Contents lists available at Curevita Journals

Frontiers of Agri and animal Innovation

journal homepage: www.curevitajournals.com

Role of Agricultural Microbiome in Ecosystem Management

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Articalinfo

Article history: Received 2 Sept 2025, Revised 18 Sept 2025, Accepted 4 Nov. 2025, Published Dec 2025

Keywords: Agricultural microbiome, soil health, ecosystem sustainability, plant-microbe interaction, climate resilience, bioremediation

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Citation: Jaiswal Dimpi. 2025. Role of Agricultural Microbiome in Ecosystem Management.Frontiers of Agri and Animal Innovation. 1,2. 138-149.

Publisher: Curevita Research Pvt Ltd

Abstract

The agricultural microbiome plays a crucial role in maintaining ecosystem balance, enhancing soil fertility, promoting plant health, and mitigating the impacts of climate change. The microbial communities in soil, rhizosphere, phyllosphere, and endosphere form the foundation of sustainable agriculture by regulating nutrient cycles, degrading pollutants, and supporting biodiversity. This paper explores the ecological functions of agricultural microbiomes, their significance in ecosystem management, and strategies to harness microbial diversity for sustainable food production and environmental resilience in India and beyond.

Introduction

Agriculture represents one of the most dynamic interfaces between human activity and the natural environment. The agricultural microbiome—a complex community of bacteria, fungi, actinomycetes, viruses, and archaea associated with plants and soils—plays a central role in maintaining ecosystem health and productivity. Traditional agriculture has long relied on microbial processes for soil fertility, organic matter turnover, and pest suppression. However, modern chemical-intensive practices have disrupted microbial diversity and ecological balance. Sustainable ecosystem management thus requires a renewed focus on restoring and utilizing beneficial microbiomes for nutrient cycling, carbon sequestration, and environmental protection. Objectives of the Study:

- To analyze the role of agricultural microbiomes in nutrient cycling and soil health.
- To evaluate their contribution to ecosystem stability and climate resilience.
- To explore microbial applications in sustainable agriculture and bioremediation.
- To propose strategies for microbiome-based ecosystem management in India.

Agricultural Microbiome: Components and Diversity

Table-1: The agricultural microbiome is composed of multiple functional groups of microorganisms

Microbial Group	Habitat	Ecological Function
Bacteria	Rhizosphere, root zone	Nitrogen fixation, phosphate solubilization, plant growth promotion
Fungi	Soil, roots, leaf surface	Mycorrhizal associations, organic matter decomposition
Actinomycetes	Soil, compost	Antibiotic production, organic matter breakdown
Archaea	Extreme soil niches	Methanogenesis, nitrogen cycling
Viruses & Phages	Soil, plant tissues	Regulate microbial populations, gene transfer

Rhizosphere microbiota—the microbes inhabiting the narrow region around plant roots—are the most active contributors to soil fertility and plant productivity.

