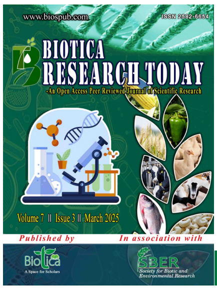

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Soil Microbial Diversity: The Hidden Key to Sustainable Agriculture

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Abstract

Soil microbial diversity refers to the variety of significant microorganisms existing within a natural habitat or community. This soil microbiome has a highly diverse microbial population in which large proportions remain unstudied. Soil-dwelling microorganisms play a pivotal role in promoting plant health and soil fertility. Various range of approaches used to quantify biological diversity are known as diversity indices. Deciphering the structural dynamics of soil microbiota is necessary for better quantification. This review summarizes the studies of soil microbial communities emphasizing on diversity indices and techniques fostering agricultural resilience.

Keywords: Agriculture, Diversity indices, Environment, Soil microbial diversity

Introduction

Soil is abundantly multifaceted and dynamic microecosystem, which is indicated in the territorial distribution and profound microbial complexity and their metabolic agility. It acts as plant support system, nutrient reservoir and habitat for soil microbiota. The soil microbial consortia have a pivotal function in the sustained stability of agroecosystem. This is due to the discrete species and associations of edaphic microorganisms having vital roles in many metabolic activities that aid agricultural systems. These metabolic processes encompass nutrient sequestration and remobilization required for phytological growth, retention of soil composition, breakdown of agrochemicals or contaminants and biocontrol of agricultural pests. Microbial biodiversity can be interpreted as an index of different kinds of microorganisms which are significant within a natural habitat or community. However, functional heterogeneity is more important compared to the taxonomic classification, which builds the extended sustainability of an ecosystem. The biodiversity of the soil microbial communities was poorly understood despite their functional role in agricultural system which supports them. The functional processes carried out by soil microbial communities are overridden by the use of agrochemicals and agronomical practices. This is mainly due to the technical difficulties in sampling and quantifying the diversity of soil microorganisms, along with the impacts of intensive agricultural practices. Agronomic measures also integrate and obscure the temporary conditions that are dependent on the functional contributions of soil microbes. To overcome this, microbial biodiversity can be quantified by different biodiversity indices such as Shannon, Simpson's, Evenness and Margalef's index. It is vital to recognize when and under what instances the functional traits of biological diversity of soil microbial communities are necessary for ensuring the soil ecosystem.

Concept of Soil Microbial Diversity

Microbial diversity refers to the variety of microorganisms present in the soil. Soil microbial diversity encompasses species diversity and genetic diversity and ecosystem biodiversity.

Species Diversity

The species diversity is defined as an integral number of diverse microbial species present in a specific ecosystem and has a relative abundance of each species in an ecosystem. Different species vary in areas in response to many different factors. It is an important component, which has a vital role in the process and services of ecosystem, which affects the

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flexibility of environmental changes and anthropological effects (Lewinsohn and Jorge, 2024).

Genetic Diversity

It is the different range of genomic attributes in the genetic makeup within a species. The species-level diversity to intraspecific heterogeneity and can be correlated to the lifespan of a species. It affects evolutionary potential and ecological elasticity of species and ecosystems. It involves variation in DNA between individuals, which is inevitable to survive in the changing environment. The interference of genetic diversity extends to different domains, including the ecosystem functioning, agricultural and conservation efforts.

Functional Diversity

Functional diversity refers to the kind of practical developments inside a community, influencing surroundings techniques and resilience. It encompasses different aspects, which include functional richness, evenness and divergence, which collectively offer a comprehensive information of how species make a contribution to atmosphere functioning. This multifaceted nature is essential for assessing the impacts of environmental changes and organic invasions.

Diversity Indices Used in Soil Microbial Studies

Biological diversity refers to the heterogeneity within the biotic components of an ecological system and commonly defined as species richness and their relative abundance across spatial and temporal scales. There are several approaches used to quantify the biological diversity. These biodiversity indices are based on two main factors that are richness and evenness. So, the measure of different kinds of organisms present in a particular community is known as richness. To measure diversity different indices are used.

Shannon-Wiener Index (H1)

Shannon-Wiener index (H1) is a measure of the uniformity or variability in a defined system which can be used and applied to environmental systems. In environment, the Shannon-Wiener index is used to quantify the scales of biological diversity, this indicator accounts for both richness of the species and relative abundance of each species contained in a given area. A greater index is a sign that either there is a comparatively large diversity of distinct species or that there is proportionally higher species evenness. Shannon index is quantified as follow:

$$H' = -\sum_{i=1}^{s} p_i \ln p_i$$

Where, p_i is relative abundance of individual species.

Simpson Index

Simpson's index, which denoted as "D", shows the possibility of two randomly sampled individual are classified under two different categories or species. This index is utilized to assess the biological variety of a designated ecosystem and incorporates both the number of species and the relative abundance of each species available. Simpson's index is quantified as follows:

$$D = \sum_{i=1}^{s} \left(\frac{n_i}{N}\right)^2$$

Where, n_i: No. of organisms belong to species (i); N: The total number of organisms.

