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Impact of Biofertilizers on Soil Enzyme Activity and Yield in Pepper Cultivation Systems

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Abstract Biofertilizers have emerged as an environmentally sustainable alternative to chemical fertilizers in modern agriculture, particularly in vegetable production systems such as pepper (*Capsicum* spp.). This study investigates the effects of biofertilizer application on soil enzyme activities and yield formation in pepper cultivation. By analyzing key soil enzymes including urease, phosphatase, and catalase, the study reveals that biofertilizers significantly enhance soil biochemical activity, thereby promoting nutrient cycling and improving soil fertility. Furthermore, biofertilizer application positively influences rhizosphere ecological functions, leading to improved root development and increased nutrient uptake efficiency. These changes contribute to enhanced plant growth, higher yield components, and improved fruit quality, including elevated levels of vitamin C and capsaicin. A case study conducted under typical cultivation conditions further validates the practical benefits of biofertilizer use. Overall, the findings demonstrate that biofertilizers play a critical role in improving soil health and increasing pepper productivity, offering promising prospects for sustainable agricultural practices.

Keywords Pepper (*Capsicum* spp.); Biofertilizer; Soil enzyme activity; Rhizosphere ecology; Yield formation

1 Introduction

Biofertilizers, broadly defined as preparations containing living microorganisms that enhance the availability and cycling of nutrients in the rhizosphere, are increasingly viewed as a cornerstone of sustainable crop production. They can improve plant nutrition through biological nitrogen fixation, solubilization of phosphorus and other minerals, and production of phytohormones, while simultaneously contributing to soil structure, organic matter dynamics, and biological activity (Mahmud et al., 2021; Pei et al., 2025). A recent meta-analysis across Chinese field conditions showed that biofertilizers increased crop yields for most major crops, improved produce quality (for example, higher protein and vitamin C and lower nitrate contents), and enhanced soil organic matter, enzyme activities (urease, phosphatase), and beneficial microbial populations, while suppressing soil-borne pathogens (Pei et al., 2025). These benefits are especially relevant in the context of intensive vegetable systems, where long-term overuse of mineral fertilizers has degraded soil health and reduced nutrient-use efficiency (Haroun et al., 2023; Ali et al., 2024). Pepper (*Capsicum* spp.) is a high-value horticultural crop with long growing cycles and high nutrient demands; in many production regions, pepper cultivation is associated with continuous cropping, soil fatigue, and yield instability, making it an ideal model for exploring biofertilizer-based strategies that can simultaneously sustain yields and restore soil ecological function (Zhang et al., 2024). Moreover, soil enzymes such as urease, phosphatase, dehydrogenase, peroxidase, and invertase are key indicators and drivers of nutrient cycling and soil biological activity, closely linked to organic matter turnover and plant-available N and P; biofertilizers that stimulate these enzymes may therefore provide a mechanistic bridge between microbial inoculation, soil process intensification, and crop performance). However, despite growing use of biofertilizers in vegetable systems, there is still limited integrative understanding of how specific biofertilizer regimes affect soil enzyme activity and yield in pepper cultivation, particularly under contrasting management contexts and resource levels.

In pepper production, biofertilizers have been tested in diverse forms, including plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), microbial organic fertilizers, bioactive composts enriched with beneficial consortia, and liquid or solid formulations derived from agro-industrial residues (Imran et al., 2022; Sini et al., 2024). Multiple studies indicate that microbial inoculants can substantially increase pepper yield, fruit number, and quality traits compared with unfertilized or solely mineral-fertilized controls, often while reducing the need for chemical fertilizers. In greenhouse and soilless systems, combinations of AMF and PGPR in capia and bell pepper increased total yield by roughly 18%-32%, improved fruit weight and soluble solids, and allowed up to 20% reduction in mineral fertilizer inputs without yield penalties. In open-field systems, biofertilizer consortia such as Ning Shield or Trichoderma-based biological organic fertilizers, especially when complemented with organic amendments, boosted pepper yields by 40-75% relative to conventional fertilization, extended postharvest shelf life, and markedly enhanced soil nutrient retention and disease suppression (Imran et al., 2022). Other work with HYT biofertilizers, bioslurries, and manure-based or agri-waste-derived inoculated composts similarly reports significant gains in plant growth, leaf area, fruit number, and marketable yield in hot and sweet pepper, often accompanied by increases in soil organic carbon, available N and P, cation exchange capacity, and microbial biomass (Appah et al., 2021). At the same time, studies in continuous pepper cropping systems highlight that microbial organic fertilizers and inoculants can reshape microbial community composition, increase the complexity of bacterial and fungal co-occurrence networks, and improve soil nutrient availability and yield, particularly when integrated with amendments such as quicklime or biochar (Zhang et al., 2024). Collectively, these findings demonstrate that biofertilizers are no longer experimental curiosities but are being deployed at scale in pepper production, yet most reports emphasize agronomic outcomes, with fewer works explicitly quantifying changes in soil enzyme activities as a central response variable.

Soil enzyme responses to biofertilizers have begun to receive more focused attention in other cropping systems, revealing strong links between bio-organic fertilization, enzymatic activity, and yield. Trichoderma-based biological organic fertilizer in pepper systems significantly increased peroxidase, urease, and invertase activities relative to chemical fertilizer alone, and redundancy analyses showed pepper yield to be positively correlated with these enzyme activities, soil organic carbon, total nitrogen, and available phosphorus, suggesting that enhanced enzymatic turnover underpins improved nutrient supply and crop performance. Similarly, long-term or short-term applications of biofertilizers in cereals and rotations have been shown to elevate urease, alkaline phosphatase, and dehydrogenase activities, enrich beneficial bacterial and fungal taxa, and improve soil nutrient status and microbial metabolic diversity, especially when biofertilizers partially replace NPK fertilizers. In black pepper (Piper nigrum), combined use of FYM with Azospirillum, phosphobacteria, and vesicular-arbuscular mycorrhiza increased urease, phosphatase, and dehydrogenase activities along with available N, P, and K, underscoring the sensitivity of soil enzymes in perennial spice systems to biofertilizer and organic-matter management. Yet, for *Capsicum* species cultivated as annual vegetables, there remains a notable gap: systematic studies explicitly designed to link specific biofertilizer regimes with changes in a suite of soil enzymes and parallel changes in pepper yield and quality are scarce, and existing reports often treat soil biochemical indicators only tangentially or not at all. Addressing this gap, the present study aims to evaluate the impact of selected biofertilizers on soil enzyme activities and yield in pepper cultivation systems, under defined fertilization and management regimes. The technical approach involves controlled field or greenhouse experiments comparing different biofertilizer types and application strategies, with concurrent measurements of key soil enzymes (for example, urease, phosphatase, dehydrogenase, and carbon-cycle-related enzymes), soil nutrient status, and pepper growth and yield parameters, followed by multivariate analyses to elucidate relationships between enzymatic activity, soil properties, microbial responses, and crop performance. By integrating soil biochemical indicators with agronomic outcomes, this work seeks to clarify the functional mechanisms through which biofertilizers enhance pepper productivity and to provide a scientific basis for optimizing biofertilizer-based fertilization schemes that maintain high yields while improving soil health in intensive pepper cultivation systems.

2 Regulatory Effects of Biofertilizers on Soil Physicochemical Properties

2.1 Changes in soil organic matter and nutrient content

Biofertilizers are typically formulated from nutrient - transforming microorganisms that accelerate organic matter turnover and improve nutrient availability, thereby enhancing soil fertility over time. Across a large body of field data, biofertilizer application has been shown to increase soil organic matter and key nutrients such as total nitrogen and available phosphorus, largely by stimulating biological N fixation, P solubilization, and root-microbe interactions (Pei et al., 2025). In saline and degraded soils, inoculated microbial consortia can markedly raise soil organic matter and total N while also boosting plant biomass, demonstrating that biofertilizer-driven improvements in carbon and nitrogen pools are coupled to crop performance (Li et al., 2024). Similar trends have been reported in systems where microbial agents promote "fast-acting" nitrogen and phosphorus, indicating that biofertilizers not only add nutrients directly but also activate native microbial communities that accelerate nutrient cycling (Li et al., 2023). These effects are especially important in intensive vegetable systems such as pepper, where sustained nutrient supply must be matched with soil quality conservation to maintain yield stability.