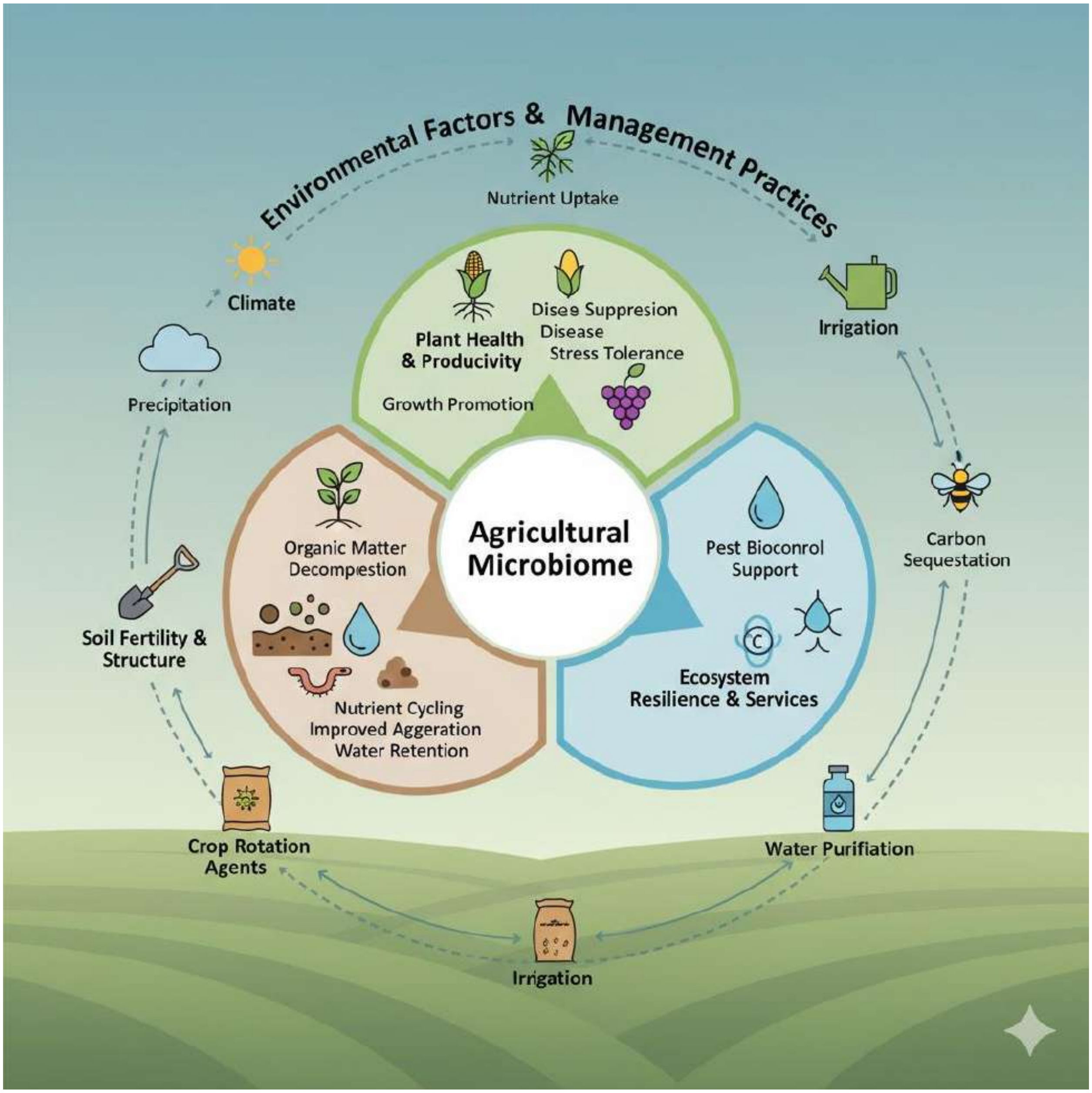

Figure 1. Schematic representation of the agricultural microbiome in ecosystem management

Role of Agricultural Microbiomes in Ecosystem Functions

Nutrient Cycling

Microbes are pivotal in the biogeochemical cycling of essential elements:

- **Nitrogen fixation:** *Rhizobium*, *Azospirillum*, and *Frankia* convert atmospheric nitrogen into bioavailable forms.
- **Phosphate solubilization:** *Bacillus* and *Pseudomonas* release organic acids that make phosphates soluble.
- **Carbon cycling:** Decomposition of organic residues enhances soil organic carbon and structure.

Soil Fertility and Structure

Microbial metabolites such as **polysaccharides and glomalin** improve soil aggregation, porosity, and water retention—key parameters of sustainable soil management.

Plant Growth and Disease Suppression

- **PGPR (Plant Growth-Promoting Rhizobacteria)** produce phytohormones (IAA, GA, cytokinins) that stimulate root development.
- Beneficial fungi like *Trichoderma* and *Glomus* outcompete pathogens through **antibiosis and mycoparasitism**, reducing dependence on chemical pesticides.

Carbon Sequestration and Climate Regulation

Soil microbes contribute significantly to **carbon sequestration**, mitigating greenhouse gas emissions by converting CO_2 into stable organic compounds. Mycorrhizal fungi enhance carbon storage in soil aggregates, contributing to **climate-resilient agriculture**.

Bioremediation and Pollution Control

Certain microbial consortia can degrade or immobilize toxic compounds such as **pesticides, heavy metals, and hydrocarbons**, preventing their entry into food chains. For example:

- *Pseudomonas putida* degrades organophosphates.
- *Bacillus subtilis* detoxifies chromium and cadmium.

Table-2: Microbiome-Based Ecosystem Management Strategies

Strategy	Description	Ecological Benefits
Biofertilizers	Application of nitrogen-fixing, phosphate-solubilizing, and potassium-mobilizing microbes	Reduces chemical fertilizer use
Biopesticides	Microbial agents that control pests and pathogens	Eco-friendly pest control
Compost inoculants	Microbes added to organic waste composts	Accelerates decomposition
Mycorrhizal technology	Fungal inoculants for roots	Improves nutrient and water uptake
Microbial consortia	Blends of synergistic strains	Multifunctional soil restoration

Adoption of **microbial technologies** in India's agriculture under schemes like *National Mission on Sustainable Agriculture (NMSA)* has demonstrated improved soil productivity and reduced environmental degradation.

Case Study: The Agricultural Microbiome and Soil Restoration in India

The **agricultural microbiome**, the vast community of bacteria, fungi, archaea, and viruses residing in and around plant roots, is foundational to soil health, nutrient cycling, and crop resilience. In India, a country with diverse agro-climatic zones and persistent soil degradation issues (including nutrient depletion, low organic carbon, and salinity), leveraging the native and engineered microbiome has become critical for **soil restoration** and sustainable productivity. This case study examines microbial strategies employed across three distinct regions.

Case Study 1: The Wheat-Rice Belt (Punjab & Haryana)

Regional Challenge

The **Indo-Gangetic Plain**, represented by states like **Punjab** and **Haryana**, is the heart of India's high-input agriculture, a legacy of the Green Revolution. Decades of intensive rice-wheat rotation, coupled with high use of synthetic fertilizers and pesticides, have resulted in a phenomenon called "soil sickness."

