

Effects of Biofertilizers on Soil Biological Activity in Vegetable Production Systems

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Abstract As a green agricultural input, biofertilizer plays a pivotal role in fostering soil health and promoting sustainable vegetable production. This paper systematically reviews the various types of biofertilizers and their underlying mechanisms of action, with a particular focus on their impact on soil biological activity within vegetable production systems. Investigations into key indicators-such as soil microbial community structure, enzyme activity, and soil respiration-reveal that biofertilizers can significantly enhance soil microbial diversity, boost the activity of critical enzymes, and facilitate nutrient cycling and transformation, thereby improving the soil ecological environment. Furthermore, by optimizing the rhizosphere micro-environment, biofertilizers indirectly contribute to improvements in both vegetable yield and quality. Through the analysis of representative case studies, the practical efficacy and potential of biofertilizers in actual production settings are further validated. Finally, this paper identifies current research gaps and outlines future directions for development, providing a theoretical foundation for the broader adoption and application of biofertilizers in vegetable production.

Keywords Biofertilizer; Soil biological activity; Vegetable production system; Microbial community; Soil enzyme activity

1 Introduction

Vegetable production systems are among the most input-intensive components of global agriculture, characterized by short rotations, high fertilizer application rates and frequent soil disturbance to achieve high yields and quality demanded by expanding populations and changing diets (Mahmud et al., 2021). Reliance on synthetic fertilizers has certainly contributed to yield gains, but it has also accelerated soil degradation, disrupted nutrient cycles and contributed to water and air pollution, raising concerns for environmental sustainability and food safety. These impacts are particularly acute in intensively managed vegetable systems, where excessive nitrogen and phosphorus inputs, coupled with high irrigation, can impair soil structure, reduce biodiversity and increase greenhouse gas emissions (Chaudhary et al., 2022). In the context of climate change, finite mineral nutrient resources and persistent food insecurity, there is a pressing need for nutrient management strategies that sustain productivity while restoring soil function. Biofertilizers-microbial inoculants that enhance nutrient availability and plant growth-are increasingly viewed as a key component of sustainable intensification pathways for high-value horticultural crops, including vegetables (Maçik et al., 2020).

Biofertilizers are typically defined as formulations containing living or dormant microorganisms that colonize the rhizosphere or plant interior and directly or indirectly stimulate plant growth by improving nutrient acquisition, modulating hormonal balance or protecting against stress and disease (Chaudhary et al., 2022). Common functional groups include nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azotobacter*, *Azospirillum*), phosphate- and potassium-solubilizing microorganisms, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi, often applied singly or as consortia (Maçik et al., 2020). These microbes mobilize nutrients through biological nitrogen fixation, solubilization or mineralization of phosphorus and other nutrients, production of siderophores and organic acids, and stimulation of root growth and architecture via phytohormones such as indole-3-acetic acid (Kour et al., 2020). Over the past four decades, research and development have evolved from simple rhizobial inoculants to diverse, microbially enhanced products, including encapsulated formulations and

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 (Maçik 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).

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 (Maçik 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 (ao 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.

3 Evaluation Indicators of Soil Biological Activity in Vegetable Production Systems

3.1 Soil microbial abundance and community structure

Soil microbial abundance in vegetable systems is commonly quantified using microbial biomass carbon and nitrogen (MBC, MBN) or gene-based proxies such as 16S rRNA and ITS copy numbers. In long-term organic vegetable production, frequent cover cropping and organic matter inputs can raise MBC to relatively high levels for sandy soils, and MBN responds in parallel, highlighting biomass as a sensitive integrator of management effects on soil biology. Global comparisons further show that microbial biomass and diversity covary strongly with soil carbon content, so shifts in soil organic matter under intensive fertilization or organic amendments directly influence biomass-based indicators (Bastida et al., 2021). These metrics therefore provide a robust, quantitative basis for assessing how biofertilizers and organic inputs modify the “size” of the active microbial community in vegetable systems.

