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The Role of Plant-Associated Microorganisms in Improving Crop Growth and Stress Tolerance

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Abstract.

Plant-associated microorganisms influence crop growth through interactions with roots, leaves, seeds, and surrounding soil. Certain bacteria and fungi support nutrient acquisition, modify plant signalling, and contribute to protection against drought, salinity, and pathogens. Their effects, however, depend on microbial strain, crop genotype, soil conditions, and management. This narrative review examines plant growth-promoting rhizobacteria, nitrogen-fixing symbioses, carbuncular mycorrhizal fungi, and entophytes, with attention to their ecological roles and proposed mechanisms. It discusses nutrient mobilization, phytohormone regulation, competition with pathogens, and physiological responses to abiotic stress, as well as methods for characterizing microbial communities and evaluating inoculants. A graph illustrates published mean responses to rhizobacteria inoculation under well-watered conditions from a meta-analysis; these values are not guaranteed yield gains and do not represent drought results. Evidence from field studies must be interpreted in relation to experimental design, environmental variability, and economic costs. The review highlights formulation, colonization, biosafety, and quality control as key challenges for translation into agriculture. It concludes that microbial technologies are most useful when evaluated as part of locally adapted crop and soil management. No new field experiment or dataset is reported.

Keywords: *plant micro biome, crop growth, rhizobacteria, mycorrhizal fungi, stress tolerance*

1. Introduction

Crops grow in association with diverse microbial communities that inhabit the soil around roots, plant surfaces, internal tissues, and seeds. These organisms interact with the plant and with one another through nutrient exchange, chemical signals, competition, and defense. Some associations improve plant nutrition or health, while others are neutral, harmful, or beneficial only under particular conditions. A microorganism that promotes growth in a laboratory experiment may not have the same effect in a different field, cultivar, or season. Water scarcity, salinity, nutrient limitations, and plant diseases constrain agricultural productivity in many regions. Microbial inoculants and management practices that support beneficial communities are being studied as possible components of more resilient farming systems. Such approaches do not remove the need for sound irrigation, soil fertility management, appropriate crop varieties, and disease control. Their value depends on whether they add a reproducible benefit under practical conditions and at a cost acceptable to farmers [1, 2].This article is a narrative review of plant-associated microorganisms and their contributions to crop growth and stress tolerance. It

explains ecological relationships, mechanisms, research methods, and practical limitations. A published meta-analysis is used to illustrate mean plant responses under well-watered conditions; the review does not present original experimental results or prescribe a product for a particular farm. Research communication should make clear what is known at each stage. A culture-plate result identifies a candidate function; a greenhouse trial tests a crop response under controlled conditions; and a field trial addresses performance in a more complex environment. None of these stages alone answers every question. Careful reporting of controls, strain identity, soil, crop variety, dose, application method, and results allows subsequent researchers to build on the work. Where evidence is limited, recommendations should remain conditional and be tested locally before large-scale adoption.

Plant Micro biome and Ecological Niches:

The rhizosphere is the region of soil influenced by roots and their secretions. Root exudates include sugars, organic acids, amino acids, and signaling molecules that can influence microbial growth and community composition. The rhizoplane is the root surface, while the root end sphere consists of internal root tissues. Aboveground surfaces form the philosopher, and microorganisms can also inhabit internal stems, leaves, flowers, and seeds. Each habitat has different nutrients, moisture, oxygen, and exposure to environmental stresses. Plant-associated communities can include bacteria, fungi, archaic, protests, and viruses. Their composition is shaped by the plant genotype, developmental stage, soil type, climate, fertilizer, irrigation, and previous crops. Microbial interactions are not restricted to the plant–microbe pair: organisms compete for nutrients, exchange metabolites, and influence each other through signaling or antagonism. Identifying an organism near a healthy plant does not prove that it caused the plant to be healthy; controlled experiments are required to establish its contribution. Plant-associated microbes are often described as beneficial, but the effect of a particular organism can change with context. A mycorrhizal fungus may enhance phosphorus acquisition when available phosphorus is limited, while the plant still pays a carbon cost to support the symbiosis. Similarly, a bacterium that promotes root growth in one cultivar may colonize another cultivar poorly. It is therefore more accurate to evaluate a defined strain with a defined host and environment than to assume that every member of a microbial genus has the same function.

