Penicillium, thereby enhancing soil fertility, nutrient cycling, and crop yields in cereal-legume systems (Figiel et al., 2025). In maize rhizospheres, Bacillus biofertilizers increase organic matter and available N, P, and K, while maintaining high abundances of Proteobacteria, Actinobacteria, and Acidobacteria and enriching bacterial functions related to amino-acid, sugar, and energy metabolism (Wang et al., 2021).

Other formulations shift dominance toward disease-suppressive or nutrient-transforming guilds. Bio-organic fertilizers containing Bacillus amyloliquefaciens stimulate indigenous Pseudomonas populations and promote synergistic biofilm-forming consortia that suppress Fusarium wilt in banana, illustrating how an inoculant can act indirectly through native keystone taxa (Tao et al., 2020; Kumar et al., 2021). Streptomyces-based biofertilizers increase beneficial bacterial genera such as Chitinophaga and Pseudoxanthomonas while decreasing phytopathogenic fungi including Cladosporium and Gibberella, and they reduce microbial network connectivity, indicating re-wiring of interaction networks and keystone roles for introduced actinobacteria (Li et al., 2022; Zhao et al., 2022). Collectively, these findings show that dominant functional groups-PGPR, actinobacteria, saprotrophic and biocontrol fungi-are pivotal levers through which biofertilizers regulate community structure and ecosystem functioning.

4.3 Improvement of the rhizosphere micro-ecological environment

Biofertilizers modify the rhizosphere micro-environment by simultaneously changing soil physicochemical properties, root exudation, and microbial interactions. In maize, Bacillus biofertilizers increase soil organic matter, total N and P, and available P and K, likely by stimulating plant root exudates that recruit beneficial bacteria and enhance nutrient dissolution, thereby reshaping community structure through resource-driven selection (Wang et al., 2021). In greenhouse cucumber, different biofertilizers applied to soil or substrate improve plant growth and reduce soil-borne pathogens, with time-dependent shifts in rhizosphere bacterial and fungal communities that reflect altered nutrient availability and microhabitat conditions around the roots (Wu et al., 2022).

Bio-organic and microbial fertilizers also foster hizosphere environments characterized by higher abundances of beneficial taxa and enhanced soil functionality. In pakchoi, a Bacillus bio-organic fertilizer increases soil pH and available K while enriching beneficial bacteria and saprotrophic fungi, and network analysis indicates that Bacillus acts as a hub stimulating colonization by other advantageous microbes in the rhizosphere (Wang et al., 2022). Actinobacterial biofertilizers applied across multiple crops increase yields by up to ~50% and shift rhizosphere fungal assemblages and assembly processes, while metagenomic and modeling work in biofertilizer-amended soils shows enrichment of genes for nitrogen transformation and plant growth promotion, supporting a more functionally complementary and nutrient-efficient rhizosphere microbiome (Li et al., 2022; Figiel et al., 2025). These micro-ecological improvements help explain the consistent links between biofertilizer-induced community modulation, enhanced soil biological activity, and improved crop performance.

5 The Impact of Biofertilizers on Soil Enzyme Activity and Metabolic Functions

5.1 Patterns of change in key enzyme activities

Biofertilizers consistently enhance a suite of extracellular enzymes that mediate nutrient release from organic and inorganic pools. A large field meta-analysis in China reported mean increases in urease and phosphatase activities of 57.6% and 43.5%, respectively, together with significant stimulation of sucrase and catalase following biofertilizer application across multiple crops, including vegetables (Pei et al., 2025). In a wheat-maize rotation, partial substitution of NPK with biofertilizer significantly increased urease, alkaline phosphatase, and sucrase activities at key growth stages, with the optimal blend (60% NPK + 20% biofertilizer) giving the largest and most persistent increases, indicating that moderate biofertilizer inputs most efficiently stimulate soil biochemical functioning (Ali et al., 2024).

Targeted studies on contaminated or degraded soils show similar directional responses in a broader enzyme suite. In heavy-metal-impacted greenhouse soils, Pseudomonas and Bacillus-based biofertilizers markedly increased urease, dehydrogenase, alkaline phosphatase, β-D-glucosidase, and arylsulfatase activities relative to the untreated control, with statistically significant treatment and dose effects for each enzyme (Haroun et al., 2023). Long-term vegetable experiments comparing compost, chemical fertilizer, and no fertilizer demonstrate that compost-based