Community structure and diversity indicators complement biomass data by revealing how taxa respond to intensive vegetable cultivation and management. High-throughput sequencing of greenhouse vegetable soils has shown that continuous cultivation can reduce bacterial and fungal richness and alter dominant phyla, with declines in OTU abundance and diversity after several years of high-input production. Conversely, agroecological and organic vegetable systems that include mulches, composts, or cover crops tend to increase bacterial and fungal diversity and shift communities toward beneficial groups such as Actinobacteria and other decomposers, changes that correlate with improved soil nutrients and organic matter (Moulin et al., 2023). Together, microbial biomass and community composition form core indicators to evaluate the impact of biofertilizers on soil biological activity and ecological resilience in vegetable production.

3.2 Soil Enzyme activity indicators

Soil enzyme activities provide functional indicators of microbial processes underpinning nutrient cycling and are widely used to assess soil quality in agroecosystems. Hydrolases such as urease, phosphatases, and β -glucosidase are particularly informative because they catalyze key steps in nitrogen, phosphorus, and carbon turnover and respond sensitively to changes in management, organic matter, and disturbance (Jat et al., 2021). Reviews emphasize that these enzymes are operationally practical and more responsive to tillage and structure modification than many physicochemical variables, making them useful early-warning indicators of biological changes in intensively managed soils (Attademo et al., 2021). In vegetable systems where biofertilizers and organic amendments are applied to improve fertility, monitoring these enzymes can directly reflect enhanced mineralization and nutrient availability.

Field and long-term management studies confirm that enzyme activities differentiate contrasting fertility regimes and cropping strategies. Under climate-smart cereal rotations, dehydrogenase, β -glucosidase, phosphatases, urease, and other enzymes vary significantly with management scenario, crop growth stage, and rhizosphere versus bulk soil, and are strongly regulated by soil organic carbon (Raimi et al., 2023). In vegetable-based systems, organic fertilization and manure inputs generally increase activities of dehydrogenase, β -glucosidase, and urease compared with conventional fertilization, with enzyme responses closely tied to microbial biomass and organic matter content (Antonious et al., 2020; Raimi et al., 2023). Because biofertilizers often supply both functional microbes and substrates, increases in these enzyme activities serve as key indicators that soil biological functioning and nutrient cycling capacity have been stimulated.

3.3 Soil respiration and microbial biomass carbon and nitrogen

Soil respiration, measured as CO₂ efflux, is a central indicator of overall microbial metabolic activity and carbon turnover. Seasonal monitoring in agricultural soils shows that microbial respiration tracks temperature and plant presence, with higher rates where soil organic carbon is greater and fresh residues are retained (Schnecker et al., 2023). In organic vegetable systems with frequent cover cropping or compost additions, soil respiration and related metrics such as the metabolic quotient often increase, reflecting enhanced decomposition and active microbial communities fueled by larger carbon inputs (Antonious et al., 2020). However, interpreting respiration alone can be misleading, so it is most informative when combined with microbial growth or biomass data to distinguish efficient biomass production from rapid C loss.

Microbial biomass C and N are therefore indispensable complementary indicators, capturing the living pool of microbial cells that mediate nutrient cycling. In multi-cropping and organic vegetable experiments across Europe, microbial C and N (Cmic, Nmic) increase under diversified cropping and higher organic inputs, and their stoichiometric ratios (Cmic/Nmic, Cmic/TOC) are used to infer shifts in nutrient limitation and carbon stabilization potential (Figure 1) (Trincherá et al., 2022). Global analyses reveal that the relationship between microbial diversity and biomass is strongly governed by soil carbon, underscoring how management-driven changes in organic matter, including biofertilizer use, cascade into microbial standing stocks and functions (Bastida et al., 2021; Schneckner et al., 2023). Consequently, integrating soil respiration with microbial biomass C and N provides a powerful set of indicators to evaluate how biofertilizers influence both the intensity and efficiency of microbial activity in vegetable production soils.