Major Groups of Plant-Associated Microorganisms:

Plant growth-promoting rhizobacteria, commonly abbreviated as PGPR, are bacteria that can improve plant performance through direct or indirect mechanisms. Research has examined strains belonging to several genera, including Bacillus, Pseudomonas, and Azospirillum. The genus name alone is not enough to predict activity or safety: properties should be established for the individual strain. Useful strains must survive formulation, reach the appropriate plant tissue, and remain active in the presence of native microorganisms. Rhizobia form nodules with compatible legumes, where some strains convert atmospheric nitrogen into forms that can support plant nutrition. The plant supplies carbon and a suitable environment for this symbiosis. Effective nitrogen fixation depends on compatible partners, nodule formation, soil conditions, and the availability of other nutrients. A seed inoculant can be helpful where effective native rhizobia are absent or insufficient, but it may add little where a well-adapted native population is already abundant.Arbuscular mycorrhizal fungi form symbioses with many, though not all, crop plants. Their hyphae extend into the soil and can improve access to less-mobile nutrients, especially phosphorus. The benefits depend on the host, fungal species, soil fertility, and environment. Some crops or crop families do not form typical carbuncular mycorrhizal associations, so compatibility must be checked before considering a fungal inoculant. Colonization alone is not evidence that the association improves yield.Endophytes live within plant tissues without necessarily causing visible disease. They may be bacteria or fungi and can originate from soil, seed, or other sources. Some studied entophytes produce metabolites or alter

plant responses to stress, but their presence does not automatically imply a beneficial function. Strain identification, confirmation of colonization, and evaluation of host effects across relevant conditions are needed before an entophyte is considered for agricultural use.

Nutrient Acquisition and Growth Promotion:

Microorganisms influence nutrient availability through several routes. Biological nitrogen fixation supplies nitrogen when compatible organisms and environmental conditions support the process. Some soil microorganisms can release phosphorus from forms that plants cannot readily access, for example by producing organic acids or enzymes. A laboratory test showing phosphate solubilization on a plate is a useful screening result, but it does not establish that a field crop will acquire more phosphorus or yield more grain. Soil chemistry, moisture, and competition all affect the result. Iron is essential to plants but can be poorly available in some soils. Certain microorganisms produce siderophores, molecules that bind iron, which may influence iron availability and competition among microbes. The benefit to a crop depends on the chemistry of the soil and whether the plant can use the resulting iron complexes. Root architecture, nutrient transporters, and the existing community also matter. Evidence should include nutrient uptake or plant performance in addition to the detection of a microbial trait. Microbes can influence plant hormone pathways through production or modification of compounds associated with axons, cytokines, gibberellins, and ethylene regulation. Some bacteria possess ACC deaminize, an enzyme that can affect the availability of a precursor to ethylene. These pathways are often proposed as mechanisms of stress mitigation, but hormone responses depend on dose, tissue, and timing. Detecting a hormone-like compound in culture does not establish that it reaches the plant at a biologically relevant concentration. A credible mechanism is supported by multiple observations. For example, researchers may combine microbial genome analysis, measurement of a metabolite, colonization tests, plant nutrient uptake, and experiments using a mutant lacking the proposed function. A response that disappears when the function is removed and returns when it is restored offers stronger evidence than a simple correlation. In practical agriculture, a mechanism must ultimately translate to outcomes such as consistent yield, quality, or reduced nutrient loss.

