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HIDDEN ENGINES OF GROWTH: MICROBES FUELING PLANT NUTRITION

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Soil microorganisms, including bacteria, fungi, actinomycetes, and archaea, are fundamental to nutrient transformation and plant nutrition. Earlier research predominantly addressed single functions such as biological nitrogen fixation by *Rhizobium* or phosphate solubilization by *Pseudomonas*. Current studies emphasize the soil microbiome as an integrated system regulating nutrient cycling and plant-soil interactions. Metagenomic and high-throughput sequencing approaches have elucidated microbial diversity and functional networks. These insights support the development of biofertilizers and sustainable nutrient management strategies. Enhancing beneficial microbial consortia is therefore critical for advancing agricultural sustainability and global food security.

Introduction: Evolution of Soil Microorganisms in Plant Nutrition

The role of soil microorganisms in plant nutrition has advanced from basic observations to molecular-level insights (Adomako et al., 2020). Initially, studies focused on nitrogen-fixing bacteria such as *Rhizobium* in legumes, later extending to phosphorus-solubilizing bacteria and mycorrhizal fungi for nutrient mobilization and soil structure improvement (Pradhan et al., 2025). High-throughput sequencing has elucidated complex microbial networks regulating nutrient availability, pathogen suppression, and plant growth. Rhizosphere microbial diversity critically influences nutrient uptake efficiency, plant resilience, and ecosystem functioning (Pandey & Saharan, 2025). Harnessing these beneficial microbes as biofertilizers enhances crop productivity and nutrient use efficiency while reducing chemical fertilizer dependence, supporting sustainable agriculture (Shimada et al., 2024).

Nitrogen Fixation

Nitrogen is a vital nutrient for plants, required for proteins, nucleic acids, and chlorophyll. Although abundant in the atmosphere, N_2 is unavailable to plants until converted into ammonia by nitrogen-fixing microorganisms. Symbiotic bacteria like *Rhizobium* form nodules on legumes (Singh et al., 2023), while free-living diazotrophs such as *Azospirillum* enhance cereals (Bashan & de-Bashan, 2010). Cyanobacteria, including *Anabaena* and *Nostoc*, contribute significantly in paddy soils. Nitrogen fixation efficiency depends on microbial species, host plants, and soil conditions. Biofertilizers based on these microbes reduce chemical fertilizer dependence and promote sustainable agriculture.

Phosphorus Solubilization

Phosphorus (P) is a key macronutrient involved in energy transfer, root development, and overall plant growth. However, much of the soil P occurs in insoluble mineral forms, limiting its bioavailability. Phosphate-solubilizing microorganisms (PSMs) enhance P availability by secreting organic acids, chelators, or enzymes that release soluble P into the rhizosphere. Bacteria such as *Pseudomonas fluorescens* and *Bacillus megaterium* improve P uptake in crops like maize and tomato (Chen et al., 2006), while fungal PSMs, including *Aspergillus niger* and *Penicillium* spp., are particularly effective in acidic soils. The use of PSM-based biofertilizers improves crop productivity and reduces dependence on chemical P fertilizers, thereby supporting sustainable agriculture.

Potassium Mobilization

Potassium (K) is a vital macronutrient involved in enzyme activation, osmoregulation, stomatal regulation, and photosynthesis. Although soils contain large reserves of K, much of it is locked in insoluble minerals such as feldspars and micas. Potassium-solubilizing bacteria (KSB) release organic acids that mobilize K^+, making it plant-available (Siddiqui et al., 2008). Strains like *Bacillus mucilaginosus* and *Frateuria aurantia* enhance crop growth by improving K uptake in crops such as tomato and maize.

Micronutrient Availability

Soil microorganisms also play a pivotal role in mobilizing essential micronutrients such as iron (Fe), zinc (Zn), and manganese (Mn), which, although required in trace amounts, are critical for plant metabolism. Siderophore-producing bacteria like *Pseudomonas* spp. enhance

Fe solubility and uptake, thereby supporting chlorophyll biosynthesis and plant growth. Zinc-solubilizing bacteria, such as *Bacillus subtilis*, improve Zn availability in crops like wheat and rice, promoting enzymatic activities vital for growth and development (Yadav et al., 2023). Similarly, Mn-mobilizing bacteria facilitate Mn uptake, contributing to seedling vigor, stress tolerance, and photosynthetic efficiency.

Rhizosphere Interactions

The rhizosphere, the narrow zone of soil around plant roots, is a hotspot of plant–microbe interactions. Root exudates such as sugars, amino acids, and organic acids provide energy for microorganisms, which in turn release enzymes and metabolites that decompose organic matter and mobilize nutrients like nitrogen, phosphorus, and micronutrients (Berendsen et al., 2012). These interactions enhance nutrient cycling, root development, and plant health. For example, co-inoculation of *Azospirillum* and *Pseudomonas* in maize improves nutrient uptake, stimulates root growth, and increases disease resistance, highlighting the vital role of rhizosphere microbes in crop productivity.

Mycorrhizal Associations

Arbuscular mycorrhizal fungi (AMF) establish symbiosis with plant roots, extending hyphae into the soil to enhance nutrient uptake, particularly phosphorus and micronutrients. In maize, AMF inoculation can improve phosphorus acquisition by up to 40% under low-P conditions (Al-Karaki, 2006). They also strengthen plant tolerance to drought and abiotic stresses while improving soil aggregation. By reducing fertilizer dependence, AMF contribute significantly to sustainable agriculture and soil health.

Impact on Soil Fertility

Soil microorganisms enhance fertility by driving humus formation, soil aggregation, and nutrient cycling. Decomposition of organic matter produces stable humus that improves soil structure, aeration, and water retention (Lal, 2015). They also regulate the availability of nitrogen, phosphorus, potassium, and micronutrients. Synergistic interactions, such as AMF with nitrogen-fixing bacteria, enrich soil organic matter and boost crop productivity.

Challenges and Future Directions

The use of microbial inoculants enhances plant nutrition and soil health but faces challenges like environmental variability, soil differences, and competition with native microbes. Developing multi-strain consortia can improve nutrient mobilization (Vessey, 2003). Genomic and metagenomic tools help predict microbial function and resilience, enabling more effective biofertilizers. Integrating inoculants with precision agriculture ensures targeted application, promoting sustainable farming and reducing chemical fertilizer reliance (Bhattacharyya & Jha, 2012).

Conclusion

Soil microorganisms are vital for agroecosystems, enhancing plant nutrition, nutrient cycling, and soil structure while reducing dependence on chemical fertilizers. Biofertilizers, microbial consortia, and integrated soil management can sustainably improve crop productivity and soil fertility. To fully exploit their potential, further research is needed on microbial community dynamics, optimized inoculant formulations, and site-specific applications. Harnessing these interactions is key to advancing sustainable, productive, and environmentally friendly agriculture.

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