- **Key Problems:** Drastically reduced **soil organic carbon (SOC)**, depletion of phosphorus and zinc, and low microbial diversity leading to poor nutrient use efficiency and increased disease susceptibility.

Microbiome Restoration Strategy

The focus here is on replenishing beneficial organisms that aid nutrient mobilization and manage crop residue.

- **Biofertilizers and PGPRs:** Extensive application of phosphate-solubilizing bacteria (**PSB**) like *Bacillus megaterium* and nitrogen-fixing bacteria like *Azotobacter* and *Rhizobium* (for legumes in the rotation) to substitute chemical inputs.
- **Residue Management:** The practice of utilizing **Pusa Decomposer** (a consortium of fungal strains, including *Trichoderma* and *Aspergillus*), developed to accelerate the decomposition of paddy straw, directly restores carbon content and fungal biomass, improving soil structure.

Case Study 2: The Semi-Arid Deccan Plateau (Maharashtra & Telangana)

Regional Challenge

States like **Maharashtra** and parts of **Telangana** fall under the semi-arid tropics, characterized by erratic rainfall, poor water retention, and widespread cultivation of rainfed crops like millets, cotton, and pulses on shallow, nutrient-poor soils (Vertisols and Alfisols).

- **Key Problems:** Severe **drought stress**, low soil moisture, high vulnerability to erosion, and emerging salinity issues in irrigated pockets.

Microbiome Restoration Strategy

Interventions focus on enhancing the soil's capacity to access and retain water and tolerate abiotic stress.

- **Arbuscular Mycorrhizal Fungi (AMF):** Promotion and field application of AMF formulations. AMF form symbiotic relationships with plant roots, effectively extending the root system to scavenge water and immobile nutrients (like phosphorus) from a greater soil volume, thus significantly boosting **drought resilience** in rainfed crops.
- **Stress-Tolerant Microbes:** Identification and application of native microbes that produce **Exopolysaccharides (EPS)**, which bind soil particles together, improving soil aggregation and water holding capacity in dry conditions.

Case Study 3: The High-Rainfall Southern Coastal Region (Kerala & Karnataka)

Regional Challenge

States like **Kerala** and the coastal regions of **Karnataka** have high rainfall and are centers for cash crops and plantations (e.g., coconut, spices, areca nut, coffee). The challenge here is less about drought and more about managing saturated conditions and intense disease pressure.

- **Key Problems:** High nutrient **leaching** due to heavy rain, significant soil erosion on slopes, and severe phytopathogen outbreaks, such as root rot and wilt diseases, which thrive in humid environments.

Microbiome Restoration Strategy

The emphasis shifts to biological disease control and efficient nutrient stabilization.

- **Biocontrol Agents:** Widespread use of microbial antagonists such as *Pseudomonas fluorescens* and **biocontrol *Trichoderma*** strains to competitively suppress or directly attack major soil-borne plant pathogens, providing a sustainable alternative to chemical fungicides.
- **Effective Microorganisms (EM) Technology:** Utilizing a blend of beneficial microorganisms (including photosynthetic bacteria, lactic acid bacteria, and yeasts) to accelerate the decomposition of organic residues (like leaf litter and coir pith), turning them into stable, disease-suppressive compost and preventing nutrient loss through leaching.

Environmental and Ecological Impact

Positive Impacts

- Enhanced **soil biodiversity** and biological balance.
- Reduced **chemical runoff** into water bodies.
- Improved **nutrient-use efficiency** and **carbon sequestration**.
- Contribution to **agroecosystem resilience** under drought and heat stress.

Challenges

- Variability in microbial performance under field conditions.
- Lack of awareness and technical know-how among farmers.
- Need for standardized formulations and quality control of microbial products.

Policy and Future Directions

- Integrate microbiome research into **agroecological planning** and **climate adaptation policies**.
- Establish **Microbiome Resource Centers** to conserve and study indigenous strains.
- Promote **public–private partnerships** in microbial biotechnology for rural development.
- Encourage **education and training** programs for farmers and extension workers on microbiome management.

Emerging tools such as **metagenomics, transcriptomics, and AI-driven soil microbiome analysis** can revolutionize ecosystem management through precision agriculture.

Conclusion

The agricultural microbiome is an invisible but powerful ally in achieving environmental sustainability and ecosystem balance. By restoring microbial diversity, enhancing nutrient cycling, and mitigating pollution, agricultural microbiomes serve as a **natural foundation for resilient ecosystems**. The diverse microbial strategies employed across **India**—from using *Trichoderma* to decompose crop residue in the North to harnessing **AMF** for drought mitigation in the semi-arid regions and deploying *Pseudomonas* for disease control in the South—underscore a pivotal shift in agricultural management. By recognizing the soil as a living ecosystem rather than just a growth medium, India is positioning the agricultural microbiome as a central pillar in its efforts toward **ecological soil restoration** and long-term food security.For India, leveraging microbiome-based technologies can simultaneously address **food security, soil health, and environmental protection**, aligning with the goals of **sustainable development and green growth**.

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