Plant growth-promoting rhizobacteria (PGPR) are central to microbial inoculants because they combine nutrient transformations with biostimulant and biocontrol functions (Prisa et al., 2023). Many PGPR strains fix atmospheric nitrogen, solubilize phosphorus, and produce siderophores and hydrolytic enzymes while simultaneously synthesizing phytohormones that stimulate root growth and enhance tolerance to abiotic stress (Mahmud et al., 2021). Field and greenhouse studies show that inoculation with compatible PGPR consortia increases nutrient uptake, microbial biomass, and crop yields in various crops, and can reduce the need for mineral fertilizers without compromising productivity (Shahwar et al., 2023; Nabati et al., 2025). However, performance is strongly context dependent; soil type, native microbiota, crop genotype, and environmental conditions can all influence establishment and function of inoculated strains, underscoring the need for site- and crop-specific inoculant selection in vegetable systems (O'Callaghan et al., 2022).

2.2 Organic biofertilizers and compound biofertilizers

Organic biofertilizers (often termed bio-organic fertilizers) combine decomposed organic materials-such as composts, manures, or agro-industrial wastes-with selected beneficial microorganisms. The organic matrix supplies slow-release nutrients, improves soil structure, and increases organic matter, while also acting as a carrier that supports survival and activity of inoculated microbes after field application. In intensively managed vegetable soils, where repeated tillage and high fertilizer use accelerate organic matter decline, such bio-organic products can restore soil physical properties and provide substrates that stimulate diverse microbial communities, thereby enhancing soil biological activity and nutrient cycling.

Compound biofertilizers extend this concept by integrating multiple functional microbial groups, and in some cases combining them with mineral fertilizers into “microbially enhanced” products (Mącik et al., 2020). For example, formulations may contain nitrogen-fixing bacteria, phosphate-solubilizing microbes, and biocontrol fungi together, designed to act synergistically on nutrient availability, root growth, and disease suppression (Tao et al., 2020). Waste-derived bio-organic fertilizers produced via microbial bioconversion of biomass (e.g., agricultural or food wastes) simultaneously address waste management and nutrient recycling while delivering active microbial consortia to the soil (Elnahal et al., 2022). Studies show that such compound or bio-organic fertilizers can more strongly modify microbial community composition, enrich beneficial taxa such as Bacillus and Pseudomonas, and increase disease-suppressive capacity compared with either organic amendments or single-strain inoculants alone (Tao et al., 2020; Schenk et al., 2024).

2.3 Mechanisms by which biofertilizers enhance soil biological activity

Biofertilizers enhance soil biological activity primarily through biogeochemical mechanisms that increase nutrient availability and energy supply for soil microbes. Core processes include biological nitrogen fixation, solubilization and mineralization of phosphorus and other nutrients, and production of siderophores that chelate iron and stimulate microbial interactions in the rhizosphere (Kour et al., 2020; Timofeeva et al., 2023). By increasing pools of plant-available nitrogen and phosphorus, biofertilizers promote plant growth and root proliferation, which in turn elevates root exudation of carbohydrates, amino acids, and organic acids that serve as energy sources for heterotrophic microbes (Mahmud et al., 2021). This positive feedback increases microbial biomass and activity, often reflected in higher activities of key soil enzymes involved in C, N, and P cycling.

Equally important are ecological and community-level mechanisms through which biofertilizers re-shape soil microbiomes. Inoculation with specific strains or consortia can selectively enrich beneficial microbial groups and alter co-occurrence networks, increasing network stability and functional redundancy (). Bio-organic fertilizers, for instance, have been shown to stimulate indigenous Pseudomonas populations and foster synergistic interactions with inoculated Bacillus, resulting in improved suppression of soil-borne pathogens and a more functionally robust microbial community (Tao et al., 2020; Schenk et al., 2024). Metagenomic analyses further indicate that biofertilizer amendments can increase the abundance of genes involved in nitrogen transformations and plant growth promotion, supporting enhanced nutrient turnover and hormone regulation in the rhizosphere (Aasfar et al., 2021). Through these intertwined biochemical and ecological pathways, biofertilizers rebuild biologically active soils that underpin sustainable, nutrient-efficient vegetable production.