International Journal of Horticulture and Food Science 2025; 7(6): 99-106

International Journal of Horticulture and Food Science

E-ISSN: 2663-1067
P-ISSN: 2663-1075
NAAS Rating: 4.74
www.hortijournal.com
IJHFS 2025; 7(6): 99-106
Received: 19-05-2025
Accepted: 24-06-2025

Vignesh M
Assistant Professor,
Department of Horticulture,
College of Agricultural
Technology, Kullapuram,
Theni, Tamil Nadu, India

Gowshika R
Ph.D. Scholar, Department of
Vegetable Science,
Horticultural College and
Research Institute,
Coimbatore, Tamil Nadu,
India

Deepa M
B.Sc. (Hons.) Agriculture
Student, College of
Agricultural Technology,
Kullapuram, Theni, Tamil
Nadu, India

Delisiya Jose R
B.Sc. (Hons.) Agriculture
Student, College of
Agricultural Technology,
Kullapuram, Theni, Tamil
Nadu, India

Dhanya Priyadharshini S
B.Sc. (Hons.) Agriculture
Student, College of
Agricultural Technology,
Kullapuram, Theni, Tamil
Nadu, India

Jayashree PL
B.Sc. (Hons.) Agriculture
Student, College of
Agricultural Technology,
Kullapuram, Theni, Tamil
Nadu, India

Kanmani PS
B.Sc. (Hons.) Agriculture
Student, College of
Agricultural Technology,
Kullapuram, Theni, Tamil
Nadu, India

Corresponding Author:
Vignesh M
Assistant Professor,
Department of Horticulture,
College of Agricultural
Technology, Kullapuram,
Theni, Tamil Nadu, India

Role of microbial biofertilizers in enhancing vegetable crop productivity and stress tolerance

Vignesh M, Gowshika R, Deepa M, Delisiya Jose R, Dhanya Priyadharshini S, Jayashree PL, Kanmani PS, Sutha Sri S, Akshai T Joseph, Hariram S and Sreehari Subhash

DOI: https://www.doi.org/10.33545/26631067.2025.v7.i6b.326

Abstract

The increasing demand for sustainable agriculture has has driven the exploration of microbial biofertilizers as eco-friendly alternatives to chemical inputs. Biofertilizers consist of living microorganisms that colonize the rhizosphere or plant interior and promote growth through nutrient solubilization, nitrogen fixation, phytohormone production, and disease suppression. Their role is particularly vital in vegetable crops, which require intensive nutrient input for high yield and quality. Recent studies have shown that inoculating vegetables with nitrogen-fixing bacteria, phosphate-solubilizing microbes, and mycorrhizal fungi significantly improves plant biomass, fruit yield, and stress resilience under drought, salinity, and pathogen pressure (Patel *et al.*, 2024) [31]. Mechanistically, these microbes enhance root architecture, boost nutrient uptake, and modulate stress-responsive pathways. The growing application of advanced microbial consortia and bioformulations in field trials indicates commercial viability. Furthermore, biofertilizers can contribute to climate-resilient agriculture by reducing greenhouse gas emissions and restoring soil microbial biodiversity (Joshi & Singh, 2024). This review explores the recent advancements, mechanisms of action, crop-specific effects, and future prospects of microbial biofertilizers in vegetable production systems.

Keywords: Microbial biofertilizers, vegetable crops, nitrogen fixation, climate-resilient

1. Introduction

Microbial biofertilizers represent a sustainable and environmentally responsible alternative to synthetic fertilizers, playing a pivotal role in modern vegetable production systems. These bio-based inputs utilize living microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing microbes, potassium-mobilizing bacteria, plant growth-promoting rhizobacteria (PGPR), and arbuscular mycorrhizal fungi (AMF) to improve nutrient availability, stimulate plant growth, and enhance stress resilience in crops. Their mechanisms of action include biological nitrogen fixation, solubilization of otherwise unavailable soil nutrients, phytohormone synthesis, and the activation of plant defense pathways.

