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Soil health and fertility management: Biochemical indicators and microbial Communities : A Review

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Abstract

Soil health and fertility form the foundation of sustainable agricultural production, directly influencing crop productivity, nutrient cycling, and ecosystem resilience.This review synthesizes current understanding of soil quality assessment through biochemical indicators, microbial community structure, and the implementation of regenerative agricultural practices. Biochemical parameters such as soil organic carbon, enzyme activities, and nutrient availability are examined as critical metrics for evaluating soil functionality. The role of microbial diversity and community dynamics is discussed in relation to nutrient transformation, disease suppression, and soil structural stability. Regenerative practices including cover cropping, crop rotation, reduced tillage, organic amendments, and integrated livestock systems are analyzed for their capacity to restore degraded soils, enhance nutrient retention, and promote carbon sequestration. Advances in molecular and omics-based tools for studying soil microbiomes are also explored, highlighting their potential to guide targeted soil management interventions. By linking biochemical indicators with microbial ecology and sustainable management strategies, this review emphasizes the need for holistic approaches to maintain and improve soil health, ensuring long-term agricultural productivity and environmental sustainability.

Keywords: *Soil health, fertility management, biochemical indicators, microbial communities, regenerative agriculture.*

Introduction

Soil health and fertility are foundational to agricultural productivity, ecosystem stability, and resilience in the face of climate and land-use change. Soil fertility is often understood in terms of the soil's capacity to supply essential nutrients in appropriate proportions for plant growth. Soil health, by contrast, is a more integrative concept, encompassing not just chemical fertility but also biological and physical soil properties that enable ecosystems to function and adapt (Bünemann et al., 2023; Cui et al., 2023).

Recent global analyses indicate that conventional practices reliant on high inputs of synthetic fertilizers risk degrading soil health reducing soil organic matter, disrupting microbial diversity, and impairing nutrient cycling (Investigating the effects of organic amendments (Bo et al., 2023). On the other hand, practices that emphasize organic inputs (e.g., compost, manure), cover crops, reduced soil disturbance, and integration of biological soil amendments are gaining empirical support for maintaining or improving fertility while restoring ecosystem services (Cui et al., 2023; Li et al., 2025). Biochemical indicators such as soil organic carbon, respiration rates, enzyme activities, and nutrient mineralization are increasingly recognized as sensitive metrics of soil health. These indicators often correlate with changes in microbial biomass and community functioning (Fertilization and Soil Microbial Community: A Review, 2022; Soil Microbial Community Structure and Carbon Stocks Following Fertilization with Organic Fertilizers, 2022). For instance, long-term studies show that organic amendments increase both the richness, diversity (e.g., Shannon index), and functional gene abundances related to nutrient transformations (Li et al., 2025)

Importance of Biochemical and Microbial Indicators

Biochemical and microbial indicators are increasingly regarded as sensitive and integrative measures of soil health and fertility. Unlike traditional chemical tests that quantify nutrient concentrations, biochemical indicators such as soil enzyme activity, respiration, and organic carbon dynamics provide insights into ongoing microbial processes that regulate nutrient availability, soil structure, and organic matter turnover (Bünemann et al., 2023). These indicators capture short-term biological responses to management practices and environmental change, making them critical for early detection of soil degradation or improvement (Fertilization and Soil Microbial Community: A Review, 2022). Soil enzymes including dehydrogenase, urease, β-glucosidase, and phosphatases serve as proxies for microbial functional activity, linking nutrient cycling with plant productivity (Cui et al., 2023). Their activities are sensitive to shifts in soil management, organic amendments, and climatic variability, offering a dynamic measure of fertility status. Similarly, soil organic carbon fractions, microbial biomass carbon, and respiration are widely used as integrative indicators because they reflect the balance between carbon inputs and microbial decomposition processes, which directly influence long-term soil fertility and carbon sequestration (Li et al., 2025).