Microbial Contributions to Drought and Salinity Tolerance:

Drought reduces water availability and can limit nutrient movement, photosynthesis, and growth. Some root-associated microorganisms may improve plant performance during water limitation by influencing root architecture, nutrient acquisition, or stress signaling. Microbial extracellular polymeric substances can contribute to aggregation and biofilm formation, potentially affecting the local environment around roots. These mechanisms are plausible in particular systems, but their magnitude and persistence vary with soil texture, watering regime, microbial survival, and plant developmental stage. Experiments in sorghum have shown that drought changes the development and composition of the root micro biome, including enrichment of some monomer bacteria [3]. Follow-up inoculation experiments suggested that certain isolates could influence growth under drought. This does not mean that every microbe enriched during stress protects the plant. Enrichment may result from microbial tolerance of dry conditions, changes in root exudates, or reduced competition. Demonstrating a protective effect requires experiments with defined organisms and appropriate controls. Salinity can impose osmotic stress and ion toxicity, restricting growth and nutrient balance. Selected microbes have been studied for effects on root growth, ion uptake, antioxidant responses, and compatible solutes under saline conditions. A microorganism that survives salty culture medium may still fail to protect a crop in saline soil. Inoculation effects should be measured at realistic salinity levels, with water quality, soil texture, plant cultivar, and the duration of exposure documented. Plant stress indicators can help interpret responses but should not replace agronomic endpoints. Relative water content, stomata conductance, photosynthetic rate, and antioxidant enzyme activity may reveal changes in

physiology. However, changes in these indicators do not automatically prove a mechanism or predict harvestable yield. Stress tolerance can involve a trade-off with growth, and responses should be assessed over time rather than at a single sampling point. Field studies should include grain yield, yield quality, and water-use context when these are relevant to the crop.

Protection against Pathogens and Biotic Stress:

Some plant-associated microorganisms suppress disease by competing with pathogens for space and nutrients, producing inhibitory compounds, or influencing plant defense responses. Siderophores, lytic enzymes, volatile compounds, and antibiotics are examples of traits studied in laboratory systems. The presence of a gene or inhibitory activity in a Petri dish does not guarantee effective disease control in soil or on leaves. The organism must survive, encounter the pathogen or host, and express relevant functions under field conditions. Induced systemic resistance describes a state in which local microbial interactions can prime plant defenses against later challenge. The response can involve plant signaling pathways and may vary with the host, microbial strain, and pathogen. Evidence for induced resistance requires appropriate experimental design, including separation of local colonization from the site of pathogen challenge where feasible. Reduced disease should not be attributed to a signaling pathway solely because a defense-related gene is expressed. Microbial products are not interchangeable with all conventional pest-management tools. Their performance can depend on application timing, weather, storage, and disease pressure. Integrated management combines resistant cultivars, sanitation, rotation, monitoring, and appropriate treatments. Non-target effects and the possibility that a strain carries undesirable traits also require evaluation. Inoculants should be identified and assessed according to the intended crop, target, and applicable local requirements.

Evidence from Experiments and Meta Analyses:

Individual experiments offer detail about a particular crop and environment but can be difficult to generalize. A meta-analysis combines results across studies using a defined method to estimate an average response and examine variability. Rubin and colleagues synthesized 52 published articles on plant growth-promoting rhizobacteria under drought and well-watered conditions [4]. For well-watered comparisons, they reported average increases of 35% in root mass, 28% in shoot mass, and 19% in reproductive yield relative to inoculated controls. These are pooled results from the included studies, not a prediction for any particular field. In designing experiments, the unit of replication matters. Multiple plants in one pot or many molecular measurements from one plot do not necessarily represent independent field replicates. Randomized blocks, untreated controls, predefined outcomes, and appropriate statistical models reduce the risk of misleading conclusions. Multisite and multisession trials reveal whether effects persist when rainfall, soil properties, management, and indigenous communities change. A useful evaluation should distinguish crop response from inoculant persistence. Quantitative methods can track a labeled or genetically identified strain over time, but detection of its DNA may persist after cells are no longer active. Combining viable counts or other measures of activity with molecular identification can help determine whether the organism survives and colonizes. Sampling should include the relevant plant compartment and should not infer root colonization from a soil sample alone. The methods used to identify introduced organisms should be capable of distinguishing them from similar native strains. Economic outcomes depend on both the average effect and the risk of an unsuccessful application. The cost of a product, its shelf life, the labor or equipment needed for application, and its interaction with existing inputs all affect its value. Farmers may prefer a modest but reliable response to an occasional large increase. Independent replicated trials can estimate variation among sites and seasons, enabling a more realistic assessment than promotional claims based on a single successful demonstration. Yield quality and market requirements may matter as much as total biomass.