In integrated fertilization schemes, combining biofertilizers with mineral or organic fertilizers often produces synergistic gains in soil organic matter and nutrient stocks (Figure 1) (Ali et al., 2024). For example, partial substitution of NPK with biofertilizer in cereal-maize rotations significantly increased soil organic matter, available N and P, and microbial metabolic activity, while maintaining or improving crop yields. In coastal saline soils, optimal rates of microbial fertilizer increased soil organic carbon and available P and K, coinciding with higher urease activity and improved sorghum yield (Wu et al., 2024). Long-term microbial fertilizer use can also enhance organic carbon and microbial biomass carbon, while increasing available phosphorus without necessarily changing total P, suggesting more efficient P mobilization from existing soil pools. Together, these findings indicate that well-designed biofertilizer regimes can rebuild soil organic matter and nutrient capital, reduce dependence on synthetic fertilizers, and create a more responsive nutrient supply system suited to high-demand crops such as pepper.

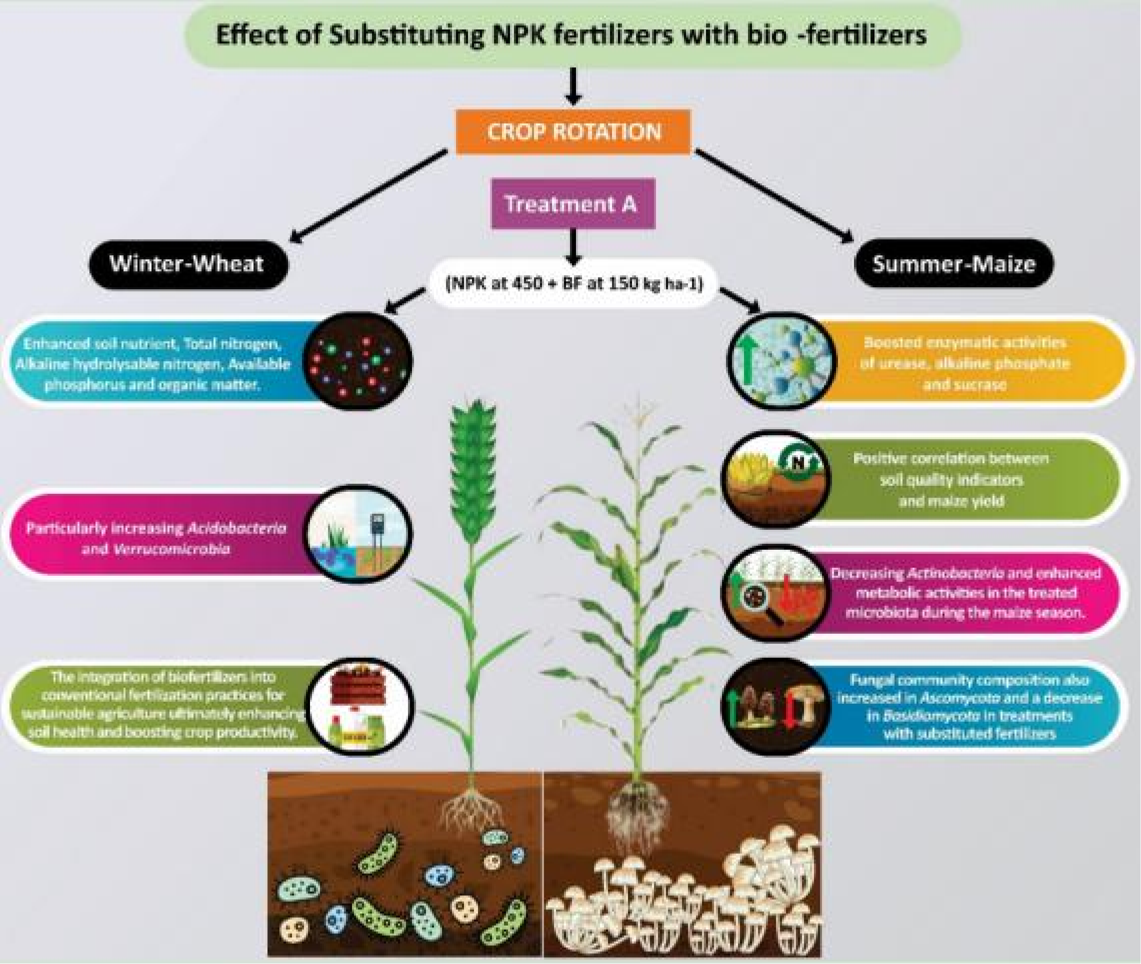

Figure 1 Proposed model of bio-fertilizers supplementation. Effects on enzymatic activities, soil properties, soil microbial community, changes in soil nutrients, and crop growth development and yield, in wheat-maize cropping seasons (Adopted from Ali et al., 2024)

2.2 Soil pH variation and structural improvement

Soil pH strongly regulates nutrient solubility, metal mobility, and microbial activity, and biofertilizers can indirectly modulate pH through microbial metabolism and organic matter accumulation. Meta-analysis of field trials indicates that while bulk soil pH often remains within a relatively stable range under biofertilizer application, electrical conductivity frequently declines, consistent with increased organic matter and improved ionic balance (Pei et al., 2025). In saline-alkali systems, application of microbial fertilizers significantly reduced soil pH and salinity while increasing soil organic carbon and available nutrients, thereby improving the chemical environment for root growth and microbial activity (Wu et al., 2024). In sugarcane rhizospheres, biofertilizer treatments alleviated soil acidification relative to conventional fertilization and shifted the main physicochemical drivers of microbial communities toward a more balanced pH-nutrient regime (Liu et al., 2021). These pH adjustments, even when modest, can be agronomically meaningful in pepper cultivation, where root health and nutrient uptake are highly sensitive to acidity and salinity stress.

Beyond pH, microbial fertilizers contribute to structural improvement through their effects on aggregation, porosity, and compaction. Microbial inoculants and their extracellular polysaccharides bind soil particles into more stable aggregates, enhancing soil structure, aeration, and water retention while reducing bulk density (Wei et al., 2024). In saline soils, structural amelioration under biofertilizer treatment is accompanied by reduced total soluble salts and improved root growth, indicating that both chemical and physical constraints are being mitigated simultaneously (Li et al., 2024). Studies of microbial and organic amendments in other crops show increases in cation exchange capacity and aggregate stability, reflecting enhanced organic matter quality and mineral-organic interactions (Fitriatin et al., 2021). For pepper systems, improved structure can moderate fluctuations in soil moisture and temperature, support deeper and more extensive rooting, and buffer against compaction from intensive management, thereby reinforcing the benefits of improved nutrient status.

2.3 Responses of soil microbial community structure

The most fundamental regulatory role of biofertilizers lies in reshaping soil microbial community structure, which in turn governs nutrient cycling and soil health. Comparative studies across fertilization regimes show that biofertilizers enrich specific bacterial and fungal taxa associated with carbon and nitrogen cycling, while also increasing the abundance of aerobic and biofilm-forming microbes that are well adapted to the rhizosphere (Zhang et al., 2025). In maize and wheat rotations, supplementing NPK with biofertilizer enhanced bacterial and fungal diversity and selectively enriched major phyla such as Proteobacteria, Acidobacteria, Actinobacteria, and Firmicutes, patterns that coincided with higher enzyme activities and nutrient contents (Ali et al., 2024). Biofertilizer-amended soils often display more complex and stable microbial co-occurrence networks than chemically fertilized controls, suggesting a transition toward community configurations characteristic of healthier soils. In leafy vegetables, Bacillus-based bioorganic fertilizers have been shown to restructure both bacterial and fungal communities, with clear separation from control treatments and enrichment of beneficial decomposers and saprotrophs that facilitate nutrient mineralization (Wang et al., 2022).

At finer functional scales, biofertilizers can stimulate nitrogen-transforming guilds and alter the resistome and functional gene repertoire of soil communities without necessarily increasing ecological risk. Metagenomic analyses of soils receiving microbial agents show enhanced abundance of nitrification genes and complementary metabolic pathways, supporting greater availability of fast-acting nitrogen and phosphorus and improved plant growth (Li et al., 2023). Other work using high-throughput qPCR indicates that while biofertilizers introduce numerous microbial taxa, they do not necessarily increase the relative abundance of antibiotic resistance genes in soil, in part because altered soil properties and native microbial competition constrain ARG proliferation (Yang et al., 2022). In perennial orchards and monocultures, periodic biofertilizer application has been found to modify bacterial diversity, increase microbial biomass, and shift community functions related to nitrogen and phosphorus cycling, while preserving core functional networks. Collectively, these responses highlight that biofertilizers act as ecological regulators, steering soil microbial communities toward more functionally diverse, nutrient-efficient, and disease-suppressive states—conditions that are particularly advantageous for sustaining enzyme activity and yield in intensively managed pepper cultivation systems.