Microbial indicators extend beyond bulk activity to encompass community composition, diversity, and functional gene abundance. Advances in high-throughput sequencing and metagenomics have allowed researchers to track specific microbial groups and genes responsible for nitrogen fixation (e.g., nifH), phosphorus mineralization (e.g., phoD), and carbon cycling (Fierer, 2017; Delgado-Baquerizo et al., 2020; updated in Cui et al., 2023). Recent studies highlight that microbial network complexity and interactions among taxa strongly predict ecosystem functions, with more diverse and connected microbial communities enhancing nutrient use efficiency and system resilience (Li et al., 2025).

The integration of biochemical and microbial indicators into soil monitoring frameworks is crucial for assessing the sustainability of regenerative practices. For instance, long-term organic fertilization and crop diversification have been shown to increase microbial biomass, improve enzyme activities, and stabilize soil organic carbon pools (Bo et al., 2023). In this way, biochemical and microbial indicators provide actionable metrics that connect soil biology to agronomic performance, guiding both scientific understanding and practical management decisions in sustainable agriculture.

Soil Health and Fertility

Soil fertility and soil health, while often used interchangeably, represent distinct but complementary concepts. Soil fertility refers specifically to the capacity of soil to supply essential nutrients in forms accessible to plants, ensuring productivity (Lehmann et al., 2020). Soil health, however, encompasses the broader integration of physical, chemical, and biological functions that allow soil to act as a living ecosystem supporting plants, animals, and microorganisms (Bünemann et al., 2023). Healthy soils not only provide nutrients but also regulate water cycles, filter pollutants, and sustain biodiversity, thus linking agricultural productivity with ecosystem services (Schreefel et al., 2020).

Dimensions of Soil Quality (Physical, Chemical, and Biological)

Soil quality assessment involves three key dimensions: physical, chemical, and biological. Physical quality refers to properties such as texture, structure, porosity, and water-holding capacity, which influence root penetration, aeration, and soil stability (Araya et al., 2023). Chemical quality covers nutrient availability, pH, cation exchange capacity, and salinity levels, which directly affect plant nutrient uptake and microbial activity (FAO, 2020). Biological quality focuses on microbial diversity, soil organic matter, enzyme activity, and faunal activity, all of which underpin nutrient cycling, carbon sequestration, and soil resilience (Cui et al.,

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2023; Li et al., 2025). Among these, biological indicators are increasingly emphasized as early and sensitive markers of soil change, providing insights into dynamic processes that are not captured by traditional chemical analyses (Fertilization and Soil Microbial Community: A Review, 2022).

Soil Health as a Driver of Ecosystem Services

Soil health directly underpins a wide range of ecosystem services vital for human and environmental well-being. Functioning soils regulate climate by sequestering carbon, mitigate floods through improved infiltration, and contribute to clean water by filtering contaminants (Lehmann et al., 2020). From an agricultural perspective, improved soil health translates to enhanced nutrient use efficiency, reduced dependency on chemical fertilizers, and increased resilience to drought and pests (LaCanne & Lundgren, 2018; Enhancing Soil Health and Plant Growth, 2024). Importantly, soil health links local farm productivity to global sustainability agendas, including the United Nations Sustainable Development Goals (SDGs), particularly those on food security, climate action, and biodiversity (FAO, 2020). As agricultural systems face mounting pressures from land degradation, population growth, and climate variability, the conceptual framework of soil health and fertility emphasizes that managing soils as living systems—rather than inert substrates will be critical for sustaining both productivity and ecological balance in the 21st century.

Soil Health and Fertility: Conceptual Framework

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Biochemical Indicators of Soil Health

Biochemical indicators are crucial tools for evaluating soil health because they provide insight into dynamic processes that regulate nutrient cycling, organic matter turnover, and microbial activity. Unlike physical and chemical properties, which may remain relatively stable, biochemical indicators respond quickly to changes in management practices and environmental conditions, making them reliable early-warning signals of soil degradation or improvement (Khurshid et al., 2021). Among the most widely recognized indicators is soil organic carbon (SOC), which not only underpins soil fertility but also plays a vital role in carbon sequestration and climate regulation. Declines in SOC levels often signal soil degradation, while its accumulation indicates improved structure, water-holding capacity, and nutrient availability (Zhang et al., 2021). In addition, soil enzymes, such as dehydrogenase, phosphatase, urease, and β-glucosidase, are increasingly used to assess soil functionality. These enzymes mediate key transformations in the nitrogen, phosphorus, and carbon cycles and serve as sensitive indicators of microbial activity and nutrient dynamics (Tripathi et al., 2022).

