

Influence of Traditional Agricultural Practices on Rhizosphere Microbiome Dynamics and Sustainable Crop Production

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The Rhizosphere: A Microbial Hotspot

The rhizosphere is a biologically active zone extending only a few millimeters from the root surface, yet it hosts a remarkable diversity of bacteria, fungi, protozoa, nematodes, algae and viruses. This region is shaped by root exudates, a complex mixture of sugars, amino acids, organic acids, phenolics and secondary metabolites released by plants. These compounds act as a chemical signal and nutrient sources, selectively recruiting beneficial microorganisms while suppressing harmful ones. Rhizosphere microorganisms influence plant physiology through multiple mechanisms. They enhance nutrient acquisition, regulate plant hormone balance, suppress soil-borne pathogens and improve tolerance to abiotic stresses such as drought, salinity and temperature extremes. Beneficial microbes such as plant growth-promoting bacteria (PGPB) and mycorrhizal fungi play a central role in maintaining soil productivity by mobilizing nutrients, improving root architecture and activating plant defense pathways.

Traditional Farming and Microbiome Stewardship

Traditional agricultural practices- crop rotation, intercropping, organic manuring, residue retention and reduced soil disturbance have historically supported diverse and stable soil microbial communities. These practices indirectly shaped the rhizosphere microbiome by modifying soil structure, nutrient availability and organic carbon content. For example, crop rotation disrupts the buildup of host-specific pathogens and promotes microbial diversity by varying root exudate profiles across seasons. Rotations involving legumes enrich nitrogen-fixing bacteria, improving soil nitrogen availability for subsequent crop. Intercropping systems, where two or more crops are grown together, increase below-ground biomass, enhance organic matter input and foster synergistic microbial interactions that suppress diseases and improve nutrient cycling. Similarly, the application of organic fertilizers, including farmyard manure, compost, vermicompost and crop residues, provides both nutrients and carbon substrate for microbial metabolism. These inputs stimulate microbial activity, enhance soil aggregation and promote beneficial taxa while reducing pathogen dominance. Such approaches exemplify how traditional farming unintentionally practiced microbiome management long before the term existed.

Tillage and chemical inputs: shaping microbial balance

Tillage intensity is a major determinant of rhizosphere microbiome structure. Frequent and intensive tillage disrupts soil aggregates, breaks fungal hyphal networks and accelerates organic matter decomposition, leading to reduced microbial diversity and soil carbon loss. In contrast, reduced or no-tillage systems preserve soil structure, enhance microbial biomass and support symbiotic fungi such as arbuscular mycorrhizal fungi (AMF), which are critical for phosphorus uptake and soil stability. The widespread use of synthetic fertilizers and pesticides has profoundly altered rhizosphere microbial dynamics. Excessive phosphorus fertilization reduces plant reliance on AMF, weakening the symbiotic relationship. High nutrient availability favors fast-growing, opportunistic microbes, often at the expense of functionally beneficial taxa. Chemical pesticides further disrupt microbial communities, suppressing non-target organisms and diminishing the natural disease suppression mechanism. Over time, these disturbances compromise soil resilience and increase dependency on external inputs.

Organic Amendments as Microbiome Restorers

Organic fertilizers offer a viable pathway to restore microbial balance while maintaining productivity. Compost, manure, biochar and bio-organic fertilizers improve soil physicochemical properties and enrich microbial diversity. These amendments enhance enzymatic activity, nutrient mineralization and disease suppression by fostering competitive and antagonistic interactions among microbes. Biochar, in particular, has emerged as a multifunctional amendment that improves water retention, adsorbs toxins and provides microbial habitat. Compost-based fertilizers have been shown to suppress soil-borne disease by enriching beneficial microbial genera such as *Bacillus*, *Pseudomonas* and *Trichoderma*. Integrating organic inputs with reduced chemical fertilization allows farmers to balance productivity with long-term soil health.

Engineering the Rhizosphere: From Tradition to Precision

While traditional practices influence microbial communities indirectly, modern agriculture increasingly explores rhizosphere microbiome engineering- the deliberate manipulation of microbial composition and function to improve plant performance. This can be achieved through two complementary strategies: indirect and direct interventions.

Indirect strategies include agronomic practices such as crop diversification, organic amendments and conservation tillage, which modify the soil environment to favor beneficial microbes. Direct strategies involve the application of microbial inoculants, including PGPB, mycorrhizal fungi and biocontrol agents. These inoculants enhance nutrient availability, suppress pathogen and improve stress tolerance. However, single-strain inoculants often show inconsistent performance under field conditions due to competition with native microbiota. To address this limitation, researchers are developing synthetic microbial consortia, combining multiple functionally complementary strains. These consortia occupy diverse ecological niches, exhibit greater resilience and provide more stable benefits than individual strains.

Microbiome Responses to Stress

The rhizosphere microbiome plays a pivotal role in helping plants cope with biotic and abiotic stress. Soil salinity, pH extremes, nutrient imbalance, moisture deficits and temperature fluctuations significantly influence microbial diversity and activity. Salinity and pH are among the strongest abiotic drivers, often reducing microbial richness and metabolic efficiency. Plants actively respond to stress by altering root exudation patterns, selectively recruiting stress-tolerant microbes that enhance osmotic regulation, antioxidant activity and immune response. Beneficial microbes can prime plant defense systems through induced systemic resistance, creating a protective barrier against pathogens. Conversely, microbiome dysbiosis increases disease susceptibility and reduces stress tolerance.

Towards Microbiome-Driven Cropping Systems

As agriculture faces the dual challenge of feeding a growing population while reducing environmental impacts, microbiome-based strategies offer a promising path forward. Integrating traditional practices with modern tools such as multi-omics technologies, microbial consortia and host-mediated microbiome selection can enable the development of microbiome-driven cropping systems.

Future approaches may include breeding crops that favor beneficial microbial recruitment, applying tailored bio-organic fertilizers and using precision inputs that support microbial functionality rather than disrupt it. While challenges remain in ensuring field-level consistency and scalability, the convergence of traditional knowledge and modern science positions the rhizosphere microbiome as a cornerstone of sustainable agriculture.

Conclusion

The rhizosphere microbiome represents a powerful yet often overlooked ally in agriculture. Traditional farming practices have long nurtured these microbial communities, sustaining soil fertility and crop resilience through ecological balance rather than chemical dependence. By re-embracing these principles and refining them with modern scientific insights, agriculture can move toward systems that are productive, resilient and environmentally sustainable. Harnessing the rhizosphere microbiome is not merely a technological innovation- it is a return to biologically informed farming that aligns productivity with ecological stewardship.
