

MANAGEMENT-DRIVEN RESTRUCTURING OF THE COCONUT RHIZOSPHERE MICROBIOME: IMPLICATIONS FOR SOIL HEALTH, NUTRIENT CYCLING AND PALM PRODUCTIVITY

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ABSTRACT

The coconut rhizosphere is an active zone where coconut roots, soil properties and microorganisms interact and influence nutrient availability, soil health and palm performance. In coconut production systems, changes in fertilizer use, organic amendments, irrigation, intercropping and biomass recycling can alter the microbial environment around the roots. These changes are important because rhizosphere microorganisms contribute to nutrient cycling, nutrient solubilization, plant growth promotion and the biological functioning of coconut soils. Beneficial bacteria, including plant growth-promoting rhizobacteria, and arbuscular mycorrhizal fungi have been associated with improved nutrient acquisition and better adaptation of coconut palms to environmental stresses. Organic resource recycling and diversified coconut-based cropping systems also provide opportunities to maintain microbial activity and improve soil quality. Recent studies using molecular approaches have expanded the knowledge of bacterial and fungal diversity in coconut rhizosphere soils and have revealed microbial associations that are difficult to characterize through conventional culture-based methods. Microbial communities also have an important role in plant health, particularly through nutrient competition, antagonistic activity and interactions with soil conditions that influence disease development. This review examines how major coconut production practices influence the rhizosphere microbiome and discusses their implications for soil health, nutrient cycling, plant growth, stress adaptation and palm productivity. The review also highlights the potential of integrating organic matter management, balanced nutrient application, suitable intercrops, water management and beneficial microorganisms for developing more resilient coconut production systems. Greater attention to long-term field studies, site-specific microbial communities and functional microbiome analysis will be important for translating these findings into practical coconut production strategies.

KEYWORDS:Coconut; Rhizosphere microbiome; Soil health; Nutrient cycling; Plant growth-promoting rhizobacteria; Arbuscular mycorrhizal fungi; Organic amendments; Intercropping.

INTRODUCTION

Coconut (*Cocos nucifera* L.) is a long-duration perennial crop in which the same root system remains in contact with the soil for many years. This prolonged interaction creates a continuous relationship between roots, soil properties and microorganisms. The rhizosphere, the narrow zone of soil influenced by plant roots, is particularly important because root exudates, organic residues, nutrients and microbial activities interact within this region. Differences in coconut production systems have been associated with changes in microbial biomass, enzyme activities and nutrient availability, showing that biological processes contribute to soil fertility in coconut plantations (1). The coconut rhizosphere supports a diverse group of bacteria and fungi with different functional capabilities. Some of these microorganisms can improve nutrient availability and influence root development through the production of growth-promoting compounds. The isolated *Serratia marcescens* and *Enterobacter* sp. from the rhizosphere of coconut palms and recorded traits such as phosphate solubilization, ammonification, indole-3-acetic acid production and ACC deaminase activity(2). Inoculation of coconut seedlings with selected isolates improved plant growth and nutrient uptake. These observations demonstrate that microorganisms associated with coconut roots can contribute directly to plant development.

The functional importance of rhizosphere bacteria is also relevant under environmental stress. The characterization ACC-deaminase-producing bacteria from coconut rhizosphere soils in the Lakshadweep Islands and identified isolates with phosphate-solubilizing, indole-3-acetic acid- and siderophore-producing abilities.

Several isolates also showed tolerance to saline conditions and promoted plant growth under salt stress(3). Such microorganisms may have an important role in maintaining plant performance when coconut palms are exposed to unfavourable soil conditions.

Culture-based investigations represent only a fraction of the microbial diversity present around coconut roots. Molecular approaches have provided a broader view of these communities. High-throughput sequencing to characterize plant-associated microbial communities in Yongxing Island and identified distinct bacterial, fungal and diazotrophic communities in rhizosphere soils(4). Their results also showed that soil characteristics were closely associated with microbial community composition. These findings highlight the complexity of the coconut rhizosphere and the importance of considering the microbial community as a whole rather than focusing only on individual cultivable organisms. Arbuscular mycorrhizal fungi (AMF) form another important component of the coconut root-associated microbiome. Their distribution and abundance can vary according to environmental and soil conditions. Investigated AMF communities across 248 coconut fields in Kerala and identified 23 species belonging to seven genera. *Acaulospora scrobiculata* was the dominant species, while AMF colonization and spore density varied with soil type, agroclimatic conditions, season and soil fertility. The widespread occurrence of AMF in coconut fields indicates that mycorrhizal associations represent an important component of below-ground biological activity in coconut production systems(5).

The rhizosphere microbiome is influenced by the way coconut plantations are managed. Fertilizer application, organic inputs and irrigation can alter the physical and chemical environment surrounding plant roots and create different conditions for microbial growth. The combinations of chemical fertilizer, organic fertilizer and irrigation in coconut plantations and observed changes in soil properties, enzyme activities and bacterial and fungal communities. Microbial community characteristics were also associated with soil pH, electrical conductivity, organic matter and available nutrients(6). The study provides direct evidence that nutrient and water management can modify the microbial environment of coconut rhizosphere soil. Intercropping can introduce another level of variation into this system. Coconut is commonly grown with crops such as pineapple, banana, cocoa, black pepper and various cover crops. Additional crops modify root distribution, nutrient demand, organic matter inputs and soil microclimate. The reported changes in soil properties and bacterial community structure in coconut rhizosphere soil under pineapple intercropping(7). Research on diversified coconut systems has also shown that crop combinations and nutrient management can influence soil biological properties, microbial activity and crop performance. These responses suggest that cropping-system design can be considered as a management tool for influencing the biological condition of coconut soils.

