5 Functional Roles of Rhizosphere Microbiota

5.1 Plant growth promotion and nutrient acquisition

Legume rhizospheres are enriched in PGPR and other beneficial microbes that promote growth via biological nitrogen fixation, phosphate solubilization, siderophore production, and phytohormone synthesis (Timofeeva et al., 2023). Rhizospheric diazotrophs and phosphate-solubilizing bacteria increase plant-available N and P, while co-inoculation strategies combining these groups often outperform single strains by simultaneously enhancing nutrient supply and root development (Zeng et al., 2022). In grain legumes, such PGPR also stimulate nodulation and strengthen rhizobium-legume symbioses, further boosting nitrogen inputs and yield (Swarnalakshmi et al., 2020).

Beyond direct nutrient mobilization, PGPR and mycorrhizal fungi improve nutrient use efficiency and root architecture, enabling legumes to exploit heterogeneous soil resources (Tahat et al., 2020; Timofeeva et al., 2023). Reviews on rhizosphere-plant interactions highlight that these microbes alter root physiology, exudation, and transporter activity, thereby increasing uptake of N, P, and micronutrients while supporting growth under nutrient deficiency (Hakim et al., 2021). Harnessing these functions through microbial fertilizers and seed inoculants is increasingly proposed as a means to reduce mineral N and P inputs without compromising productivity (De Andrade et al., 2023).

5.2 Disease suppression and stress resistance

Rhizosphere microbiota contribute to legume health by forming a first line of defense against soil-borne pathogens. Beneficial bacteria and fungi protect roots via antibiosis, competition for nutrients and niches, parasitism, and induction of systemic resistance (Tahat et al., 2020; Hakim et al., 2021). In common bean, cultivars bred for resistance to *Fusarium oxysporum* harbor rhizospheres enriched in *Pseudomonadaceae*, *Bacillaceae*, and *Cytophagaceae*, along with genes for antifungal metabolites, indicating that host genetics can co-select disease-suppressive communities.

Microbiome-mediated resistance also extends to abiotic stresses such as drought, salinity, and heat. Reviews on harnessing plant-microbe interactions and rhizosphere engineering note that tailored microbial consortia and stress-resilient PGPR can improve water use efficiency, modulate stress hormones, and maintain growth under adverse conditions (Yusuf et al., 2025). Specific PGPR strains from legume rhizospheres, such as Pseudomonas chlororaphis IRHB3 in soybean, both recruit functional bacteria involved in nutrient cycling and activate jasmonate-mediated resistance, thereby simultaneously enhancing growth and suppressing root rot in the field (Kumar and Dubey, 2020; Wei et al., 2024).

5.3 Soil health and ecosystem sustainability

Soil health is tightly linked to the diversity and activity of rhizosphere microorganisms, which regulate nutrient recycling, aggregate stability, and greenhouse gas fluxes (Tahat et al., 2020; Xing et al., 2025). Beneficial rhizosphere microbes in legume systems improve soil structure and organic matter turnover, support balanced nutrient cycles, and increase resilience of soil functions to disturbance (Hakim et al., 2021; Sharma et al., 2025). Leguminous cover crops and legume-based intercropping have been shown to enhance rhizosphere microbial diversity, enrich taxa involved in nitrogen fixation and organic matter decomposition, and improve soil pH, organic carbon, and nutrient availability relative to monocultures (Jalloh et al., 2024; Pokharel et al., 2025).

Microbial-based strategies are increasingly recognized as central to sustainable agriculture, providing eco-friendly alternatives to intensive chemical inputs. Reviews on soil microbial resources and rhizosphere manipulation emphasize that bio-inoculants and management practices that favor native beneficial communities can simultaneously enhance crop productivity, soil fertility, and environmental quality (Mahmud et al., 2021; Sharma et al., 2025). Dissecting rhizosphere microbiomes into environment-dominated and plant genetic-dominated components further suggests complementary levers-agronomic management and breeding-for designing legume systems that maintain functionally robust microbiomes and deliver long-term ecosystem services (Xun et al., 2024; Xing et al., 2025).