Another important indicator is soil respiration, which reflects microbial activity and the decomposition of organic matter. While higher respiration rates generally indicate active microbial communities, excessive rates may signal unsustainable carbon loss under intensive land use (Chen et al., 2020). Similarly, measurements of microbial biomass carbon and nitrogen provide valuable information on the size and activity of microbial communities, thereby linking biochemical processes to soil fertility outcomes (Tirado-Corbala et al., 2022).

Emerging studies also highlight the role of biochemical ratios, such as the carbon-to-nitrogen (C:N) ratio and enzyme stoichiometry, in understanding nutrient imbalances and soil resilience (Albright et al., 2020). When combined, these indicators offer a holistic assessment of soil function, enabling the monitoring of management interventions such as organic amendments, crop rotations, and reduced tillage. Overall, biochemical indicators provide an integrated framework to measure soil health by linking nutrient cycling efficiency, microbial functioning, and ecosystem resilience, thereby guiding regenerative and sustainable land management strategies.

Microbial Communities and Soil Fertility

Soil microbial communities are central to soil fertility because they regulate critical ecosystem processes such as nutrient cycling, organic matter decomposition, and plant–soil interactions. Microorganisms, including bacteria, fungi, archaea, and actinomycetes, mediate the transformation of essential elements like nitrogen, phosphorus, and sulfur, thereby enhancing nutrient availability for plants (Fierer, 2022). In addition, microbial communities improve soil structure through the production of extracellular polysaccharides and mycorrhizal networks, which stabilize aggregates and increase water retention (Wagg et al., 2021). One of the most important microbial contributions to fertility is biological nitrogen fixation, primarily performed by symbiotic bacteria such as Rhizobium and free-living diazotrophs. This process reduces dependency on synthetic nitrogen fertilizers, thereby supporting sustainable agriculture (Mus et al., 2021). Similarly, phosphorus-solubilizing microorganisms release organic acids and enzymes that mobilize otherwise unavailable phosphorus pools, improving plant uptake efficiency (Zhang et al., 2022). Decomposer fungi and bacteria also play a vital role by breaking down complex organic matter into simpler compounds that replenish soil nutrient pools (Penton et al., 2021).

Beyond nutrient transformations, microbial diversity and community stability are increasingly recognized as determinants of soil resilience. High microbial diversity buffers soils against disturbances such as drought, salinity, and pathogen outbreaks, ensuring long-term fertility and productivity (Jansson & Hofmockel, 2020). Conversely, disturbances caused by intensive tillage, agrochemical overuse, and monocropping often reduce microbial diversity, leading to nutrient imbalances and reduced soil quality (Trivedi et al., 2020).

Emerging research using next-generation sequencing and metagenomics has expanded understanding of soil microbial ecology, providing new insights into functional guilds, microbial networks, and plant–microbe interactions. These findings highlight the potential for managing microbial communities through practices such as organic amendments, reduced tillage, and crop diversification to restore soil fertility and ecosystem sustainability (Banerjee et al., 2022). Thus, microbial communities represent not only drivers but also sensitive indicators of soil fertility, offering pathways for designing regenerative soil management strategies that align with ecological and agricultural goals.

Conclusion

Healthy soil are vital for sustainable agriculture and environmental resilience. Biochemical indocators and microbial communities provide key insights into soil fertility by driving nutrient cycling and reducing reliance on synthetic inputs. Regenative practices such as cover cropping, organic amendments and reduced tillage restore soil heath, enhance biodiversity and support climate change mitigation. Strenghthening the link between soil biology, fertility and sustainable management offers a pathway to resilient food systems and long term environmental sustainabililty.

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