Ground vegetation within coconut plantations may also influence the composition and functioning of soil microbial communities. Living ground cover provides additional root inputs and organic residues and maintains biological activity within the soil. Recent field research has shown that differences in management intensity in coconut plantations can be associated with changes in fungal communities, including shifts in beneficial and potentially pathogenic groups (8). Such observations raise the importance of evaluating plantation management not only in terms of nutrient supply and yield, but also in relation to the biological diversity maintained within the soil. Microorganisms are closely involved in processes that regulate nutrient availability to coconut palms. Rhizosphere bacteria can participate in nitrogen transformation and phosphorus solubilization, while mycorrhizal fungi can contribute to nutrient acquisition through their association with plant roots. Microbial enzymes are also involved in the decomposition of organic materials and the release of nutrients from soil organic matter. Consequently, changes in microbial community composition may influence nutrient cycling and the nutritional environment of coconut roots. Experimental studies on coconut-associated bacteria and recent investigations of microbial communities under different management practices provide evidence for this connection (2, 3, 6).

Research on coconut-associated microorganisms has increased considerably, but the available evidence is distributed across different areas such as plant-growth-promoting bacteria, AMF ecology, fertilization, irrigation, intercropping and soil biological activity. Most studies have examined individual components of the system, while the connection between agricultural management and restructuring of the complete rhizosphere microbiome has received comparatively less attention. A better understanding of this relationship is important because management practices simultaneously influence soil properties, microbial communities, nutrient cycling and the biological environment surrounding coconut roots. This review therefore examines the management-driven restructuring of the coconut rhizosphere microbiome and its implications for soil health, nutrient cycling and palm productivity. Particular attention is given to fertilizer management, organic amendments, irrigation, intercropping and ground vegetation and their effects on bacterial, fungal and AMF communities. The functional contribution of beneficial microorganisms to nutrient mobilisation, plant growth, stress tolerance and disease-related processes is also discussed. Integrating these aspects can provide a clearer understanding of how management practices influence the biological functioning of coconut soils and can support the development of microbiome-informed approaches for sustainable coconut production.

2. Coconut Rhizosphere and Soil Environment

The coconut rhizosphere is an active zone where roots, soil and microorganisms interact continuously. Root growth and associated microbial activity influence nutrient availability, organic matter decomposition and enzyme activity in the soil. The higher microbial biomass and biological activity in coconut-based multistoreyed

cropping systems compared with coconut monocropping, highlighting the importance of the rhizosphere in maintaining soil fertility(1). The microbial community associated with coconut roots includes bacteria with important plant-growth-promoting functions. Phosphate-solubilizing bacteria have been isolated from coconut rhizosphere and root environments across different coconut-growing regions (9). Other studies have identified ACC-deaminase-producing bacteria with phosphate-solubilizing, siderophore-producing and salt-tolerant characteristics, indicating the functional diversity of coconut-associated microorganisms (3). Soil properties strongly influence the composition and activity of these microbial communities. Factors such as pH, organic matter, electrical conductivity and available nutrients have been associated with differences in microbial abundance and community structure in coconut soils (6). Intercropping can also modify the rhizosphere environment through changes in root distribution, nutrient demand and organic matter inputs. Pineapple intercropping, for example, altered both soil properties and bacterial community structure in coconut rhizosphere soil (7).

Arbuscular mycorrhizal fungi are another important component of the coconut rhizosphere. Field studies have demonstrated considerable AMF diversity in coconut plantations, with their colonization and abundance varying according to soil and environmental conditions (5). These microbial associations contribute to the biological functioning of the root zone and may influence nutrient acquisition by coconut palms. The coconut rhizosphere is shaped by the interaction of soil properties, root activity and plantation management. Understanding these relationships provides a basis for examining how fertilizer use, organic amendments, irrigation and intercropping can restructure the rhizosphere microbiome and influence soil health and coconut productivity.

3. Management Factors Shaping the Coconut Rhizosphere Microbiome

Coconut rhizosphere microbial communities are influenced by the management practices followed within the plantation. Fertilizer application, organic amendments and irrigation can modify soil nutrient status, organic matter and moisture, creating different conditions for microbial growth. The clear differences in bacterial and fungal communities under combinations of chemical fertilizer, organic fertilizer and irrigation(6). The changes were also associated with soil enzyme activities and nutrient-related soil properties. Organic inputs can provide carbon substrates that support microbial growth and stimulate biological activity in the root zone. In coconut-based systems, the incorporation of organic materials and retention of plant residues can increase the availability of substrates for soil microorganisms and contribute to nutrient cycling. Changes in soil organic matter are particularly relevant because microbial biomass and enzyme activity depend strongly on the quantity and quality of organic resources available in the soil. Water management also affects the microbial environment of coconut roots. Irrigation changes soil moisture and can influence microbial activity, nutrient transformation and the distribution of aerobic and moisture-sensitive microorganisms. The differences in microbial diversity and enzyme activity when irrigation was combined with fertilizer and organic inputs, demonstrating that nutrient and water management can act together in shaping the rhizosphere environment(6).

Cropping-system diversification provides another means of modifying the coconut rhizosphere. Intercrops introduce additional root systems and alter the flow of carbon and nutrients into the soil. Under coconut–pineapple intercropping, changes in soil properties were accompanied by differences in bacterial community structure (7). Similar responses can be expected in diversified coconut systems where intercrops, cover crops and ground vegetation contribute additional organic residues and rhizodeposits. Management intensity may also determine the balance between beneficial and potentially harmful microorganisms. Maintaining ground vegetation and organic inputs can provide continuous resources for soil microbial communities, whereas intensive removal of vegetation and repeated disturbance may reduce the diversity of available microbial habitats. Recent research in coconut plantations has linked biodiversity-inclusive management with differences in soil fungal communities and maintenance of coconut productivity (8). The management practices influence the coconut rhizosphere through their effects on nutrient availability, organic matter, soil moisture, root interactions and habitat conditions. The combined effect of these factors determines the structure and functioning of the rhizosphere microbiome and provides an important basis for sustainable nutrient and soil management. Coconut plantation management practices influence the rhizosphere environment by altering soil nutrient availability, organic matter, moisture conditions and microbial habitats. These changes can reshape the composition and functional activity of rhizosphere microorganisms, thereby affecting nutrient cycling, soil health and coconut productivity. The major interactions between management practices, the rhizosphere microbiome and associated soil–plant outcomes are presented in Figure 1.