3 Effects and Mechanisms of Biofertilizers on Soil Enzyme Activities

3.1 Changes in urease activity and nitrogen cycling responses

Biofertilizers frequently alter soil urease activity, thereby regulating the rate at which urea is hydrolyzed to ammonium and shaping nitrogen availability for crops. In double-cropping rice, partial substitution of urea with biochar markedly enhanced urease activity by about 25% on average, indicating that biologically active amendments can stimulate N-mineralizing enzymes and support sustained nitrogen supply to plants (Ullah et al., 2023). Similar increases in urease and alkaline phosphatase were observed when biofertilizers were integrated with reduced NPK in wheat-maize rotations, where enhanced enzyme activities correlated positively with soil total and available N and higher yield, suggesting that moderate biofertilizer doses intensify N cycling without sacrificing productivity (Ali et al., 2024). In rapeseed systems, combining high N fertilization with biochar raised urease activity by more than 70%, further illustrating that bio-based amendments can greatly expand the enzymatic capacity for urea hydrolysis under intensive fertilization (Khan et al., 2022). Such responses imply that in pepper cultivation, appropriate biofertilizer regimes are likely to accelerate urea turnover, maintain higher pools of plant-available N in the rhizosphere, and underpin improved growth and yield.

However, the relationship between urease activity, nitrogen retention, and gaseous losses is not always linear, and some biofertilizer strategies intentionally moderate urease to reduce ammonia volatilization. Field experiments with Bacillus amyloliquefaciens and *B. subtilis* biofertilizers in alkaline soils showed marked reductions in urease activity and ureC gene abundance, accompanied by enhanced potential ammonia oxidation and increased amoA-bearing nitrifiers, which together decreased NH_3 emissions by 44%-68% while maintaining or increasing crop yield (Xue et al., 2021). Long-term biochar incorporation can also boost total urease activity by 30%-200% yet simultaneously modify urea hydrolysis rates and soil pH in ways that affect nitrogen retention differently across upland, paddy, and greenhouse soils (Zhao et al., 2022). Other studies report that coupling biochar or bacterial agents with N fertilizers increases fast-acting nitrogen and nitrification-related genes, while biofertilizer-driven shifts in ammonium oxidation pathways help explain observed gains in N uptake and plant growth (Li et al., 2023). For pepper systems, these findings highlight a key mechanistic trade-off: biofertilizers can either stimulate urease to enhance rapid N release or, when formulated with specific strains and carriers, temper urease while favoring nitrification, thereby synchronizing N availability with pepper demand and mitigating ammonia loss.

3.2 Changes in phosphatase activity and phosphorus transformation processes

Phosphatase enzymes are central to the mineralization and mobilization of organic and inorganic phosphorus, and biofertilizers consistently upregulate their activity, thereby restructuring soil P pools. In a wheat-maize rotation, integrating biofertilizer with reduced NPK significantly increased alkaline phosphatase activity alongside improvements in soil organic matter and available P, indicating that microbial inoculants can enhance enzymatic P release while supporting sustainable fertilization regimes (Ali et al., 2024). A large meta-analysis across Chinese field conditions further quantified these effects, reporting average increases of about 44% in soil phosphatase activity following biofertilizer application, along with higher total and available P and enhanced plant P nutrition (Pei et al., 2025). In maize-cabbage rotations, long-term co-application of biochar and organic fertilizer elevated both acid and alkaline phosphatase activities by 8-49% relative to unfertilized controls, and these enzymatic increases were more closely related to maize P uptake and yield than were changes in bulk P fractions, underscoring the regulatory role of phosphatases in P bioavailability (Hu et al., 2023). These patterns suggest that in pepper systems, biofertilizers can intensify phosphatase-mediated P cycling, improving access to both native and applied P sources.

At the mechanistic level, biofertilizers influence not only phosphatase activity but also the abundance and composition of P-acquiring microbial guilds and functional genes. Phosphorus biofertilizer enriched with beneficial microbes in degraded Brunic Arenosol increased soil acid phosphomonoesterase and β-glucosidase activities, expanded taxa linked with P pathways, and raised phytoavailable P, thereby reversing some effects of long-term soil degradation (Mącik et al., 2021). Similarly, long-term combination of biochar and organic fertilizers enriched phoD-harboring microbial communities and increased the abundance of multiple P-acquiring genes (phoD, phoX, ppx, ppk, phnK), with plant P uptake and yield strongly correlated to both phosphatase activities and these gene pools (Hu et al., 2023). In saline-alkali soils, biochar combined with different phosphate fertilizers altered acid, neutral, and alkaline phosphatase activities and shifted phoD-bearing community composition, with certain genera (for example Rhodopseudomonas) showing strong associations with specific inorganic and organic P fractions (Hou et al., 2024). Translating these insights to pepper cultivation implies that selecting biofertilizers that stimulate both phosphatase activity and P-acquisition genes can transform poorly available soil P into readily usable forms, reducing P fertilizer inputs while safeguarding yields.

3.3 Changes in catalase and other redox enzyme activities

Redox-related enzymes such as catalase, dehydrogenase, and oxidases provide sensitive indicators of soil microbial oxidative metabolism and stress status, and biofertilizer use often modifies their activity in complex ways. In rice paddies, combining nitrogen fertilizers with biochar increased urease, β-glucosidase, and dehydrogenase activities by around 13-19%, yet catalase activity decreased by roughly 12-15%, suggesting a shift toward higher microbial metabolic intensity but lower apparent oxidative stress in biochar-amended soils. A similar pattern was observed in double-cropping rice where biochar addition raised urease, dehydrogenase, polyphenol oxidase, and chitinase activities by 14-68% while reducing catalase activity by about 15%, implying that enhanced nutrient cycling and microbial respiration can coincide with down-regulated catalase under improved soil conditions (Ullah et al., 2023). In rapeseed pots, biochar at high rates increased soil catalase activity by 16-17% and alkaline phosphatase by up to 19%, but these responses depended strongly on nitrogen dosage, indicating that redox enzymes integrate both carbon and N management regimes. Across a broad range of field studies synthesized in a meta-analysis, catalase activity increased by about 25% under biofertilizer application, paralleling gains in other enzymes and reflecting generally improved soil biochemical functioning. These findings collectively indicate that in pepper soils, biofertilizers and biochar-based formulations can recalibrate the balance between oxidative protection and metabolic activity, with catalase and related enzymes serving as key readouts of this process.

Mechanistically, adjustments in redox enzyme activities under biofertilization are closely tied to shifts in microbial community structure, substrate availability, and nitrogen transformation pathways. Biofertilizer-amended soils commonly exhibit enriched nitrifiers and complementary N-cycling genes, along with higher fast-acting N and P, indicating that intensified microbial metabolism demands robust antioxidant systems, even when catalase itself is sometimes down-regulated at the bulk soil scale (Abdo et al., 2022; Li et al., 2023). In studies coupling biochar or bio-organic fertilizers with N sources, increases in dehydrogenase and oxidase activities have been attributed to greater microbial biomass and improved habitat conditions, as porous carbon matrices supply labile C and microsites for enzyme stabilization. Meanwhile, hydrothermal organic amendments that strongly stimulate urease and ureC can elevate ammonification and N loss, with high soil organic matter and pH jointly influencing nitrifier populations and redox-linked gene expression. For pepper cultivation systems, these mechanisms imply that the design of biofertilizer regimes should consider not only nutrient-transforming enzymes such as urease and phosphatase but also catalase and linked redox enzymes, which reflect the resilience and efficiency of the microbial engine driving nutrient cycling, stress mitigation, and ultimately pepper yield and quality.

4 Role of Biofertilizers in Enhancing Rhizosphere Ecological Functions of Pepper

4.1 Changes in rhizosphere microbial activity

Biofertilizers based on arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) markedly intensify microbial activity in the pepper rhizosphere. In greenhouse bell pepper, AMF and bacterial consortia (Azotobacter, Azospirillum, Enterobacter, Pseudomonas, Bacillus) significantly increased rhizosphere microbial populations, especially when combined with organic fertilizer, and this was accompanied by higher yield and nutrient uptake (Sini et al., 2024). Similar stimulation of rhizosphere microbial biomass and functional taxa was observed when biochar was combined with nitrogen fertilizer in field-grown pepper: porosity and organic matter improved, and bacterial and fungal communities were enriched in groups associated with carbon and phosphorus cycling (Wu et al., 2025). Effective microorganism (EM) agents in continuously cropped pepper further enhanced urease, sucrase, and peroxidase activities in the rhizosphere, reflecting a broad activation of microbial metabolism that paralleled yield gains of nearly 75% over the control (Liu et al., 2024).