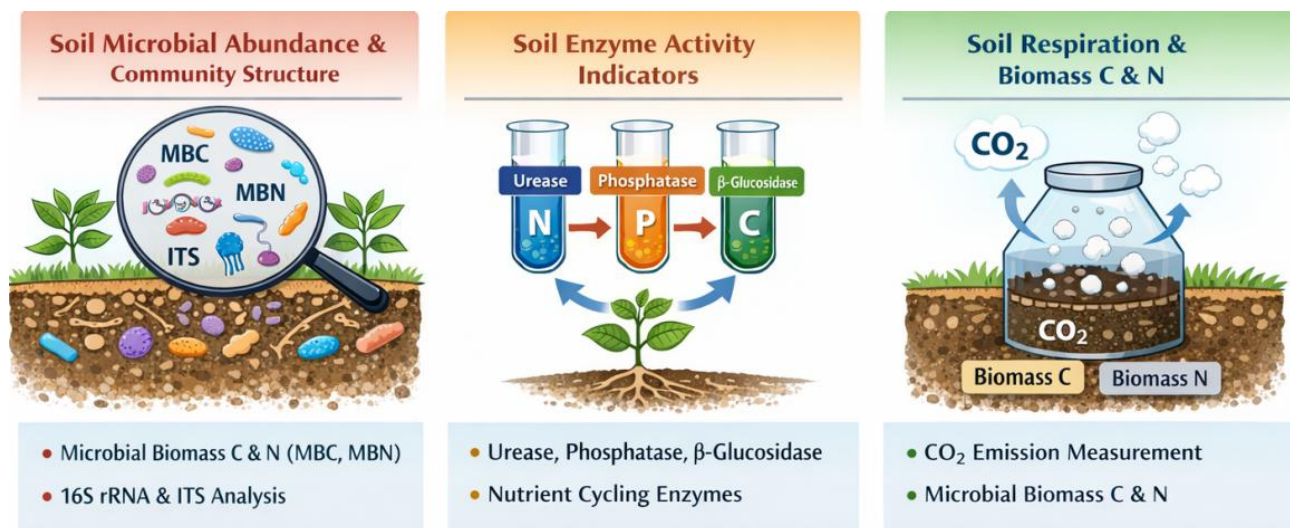


Figure 1 Evaluation indicators of soil biological activity in vegetable production systems

4 The Impact of Biofertilizers on Soil Microbial Community Structure

4.1 Changes in microbial diversity

Biofertilizers frequently alter α -diversity (richness and evenness) and β -diversity (community dissimilarity) of soil and rhizosphere microbiota in vegetable and other cropping systems. In greenhouse cucumber, different biofertilizers applied to soil or substrate significantly modified bacterial and fungal diversity over the season, with distinct community trajectories between fertilized and unfertilized treatments (Wu et al., 2022). In maize, *Bacillus*-based biofertilizers generally increased rhizosphere bacterial richness and diversity relative to the control, although consortia of multiple strains sometimes reduced overall diversity, suggesting a directional enrichment of specific functional taxa at the expense of community evenness (Wang et al., 2021; Zhang et al., 2025).

Patterns are not universally positive for diversity, underscoring that biofertilizers reshape communities rather than simply “add” diversity. A *Bacillus* bio-organic fertilizer applied to pakchoi reduced both bacterial and fungal diversity compared with unfertilized soil, while strongly shifting composition and enriching particular beneficial groups (Tao et al., 2020). Actinobacterial biofertilizers containing *Streptomyces* spp. likewise altered fungal community composition and co-occurrence networks across several crops without consistently increasing bacterial or fungal α -diversity, indicating that functional reassembly can occur even when richness is stable (Li et al., 2022; Zhao et al., 2022). These results highlight that diversity responses depend on formulation, dosage, and substrate, but shifts in β -diversity and taxonomic structure are almost ubiquitous following biofertilizer application.