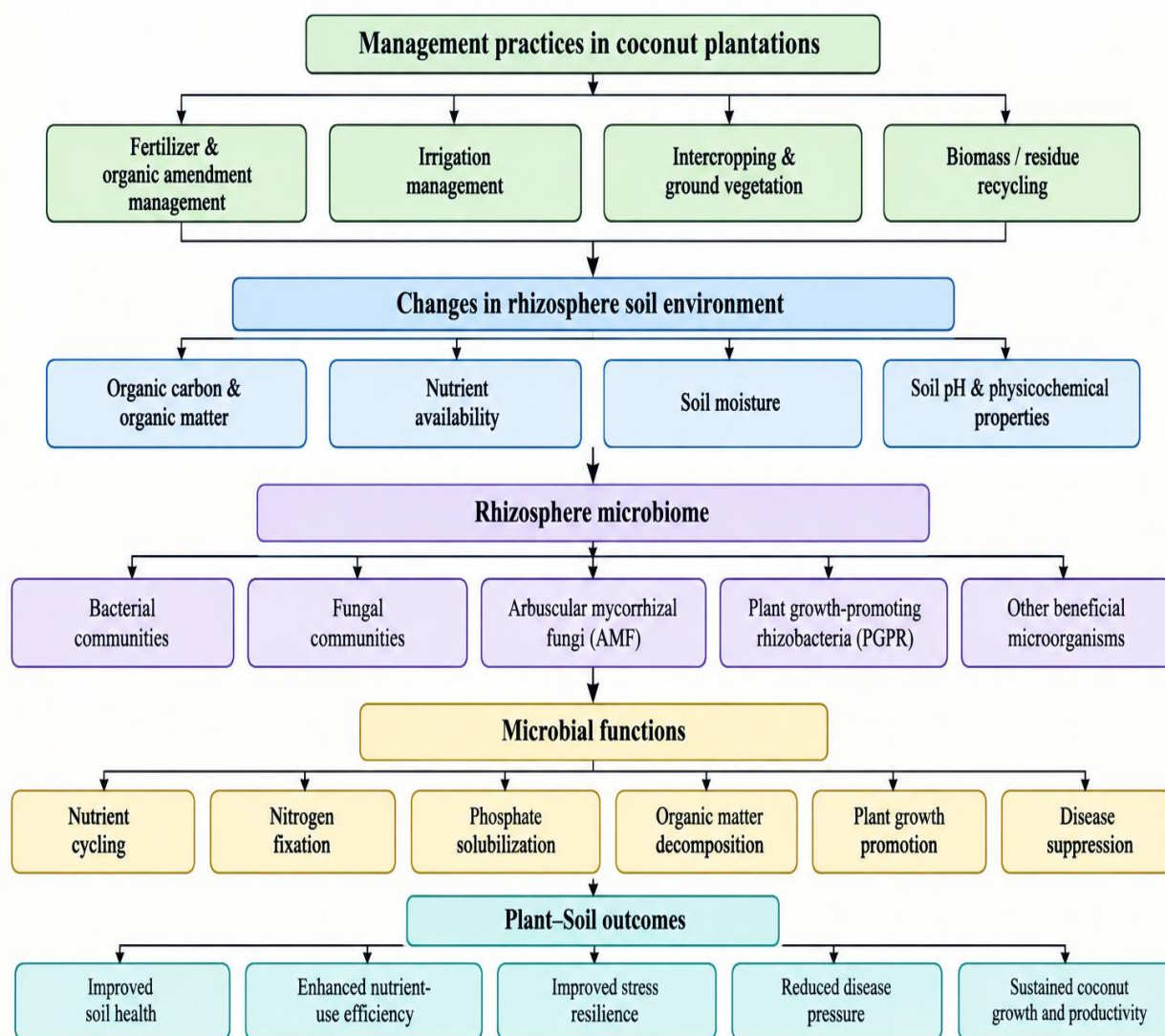


Figure 1. Management-driven restructuring of the coconut rhizosphere microbiome and its implications for soil health, nutrient cycling and palm productivity

3.1 Fertilizer and Organic Amendment Management

Fertilizer management is one of the major factors influencing the biological environment of coconut soils. Chemical fertilizers directly modify nutrient availability, while organic amendments additionally supply carbon and other substrates that can support microbial growth. That different combinations of chemical fertilizer, organic fertilizer and irrigation altered soil nutrient status, enzyme activities and bacterial and fungal community structure in coconut rhizosphere soil(6). The response of microbial communities was closely associated with changes in soil physicochemical properties. Organic amendments can also improve microbial activity through the addition of readily decomposable organic materials. That long-term application of vermicomposted coconut leaves, either alone or in combination with inorganic fertilizers, increased soil organic carbon and enhanced populations of fungi and phosphate-solubilizing microorganisms(10). Integrated nutrient management also improved coconut nutrient status and nut yield compared with the use of organic manure or inorganic fertilizer alone. Recent evidence from coconut farms managed under organic and conventional systems supports the importance of long-term organic management. The higher soil microbial activity and differences in bacterial community composition in organically managed coconut farms compared with conventional farms(11). Organic farms also showed improved soil physical and chemical characteristics, suggesting that sustained organic management can influence both the microbial community and the broader soil environment. The available evidence suggests that fertilizer source, organic matter input and biomass recycling can influence the coconut rhizosphere through changes in nutrient availability, soil organic carbon and microbial activity. Integrated nutrient management therefore provides an important approach for maintaining soil biological functions while sustaining coconut productivity.

