same time, factors such as plant species, soil type, and land-use history jointly shape microbial community structure, with bulk soil serving as the main reservoir from which rhizosphere communities are selected. These insights highlight both the selectivity of legumes in recruiting beneficial microbes and the context dependence of microbiome composition across soils and management regimes.

Despite rapid progress, important knowledge gaps remain in how rhizosphere microbial diversity in legume systems can be systematically characterized, predicted, and managed at field and farming-system scales. Most work has focused on individual symbioses or single legume species, while the broader networks of beneficial, pathogenic, and even human-pathogenic microorganisms in the legume rhizosphere remain only partially resolved. The present review aims to synthesize current knowledge on the taxonomic and functional diversity of rhizosphere microbiomes in legume cropping systems, with particular attention to nitrogen fixation, plant health, and agroecosystem services. It also seeks to integrate emerging omics-based insights with ecological theory on community assembly, and to identify opportunities to manipulate rhizosphere communities-via breeding, inoculants, and cropping system design-to enhance the sustainability and resilience of legume-based agriculture.

2 Characteristics of the Rhizosphere Microenvironment in Legume Cropping Systems

2.1 Root exudates and rhizosphere formation

Legume roots release a wide array of primary and secondary metabolites (sugars, organic acids, amino acids, flavonoids, phenolics) that both feed and signal to rhizosphere microorganisms, thereby structuring the microbial community close to the root (Chen and Liu, 2024). Temporal shifts in exudate composition during plant development generate a “chemical succession” that selects for microbes with matching substrate preferences, creating predictable patterns of community assembly along the soil-root interface (Zhou et al., 2022).

Specific exudate components, especially flavonoids and related phenolic compounds, act as key signaling molecules guiding symbioses and broader rhizomicrobiome recruitment in legumes (Chen et al., 2022; Kumar et al., 2024). These compounds mediate chemotaxis and colonization by beneficial rhizobacteria and mycorrhizal fungi, and under nutrient limitations or other stresses can be modulated to favor microbes that enhance nutrient acquisition and stress tolerance (Gong et al., 2023). In diversified or intercropped systems, changes in legume rhizodeposition can further adjust metabolite profiles and microbial functions, strengthening beneficial interactions (Qiao et al., 2024).

2.2 Soil physicochemical properties in legume rhizospheres

Legume establishment and rhizosphere activity progressively modify soil physicochemical properties, often improving pH status, organic matter, and nutrient availability. For example, legume planting in saline or degraded soils has been associated with decreased salinity and pH, and increased soil organic carbon and nitrogen pools, promoting more diverse and functionally complex bacterial networks (Liu et al., 2021; Amaya-Gómez et al., 2025). Over years of perennial or woody legume growth, rhizosphere soils can show rising organic matter and available P and K, coupled with elevated enzyme activities (e.g., urease, phosphatase) that support nutrient turnover and microbial proliferation (Ren et al., 2021; Mu et al., 2024).

Soil pH emerges as a central driver of rhizosphere bacterial diversity, composition, and function, often outweighing vegetation type or other variables (Wan et al., 2020). In acidic cropping soils, lower pH (≤ 5.5) is linked to reduced bacterial abundance and downregulated genes involved in C, N, P, and S cycling, which can constrain crop yield (Abd-Alla et al., 2023). Conversely, amendments such as lime, organic manure, or biochar can adjust pH and nutrient status, shifting bacterial communities toward taxa (e.g., Actinobacteria, Proteobacteria) associated with enhanced disease suppression and improved plant physiological status (Ren et al., 2021; Chen et al., 2022).

2.3 Symbiotic nitrogen fixation and nutrient cycling

Symbiotic nitrogen fixation (SNF) between legumes and rhizobia is a core process structuring rhizosphere function, converting atmospheric N_2 into plant-available ammonia in nodules and enriching soil N pools (Neda, 2021). The effectiveness of SNF varies among rhizobial strains and is strongly influenced by soil conditions and