4.2 Regulatory roles of dominant functional microbial groups

A central ecological effect of biofertilizers is the enrichment or suppression of dominant functional groups that drive nutrient cycling and plant health. *Bacillus*- and *Trichoderma*-amended biofertilizers increase the relative abundance of plant-beneficial bacteria and fungi, including *Bacillus*, *Rhodanobacter*, *Massilia*, *Trichoderma*, and

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 rhizosphere 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

organic fertilization-functionally analogous to many bio-organic fertilizers-substantially enhances dehydrogenase, β -glucosidase, protease, urease, arylsulfatase, and acid/alkaline phosphatases, and that enzyme activities correlate strongly and linearly with soil organic matter content.

5.2 Responses of enzymes related to carbon and nitrogen cycling

Enzymes involved in carbon acquisition, such as β -glucosidase and related glycosidases, frequently increase under biofertilizer or biochar-based fertilizer regimes, reflecting enhanced decomposition and turnover of plant residues and organic amendments. In a wheat-maize system, biofertilizer additions significantly elevated sucrase activity, interpreted as a sign of stimulated microbial metabolism and accelerated organic matter decomposition in maize soils (Ali et al., 2024). Long-term substitution of conventional fertilizer with biochar-based fertilizer increased activities of α -glucosidase, N-acetyl- β -D-glucosidase, and leucine aminopeptidase, with these C- and N-acquiring enzymes tightly linked to improved soil quality indices and higher maize yields, underscoring the central role of enzyme-mediated C and N cycling in productivity gains (Wang et al., 2025).

Nitrogen-cycling enzymes and associated processes also respond strongly to biologically enriched fertilization. The China-wide meta-analysis showed that biofertilizer use increased nitrification rates by over 70%, in parallel with the large increases in urease activity, and reduced ammonium losses, indicating more complete and efficient N mineralization and transformation in the soil-plant system (Pei et al., 2025). A global meta-analysis of biochar field trials further demonstrated that biochar application significantly enhanced N mineralization, nitrification, and N fixation as well as N-acetyl-glucosaminidase activity, while simultaneously increasing the abundance of key nitrification and denitrification genes (*amoA*, *narG*, *nirS/nirK*, *nosZ*), confirming that enzyme stimulation is coupled with upregulation of microbial N-cycling potential under organic-rich amendments (Zhang et al., 2021).

5.3 Enhancement of soil nutrient transformation efficiency

By jointly stimulating enzyme activities and reshaping microbial communities, biofertilizers improve the efficiency with which soils transform and retain nutrients. Across 107 field studies, biofertilizers increased total soil N by about 16.7% and available P by 11.0%, while markedly boosting urease and phosphatase activities, reducing nitrate losses, and lowering electrical conductivity, a pattern interpreted as more efficient N and P cycling together with improved ionic balance and organic matter accumulation (Pei et al., 2025). Metagenomic analysis of soils amended with a bacterial biofertilizer showed 46.7% and 88.6% increases in fast-acting (available) N and P, respectively, along with enrichment of nitrification genes and plant growth-promotion traits, indicating that nutrient transformation efficiency is enhanced through both biochemical (enzyme) and genetic (functional gene) pathways (Li et al., 2023).

Biofertilizer and organic-amendment strategies in intensive vegetable and arable systems can also alter coenzymatic stoichiometry, shifting microbial resource limitation and thereby optimizing nutrient capture. In greenhouse tomato soils, diverse organic materials (including biochar and manure) reduced C limitation while increasing microbial N demand, with biochar particularly effective at enhancing C-, N-, and P-acquiring enzyme activities and organic C sequestration across soil types (-). Studies of enzyme stoichiometry and N management in semi-arid croplands further show that fertilization regimes which intensify microbial P limitation can down-regulate the abundance of nitrification and denitrification genes, constraining N losses via gaseous pathways and highlighting how managing enzyme-mediated nutrient demand can be leveraged to synchronize N availability with crop uptake and reduce environmental leakage (Cui et al., 2020).