3.2. Intercropping and Ground Vegetation

Intercropping changes the biological environment of coconut plantations by introducing additional root systems, organic inputs and nutrient demands into the soil. The resulting changes can influence both soil properties and microbial communities. The evaluation *Artemisia argyi*, *Dioscorea esculenta* and *Arachis pintoi* grown with coconut and found that intercropping increased the diversity of soil bacterial and fungal communities(12). The microbial response varied with the intercrop and soil depth, showing that different ground crops can create distinct microbial environments within coconut plantations. The type of intercrop can also influence specific microbial groups and nutrient-related properties. In the same study, *A. pintoi* increased soil phosphorus and potassium and was associated with greater abundance of *Bacillus*, while some potentially pathogenic fungal groups decreased under intercropping. Soil phosphorus was identified as an important factor associated with changes in microbial community composition. Field-level evidence from South India also supports the role of diversified coconut systems in improving soil biological conditions. The evaluation of integrated nutrient management in a coconut plantation intercropped with black pepper, banana and cocoa. Organic nutrient sources improved soil physical properties and moisture retention, while integrated nutrient management was associated with higher bacterial and fungal populations and better soil health(13). More recent work in Kerala demonstrated that the choice of intercrop can influence both productivity and soil biological characteristics. The coconut-based systems involving banana, papaya, turmeric, ginger, cassava and elephant foot yam. Systems involving banana and turmeric showed improved soil organic carbon, microbial populations and enzyme activities along with higher system productivity(14). Ground vegetation and intercrops therefore act as important components of coconut plantation management rather than simply occupying unused space. Their effects on root interactions, nutrient availability, soil organic matter and microbial communities can contribute to the biological functioning of the plantation. Selection of compatible intercrops and appropriate nutrient management may consequently provide a practical approach for maintaining a diverse rhizosphere microbiome. The major management practices adopted in coconut plantations can modify the physical, chemical and biological conditions of the rhizosphere. Fertilizer application, organic amendments, irrigation, intercropping, biomass recycling and maintenance of ground vegetation influence soil nutrient availability, organic matter, moisture conditions and microbial habitats. These changes can subsequently affect the composition and activity of rhizosphere microbial communities and their functional roles in nutrient cycling and soil health. The major management factors and their reported effects on the coconut rhizosphere microbiome are summarized in Table 1.

Table 1. Major management factors and their reported effects on the coconut rhizosphere microbiome

Management factor	Major changes in the rhizosphere environment	Microbial response / observed effect	Functional implication	Reference
Chemical and organic fertilizer management	Alters nutrient availability, organic matter and soil physicochemical properties	Changes bacterial and fungal community structure and enzyme activities	Influences microbial functioning and nutrient cycling	(6)
Organic amendments	Increases organic carbon and provides substrates for microbial activity	Enhances microbial activity and populations of beneficial microorganisms	Supports nutrient cycling and soil biological activity	(10, 11)
Irrigation management	Modifies soil moisture and nutrient-related soil conditions	Influences microbial diversity and enzyme activity	Regulates the biological environment surrounding coconut roots	(6)
Intercropping	Alters root distribution, nutrient demand and organic matter inputs	Changes bacterial community structure and soil biological properties	Supports diversified nutrient cycling and soil functioning	(7, 12, 13)
Biomass and residue recycling	Increases organic matter and returns nutrients to the soil	Provides substrates for microbial decomposition and nutrient recycling	Supports nutrient availability and carbon-related soil functions	(19, 21, 23)
Biodiversity-inclusive management and ground vegetation	Maintains additional organic inputs and microbial habitats	Associated with changes in soil fungal communities	Supports biological diversity and sustained coconut productivity	(8)

3.3. Arbuscular Mycorrhizal Fungi and Beneficial Microorganisms

Arbuscular mycorrhizal fungi (AMF) form an important biological component of the coconut rhizosphere and establish symbiotic associations with coconut roots. Their occurrence is influenced by soil conditions, season and palm characteristics. A field investigation across coconut plantations in Kerala identified 23 AMF species belonging to seven genera, with *Acaulospora scrobiculata* occurring most frequently. AMF colonization and spore density were associated with soil type and fertility characteristics, indicating that the surrounding soil environment plays an important role in maintaining these associations (5). AMF can also contribute to nutrient acquisition under conditions where nutrient availability is limited. The effect of biochar on AMF-mediated nutrient uptake in coconut seedlings grown in a sandy soil. The study used root-exclusion and isotope-based approaches to distinguish nutrient acquisition associated with microbial and mycorrhizal activity. Their results showed that biochar application influenced plant nutrient acquisition and the microbial environment, particularly under different soil-moisture conditions(15). The natural AMF community of coconut also changes with season and location. AMF associated with coconut roots in Yucatán, Mexico using next-generation sequencing together with morphological identification. AMF communities differed between sampling periods and plantation environments, demonstrating that seasonal and site-specific conditions contribute to variation in coconut mycorrhizal communities(16). Beneficial bacteria represent another important group within the coconut rhizosphere. Their functional traits include nutrient solubilization, hormone production and stress tolerance, allowing them to interact with coconut roots under different soil conditions. The coexistence of AMF and beneficial bacteria provides a broader microbial network through which nutrient availability and plant–soil interactions can be influenced. Overall, AMF and beneficial bacteria contribute to the biological functioning of coconut rhizosphere soil. Their abundance and activity are closely related to soil conditions and management practices, making them important microbial groups to consider when developing sustainable nutrient and soil-health strategies for coconut cultivation.

