biofilm-based technologies, supported by a rapidly expanding global biofertilizer market driven by demand for organic and residue-free vegetables (Samantaray et al., 2024). Nevertheless, field performance remains variable, influenced by strain selection, formulation quality, application method, soil properties and crop species, underscoring the importance of understanding biofertilizer-soil-plant interactions in specific production systems (Basu et al., 2021).

At the core of biofertilizer function is their impact on soil biological activity, a critical dimension of soil health encompassing the abundance, diversity and functional processes of soil organisms that drive nutrient cycling, organic matter turnover and aggregate formation (Chaudhary et al., 2022). Soil microorganisms, estimated to comprise most of the soil biomass, decompose organic matter, mineralize nutrients, form humus and contribute to soil structure, thereby underpinning soil fertility and plant productivity. Intensive use of mineral fertilizers without sufficient organic inputs can simplify microbial communities, disrupt beneficial interactions and depress key enzymatic activities, whereas inoculation with beneficial microbes, particularly when combined with organic amendments, generally enhances microbial biomass, shifts communities toward more beneficial taxa and increases activities of enzymes such as urease and phosphatases. Meta-analyses and field studies show that biofertilizers can significantly increase soil organic matter, stimulate beneficial bacterial and fungal populations and enhance enzyme activities while suppressing soil-borne pathogens, leading to improved nutrient availability and resilience. Because vegetable systems often experience rapid organic matter decline and biological depletion due to repeated tillage and high nutrient extraction, interventions that revive and stabilize soil biological activity are especially important for maintaining long-term productivity and environmental performance (Mahmud et al., 2021; Medisetti, 2025).

Despite growing evidence that biofertilizers enhance crop yield, nutrient use efficiency and soil quality, relatively fewer studies have focused explicitly on their effects on soil biological activity within intensive vegetable production systems (Basu et al., 2021; Chaudhary et al., 2022). Many quantitative syntheses aggregate across crop types, management regimes and climates, making it difficult to disentangle responses specific to high-input vegetables, which frequently show strong yield responses but may also exhibit distinct soil-biological dynamics due to heavy fertilization and irrigation. Meta-analytical work indicates particularly large yield benefits of biofertilizers in vegetable crops and highlights substantial increases in soil microbial abundance and enzyme activities under biofertilizer use, yet it also points to strong context dependence related to soil fertility status, organic matter content and fertilizer management.

Furthermore, bibliometric analyses reveal that the most recent phase of biofertilizer research increasingly emphasizes their role in improving soil environments and microbiomes, reflecting a shift from solely plant-centered metrics toward integrated soil-plant systems (Mitter et al., 2021). In this context, elucidating how biofertilizers modify soil biological activity-microbial communities, functional groups and enzyme processes-in vegetable production is essential for optimizing formulations and management strategies that simultaneously support high yields, soil health and environmental sustainability. The present study therefore investigates the impact of biofertilizers on soil biological activity in vegetable production systems, aiming to clarify their potential and constraints as core tools in sustainable horticultural nutrient management.

2 Types and Mechanisms of Action of Biofertilizers

2.1 Microbial inoculants

Microbial inoculants are biofertilizer formulations containing live microorganisms-mainly bacteria and fungi-that colonize the rhizosphere, root interior, or phyllosphere to improve plant nutrition and soil health (Mącik et al., 2020). Typical groups include free-living and symbiotic nitrogen fixers (e.g., Azotobacter, Rhizobium), phosphate- and potassium-solubilizing bacteria, cyanobacteria, and arbuscular mycorrhizal fungi, often used singly or as consortia to complement or partially replace synthetic fertilizers (Kour et al., 2020). In vegetable production systems, these inoculants are usually delivered as seed coatings, root dips, soil drenches, or mixed with substrates, and they are increasingly formulated as stable liquid or solid products with protective carriers to ensure viability under intensive management conditions (Fasusi et al., 2021).