Beyond overall biomass, biofertilizers restructure rhizosphere communities toward more beneficial and stress-resilient configurations. Actinobacteria-based biofertilizer containing Streptomyces strains increased yields of pepper and other crops by 7.7%-55.6%, while enriching beneficial taxa such as Chitinophaga and Pseudoxanthomonas and reducing phytopathogens like Cladosporium and Gibberella in the rhizosphere (Li et al., 2022). Insect frass and exuviae, functioning as organic-microbial amendments, enhanced enzyme activities (catalase, β-glucosidase, urease, alkaline phosphatase) and enriched plant-beneficial genera such as Sphingobium and Steroidobacter in chili pepper rhizospheres (Zhou et al., 2025). Under antimony stress, inoculation with Sb-tolerant PGPR in pepper increased total N, total P, soil organic matter and acid phosphatase activity, while building more complex and connected bacterial co-occurrence networks (Sheng et al., 2025). Collectively, these shifts indicate that biofertilizers promote a more active, functionally diverse, and disease-suppressive rhizosphere for pepper.

4.2 Interactions between root exudates and microecology

Root exudates are central to rhizosphere assembly, and fertilization or biofertilization regimes can indirectly reprogram exudation patterns, thereby shaping microbial communities. In substrate-grown pepper, different fertilization levels and intervals significantly altered rhizosphere microbial community composition and were closely linked to shifts in rhizosphere metabolites enriched in alanine, aspartate, glutamate, and butanoate pathways, suggesting that C- and N-rich exudates co-determine microbial structure and activity (Di et al., 2025). Comparative work on root-soil interactions in pepper under organic versus conventional management showed that genotypes modified rhizosphere functionality through rhizodeposits and root border cells, influencing microbial counts, enzyme activities, and N mobilization in a highly genotype- and management-dependent manner (Morales-Manzo et al., 2023). At a broader scale, root exudates are known to modulate pH, chelate toxins, attract mycorrhizal fungi and PGPR, and release antimicrobial compounds, providing a mechanistic framework for how exudate changes under biofertilization might cascade to rhizosphere ecology.

Biofertilizers amplify or redirect these exudate-microbe feedbacks. In maize, PGPR-based biofertilizers increased soil organic matter and available N, P, and K, with authors attributing the enrichment of beneficial rhizosphere bacteria to enhanced root exudation of sugars, amino acids, organic acids, and vitamins that selectively recruit functional communities. In wheat, seed-applied bacterial and mycorrhizal consortia boosted rhizosphere enzymatic activities (e.g., β-glucosidase, mannosidases, xylosidase) and microbial biomass without altering overall biodiversity, implying that inoculants modulated the functional interface between exudates and decomposer microbes rather than simply adding taxa. Pepper-maize intercropping further illustrates how altered exudate patterns can restructure rhizosphere and bulk microbial communities, increasing bacterial and fungal diversity and enriching flavonoids and alkaloids in the intercropped pepper rhizosphere (Figure 2) (Chen et al., 2024). In pepper systems receiving biofertilizers, such exudate-driven selection is likely reinforced, strengthening beneficial symbioses and suppressing pathogens.

4.3 Improvement of nutrient transformation and uptake efficiency in the rhizosphere

Biofertilizers improve nutrient transformation in the pepper rhizosphere by coupling microbial processes with root uptake capacity. In greenhouse bell pepper, AMF and PGPR consortia significantly increased N, P, K, Zn and Fe uptake, with Azotobacter-Azospirillum inoculation maximizing N absorption and AMF enhancing Fe acquisition, and these changes paralleled yield increases up to 18% over the control. Field application of EM microbial agents in continuously cropped pepper raised soil available N and P during flowering and maturity, and simultaneously increased sucrase, urease, and peroxidase activities, indicating more active C and N cycling that supported 42.9% higher single-fruit weight and 74.7% higher yield When biochar was combined with optimal nitrogen rates in pepper, porosity, organic matter, and cation exchange improved, and functional taxa related to carbon and phosphorus cycling (e.g., Chloroflexi, Mortierellomycota) were enriched, helping to retain nutrients and enhance their availability to roots (Wu et al., 2025). Manure substitution studies in pepper further showed that replacing

30%-40% of mineral P with organic manure increased alkaline phosphatase activity, arbuscular mycorrhizal colonization, soil labile P, and root length, thereby improving P uptake while moderating available P levels (Sun et al., 2024).

Enhanced nutrient transformation translates directly into higher nutrient use efficiency and crop performance. A biofertilizer-compost combination in pepper fields improved soil organic matter and available NPK after one season, increased yield and fruit quality, and provided strong disease control, demonstrating that PGPR plus organic substrates can simultaneously sustain fertility and suppress pathogens through rhizosphere processes. Actinobacterial biofertilizer containing Streptomyces strains increased pepper yield and altered rhizosphere assembly so that beneficial decomposers and nutrient cyclers became more abundant while phytopathogens declined, indicating tighter coupling between decomposition, nutrient mineralization, and root uptake (Li et al., 2022). Insect frass and exuviae amendments also raised enzyme activities and enriched microbial functions related to chitinolysis and cellulolysis, increasing nutrient bioavailability and improving photosynthesis and chili pepper growth. Under heavy metal stress, Sb-tolerant PGPR in pepper improved total N, P, and soil organic matter, increased acid phosphatase by over 80%, reduced Sb accumulation in shoots, and boosted biomass, showing that rhizosphere nutrient cycling and detoxification can be co-optimized by tailored biofertilizers. Together, these results support the view that in pepper cultivation, biofertilizers are powerful tools to upgrade rhizosphere nutrient transformations and root uptake efficiency, thereby underpinning higher yields and better fruit quality under both optimal and stressful conditions.

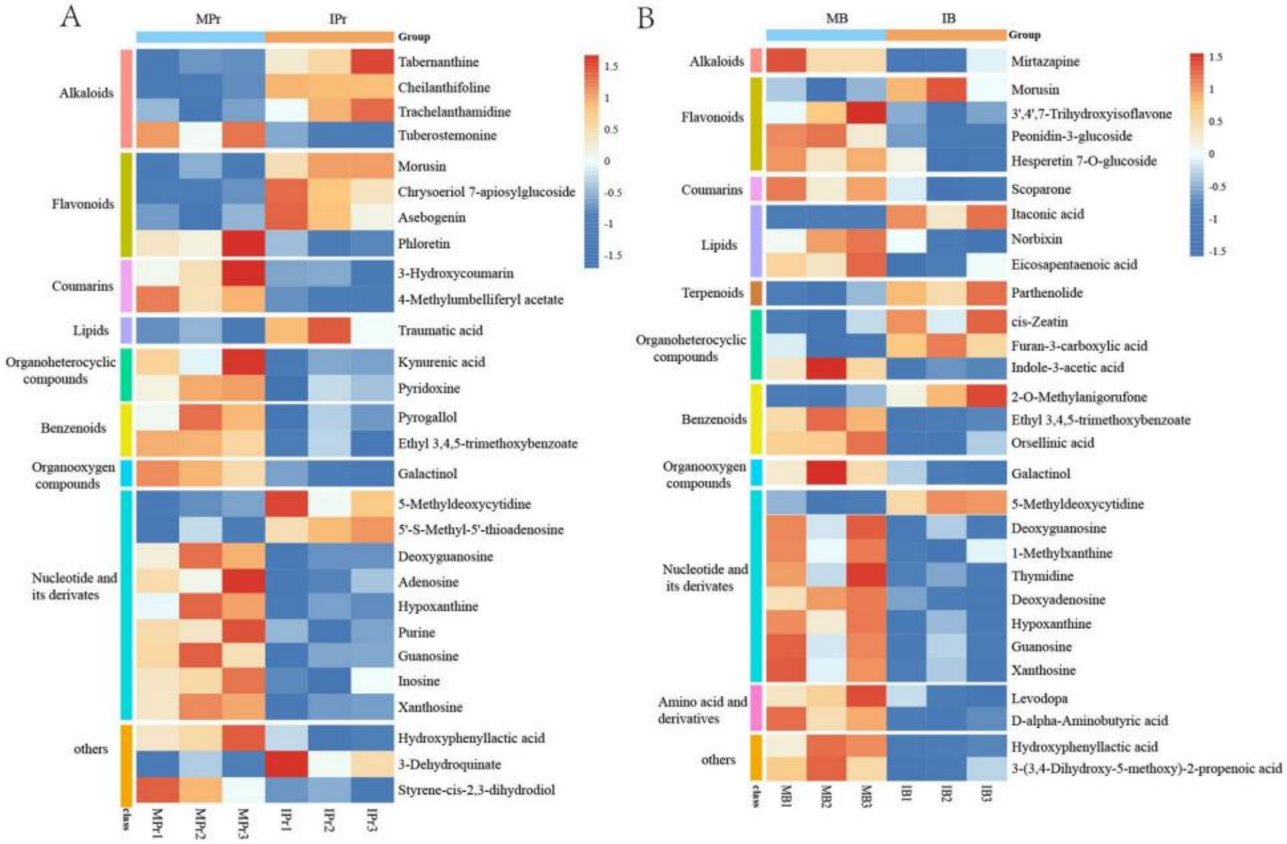

Figure 2 Heatmap analysis of the differential expressed metabolites in MPr vs. IPr (A) and MB vs. IB (B) (Adopted from Chen et al., 2024)