4. Nutrient Cycling and Microbial Functions

Microorganisms play an important role in nutrient cycling within coconut soils by regulating the decomposition of organic residues and transformation of nutrients into plant-available forms. Evidence from Lakshadweep coconut plantations showed that nutrients returned through coconut biomass residues can be recycled through soil microbial communities. The coconut litter supplied substantial amounts of carbon, nitrogen, phosphorus and potassium to the soil, while bacteria, phosphate-solubilizing microorganisms, actinomycetes and arbuscular mycorrhizal fungi were associated with this nutrient-recycling process(17). Microbial enzyme activity provides an important indication of these nutrient-transforming processes. The changes in dehydrogenase, phosphatase and cellulase activities in coconut rhizosphere soil under elevated carbon dioxide and temperature conditions(18). The changes in enzyme activity were accompanied by alterations in soil nutrient status, showing that environmental conditions can influence microbial processes involved in nutrient cycling.

Coconut residues themselves can also influence microbial activity during decomposition. The decomposition of coconut husk in tropical soil and monitored microbial biomass, respiration, carbon-cycle enzymes and inorganic nitrogen(19). The study showed that residue quality strongly influenced decomposition and microbial responses, indicating that the type of organic material returned to soil is an important factor determining nutrient cycling. The microbial decomposition, enzyme activity and nutrient transformation form an interconnected process in coconut soils. Maintaining regular organic residue inputs and favourable conditions for beneficial microorganisms can support nutrient recycling and reduce dependence on external nutrient inputs. Rhizosphere microorganisms perform diverse functions that contribute to nutrient availability, plant growth and biological activity in coconut soils. Plant growth-promoting bacteria, phosphate-solubilizing bacteria, nitrogen-fixing microorganisms and arbuscular mycorrhizal fungi are involved in nutrient mobilisation and acquisition, while other beneficial microorganisms contribute to plant growth and stress adaptation. The principal microbial groups associated with the coconut rhizosphere and their reported functional contributions are summarized in Table 2.

Table 2. Functional microbial groups associated with the coconut rhizosphere

Microbial group	Major reported function	Potential/observed contribution to coconut	Reference
Plant growth-promoting rhizobacteria (PGPR)	Plant growth promotion through multiple beneficial traits	Supports plant growth and nutrient acquisition	(2, 28)
Phosphate-solubilizing bacteria	Solubilization of otherwise unavailable phosphorus	Improves phosphorus availability to coconut roots	(9, 34)
ACC-deaminase-producing bacteria	Reduces stress-associated ethylene effects and exhibits plant-beneficial traits	Supports coconut growth under saline or stressful conditions	(3)
Nitrogen-fixing bacteria including <i>Azospirillum</i>	Biological nitrogen fixation and association	Contributes to nitrogen availability and microbial	(17, 30)

	with coconut-based farming systems	nutrient cycling	
Arbuscular mycorrhizal fungi (AMF)	Root-associated symbiosis and contribution to nutrient acquisition	Supports nutrient uptake and root-associated biological functioning	(5, 15, 16)
Bacillus spp.	Plant growth promotion and beneficial plant-microbe interactions	Enhances coconut seedling performance under reduced chemical fertilization	(29)
Serratia and Enterobacter spp.	Multiple plant growth-promoting traits	Contributes to plant growth promotion in coconut-associated environments	(2)
Indigenous rhizobacteria	Nutrient mobilisation and abiotic-stress tolerance	Promotes vigorous coconut seedling growth and nutrient uptake	(28)
Soil microbial community	Organic matter decomposition and nutrient recycling	Contributes to nutrient availability and maintenance of soil biological activity	(1, 17)

5. Soil Health and Coconut Productivity

Soil health is closely associated with the long-term productivity of coconut plantations because nutrient availability, soil organic matter, physical condition and biological activity collectively influence root growth and nutrient acquisition. Integrated nutrient management has been shown to improve these soil attributes while sustaining coconut productivity. In a long-term coconut-based cropping experiment in Maharashtra, integrated nutrient management involving organic recycling improved soil fertility properties, leaf nutrient status and coconut yield compared with monocropping. The improvement was associated with greater organic carbon accumulation and better nutrient recycling within the cropping system (20). Soil organic carbon plays an important role in maintaining the functional quality of coconut-growing soils. Residue retention and reduced soil disturbance can improve organic carbon storage and soil physical properties. That residue mulching and reduced tillage improved soil organic carbon, aggregate stability, porosity, bulk density and water-holding capacity in coconut-based cropping systems(21). These changes were associated with improved crop performance and economic returns, demonstrating the importance of conserving soil organic matter in perennial coconut systems. Integrated nutrient management can also contribute to carbon sequestration while improving system productivity. The greater above- and below-ground carbon storage under coconut-based systems receiving organic recycling, vermicompost, biofertilizers and green manuring(22). The integrated treatments also produced higher coconut yields than the monocropping system, indicating that carbon management and productivity can be developed together through diversified nutrient management.

Recent field research from the East Coast region of Andhra Pradesh further demonstrated the contribution of biomass recycling to soil health. The integrated nutrient management using vermicompost, vermiwash, biofertilizers, green manuring and coconut biomass recycling improved soil organic carbon, soil moisture and beneficial microbial populations while increasing coconut and intercrop productivity(23). The results support the use of internally generated biomass as an important component of sustainable nutrient management in coconut-based systems. The available evidence shows that coconut productivity is strongly connected with the biological and physical condition of the soil. Management practices that retain organic residues, recycle biomass and maintain diversified cropping systems can simultaneously improve soil organic carbon, nutrient availability, microbial activity and crop productivity. This provides a strong basis for considering soil health as an important outcome of management-driven restructuring of the coconut rhizosphere microbiome.