Evenness Index

Species evenness (E) quantifies the similarity in abundance among a range of species present in an ecological community. Species evenness ranges from 0 to 1. If evenness is near to 0, the species dispersal of organisms inside the community is not even (species composition exhibits dominance by one or a few taxa). If the evenness is close to 1, the distribution of organisms is even in the community (species abundance is homogenously distributed within the community).

$$J = \frac{H}{H_{max}}$$

Margalef's Index

Margalef's index is the measure of species richness and diversity. It is a simple metric index which is useful for comparing species richness across different ecosystems of the soil.

$$D = \frac{S-1}{\log N}$$

Where, D: Margalef diversity index; N: Number of observations; S: Number of species.

Techniques for Assessing Soil Microbial Diversity

Methods to assess microbial diversity can be categorized into two groups: traditional methods and molecular methods (Table 1). Biodiversity assessments involve determining the relative species richness of communities along a stress continuum as well as assessing disturbances or modifications in biotic and abiotic parameters.

Table 1: Different categories of soil microbial diversity

Category	Method	Uses
Traditional Methods	Culture-Dependent Techniques	Isolation of microorganisms using selective media (nutrient agar). Identifying the microbes through morphological characteristics (colony shape, color) and biochemical tests (catalase, oxidase tests).
	Dilution Plating & CFU Counts	Estimates viable microbial populations in soil samples by counting colony-forming units (CFUs). Used as an indicator of soil health and microbial abundance.
	Community Level Physiological Profiling (CLPP)	Assesses metabolic diversity using the BiologEcoPlate method. Measures functional shifts in microbial communities due to environmental changes (*e.g.*, pH, temperature, pollution).
	Microscopy (Fluorescence Microscopy)	Visualizes microbial cells directly in soil samples. Uses stains like DAPI or SYBR Green to count microbial cells.

Table 1: Continue...

Category	Method	Uses
Molecular Methods	16S rRNA Gene Sequencing	It identifies bacterial diversity by sequencing rRNA gene. Provides report on microbial community composition and phylogenetic relationships.
	Quantitative PCR	Quantifies microbial populations at the molecular level. Offers high sensitivity in detecting microbial abundance.
	Metagenomic and Omics Approaches	Includes metagenomics, metatranscriptomics, metaproteomics and metabolomics. Analyses microbial genomes and functional roles comprehensively.
	DNA Microarrays (PhyloChip, GeoChip)	Detects and quantifies specific microbial genes or taxa. Used for high-throughput analysis of microbial communities.

Importance of Soil Microbial Diversity in Agriculture

Soil microbial variation plays a major role in maintaining the ecosystem of soil by nutrient cycling, decrease in organic materials, soil structure and growth of plants. The microbial variety in the soil is influenced by various factors, including environmental conditions, man-made activities and earth properties (Table 2).

Factors Affecting Soil Microbial Diversity

Soil microbial community is affected by various factors; like soil moisture, organic and inorganic chemicals, organic matter of soil and environment. The different environmental conditions like climate, soil practices and land use practices affect soil microbial community. Climate is the major factor which influences microbial community structures; the temperature fluctuations caused by climate change promote the coexistence of different microbial community when compared to the stable environment. Soil properties also have a significant impact on the microbial community particularly pH and depth. Soil pH and depth influence the prevalence of the specific genotype of the microbial species, which shows low biomass environment in deeper soil layer tend to support more diverse microbial population due to reduced surface area. Land use practices such as deforestation and intensive agriculture alter the soil characteristics and nutrient availability of the soil which leads in microbial community disruptions. The microbial populations of soil, including various biochemical groups such as denitrifying bacteria, show alteration in their occurrence in response to different land use practices (Yoon *et al.*, 2024). These imposed management changes influence microbial community by altering nutrient availability and habitat conditions. This change may either promote or suppress the growth of specific microorganisms which leads to shift in their abundance. So, implementing the application of good management practices is crucial in maintaining soil microbial diversity and ecosystem stability.

Table 2: Importance of soil microbial diversity

Importance	Aspects
Role in nutrient cycling and soil fertility	Nitrogen transformation and nutrient release for plant uptake.
	Support carbon storage and nutrient cycling, promoting plant growth and productivity.
Impact of environmental and anthropogenic factors	Factors like pH, temperature and altitude impact microbial diversity.
	Anthropogenic activities (industrial and agricultural practices) modulate microbial ecosystem balance.
	Land-use changes and climate fluctuations drive microbial equilibrium and adaptive potential.
Soil health and ecosystem services	Microbial diversity is a key indicator of soil health and plays a role in biogeochemical processes.
	Supports plant growth by breaking down organic matter into bioavailable nutrients.
	Contributes to disease suppression by maintaining a balanced microbial ecosystem.

Conclusion

As agricultural environments are dynamic, understanding the role of microbial communities in supporting ecological diversity and system stability is crucial. In ecosystem within the soil, microorganisms play a significant role, with all symbiotic microorganisms located around the rhizosphere. These microorganisms indicate soil health and productivity. Several different indices quantify the soil's microorganism content, and the ecosystem is monitored over time for species richness and evenness. This enables quantitative measure of the different species that exist within the community, helping to understand biodiversity.

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