Methods for Studying Plant–Microbe Interactions:

Microbial cultivation and isolate characterization provide material that can be tested directly. Researchers can identify strains using genomic or marker-based approaches, test survival under stress, and screen for possible functions such as nitrogen fixation or phosphate mobilization. Culture-based work is valuable but does not capture all organisms in a community. Screening tests should be followed by controlled plant experiments and confirmation that the strain establishes at the relevant site.Amplicon sequencing of bacterial 16S reran genes or fungal marker regions can describe community composition, while met genomics can identify a wider range of genetic potential. Metatranscriptomics can help assess which genes are expressed under particular conditions. These methods have limits: DNA detection does not establish viability or activity, and a gene's presence does not prove that it is expressed or benefits the host. Sampling time, extraction methods, contamination controls, reference databases, and sequencing depth influence results. Metabolomics and plant physiological measurements can complement microbial data by showing chemical and functional changes. Stable-isotope approaches can help trace nutrient movement, while microscopy can show location or colonization. Synthetic communities containing defined strains provide a way to test interactions, but they simplify a much more complex field ecosystem. Castillo and colleagues used a defined bacterial community in work examining the connection between phosphate responses, immunity, and root micro biota [7]. Such mechanistic studies provide hypotheses that require validation in agricultural settings. Methods should match the question. If the objective is to establish whether an inoculant increases crop yield, a sequencing profile alone is insufficient. If the objective is to understand why a strain influences root growth, comparing wild-type and function-deficient strains may be more informative. Sharing sampling protocols, sequence-processing workflows, metadata, and experimental controls allows others to assess and reproduce the findings.

Field Application, Formulation and Sustainable Management:

Microbial inoculants may be delivered as seed treatments, soil amendments, root dips, or liquid formulations. The chosen route affects survival, distribution, and contact with the crop. A viable laboratory culture is not automatically a stable product: carriers, temperature, shelf life, packaging, and compatibility with seed coatings or pesticides can influence the number of living cells delivered. Labels and quality control should specify the strain identity, viable concentration, storage conditions, and expiry date where applicable. Field establishment is often uncertain because introduced organisms must compete with existing communities and tolerate local conditions. Soil pH, temperature, moisture, fertilizer use, and crop genotype can affect colonization. Applying more inoculant does not necessarily produce a larger benefit, and mixtures of strains can interact positively or negatively. When a product contains multiple organisms, each strain and the mixture should be evaluated for compatibility, stability, and performance rather than assuming their effects are additive. Management practices such as crop rotation, organic amendments, reduced soil disturbance, and cover crops can affect soil microbial communities, although their effects are context dependent. Practices should be evaluated for the whole farming system, including water availability, pests, nutrient balances, labor, and cost. A change that favors one microbial group may have unintended consequences for another function. Locally adapted trials and farmer participation help determine whether a microbial intervention is practical and economically worthwhile. Biosafety and environmental stewardship are essential. Some organisms within commonly studied genera include opportunistic pathogens or strains with undesirable genes. Assessment should consider strain identity, antimicrobial resistance, non-target effects, and potential environmental persistence, using the relevant regulatory framework. Introducing a microorganism should be justified by credible benefits and a proportionate evaluation of risks.