5 Regulatory Effects of Biofertilizers on Pepper Growth and Development

5.1 Changes in plant morphological growth parameters

Biofertilizers consistently enhance aboveground growth of pepper, including plant height, stem thickness, canopy size, and leaf area. In greenhouse bell pepper, consortia of arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) significantly increased plant height and overall biomass while raising yield by about 18% compared with the uninoculated control (Sini et al., 2024). Similar responses were reported in sweet pepper where increasing doses of liquid organic nutrients and biofertilizer (up to 4 mL/L) produced the tallest plants, greatest leaf area, and most leaves per plant, indicating that microbial inoculants in compatible carriers strongly stimulate vegetative growth (Omar and Fadala, 2025). Hot pepper supplied with HYT biofertilizers and biochar also showed significant increases in plant height, stem girth, and leaf number, with the best combinations of biofertilizer and biochar delivering the highest yields and demonstrating that morphological gains are tightly coupled to productivity (Appah et al., 2021).

Field and protected-culture studies confirm that different microbial formulations and application methods can be tuned to optimize structural growth. In green pepper, applying biofertilizer both by root dipping and soil drench produced the tallest plants and greatest branch number, which translated into higher fruit numbers and a 42% yield increase over the control. Under greenhouse conditions, seed or transplant inoculation with *Azotobacter chroococcum*, *Azospirillum brasilense*, *Bacillus subtilis*, and *Pseudomonas fluorescens* significantly increased plant height relative to uninoculated plants, reflecting the role of N fixation, P solubilization, and microbial growth regulators in driving shoot elongation and stem expansion (Ahmed et al., 2021). Goat-manure biofertilizer applied at 40%-60% concentrations under field conditions likewise improved early plant height and canopy development of chili pepper, with four applications at around 46-48% giving the best morphological performance in the seedling stage. Together, these findings indicate that well-formulated biofertilizers can reliably upgrade pepper canopy architecture, supporting greater light interception and assimilate production.

5.2 Improvement of root system structure and function

Root traits are particularly sensitive to biofertilization, and many studies show pronounced improvements in root length, volume, and functional capacity. In bell pepper, a consortium of AMF and PGPR improved root development alongside shoot growth, with mycorrhizal inoculation increasing nutrient uptake (especially P, K, Zn, and Fe) and supporting higher yields, implying a more extensive and efficient root system. Mycorrhizal biofertilizer combined with rock phosphate in cayenne pepper increased root volume, root infection rate, and root dry weight while also enhancing P uptake, demonstrating how symbiotic fungi expand the absorptive surface and strengthen root-soil contact (Rinindra and Hermiyanto, 2024). In California Wonder bell pepper, biochar combined with VAM or Azospirillum increased root volume and mycorrhizal colonization, and plants in these treatments accumulated more total dry matter and root biomass, showing clear structural gains in the belowground system (Samyukta et al., 2024).

More detailed studies highlight biochemical and ultrastructural changes in roots that underpin improved function. Micro-carbon-based humic biostimulant fertilizers in hydroponic pepper produced striking alterations in root cell morphology: root cells developed very large central vacuoles occupying 68-83% of cell area, a configuration interpreted as increased membrane permeability and capacity for water and nutrient storage. Mycorrhizal biofertilizer combined with rice-washing water and eggshell powder in cayenne pepper significantly increased root number, root length, and root dry weight across several dose combinations, indicating that nutrient-rich organic carriers can further potentiate mycorrhizal effects on root proliferation (Sari et al., 2024). In chili pepper on Plinthic Ferralsols, Rhizophagus intraradices and Azolla biofertilizer each improved plant height, stem diameter, and leaf dimensions; the authors attributed much of the growth response to mycorrhiza-mediated enhancement of root development and nutrient acquisition in nutrient-poor soils (René et al., 2025). These structural and functional upgrades of the root system form the foundation for improved water and nutrient capture in biofertilized pepper.

5.3 Regulation of physiological and metabolic characteristics

Beyond morphology, biofertilizers act as biostimulants that reprogram pepper physiology and metabolism. In sweet pepper, liquid biofertilizer from cocoa shells increased plant height and stem diameter and, importantly, enhanced leaf chlorophyll content (up to 35.4 SPAD units) at optimal doses, reflecting improved N status and photosynthetic capacity (Solórzano et al., 2025). Another greenhouse study showed that organic nutrients and biofertilizer at 4 mL/L elevated total chlorophyll, carbohydrate content, vitamin C, and capsaicin concentration in pepper fruits, indicating a broad stimulation of primary and secondary metabolism linked to higher assimilate production and fruit quality. In serrano pepper, Bacillus-based PGPMs and seaweed extracts produced nuanced physiological responses: Bacillus inoculation increased leaf area, biomass, and yield but slightly reduced chlorophyll and carotenoids, whereas seaweed and combined treatments enhanced nitrate reductase and total chlorophyll, suggesting treatment-specific modulation of photosynthetic pigments and N assimilation pathways (Espinosa et al., 2025).

Metabolomic and gas-exchange analyses provide mechanistic evidence that microbial inoculants reshape hormonal and metabolic networks. In a controlled study with serrano-type pepper, a microbial biostimulant composed of AMF and endophytic fungi increased total yield by 23.7% while significantly altering leaf metabolite profiles: patterns of gibberellins, auxins, and cytokinins were rebalanced, and accumulation of carotenoids, saponins, and phenolic compounds was stimulated, linking yield gains to up-regulation of growth and defense pathways (Figure 3) (Bonini et al., 2020). Co-inoculation of poblano pepper with AMF and PGPR improved photosynthetic performance by increasing stomatal conductance, internal CO_2 concentration, transpiration, and net photosynthesis (Pn), while also boosting leaf P content and dry biomass, indicating that enhanced nutrient status and hormonal crosstalk translate directly into superior carbon assimilation (González-Mancilla et al., 2024). Complementary work on nitrogen-biochar interactions in pepper shows that optimized N plus moderate biochar rates raise chlorophyll content, root activity, and antioxidant enzyme activities such as superoxide dismutase, thereby strengthening both photosynthetic efficiency and oxidative stress tolerance (Wu et al., 2024). Collectively, these findings demonstrate that biofertilizers do not merely supply nutrients but orchestrate a complex reprogramming of pepper physiology, resulting in more robust growth, improved fruit quality, and greater resilience to environmental stress.