6 Indirect Impacts of Biofertilizers on Vegetable Yield and Quality

6.1 The relationship between soil biological activity and crop growth

Enhanced soil biological activity is a central pathway through which biofertilizers indirectly stimulate vegetable growth. A large meta-analysis in China showed that biofertilizers increased soil organic matter, boosted urease and phosphatase activities, and promoted beneficial microbial populations, while suppressing pathogens; these shifts in biological functioning were closely associated with higher root volume and reduced disease incidence, explaining much of the observed yield response across crops including vegetables (Pei et al., 2025). A global meta-analysis similarly linked biofertilizer use with improved nitrogen and phosphorus use efficiency,

highlighting that microbial inoculants enhance plant access to soil and fertilizer nutrients, particularly under suboptimal resource conditions, thereby supporting more vigorous crop growth for a given external input level.

System-level vegetable experiments further confirm that more active soil microbial communities translate into improved crop performance. In an intensified organic vegetable rotation using plant-based fertilizers, cover crops, and reduced tillage, β -glucosidase and dehydrogenase activities and potential N mineralization were markedly higher than under common practice, and these improvements in microbial activity coincided with 1.3-2.7-fold increases in marketable yields and greater plant N uptake without increasing N leaching risk (Hefner et al., 2023). A broader systematic review on microbial activity and nutrient cycling likewise concluded that most studies report microbial-driven enhancement of soil fertility and crop productivity, supporting the view that managing soil microbes is a powerful lever for sustaining growth in intensive systems such as vegetable production (Bayu, 2024).

6.2 Promoting effects on vegetable yield

Across crops and environments, biofertilizers consistently promote yield, with particularly strong effects documented for vegetables. A comprehensive Chinese meta-analysis found that biofertilizers increased yields for 21 of 23 crops, with vegetables such as Chinese cabbage and ginger showing gains of roughly 36-39%, attributing these responses to improved nutrient availability, better root growth, and reduced disease incidence (Pei et al., 2025). A global synthesis of field trials reported average yield increases of around 8-20% depending on climate, and showed that combinations of N-fixers, P-solubilizers and mycorrhiza are especially effective when soil phosphorus is not severely limiting, underscoring that yield benefits depend on matching microbial traits to soil conditions.

Vegetable-focused experiments under greenhouse and field conditions provide more specific evidence for yield promotion and fertilizer savings. In lettuce and broccoli, treatments combining biofertilizer with full or reduced chemical fertilizer rates achieved total and marketable yields comparable to or higher than full mineral fertilization alone, indicating that biofertilizers can maintain productivity while allowing 50% reduction in chemical NPK inputs (Demir et al., 2023). For Swiss chard, vermicompost-functionally analogous to many bio-organic fertilizers-applied alone or with biochar increased yield by about 140% relative to untreated or biochar-only soils, demonstrating that biologically active organic amendments can match mineral N in supporting high productivity while simultaneously improving soil quality (Libutti et al., 2023).

6.3 Impacts on quality

Biofertilizers indirectly enhance vegetable quality by improving plant nutrition and reducing physiological imbalances such as excessive nitrate accumulation. In the Chinese field meta-analysis, biofertilizer application significantly increased vitamin C, protein, and carotenoid contents while decreasing nitrate concentrations by about 22%, indicating that microbial inoculants can shift the balance toward more nutrient-dense and safer produce across a wide range of crops (Pei et al., 2025). A review on biofertilizers and food security similarly reported crop yield increases of 10%-40% accompanied by higher protein, essential amino acids, and vitamins, emphasizing that microbially mediated nutrient mobilization often improves nutritional profiles rather than simply increasing biomass (Daniel et al., 2022).

Recent vegetable studies confirm these quality effects under practical cultivation scenarios. In tomato, brinjal, and okra, replacing part of the chemical fertilizer with diverse organic sources plus a microbial consortium increased soil microbial populations and improved nutritional, organoleptic, and nutraceutical attributes, including higher antioxidant contents, relative to conventional fertilization alone (Bhardwaj et al., 2025). In Swiss chard, vermicompost and its mixtures with biochar not only raised yield but also increased specialized metabolites and antioxidant activity, while keeping leaf nitrate within regulatory safety thresholds, illustrating that biologically enriched fertilization can simultaneously support high productivity, nutritional quality, and nitrate safety in leafy vegetables (Libutti et al., 2023).