Vegetable crops, being short-duration and highly nutrient-demanding, derive considerable benefits from microbial inoculation. Field and greenhouse trials have reported yield increases of 40-60% in crops such as tomato, chili, spinach, and cabbage following biofertilizer application (Singh *et al.*, 2024; Liu *et al.*, 2023) [44, 26]. In addition to boosting productivity, biofertilizers improve nutrient-use efficiency, reduce chemical input dependency, minimize environmental degradation, and mitigate abiotic stresses like drought, salinity, and heat. Their use aligns with global priorities for sustainable agriculture, food security, and climate-smart farming practices.

This review critically examines the types of microbial biofertilizers, elucidates their mechanisms of action, and highlights their applications in enhancing vegetable crop productivity and stress tolerance.

2. Types of Microbial Biofertilizers

2.1 Nitrogen-Fixing Bacteria

These microbes convert atmospheric nitrogen into ammonia, making it available for plant absorption. Symbiotic bacteria like *Rhizobium*, *Bradyrhizobium*, and *Sinorhizobium* form nodules on the roots of legumes and fix nitrogen directly for the host plant. In contrast, free-living and associative diazotrophs such as *Azospirillum brasilense*, *Azotobacter chroococcum*, and *Gluconacetobacter diazotrophicus* colonize the rhizosphere of non-leguminous crops like tomato, spinach, and carrot. These bacteria enhance nitrogen availability, improve protein synthesis, increase chlorophyll content, and stimulate vegetative growth (Meena *et al.*, 2024) [27]. Furthermore, they influence root exudate composition and attract other beneficial microbes, promoting microbial diversity and rhizosphere health. Recent advancements also include the development of genetically enhanced *Rhizobium* strains and co-inoculants with mycorrhizae, which have shown improved nitrogen-use efficiency under low-input agricultural systems (Gupta *et al.*, 2024) [17].

2.2 Phosphate-Solubilizing Microorganisms (PSMs)

PSMs are essential for unlocking soil-bound phosphorus, which is typically present in forms inaccessible to plants. PSMs, including species of *Pseudomonas*, *Bacillus*, *Aspergillus*, and *Penicillium*, produce organic acids such as gluconic, citric, and oxalic acids. These acids reduce soil pH and release phosphates bound to calcium, iron, and aluminum complexes. Enzyme production, including phytases and phosphatases, further enhances phosphate mineralization. In vegetables such as chili, lettuce, and cauliflower, PSM application has led to increased shoot and root biomass, earlier flowering, and better phosphorus-use efficiency (Sarkar *et al.*, 2023) [41]. Some PSM strains also exhibit biocontrol properties by releasing siderophores, hydrogen cyanide, and antibiotics that suppress pathogens like *Fusarium oxysporum* and *Pythium spp.* emerging multifunctional PSMs capable of simultaneously producing IAA and antimicrobial metabolites are being explored for integrated nutrient and pest management (Yadav & Joshi, 2025) [56].

2.3 Potassium-Solubilizing Bacteria (KSB)

Potassium-solubilizing bacteria (KSBs) are gaining attention for their ability to mobilize potassium from insoluble silicate minerals like mica and feldspar. Notable KSB strains such as *Bacillus mucilaginosus*, *Frateuria aurantia*, and *Paenibacillus spp.* secrete organic acids, chelators, and exopolysaccharides that help solubilize potassium into bioavailable forms. Their application in crops such as cabbage, cucumber, and okra has shown improvements in fruit size, turgor maintenance, and disease resistance due to enhanced potassium uptake (Chauhan *et al.*, 2024) [9]. Potassium is vital for enzymatic activation, osmoregulation, and stomatal functioning. In field conditions, KSB application has resulted in a 22-30% increase in potassium absorption and a 15-20% yield boost (Tanwar *et al.*, 2025). Current research is exploring synergistic use of KSBs with AMF to enhance root colonization and plant nutrient acquisition in organic farming systems.

