in microbial biomass, enzyme activity, community composition, nutrient cycling, and pesticide degradation.

Microbial Indicators and Plant Health

Soil microbial diversity and activity are important indicators of soil fertility and plant health. A healthy rhizosphere microbiome improves nutrient availability, soil structure, and plant tolerance to environmental stress.

Plant Growth Promotion: Beneficial microorganisms support plant growth through nutrient mobilization, phytohormone production, and disease suppression [17, 19].

Nutrient Solubilization and Biofertilization: Soil microorganisms improve nutrient availability through several mechanisms:

- **Nitrogen Fixation:** Bacteria such as *Rhizobium*, *Azotobacter*, and *Azospirillum* convert atmospheric nitrogen into ammonia.
- **Phosphate Solubilization:** *Bacillus* and *Pseudomonas* release organic acids that help solubilize insoluble phosphorus compounds.
- **Siderophore Production:** Certain microorganisms produce iron-chelating compounds that bind ferric iron (Fe^{3+}) and improve its availability to plants [19].

Phytohormone Regulation: Beneficial microorganisms produce plant growth regulators, including auxins (IAA), gibberellins, and cytokinins, which promote root development, root hair formation, and cell division [19].

Disease Suppression: Beneficial soil microorganisms restrict the establishment and multiplication of soil-borne pathogens through various biological mechanisms [17].

Induced Systemic Resistance: Certain beneficial rhizosphere microorganisms activate induced systemic resistance (ISR), enhancing the plant's defensive capacity against pathogens [18].

Conclusion

Soil microorganisms play a central role in maintaining soil health through nutrient cycling, organic matter decomposition, soil aggregation, and plant growth promotion. Microbial indicators, including biomass carbon, soil respiration, enzyme activities, and microbial diversity, provide useful information on soil biological functioning and help detect early signs of degradation or recovery [20]. Environmental stresses such as drought, salinity, climate change, heavy metal contamination, and pesticide application can affect microbial communities and their functions. Sustainable practices, including organic farming, conservation agriculture, and integrated nutrient management, can help maintain microbial activity and improve soil resilience [21]. Integrating microbial indicators with physical and chemical soil assessments provides a more comprehensive understanding of soil health. Such an approach can support better soil management, improve crop productivity, and promote long-term agricultural sustainability [22].

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