7 Case Study

7.1 Experimental design for biofertilizer application on a typical vegetable crop

A representative case study can be framed around field-grown tomato under conventional fertilization contrasted with a regime where mineral inputs are partially replaced by a *Trichoderma*-enriched bio-organic fertilizer. Ye et al. evaluated four fertilization strategies: full-rate chemical fertilizer (CF, 100% conventional NPK), reduced chemical fertilizer plus *Trichoderma* bio-organic fertilizer (75% NPK + BF), reduced NPK plus uninoculated organic fertilizer (OF), and reduced NPK plus *Trichoderma* spore suspension alone (SS), allowing isolation of microbial, organic-matter, and combined effects under realistic agronomic conditions (Ye et al., 2020). Experimental plots were arranged in a randomized design with multiple replicates, and both field and pot trials were implemented to capture responses across soil environments while controlling for confounding variation in microclimate and root-zone conditions (Ye et al., 2020).

A similar structure can be adapted for cucumber within organic or low-input systems, where biofertilizer is applied either via soil, foliar spray, or both. For instance, a randomized block 6×2 factorial design was used to test six concentrations of a liquid plant-based biofertilizer (0-5% in water) combined with presence or absence of soil application in organically grown Aodai cucumber, with four replications and eight plants per plot to ensure adequate statistical power (Da Silva Tamwing et al., 2020). Biofertilizer was applied at sowing to the soil and then at 7-day intervals via foliar sprays up to 28 days after sowing, with yield-related traits (fruit number, mean fruit mass, marketable yield) and morphological parameters (fruit length, diameter) measured at each harvest (Da Silva Tamwing et al., 2020). This kind of design, incorporating factorial combinations of dose and application pathway, is directly transferable to other greenhouse vegetable crops and enables optimization of biofertilizer regimes (Figure 2).