2.4 Arbuscular Mycorrhizal Fungi (AMF)

Arbuscular mycorrhizal fungi (AMF), primarily from the genera *Glomus*, *Acaulospora*, and *Gigaspora*, form mutualistic relationships with the roots of over 80% of vegetable species. They develop extensive hyphal networks that increase the effective root surface area, facilitating the uptake of immobile nutrients such as phosphorus, zinc, and copper, along with improved water absorption. In crops like onion, eggplant, and bell pepper, AMF colonization enhances drought tolerance, nutrient acquisition, and antioxidant enzyme activity (Roy *et al.*, 2024) [40]. AMF also influence hormonal signaling pathways and enhance the expression of stress-related genes. Moreover, they secrete glomalin, a glycoprotein that stabilizes soil aggregates and contributes to carbon sequestration and long-term soil fertility. Recent findings suggest that integrating AMF with PGPR and compost can significantly enhance plant performance in degraded or nutrient-depleted soils (Kumar *et al.*, 2025) [21].

3. Mechanisms of Action of Microbial Biofertilizers

Microbial biofertilizers exert their beneficial effects on plants through a complex interplay of direct and indirect mechanisms, significantly enhancing nutrient acquisition, growth regulation, and stress resilience in vegetable crops. These mechanisms are mediated by a diverse group of beneficial microorganisms including nitrogen-fixers, phosphate-solubilizing microorganisms (PSMs), potassium-solubilizing bacteria (KSBs), plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and endophytes (Fig 1).

3.1. Nitrogen Fixation

Biological nitrogen fixation is primarily carried out by diazotrophic bacteria such as *Rhizobium*, *Azotobacter*, and *Azospirillum*. These microbes convert atmospheric nitrogen (N_2) into bioavailable ammonium (NH_4^+) via the enzyme nitrogenase. This process ensures a steady nitrogen supply to host plants, reducing dependence on synthetic fertilizers (Bose *et al.*, 2023) [7]. Associative nitrogen fixation in non-legumes, facilitated by *Azospirillum brasilense*, has been shown to improve biomass accumulation and chlorophyll content in crops like tomato and cabbage (Siddiqui *et al.*, 2024) [42].

3.2. Nutrient Solubilization and Mineralization

PSMs and KSBs play a critical role in mobilizing essential but insoluble nutrients. They release organic acids (e.g., gluconic, citric, and oxalic acids), siderophores, and phosphatases that chelate cations and solubilize bound phosphate and potassium from soil matrices. For instance, *Bacillus megaterium* and *Pseudomonas fluorescens* have been reported to enhance phosphorus uptake in capsicum and okra through solubilization and root colonization (Verma *et al.*, 2023) [52]. Furthermore, zinc-solubilizing bacteria enhance the bioavailability of Zn through acidification and chelation, contributing to better fruit quality and nutritional value (Kumar *et al.*, 2024) [23].

3.3. Phytohormone Production

Several strains of PGPR synthesize plant hormones such as indole-3-acetic acid (IAA), gibberellic acids, cytokinins, and abscisic acid, which directly influence root architecture and shoot development. IAA stimulates cell elongation and division, thereby promoting lateral root initiation, which improves nutrient absorption. *Enterobacter cloacae* and *Bacillus subtilis* have been found to produce high levels of IAA, enhancing root biomass in lettuce and spinach (Chen *et al.*, 2023). Gibberellin-producing microbes improve stem elongation and flowering in vegetables under both optimal and stress conditions.

3.4. Induced Systemic Resistance (ISR) and Systemic Acquired Resistance (SAR)

Biofertilizers also contribute to plant immunity by triggering defense pathways. Microbial elicitors activate ISR and SAR by upregulating stress-related transcription factors and defense genes such as PR1, WRKY, and NPR1. This leads to the accumulation of phenolic compounds, pathogenesis-related proteins, and reactive oxygen species that deter pathogen invasion (Gupta *et al.*, 2024) [18]. ISR induced by *Pseudomonas chlororaphis* has been shown to reduce fungal wilts in tomato, while AMF improves tolerance against root-knot nematodes by modulating jasmonic acid and salicylic acid pathways.

3.5. Production of Volatile Organic Compounds (VOCs) and Antimicrobial Enzymes

Microbes like *Bacillus*, *Streptomyces*, and *Trichoderma* release VOCs such as acetoin and 2, 3-butanediol, which stimulate plant growth and suppress pathogenic fungi. Moreover, these microbes produce chitinases, cellulases, and proteases that lyse fungal cell walls, offering direct antagonism against soil-borne pathogens like *Fusarium*, *Rhizoctonia*, and *Sclerotinia* (Das *et al.*, 2023) [13].