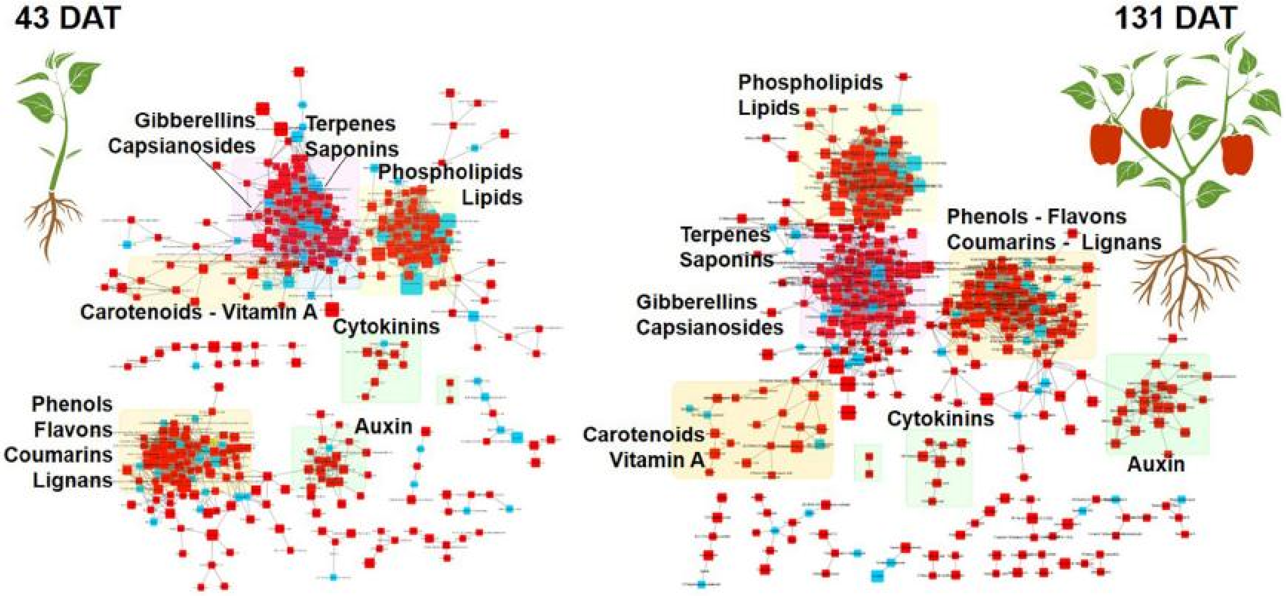

Figure 3 MetaMapp Metabolomic network maps of pepper leaves at 43 (vegetative stage) and 131 days after transplanting (reproductive stage). Microbial-based biostimulant treated plants were compared to control ones. The red squares are compounds with an increase in fold change, while the blue ones represent compounds with a decrease in fold changes. Chemical similarity and KEGG reaction were utilized to draw the clusters and nodes (Adopted from Bonini et al., 2020)

6 Influence of Biofertilizers on Yield Formation Mechanisms in Pepper

6.1 Variation in yield components

Biofertilizers modify yield components of pepper by increasing both fruit number and individual fruit size. In organic systems, combined applications of microbial products Baikal EM-1Y and Lumbrical increased standard yield of ‘Sofiiska Kapiya’ by up to 45% over the unfertilized control, mainly through higher fruit number per plant and greater fruit mass. Similar patterns were observed under greenhouse conditions where *Azotobacter chroococcum* inoculation raised plant yield from 880 to 1 344 g per plant, with clear increases in fruit number and average fruit weight compared with the uninoculated control (Ahmed et al., 2021). These shifts in yield components indicate that biofertilizers support both reproductive sink formation and assimilate partitioning to developing fruits.

In soilless capia pepper, combining 80% mineral fertilizer with AMF and PGPR increased total fruit yield by 32.4% relative to 100% mineral fertilizer alone, while also raising single-fruit weight, diameter, and volume, evidencing more robust fruit set and fruit growth under reduced chemical inputs. Effective microorganism agents in a continuous-cropping system likewise improved fruit width, single-fruit weight, and total yield, with fruit weight rising by 42.9% and yield by 74.7% compared with the control, linking microbial activation of soil processes to heavier marketable fruits (Liu et al., 2024). Together, these studies show that biofertilizers consistently enhance key yield components—fruit number, size, and standard yield—across field, organic, and soilless pepper systems.

6.2 Reproductive growth and yield accumulation processes

Reproductive growth in pepper responds strongly to biofertilizer-mediated improvements in nutrient supply and root-shoot balance. In greenhouse bell pepper, AMF and diverse PGPR consortia increased N, P, K, Zn, and Fe uptake while raising total yield by 18%, suggesting that enhanced mineral nutrition during flowering and fruit set underlies more sustained reproductive growth and fruit filling (Sini et al., 2024). An integrated PGPR-humic acid treatment in field pepper similarly produced the highest fruit yield (110.2 q/ha) together with increases in plant height and branch number, implying that early vegetative stimulation and improved nutrient status support a larger reproductive sink later in the season (Lalkhumliana et al., 2025).

Biofertilizers also interact with fertilization and irrigation regimes to modulate the trajectory of yield accumulation. In traditional pepper varieties grown under low-input management, microbial biostimulants containing N-fixing and P-/K-solubilizing bacteria plus AMF partly compensated for reduced fertilization, increasing total yield in some genotypes by boosting fruit number despite lower nutrient solution strength (Sánchez-Sánchez et al., 2022). In soilless capia pepper, using 80% mineral fertilizer with bacteria or with bacteria plus AMF increased yield by 24.2%-32.4% over full fertilization, indicating that reproductive yield accumulation can be maintained or enhanced when microbial inoculants improve nutrient use efficiency and root activity during the critical flowering and fruit-development stages. These findings point to biofertilizers as tools for steering reproductive growth curves toward higher cumulative yields with lower external inputs.

6.3 Analysis of key limiting factors affecting yield improvement

Despite generally positive responses, the yield-enhancing effect of biofertilizers is constrained by several key limiting factors. Soil fertility status and N availability strongly condition the performance of microbial products: a Bacillus-containing bioproduct increased bell pepper marketable yield by 30-34% only at 100% recommended N, while no significant yield benefit occurred under 25% N, even though early root growth improved in both cases. Similarly, combined microbial organic fertilizer and inoculant applications in continuous-cropping pepper increased yield by about 30% chiefly through higher soil available N, P, and K and more complex microbial networks, with Mantel tests underscoring soil available N and bacterial diversity as primary drivers of yield (Zhang et al., 2024). These results indicate that insufficient baseline nutrients or severely degraded microbial communities may limit how far biofertilizers can raise yield.

Crop genotype, management intensity, and environmental stress further modulate yield responses. Under reduced fertilization and irrigation, microbial biostimulants increased yield in one traditional pepper variety but decreased it in another, despite similar treatments, suggesting strong genotype-specific interactions that can shift the balance between fruit number and mean fruit weight (Sánchez-Sánchez et al., 2022). In a long-season organic system, the highest yields were obtained when microbial biofertilizers were combined with vermicompost-based Lumbrical, whereas single products were less effective, highlighting the importance of matching microbial consortia with compatible organic substrates to sustain nutrient release over the crop cycle. Even in successful EM-based interventions, continuous-cropping stress and pathogen pressure remain underlying constraints, meaning that biofertilizers must be integrated with balanced fertilization, appropriate irrigation, and disease management to fully realize their potential for yield improvement (Liu et al., 2024).

7 Case Study: Evaluation of Biofertilizer Application under Typical Cultivation Systems

7.1 Characteristics of the study area and cultivation conditions

Typical pepper-growing regions where biofertilizers have been evaluated span humid tropical to temperate monsoon climates, providing a realistic basis for extrapolating results to diverse production systems. In Calabar, Nigeria, hot pepper was grown on acidic soils (pH 4.7-4.8) under field conditions during both dry and wet seasons, with rainfall and temperature patterns representative of West African smallholder systems. Application of biofertilizers derived from cow dung and mixed fruit peels under these conditions raised soil pH into a near-neutral range (6.7-8.2) and improved cation exchange capacity, mimicking the gradual reclamation of degraded, acid-leached soils often encountered in tropical pepper belts. In contrast, a temperate continental monsoon site in Changchun, China, used ‘Jinfu 803’ pepper under open-field management and showed that combined biochar and nitrogen fertilization could enhance soil porosity by 12.3%-28.6%, reflecting constraints of compacted, intensively tilled soils typical of mechanized systems (Wu et al., 2025).

Greenhouse and high-tunnel environments offer another representative cultivation context for biofertilizer use in pepper. In a Mediterranean greenhouse, capia pepper was produced hydroponically using inert substrates and precisely controlled nutrient solutions, with AMF and PGPR introduced to partially replace mineral fertilizers in a soilless system. Similar protected structures were used for sweet pepper in Romania, where biological fertilizer (Micoseed) and organic fertilizer (Orgevit) were tested against chemical fertilization under high-tunnel conditions that minimized rainfall variability while exposing plants to seasonal fluctuations in temperature and radiation (Stoleru et al., 2023). Greenhouse bell pepper trials in Iran also incorporated organic fertilizer and a range of AMF and PGPR inoculants in split-plot designs, simulating commercial protected cultivation that relies on fertigation and controlled microclimates (Sini et al., 2024). Together, these environments—acidic tropical field soils, intensively managed temperate fields, and protected soilless or soil-based systems—capture the diversity of “typical” pepper cultivation settings where biofertilizers can be integrated.