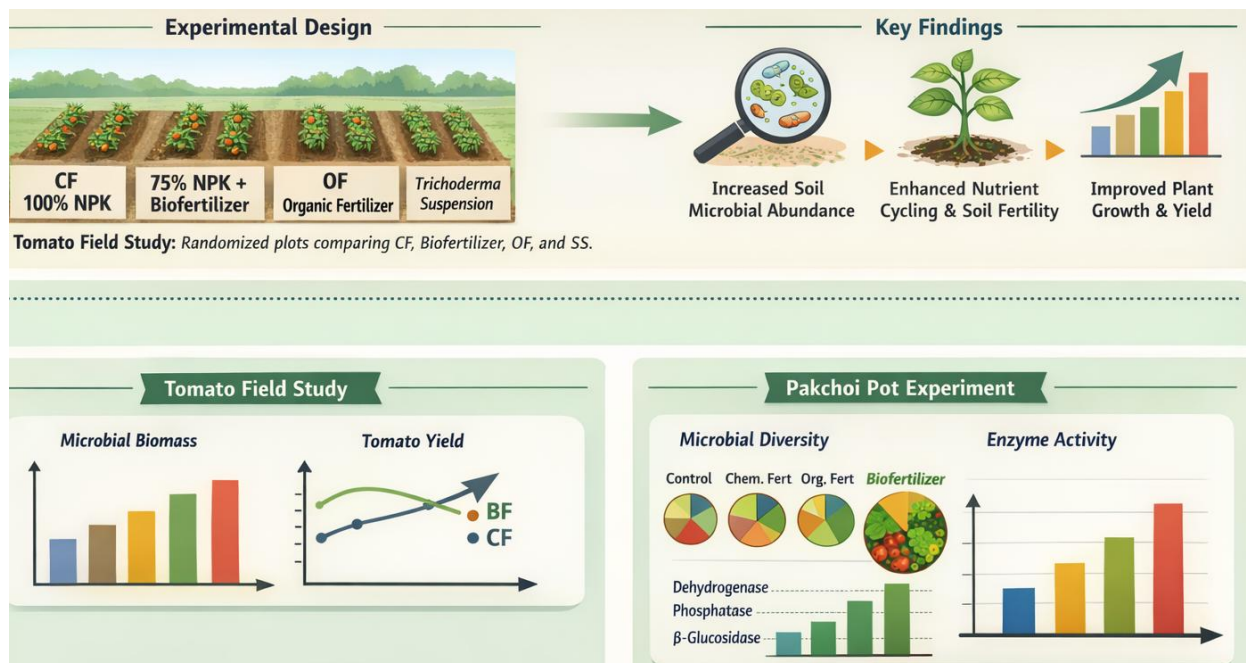


Figure 2 Experimental designs and key outcomes of biofertilizer application in vegetable crops

7.2 Changes in soil biological activity and data analysis

In the tomato case, reduced chemical fertilizer plus *Trichoderma* bio-organic fertilizer induced measurable shifts in soil biological activity relative to full mineral fertilization. Ye et al. observed that the BF treatment substantially increased soil microbial abundance and improved indices of soil fertility compared with CF, with many soil biological parameters showing significant positive linear relationships with yield, suggesting that enhanced microbial activity and community size mediated the agronomic response (Ye et al., 2020). In addition, correlations between microbial abundance and soil nutrient pools in BF-treated soils suggested a tighter coupling of mineralization and plant demand, helping to stabilize yields despite a 25% reduction in mineral inputs.

A complementary view comes from pakchoi grown in pots with four fertilization treatments: control (no input), chemical fertilizer, organic fertilizer, and a *Bacillus*-containing bio-organic fertilizer (BF). After 30 days, BF treatment significantly increased plant height and biomass and raised soil available potassium and pH relative to unfertilized soil, while high-throughput sequencing revealed a marked restructuring of bacterial and fungal communities, including enrichment of beneficial genera such as *Streptomyces* and *Mortierella* (Wang et al., 2022). Network and functional predictions indicated that BF promoted bacterial dominance, enhanced mineral element metabolism, and increased saprotrophic fungi, supporting a mechanistic link between inoculant addition, microbial community assembly, and nutrient-related enzyme functions in the rhizosphere (Wang et al., 2022). Together, these results illustrate that case-study designs can combine agronomic measurements with molecular and biochemical indicators to quantify changes in soil biological activity.

7.3 Evaluation of application effectiveness and practical significance

Evaluation of application effectiveness in tomato systems centers on whether biofertilizers can maintain yield while reducing mineral fertilizer and simultaneously improve fruit quality. Under field and pot conditions, the combination of 75% conventional NPK with *Trichoderma*-enriched bio-organic fertilizer produced tomato yields equivalent to those achieved with 100% NPK alone, demonstrating that a quarter of the chemical fertilizer could be saved without yield penalty (Ye et al., 2020). Moreover, the BF treatment significantly increased total soluble sugars and vitamin C by up to 24% and 57%, respectively, while reducing nitrate accumulation by as much as 62% relative to CF, implying substantial gains in nutritional value and safety that go beyond mere yield maintenance. From an environmental and economic standpoint, such a regime reduces reliance on synthetic fertilizers, lowers potential nitrate leaching and residue risks, and can improve marketability due to enhanced quality traits.

Cucumber case studies in organic systems highlight the capacity of plant-based biofertilizers to raise productivity through optimized foliar dosing. In Aodai cucumber, foliar application of a plant-residue biofertilizer significantly increased the number of marketable fruits per plant, mean fruit mass, and both marketable and total yields, with a 3% solution identified as the most efficient concentration for yield enhancement under the tested conditions (Da Silva Tamwing et al., 2020). The authors attributed the effectiveness of foliar application to rapid leaf uptake of macro- and micronutrients and the stimulation of plant defense metabolism, which reduced the need for additional pest and disease control interventions during the cycle. Collectively, these tomato and cucumber case studies suggest that, when appropriately formulated and combined with moderate mineral or organic inputs, biofertilizers can be practically significant tools for improving soil biological activity, sustaining or increasing yields, and enhancing vegetable quality within sustainable production systems.