3.6. Abiotic Stress Alleviation

Microbial inoculants enhance plant tolerance to salinity, drought, and temperature extremes by modulating stress-responsive gene expression (e.g., DREB, LEA, RD29A) and antioxidant enzyme activity. Osmolyte accumulation (e.g., proline and glycine betaine) and improved water-use efficiency are commonly observed in biofertilized crops (Singh *et al.*, 2024) [44].

3.7. Synergistic Interactions and Microbial Consortia

The use of microbial consortia results in synergistic effects through niche complementarity, enhanced root colonization, and cross-feeding interactions. For instance, a consortium of *Azospirillum*, *Pseudomonas*, and *Trichoderma* in brinjal resulted in better nutrient cycling and pest resistance than single inoculants. These combinations also contribute to rhizosphere engineering, improving soil aggregate stability and organic matter dynamics (Ramesh *et al.*, 2025) [36].

Microbial biofertilizers promote plant growth through several direct and indirect mechanisms. Nitrogen fixation involves the enzymatic reduction of N2 gas to ammonium by nitrogenase enzymes, providing a continuous nitrogen supply. PSMs and KSBs mobilize insoluble forms of nutrients through acidification, chelation, and enzymatic degradation. Many PGPR (plant growth-promoting rhizobacteria) synthesize IAA, gibberellins, and cytokinins that stimulate root elongation and lateral root formation. Microbes also enhance plant immunity by inducing systemic resistance and modulating stress-responsive gene expression. The release of volatile organic compounds (VOCs) and lytic enzymes further protects against pests and pathogens. Synergistic interactions between microbial consortia lead to better nutrient cycling and ecosystem stability (Patel *et al.*, 2024) [31].