7.2 Biofertilizer application strategies and management practices

Biofertilizer strategies in pepper cultivation vary from simple single-product use to complex combinations with organic amendments and mineral fertilizers. In Calabar, anaerobically digested bioslurries made from cow dung and mixed fruit peels were applied directly to field plots as soil amendments, with 11 formulations compared against unfertilized and NPK-fertilized controls; these slurries simultaneously supplied nutrients and active microbial consortia, reflecting low-cost, on-farm production systems. In Iran, greenhouse bell pepper received AMF and different PGPR consortia at transplanting, with or without organic fertilizer; the highest yields were obtained when organic fertilizer was combined with AMF or Azotobacter-Azospirillum inoculation, illustrating a strategy where microbial inputs are layered onto compost-based fertility programs in protected cultivation (Sini et al., 2024).

More intensive strategies integrate biofertilizers into soilless or high-input systems to reduce mineral fertilizer dependence. In hydroponic capia pepper, inoculation with AMF and PGPR was combined with a 20% reduction in mineral fertilizer, and treatments were supplied through nutrient solution and root-zone inoculation, achieving higher yield at 80% of conventional fertilization. In continuous-cropping pepper fields in China, microbial organic fertilizer and microbial inoculants were applied alone or in combination with quicklime, targeting both nutrient supply and remediation of soil biological fatigue, while maintaining standard agronomic practices such as transplanting and drip irrigation (Zhang et al., 2024). Biochar-based strategies, such as applying 0.7% corn-straw biochar with intermediate N rates, were implemented through basal incorporation, followed by conventional N topdressing, thereby embedding biofertilizers and soil amendments within existing fertilizer schedules rather than replacing them outright (Wu et al., 2025). These approaches demonstrate that successful biofertilizer management in pepper depends on matching inoculant type, carrier, and timing with prevailing fertilization regimes, soil constraints, and production intensity.

7.3 Integrated analysis of soil enzyme activity and yield responses

Although most case studies in pepper focus on yield and microbial communities, complementary evidence from black pepper systems helps illuminate how biofertilizers regulate soil enzyme activity alongside productivity. Under black pepper in India, combined applications of farmyard manure with Azospirillum, phosphobacteria, and vesicular-arbuscular mycorrhiza significantly increased urease, phosphatase, and dehydrogenase activities relative to other organic or single-biofertilizer treatments, while also elevating available N, P, and K. These enzymes are central to N mineralization, organic P hydrolysis, and overall microbial respiration, suggesting that similar consortia under *Capsicum* could accelerate nutrient cycling and support sustained nutrient availability during long pepper cropping cycles. In Chinese continuous-cropping pepper fields, microbial organic fertilizer and inoculants enhanced soil available N, P, and K and increased the complexity of bacterial and fungal co-occurrence networks; Mantel tests highlighted soil available N and bacterial diversity as key correlates of yield gains, implying that enriched microbial activity and associated enzyme systems underpin productivity in degraded soils (Zhang et al., 2024).

Yield responses across case studies consistently align with these improvements in soil biological functioning. In Calabar, multi-substrate bioslurry treatments increased soil organic carbon above 1.5% and total N above 0.2%, leading to taller plants, greater leaf area index, and fresh fruit yields up to 13.61 t/ha, markedly higher than unamended or NPK-only controls. Similarly, the optimal biochar-N combination (0.7% biochar plus 375 kg N ha^{-1}) in Changchun increased yield by 42.35% over the unfertilized control while enriching functional microbial taxa involved in C and P cycling, such as Chloroflexi and Mortierellomycota, which were positively associated with improved soil properties (Wu et al., 2025). In hydroponic capia pepper, combining AMF and PGPR with 80% mineral fertilizer not only raised total fruit yield by 32.4% but also increased leaf macro- and micronutrient contents, consistent with more active rhizosphere processes and enhanced nutrient mobilization. Integrated across these systems, the case evidence supports a mechanistic link in pepper cultivation whereby biofertilizers and organic amendments stimulate soil microbial activity and enzyme-mediated nutrient transformations, which in turn improve plant nutrition and translate into substantial yield gains.

8 Comprehensive Effects of Biofertilizers on Pepper Quality Formation

8.1 Changes in nutritional quality indicators (e.g., vitamin C)

Biofertilizers and microbial biostimulants often enhance the nutritional density of pepper fruits, particularly vitamin C and antioxidant compounds. In greenhouse systems with reduced mineral fertilization, natural biostimulants increased vitamin C and total phenolic content in sweet yellow pepper, together with higher DPPH and ABTS antioxidant activities, indicating an overall improvement in nutraceutical quality under more sustainable management. Similar trends were recorded in a protected sweet pepper crop, where biological fertilization with Micoseed and organic fertilization with Orgevit increased total phenolics, lycopene, β-carotene, and antioxidant activity relative to chemical fertilization, while also enriching phenolic profiles such as chlorogenic and p-coumaric acids (Stoleru et al., 2023). These results suggest that biofertilization regimes stimulate secondary metabolism, leading to peppers richer in vitamins and phenolic antioxidants.

Recent field and greenhouse trials further support the capacity of microbial inputs to raise vitamin C content in fruits. In jalapeño pepper, growth-promoting bacteria containing Bacillus, Azospirillum, Azotobacter, and Pseudomonas increased vitamin C concentration to about 123 mg/100 g fresh weight, outperforming purely chemical fertilization and demonstrating that beneficial microorganisms can directly improve key nutritional indices (Márquez-Mendoza et al., 2025). In sandy-loam greenhouse conditions, increasing the rate of organic nutrient and biofertilizer application in sweet pepper led to the highest plant vitamin C content at the top treatment level, in parallel with gains in growth and chlorophyll, implying that enhanced physiological status and nutrient uptake are closely coupled with vitamin C accumulation (Omar and Fadala, 2025). Across diverse cultivars and environments, these findings highlight that well-designed biofertilizer programs reliably raise antioxidant vitamin levels in pepper fruits.

8.2 Accumulation characteristics of flavor compounds (e.g., capsaicin)

The formation of characteristic pepper flavor and pungency is also shaped by biofertilizer use, particularly through effects on capsaicinoid biosynthesis. Under different shading levels, application of a PGPR-VAM consortium to chili pepper increased capsaicin content together with total dry weight and nutrient absorption, and capsaicin concentration was positively associated with fruit mass and plant nitrogen uptake, indicating that biofertilizers promote pungency partly by improving N nutrition and assimilate supply to fruits. In jalapeño pepper, biofertilization with a consortium of growth-promoting bacteria raised capsaicin content to about 250 mg/mL, while simultaneously increasing flavonoids and vitamin C, suggesting coordinated stimulation of both pungent and antioxidant metabolites under microbial treatments (Márquez-Mendoza et al., 2025). These responses imply that capsaicin accumulation is sensitive to rhizosphere biological activity and nutrient dynamics shaped by biofertilizers.

In sweet pepper, where intrinsic pungency is low, biofertilizers influence flavor mainly via sugars, organic acids, and phenolic compounds that determine sweetness, acidity, and aroma. Co-application of vermicompost and biochar in greenhouse sweet pepper significantly increased total soluble solids, titratable acidity, ascorbic acid, β-carotene, and total phenolic content, thereby enhancing sweetness and flavor complexity while also improving physical quality attributes such as fruit weight and flesh thickness (Figure 4) (El-Mogy et al., 2024). Humic-acid-based treatments in sweet pepper similarly modified sugar composition during storage, with biostimulant-treated fruits showing altered sucrose and glucose profiles and higher phenolic content after storage compared with controls, changes that likely translate into a more balanced sweet-acid taste and richer flavor after shelf life (Zamljen et al., 2025). Together, these studies indicate that biofertilizers not only affect capsaicin in pungent types but broadly modulate flavor-related metabolites in both hot and sweet peppers.