6. Disease Suppression and Coconut Plant Health

The coconut rhizosphere can contribute to disease suppression through interactions among beneficial microorganisms, soil properties and plant defence mechanisms. Beneficial bacteria and fungi associated with coconut roots can produce hydrolytic enzymes, siderophores, antibiotics and other metabolites that restrict soil-borne pathogens. The coconut-associated *Serratia marcescens* and *Enterobacter* exhibited multiple plant growth-promoting and antagonistic traits, highlighting the functional potential of native rhizosphere microorganisms in maintaining coconut plant health(2). Biological control microorganisms can also activate the plant's own defence responses. The soil application of *Pseudomonas fluorescens*, *Trichoderma viride* and *T. harzianum* with chitin induced phenolic accumulation and defence-related enzymes in coconut roots affected by *Ganoderma lucidum* (24). The response suggests that rhizosphere microorganisms can contribute to disease resistance not only through direct antagonism but also through stimulation of host defence mechanisms. Field-level disease management studies provide additional evidence for the importance of microbial consortia. The combinations of *Pseudomonas fluorescens*, *Bacillus subtilis* and *Trichoderma viride* against coconut root-wilt disease and

reported improvement in physiological characteristics and yield-related responses of treated palms(25). Such consortia may provide broader disease-management effects than individual microbial inoculants by combining different modes of action.

Recent research has strengthened the connection between soil physicochemical properties and disease-suppressive microbial communities. The suppression of *Ceratocystis paradoxa*, associated with coconut stem bleeding, was linked to interactions between the rhizosphere microbiome and calcium availability in tropical coconut soils(26). The study highlights the importance of managing soil conditions alongside microbial communities when developing sustainable disease-suppression strategies. The disease-suppressive potential of the coconut rhizosphere is therefore influenced by both microbial composition and the surrounding soil environment. Maintaining beneficial microbial populations through organic inputs, balanced nutrient management and biologically based interventions could strengthen natural disease suppression while reducing dependence on chemical control. Future management strategies should focus on identifying stable microbial consortia and the soil conditions that favour their establishment and activity.

7. Molecular and Omics Approaches in Coconut Rhizosphere Microbiome

Conventional culture-based methods provide valuable information on cultivable microorganisms, but they represent only a fraction of the microbial diversity present in the coconut rhizosphere. Molecular approaches such as 16S rRNA sequencing, fungal ITS analysis and whole-genome sequencing have expanded the understanding of microbial diversity and functional potential. High-throughput sequencing of coconut rhizosphere samples has enabled simultaneous assessment of bacterial and fungal communities and their relationships with soil properties and management practices. Whole-genome sequencing has provided functional information beyond microbial identification. The plant growth-promoting bacterial isolates obtained from coconut, cocoa and arecanut rhizospheres. The coconut-associated isolate contained genes associated with phosphate solubilization, siderophore production, ACC deaminase, chitinase, phenazine production, stress tolerance and utilization of organic compounds(27). Such genomic information helps explain the molecular basis of beneficial interactions between rhizobacteria and coconut plants. Amplicon sequencing has also improved the characterization of complex microbial communities directly from coconut soil. Using Illumina high-throughput sequencing to examine bacterial communities under coconut–pineapple intercropping and identified differences in community composition associated with soil physicochemical properties. This approach allows management-induced changes in microbial communities to be evaluated without depending exclusively on microbial cultivation(7). Molecular approaches are particularly useful for studying disease-suppressive coconut soils. Using 16S rRNA-based metataxonomic sequencing to compare suppressive and disease-conducive coconut soils associated with *Ceratocystis paradoxa*. The study linked differences in bacterial communities with soil physicochemical characteristics and calcium availability, demonstrating how microbiome profiling can be integrated with soil measurements to identify potential biological indicators of disease suppression(26).

The increasing availability of sequencing technologies provides opportunities to move from descriptive microbial inventories towards functional microbiome analysis. Metagenomics, metatranscriptomics, metabolomics and microbial network analysis could help identify microorganisms, genes and metabolic pathways associated with nutrient cycling, stress tolerance, plant growth promotion and disease suppression. Integrating these datasets with soil properties, management practices and coconut productivity could support the development of microbiome-based indicators for sustainable coconut production.

8. Microbial Functions in Nutrient Acquisition and Plant Growth Promotion

Microorganisms associated with the coconut rhizosphere contribute to plant nutrition through phosphate solubilization, nitrogen fixation, siderophore production and phytohormone synthesis. These activities increase the availability of nutrients around the root zone and can improve nutrient acquisition by coconut seedlings. The functional diversity of rhizobacteria is particularly important in perennial coconut systems where nutrient availability is influenced by continuous biomass turnover and long-term soil–root interactions. The role of indigenous rhizobacteria in improving nutrient acquisition, the bacteria isolated from healthy and high-yielding coconut palms(28). Selected *Pseudomonas* and *Bacillus* isolates possessing abiotic-stress tolerance and plant growth-promoting characteristics enhanced coconut seedling growth and nutrient uptake. The results indicate that native rhizobacteria can provide both nutritional and stress-adaptation benefits to coconut seedlings. Phosphate solubilization is another important microbial function in coconut nutrition. Beneficial bacteria associated with coconut roots can transform poorly available phosphorus into forms accessible to plants. Their activity is often accompanied by production of indole acetic acid, siderophores and other growth-promoting compounds, allowing a single microbial population to influence both nutrient availability and root development. The potential of microbial inoculation to reduce dependence on inorganic fertilizers using *Bacillus cereus* UFRABC40 isolated from coconut-associated rhizobacteria(29). Inoculation improved coconut seedling growth and nutrient accumulation when chemical fertilizer application was reduced. The bacterium showed phosphate-solubilizing, siderophore-producing and IAA-producing characteristics, supporting its role as a multifunctional plant-growth-promoting microorganism.