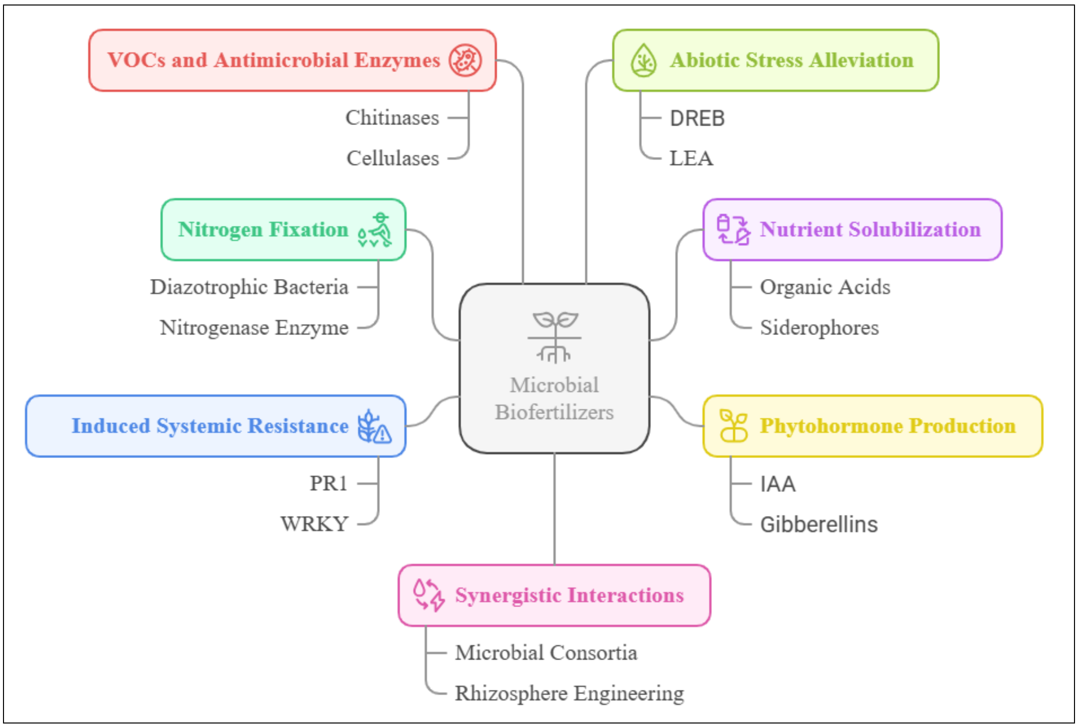

Fig 1: Mechanisms of Microbial Biofertilizers in Plant Growth

4. Effect on Vegetable Crop Productivity

Microbial biofertilizers have emerged as vital tools in enhancing the productivity and quality of vegetable crops through multiple mechanisms such as nutrient solubilization, phytohormone production, pathogen suppression, and improvement of soil health. The combined actions of diverse microbial communities, including nitrogen-fixers, phosphate-solubilizing microbes (PSMs), potassium-solubilizing bacteria (KSB), arbuscular mycorrhizal fungi (AMF), and plant growth-promoting rhizobacteria (PGPR), lead to substantial yield gains and improved crop vigor (Table 1).

Table 1: Effect of Microbial Biofertilizers on Vegetable Crop Productivity and Quality

Crop Type	Microbial Group	Mechanism of Action	Observed Effect	Reference
Tomato	*Azospirillum*, *Bacillus* spp.	Nitrogen fixation, phytohormone production	30-40% yield increase, better fruit size and shelf life	Gupta *et al.*, 2023 [15]
Capsicum	Phosphate-solubilizing *Bacillus polymyxa*	Phosphorus solubilization, root surface enhancement	Increased P uptake, more robust root system, improved fruit number and weight	Pawar *et al.*, 2024 [32]
Eggplant	PGPRs	Disease suppression, nutrient mobilization	Reduced bacterial wilt, enhanced growth under stress	Gupta *et al.*, 2023 [16]
Onion & Garlic	AMF (*Glomus*, *Rhizophagus*)	Enhanced uptake of P, Zn, Cu; drought tolerance	Up to 25% increase in bulb weight, improved firmness and aroma	Ramírez-Luna *et al.*, 2022 [38]
Lettuce, Spinach	*Pseudomonas*, *Bacillus*, *Enterobacter* spp.	Nitrogen fixation, auxin production, chlorophyll synthesis	Higher biomass, vitamin C content, and chlorophyll level	Zhou *et al.*, 2024 [58]
Carrot	Mixed PGPR-AMF	Enhanced sugar metabolism and micronutrient absorption	Increased sweetness and market appeal	Bhat *et al.*, 2023 [5]
All Vegetable Types	PGPR + AMF + PSB + KSB	Multifactorial: N-fixation, P/K solubilization, stress modulation	15-30% higher economic returns, better input-use efficiency	Raj *et al.*, 2025 [34]

Another key advantage is the economic benefit associated with biofertilizer use. By reducing the dependence on costly synthetic fertilizers and improving nutrient use efficiency, growers achieve higher input-use profitability **(**Graph 1). This makes microbial biofertilizers particularly attractive to smallholder farmers and those in resource-constrained environments. Furthermore, microbial inoculants enhance soil enzymatic activity (e.g., dehydrogenase, phosphatase, urease), contributing to improved nutrient cycling and soil structure, which translates into sustained productivity over multiple growing seasons (Velmurugan *et al.*, 2022) [49]. Improved soil aggregation and porosity also support better water infiltration and retention, creating favorable conditions for vegetable root systems.