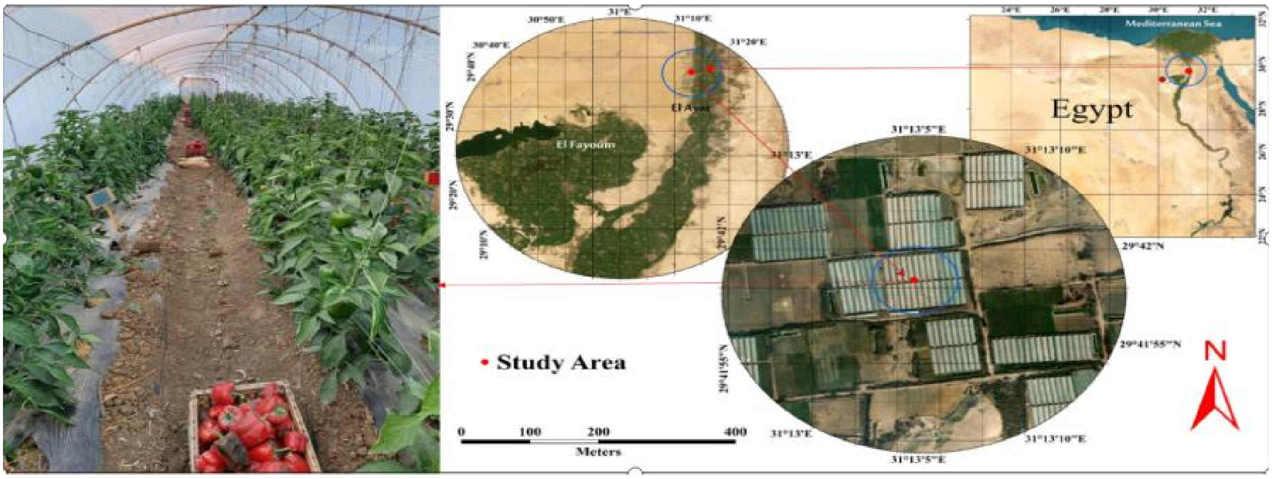

Figure 4 Shows the site of the study area (Adopted from El-Mogy et al., 2024)

8.3 Evaluation of market quality and quality stability

From a market perspective, biofertilizers can improve both **external quality traits** and the stability of these traits during postharvest handling. In bell pepper grown in greenhouses, combinations of organic fertilizer with AMF or Azotobacter-Azospirillum inoculation increased fruit phenolic and ascorbic acid contents while also raising yield, indicating that higher nutritional quality can be achieved without compromising productivity, an important requirement for commercial acceptance (Sini et al., 2024). In capia pepper under soilless culture, using 80% mineral fertilizer with bacteria and mycorrhiza produced heavier fruits with larger diameter and volume, along with higher total soluble solids and fruit juice electrical conductivity, parameters closely linked to consumer perception of sweetness, juiciness, and overall eating quality. These improvements suggest that biofertilizers can support premium-grade fruit size and internal quality while reducing reliance on mineral fertilizers.

Quality stability during storage is another key dimension where biostimulant-based nutrition shows benefits. In sweet pepper, foliar application of a microbial biofertilizer (Biofertile) increased fruit firmness, total soluble solids, and ascorbic acid at harvest, and fruits from treated plants exhibited lower weight loss and better retention of color and firmness after 28 days at 10 °C and high humidity, indicating enhanced storability and prolonged marketable life. Humic acid fertilization of 'Cuccino Orange' pepper similarly improved post-storage pericarp thickness and water retention while increasing total phenolic content relative to the control, pointing to better structural integrity and antioxidant protection during storage (Zamljen et al., 2025). However, not all microbial biostimulant programs guarantee economic benefits; in some tunnel-grown peppers, combined microbial-based products produced only minor or inconsistent improvements in sugars and organic acids, raising questions about cost-effectiveness under certain cultivars and conditions (Majkowska-Gadomska et al., 2021). Overall, evidence indicates that carefully selected biofertilizer strategies can elevate market quality and postharvest stability of peppers, but responses remain genotype- and product-dependent, underscoring the need for system-specific optimization.

9 Comprehensive Benefits and Future Prospects of Biofertilizer Application

Long-term ecological benefits of biofertilizer use in pepper systems arise primarily from improved soil quality and more efficient nutrient cycling. In continuous-cropping pepper on karst yellow soil, the combined application of biochar and vermicompost raised soil organic matter, total N, available P and K, and cation exchange capacity, while also increasing fresh and dry pod yield, indicating simultaneous restoration of soil fertility and productivity in a fragile environment. Similar patterns emerged when coffee-pulp biochar and compost were used in hot pepper, where the highest biochar dose significantly increased soil pH, organic carbon, total N and exchangeable bases, while reducing bulk density, thereby enhancing both chemical and physical soil health indicators under field conditions. These findings show that organic-microbial amendments can counteract acidification, structural degradation, and nutrient depletion often caused by long-term mineral fertilization. Biofertilizers and related amendments also support more sustainable nutrient use by improving fertilizer efficiency and reducing leaching and pollution risks. In pod pepper grown with reduced chemical fertilizer plus biochar, nitrogen partial factor productivity increased markedly at moderate N rates, while yields and fruit quality were maintained or improved compared with conventional high-N fertilization, demonstrating that fewer synthetic inputs can produce equal or greater output when soil biological functioning is enhanced. At a broader scale, a global meta-analysis across many crops found that microbial inoculants consistently increased yield and N and P use efficiency, with the strongest responses in dry climates, supporting their role as a key tool for conserving finite phosphorus resources and lowering the environmental footprint of fertilization. When integrated into pepper systems, these mechanisms translate into lower nutrient losses, better soil biological activity, and greater resilience of soil functions under climate and management stresses.

Economic analyses from pepper trials indicate that biofertilizer-based strategies can improve profitability despite, and sometimes because of, higher upfront input costs. In continuous-cropping pepper on karst soils, co-application of biochar and vermicompost increased fresh pod yield by up to about 50% and dry pod yield by over 70% relative to traditional fertilization, and although amendment costs rose, the net income increased by 0.77-22.34% in the first year and 8.82-59.96% in the second, particularly when both amendments were applied at higher rates. A complementary study where biochar was combined with reduced chemical fertilizer in pod pepper showed that treatment with 70% of conventional fertilizer plus biochar improved both yield and fertilizer use efficiency, and overall economic efficiency increased because savings in mineral fertilizer and added yield more than offset the cost of biochar. These results suggest that, under appropriate rates, bio-based inputs can generate favorable benefit-cost ratios in open-field pepper production. Biofertilizer adoption can also enhance income in lower-input or smallholder contexts and in protected cultivation.

In Afghanistan, applying biofertilizer through both root dipping and soil application raised green pepper yield from 3.8 to 5.4 t/ha, and economic evaluation showed that this combined method generated the highest net income among inoculation strategies, encouraging farmers to shift away from exclusive reliance on chemical fertilizers. Field experiments with organic biofertilizers in bell pepper similarly reported yield increases above 40 t/ha and a benefit-cost ratio near 1.9 for the best treatment, reflecting substantial economic gains relative to untreated controls under commercial-like conditions. In soilless capia pepper, substituting 20% of mineral fertilizer with PGPR and AMF raised yield by 32.4%, indicating that biofertilizers can reduce dependence on costly mineral nutrients in intensive greenhouse systems and lower long-term input expenditure while preserving product quality.

The breadth of pepper production contexts where biofertilizers perform well underscores their application potential, but it also highlights the need for system-specific optimization and deeper mechanistic understanding. In greenhouse bell pepper, combining organic fertilizer with AMF or Azotobacter-Azospirillum inoculation simultaneously increased yield, nutrient uptake, and fruit quality, proving that microbial products can be successfully integrated into high-input protected systems and contribute to eco-efficiency goals. In soilless capia pepper, PGPR and AMF enabled a 20% reduction in mineral fertilizer with improved yield and fruit quality traits, demonstrating that these technologies are compatible with technologically advanced hydroponic systems and can help greenhouse producers meet environmental certification standards. However, responses can vary with cultivar, inoculant strain, and baseline soil conditions, and some studies report only modest quality gains, suggesting that matching inoculant traits to local constraints remains a critical research frontier. Future work should focus on multi-season trials that link soil enzyme dynamics, microbial network structure, and long-term yield stability under continuous pepper cultivation, particularly in degraded or karst landscapes where soil resilience is fragile.

Continuous-cropping studies with microbial organic fertilizers and quicklime have already shown that modifying microbial communities and enhancing available N, P, and K can raise yield and alter co-occurrence network complexity, but the durability of these effects and their economic thresholds require further evaluation. At the global level, meta-analytic evidence indicates that climate, soil P status, and organic matter strongly condition biofertilizer performance, implying that future pepper research should integrate these factors into decision-support tools that recommend suitable inoculant types and application rates for specific environments. Priority areas include developing cost-effective consortia tailored to pepper, optimizing combinations with organic wastes such as composted residues or liquid by-products, and assessing life-cycle environmental benefits so that biofertilizers can be credibly positioned as core components of climate-smart, enzyme-driven nutrient management in pepper cultivation.

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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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