Table 1 Examples of plant-associated microorganisms and proposed functions

Microbial group	Potential contribution	Key condition or limitation
Rhizobia	Nitrogen fixation in legume nodules	Requires compatible host and effective strain
Carbuncular mycorrhizal fungi	Improve access to soil phosphorus	Benefits depend on crop and soil fertility
Growth-promoting rhizobacteria	Influence roots, nutrients and stress signals	Field performance is strain- and site-dependent
Bacterial or fungal entophytes	May affect host physiology or defense	Presence alone does not prove benefit
Bio control microorganisms	May suppress specific pathogens	Need survival, timing and non-target evaluation

Research Priorities and Future Directions:

Future research should prioritize reproducible, agronomic ally meaningful outcomes. A useful trial measures not only microbial abundance and early biomass but also harvestable yield, quality, resource use, and economic return. Trials should compare the microbial treatment with the farmer's current practice and include relevant controls for carrier materials and application procedures. Reporting negative results and variability is as important as reporting the best-performing plot. Breeding crops with favorable micro biome interactions is an area of research, but community composition is influenced by both plant genetics and the environment. A cultivar that supports a beneficial association in one soil may not do so elsewhere. Combining plant genetics, microbial ecology, and field experiments can help identify robust traits, while avoiding the assumption that a single ideal micro biome exists for all farms. The consequences for native biodiversity and other soil functions should also be assessed. More precise formulation and delivery may improve consistency, but such improvements must be tested against simpler alternatives. A product that survives storage but fails to colonize the crop will not deliver its intended benefit. Repeated monitoring can distinguish failure of survival, failure to establish, and establishment without a measurable plant response. These distinctions help researchers decide whether to improve the formulation, select another strain, or abandon a proposed mechanism. Interdisciplinary collaboration is needed to translate evidence into practice. Microbiologists can characterize organisms, soil scientists can assess nutrient and water conditions, plant scientists can measure stress responses, and farmers can identify constraints in real production systems. Economic and environmental evaluation should include application cost, yield variability, impacts on existing practices, and unintended effects. A microbial technology should complement locally effective management and demonstrate value across the conditions in which it is intended to be used. The timing and severity of stress deserve particular attention in future trials. A brief dry period during vegetative growth differs from drought during flowering or grain filling, when reproductive development can be especially sensitive. Trials should document the timing and intensity of water limitation using soil-water measurements or clearly described irrigation schedules. Comparing treatments under both adequate and limited water can show whether an inoculant changes the crop response to stress or simply promotes growth under a broad range of conditions. Weather records are necessary for interpreting field experiments. Soil nutrient status can also change the outcome of inoculation. When phosphorus is readily available, the plant may obtain little extra benefit from a symbiotic association that carries a carbon cost. In a nutrient-poor soil, the same association may be more valuable, provided that other constraints do not prevent growth. Researchers should measure soil properties and nutrient inputs rather than assuming that an inoculant acts in isolation. Fertilizer replacement claims

require direct comparisons across appropriate fertilizer rates and measurements of nutrient uptake, yield, and potential losses.

Summary:

Plant-associated microorganisms can support crops through nutrient exchange, changes in root and plant signaling, and interactions with pathogens. Rhizobia, carbuncular mycorrhizal fungi, rhizobacteria, and entophytes have distinct ecological roles, and their effects vary by strain, host, soil, climate, and management. Mechanistic claims require evidence beyond microbial presence or an isolated laboratory screening test.The published meta-analysis illustrated in the graph reported positive average responses under well-watered conditions; those figures are not guaranteed field outcomes or drought-specific values. Robust field trials, quality-controlled inoculants, biosafety assessment, and comparison with existing practices are necessary to determine where microbial approaches can improve crop growth and stress resilience. This narrative review reports no new experiment.

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