8 Conclusion and Outlook

Research over the past decades shows that biofertilizers are central to linking soil biological activity with crop productivity. Microbial inoculants such as plant growth-promoting rhizobacteria, arbuscular mycorrhizal fungi, and microbial consortia enhance nutrient availability, modulate phytohormones, and improve plant tolerance to abiotic and biotic stresses, thereby supporting higher yields with lower dependence on synthetic fertilizers. Global and national meta-analyses confirm that, under field conditions, biofertilizers significantly increase yields across many crops, including vegetables, while also improving soil enzymatic activities, organic matter, and the abundance of beneficial microbial groups that underpin long-term soil fertility.

In vegetable systems, biofertilizers and bio-organic formulations improve not only productivity but also nutritional quality and safety, largely through soil-mediated effects. Field synthesis for China shows that biofertilizer application increases vitamin C, protein, and carotenoids while reducing nitrate accumulation, and these quality gains coincide with higher soil urease and phosphatase activities and a shift toward beneficial microbiota. Case studies and reviews focused on vegetable crops similarly highlight that combining biofertilizers with organic amendments and/or reduced mineral fertilization enhances soil biota diversity and supports sustainable vegetable production, providing a viable pathway to reconcile yield goals with environmental protection.

Despite clear benefits, field performance of biofertilizers remains inconsistent, especially under diverse soil and climate conditions typical of vegetable production regions. Meta-analytical and review work emphasizes that the effectiveness of a given inoculant depends strongly on crop species, soil physicochemical properties, native microbiota, and climate; strain-environment mismatches can result in weak or negligible responses under farmer conditions. Large-scale field syntheses also caution that current data mostly reflect real-world but sub-optimal formulations and management, implying that observed benefits may underestimate biological potential while still displaying substantial variability across sites and crops.

A second major challenge is the translation of laboratory and greenhouse successes into robust, scalable technologies suitable for commercial vegetable systems. Reviews on formulation and commercialization highlight that poor survival of inoculants during storage, transport, and application, lack of quality control, and inadequate regulatory frameworks all contribute to variable outcomes and limited farmer trust. Regional assessments (e.g., Iran) further show that low soil organic matter, strong reliance on chemical fertilizers, and weak coordination among research, industry, and extension institutions have slowed adoption, underscoring that socio-economic and institutional bottlenecks are as important as technical ones.

Future work on biofertilizers in vegetable production needs to integrate multi-omics and systems approaches with agronomic experimentation to better match strains, formulations, and management to specific soils and crops. Advances in metagenomics, transcriptomics, and metabolomics are already clarifying how microbial consortia assemble in the rhizosphere and influence nutrient cycling; leveraging these tools can guide the design of targeted, crop and region specific biofertilizers with improved colonization and function. Large meta-analyses also suggest that trait-based selection (e.g., N fixation, P solubilization, stress tolerance) aligned with soil P levels, organic matter content, and pH can markedly increase success rates, providing a quantitative framework for precision biofertilization in intensive vegetable systems.

At the application level, research should prioritize long-term field trials in vegetable rotations, testing integrated strategies that combine microbial consortia with organic amendments, reduced mineral fertilization, and agroecological designs (e.g., push-pull, diversified rotations). Recent reviews argue that coupling biofertilizers with such systems can enhance soil health, pest regulation, and resilience to climate stresses, but require refined delivery methods, robust formulation technologies, and stringent quality control to ensure consistent performance. Strengthening links between microbiologists, agronomists, industry, and extension services will be crucial for scaling up these innovations, improving farmer awareness, and positioning biofertilizers as cornerstone inputs for climate-smart, high-quality vegetable production.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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