Nitrogen-fixing microorganisms also form an important component of the coconut-associated microbial community. The occurrence of *Azospirillum* spp. in several coconut-based farming systems, including multispecies, mixed-cropping and intercropping systems. Their occurrence across diversified coconut systems indicates that biological nitrogen inputs can form part of nutrient cycling within coconut-based production systems(30).

The importance of microbial inoculants can extend beyond direct nutrient supply. PGPR may modify root architecture, improve nutrient-use efficiency and support plant growth under environmental stress. When combined with organic nutrient sources, such microorganisms can contribute to integrated nutrient management by improving the efficiency with which available nutrients are captured by plants. Field research using a coconut-rhizosphere *Azospirillum* strain in a coconut-based mixed-farming system also demonstrated the potential for combining microbial inoculation with organic nutrient recycling to reduce dependence on external inputs. Overall, nutrient-acquiring microorganisms represent an important functional component of the coconut rhizosphere microbiome. Phosphate solubilization, biological nitrogen fixation, siderophore production, phytohormone synthesis and improved nutrient-use efficiency provide multiple pathways through which microorganisms can support coconut growth. Future management strategies should focus on selecting locally adapted microbial consortia and integrating them with organic amendments and balanced fertilization rather than relying on individual microbial functions in isolation.

9. Environmental Stress, Soil Moisture and Microbiome Adaptation

Coconut plantations are frequently exposed to environmental stresses such as salinity, temporary soil-moisture deficits and fluctuations in temperature. These conditions can alter root activity, nutrient availability and microbial interactions in the rhizosphere. Microorganisms possessing stress-tolerant traits can help maintain plant growth under such conditions through improved nutrient acquisition, modulation of stress ethylene and production of growth-promoting compounds. Salinity is particularly relevant to coconut cultivation in coastal and island environments. Characterization ACC deaminase-producing bacteria from coconut rhizosphere soils of the Lakshadweep Islands and identified diverse bacterial groups belonging to *Pseudomonas*, *Bacillus*, *Azospirillum*, *Azotobacter*, *Paenibacillus*, *Burkholderia* and *Klebsiella*. Several isolates possessed phosphate-solubilizing, siderophore-producing and other plant-growth-promoting properties, while selected strains showed salt tolerance(3). The study demonstrates that coconut-associated rhizobacteria can represent a reservoir of microorganisms adapted to saline environments. The stress tolerance of rhizobacteria is also associated with their ability to regulate plant ethylene responses. ACC deaminase-producing microorganisms can reduce the accumulation of stress-associated ethylene by metabolizing its precursor ACC. This mechanism can support root development and nutrient and water uptake when plants experience adverse environmental conditions. The occurrence of such bacteria in coconut rhizospheres suggests that microbial adaptation may form an important component of the coconut palm's response to stressful coastal environments. Soil moisture can also influence microbial-root interactions. The coconut seedlings grown in a sandy Regosol under wet and dry conditions and demonstrated that biochar amendment modified mycorrhiza-mediated nutrient acquisition under moisture stress(15). Biochar derived from *Gliricidia sepium* improved plant growth under dry conditions and altered the soil microbial environment towards greater fungal abundance. The study indicates that soil amendments capable of improving the rhizosphere environment may help maintain microbial nutrient-acquisition functions during temporary moisture deficits.

Temperature and atmospheric changes can modify rhizosphere biochemical processes as well. Experimental exposure of coconut seedlings to elevated temperature and CO₂ altered several soil enzyme activities, nutrient concentrations and soil chemical characteristics, suggesting changes in microbial mineralization and nutrient cycling (18). Such responses indicate that climate-related changes may influence the functioning of the rhizosphere microbiome even when visible changes in coconut growth are not immediately apparent. The available evidence suggests that environmental stress does not act independently of rhizosphere management. Moisture conservation, organic amendments and the maintenance of stress-tolerant microbial populations can potentially improve the resilience of coconut root systems. Future research should combine microbial community profiling with physiological measurements of coconut palms under drought, salinity and temperature stress to identify microbial indicators associated with climate resilience.

10. Microbiome-Based Strategies for Sustainable Coconut Production

Management of the coconut rhizosphere microbiome can be approached through the combined use of organic inputs, microbial inoculants, biomass recycling and suitable cropping systems. The microbiological properties of coconut root-zone soils varied considerably among different soil series in Sri Lanka. Differences were observed in bacterial and fungal populations, microbial biomass carbon and nitrogen, carbon dioxide evolution and nitrogen mineralization. These indicate that the effectiveness of microbiome-oriented management is closely linked to the inherent biological characteristics of the soil(19). The relationship between soil environment and microbial activity is also evident in coconut-based cropping systems. The coconut grown with different intercrops and reported differences in soil bacterial, fungal and actinomycete populations together with changes in soil N, P and K status. The study showed that cropping-system design can influence both soil microbial activity and coconut productivity, supporting the use of diversified production systems as a practical means of

maintaining biological activity in coconut soils(31). Microbial inoculation can be combined with organic nutrient recycling to improve the efficiency of nutrient management. A coconut-rhizosphere *Azospirillum* strain together with cow-dung slurry and coconut-leaf vermicompost in a coconut-based mixed-farming system. The integrated treatment improved nutrient-use efficiency and reduced dependence on external inputs, demonstrating the potential of combining beneficial microorganisms with locally available organic resources(32). Microbiome-oriented management may also be useful in coconut plantations affected by root-wilt disease. Comparing fertilizer application with an integrated treatment involving reduced fertilizer, vermicompost and green manure in root-wilt-affected coconut palms(33). The integrated treatment maintained palm health and was associated with higher copra production compared with fertilizer application alone. Their findings support the importance of improving the nutritional and biological environment of the root zone as part of long-term management of diseased palms. The development of microbiome-based coconut production should consequently move beyond the application of individual microbial inoculants. The soil type itself can determine the abundance and activity of microbial communities(19), while the practical value of combining an indigenous microbial strain with organic nutrient sources(32). A management strategy that considers soil characteristics, organic carbon inputs, microbial inoculation, crop diversification and nutrient supply together could provide a more stable rhizosphere environment. Such an integrated approach may improve nutrient cycling, soil biological activity and palm productivity while reducing dependence on external inputs.

11. Research Gaps and Future Prospects

Despite increasing evidence on the functional importance of coconut-associated microorganisms, major gaps remain in understanding how management practices consistently reshape the rhizosphere microbiome under field conditions. Existing studies have largely focused on cultivable bacteria, individual microbial functions or specific management treatments. The isolation and characterization of beneficial rhizobacteria from healthy coconut palms growing in root-wilt disease endemic areas and demonstrated the presence of bacteria with multiple nutrient-solubilizing and plant growth-promoting traits(34). Such studies provide a useful microbial resource, but the ecological interactions among these organisms within the complete rhizosphere community require greater attention. A major research priority is the transition from culture-dependent screening towards community-level functional analysis. Genome-level characterization of coconut-associated PGPRs has already revealed genes related to phosphate solubilization, siderophore production, ACC deaminase activity, chitinase production and abiotic-stress tolerance. Coconut-associated PGPRs possess a broad genetic repertoire supporting plant growth promotion and adaptation to stressful rhizosphere conditions(27). Future studies combining metagenomics, metatranscriptomics and metabolomics could determine whether these functional traits are actively expressed under different soil and management environments. Another important gap concerns the development of site-specific microbial management strategies. Coconut plantations occur across contrasting soil types, rainfall regimes and nutrient environments, and microbial communities may respond differently to these conditions. Variation in the microbiological properties of coconut root-zone soils among different soil series, highlighting the influence of soil characteristics on microbial abundance and activity(19). Future research should therefore integrate soil type, moisture, organic carbon, nutrient status and cropping system when selecting microbial inoculants or designing microbiome-based management practices.

Long-term field validation is also required before microbial technologies can be widely adopted in coconut production. Laboratory screening frequently identifies promising PGPR strains, but their establishment, persistence and interaction with indigenous microbial communities may vary under field conditions. Coconut-derived *Serratia marcescens* and *Enterobacter* sp. possessed multiple plant growth-promoting traits and improved growth and nutrient uptake of coconut seedlings following inoculation(2). Future experiments should evaluate such microorganisms over multiple seasons and across different coconut-growing environments, with emphasis on palm growth, nutrient-use efficiency, disease incidence and yield. The identification of disease-suppressive microbial communities represents another promising research direction. Healthy coconut palms growing within root-wilt disease endemic regions provide an important biological resource for identifying microorganisms associated with palm resilience. The healthy palms harboured rhizobacteria with multiple phytobeneficial characteristics, including nutrient-solubilizing activity and plant-growth-promoting traits(34). Future research could compare healthy and diseased palms using high-throughput sequencing and functional assays to identify microbial indicators associated with disease tolerance and plant health. Future coconut microbiome research should ultimately move towards an integrated soil–microbe–plant management framework rather than treating microbial inoculation as an independent input. Combining organic matter management, balanced nutrient application, crop diversification, moisture management and beneficial microorganisms may create a more stable rhizosphere environment. Such approaches could improve nutrient cycling, strengthen plant resilience and support sustainable coconut productivity while reducing dependence on external agricultural inputs.

12. CONCLUSION

The coconut rhizosphere represents a dynamic biological interface where soil properties, root activity and microbial communities interact to influence nutrient availability, plant health and long-term palm productivity. The available evidence demonstrates that fertilizer management, organic amendments, irrigation, intercropping, biomass recycling and soil conditions can substantially influence rhizosphere microbial communities and their

functional activities. Maintaining a biologically active rhizosphere is important for efficient nutrient cycling and soil health in coconut-based production systems. Organic matter addition, recycling of coconut biomass, balanced nutrient management and diversified cropping systems can support microbial activity and improve the biological quality of the soil. Beneficial microorganisms, including plant growth-promoting bacteria and arbuscular mycorrhizal fungi, provide additional opportunities for improving nutrient acquisition and strengthening plant performance. Microbiome-based approaches also offer potential for improving coconut resilience against environmental stresses and soil-borne diseases. The integration of beneficial microorganisms with suitable soil and crop management practices may provide more stable and sustainable benefits than the use of individual microbial inputs. Molecular and omics-based approaches can strengthen the understanding of microbial diversity, functional interactions and plant–microbe relationships within the coconut rhizosphere. Overall, a management–microbiome–soil health–productivity framework provides a promising basis for sustainable coconut production. Future research should focus on long-term field validation, site-specific microbial consortia, management-responsive microbial indicators and functional microbiome analysis. Integrating microbial ecology with practical nutrient, water and cropping-system management can contribute to improved soil health, efficient nutrient use, greater palm resilience and sustainable coconut productivity.

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Author Contributions

VN has written the whole manuscript. MM guided in providing technical support to write the manuscript in a proper format and equally contributed and approved the final manuscript. SV, PM and GA guided to write the manuscript in a proper format and approved the final manuscript. All authors read and approved the final manuscript.

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