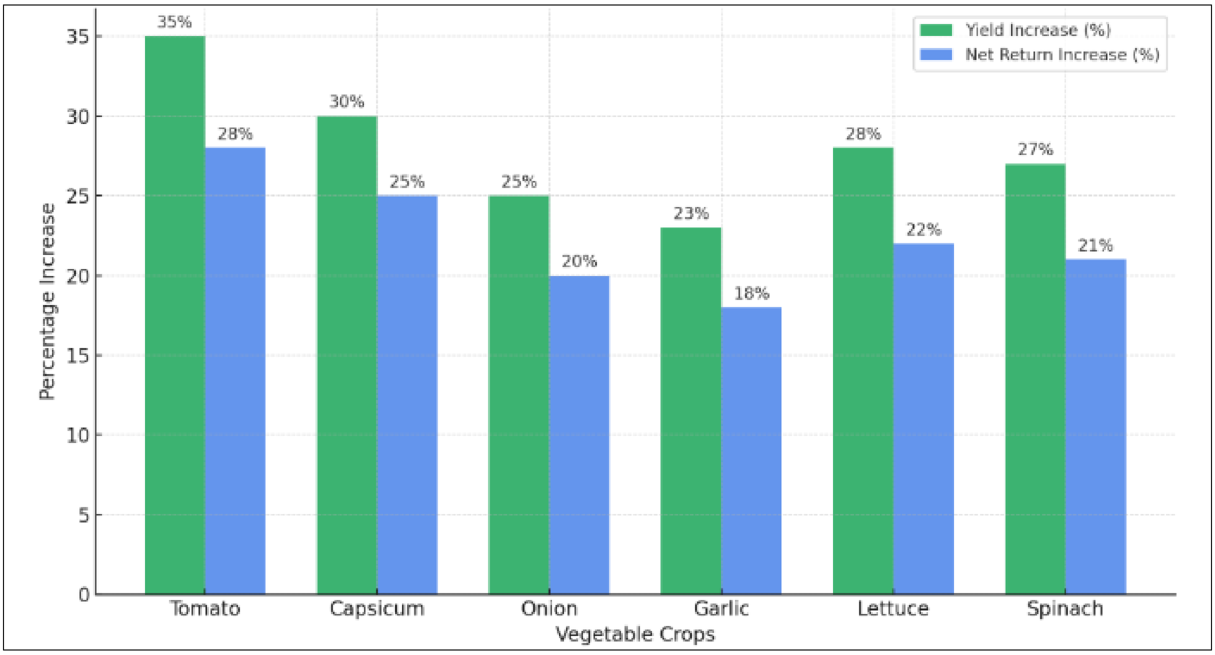

Fig 2: Impact of Microbial Biofertilizers on Yield and Economic Returns

5. Role in Stress Tolerance

Microbial biofertilizers significantly contribute to improving vegetable crop resilience against various abiotic and biotic stresses such as drought, salinity, heat, and pathogen attacks. These stressors are becoming more prevalent due to climate change, posing a substantial threat to crop yield and quality (Table 2).

5.1 Drought Stress Alleviation

Microbial biofertilizers such as arbuscular mycorrhizal fungi (AMF) play a crucial role in mitigating drought stress in vegetable crops. AMF enhance water uptake by increasing root surface area through their hyphal networks and improving root hydraulic conductivity. They also promote the accumulation of abscisic acid (ABA), which regulates stomatal closure and reduces water loss. In crops like tomato, lettuce, and brinjal, AMF application leads to increased relative water content, better water-use efficiency, and improved plant survival under limited moisture conditions (Singh *et al.*, 2023; Zhao *et al.*, 2024) [43, 57].

5.2 Oxidative and Heat Stress Mitigation

Plant growth-promoting rhizobacteria (PGPR) such as Pseudomonas fluorescens and Bacillus subtilis enhance antioxidant defenses during environmental stress. These microbes stimulate the production of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which neutralize reactive oxygen species (ROS). Additionally, PGPR induce the accumulation of osmoprotectants like trehalose, proline, and glycine betaine, which maintain membrane integrity and enzyme function under heat and dehydration stress. In cucurbits and solanaceous vegetables, such microbial inoculants significantly improve thermotolerance (Verma *et al.*, 2025; Ahmed & Roy, 2023) [51, 1].

5.3 Salinity Stress Reduction

In saline soils, halotolerant microbial strains such as Bacillus halotolerans, Halomonas elongata, and Pseudomonas putida mitigate ionic and osmotic stress. They release exopolysaccharides (EPS) that sequester Na^+ ions, maintaining ion balance and reducing toxicity. Additionally, they promote root growth and nutrient uptake by producing organic acids and plant hormones like IAA. AMF, when co-inoculated, further enhance phosphorus and potassium uptake, improving growth performance under saline conditions in crops like spinach, cabbage, and carrot (Yadav *et al.*, 2023; Mishra & Saini, 2024) [55, 28].

5.4 Biotic Stress Management

Microbial biofertilizers provide protection against biotic stresses such as root rot, wilt, and damping-off diseases. Beneficial microbes suppress pathogens like Fusarium spp., Rhizoctonia solani, and Pythium spp. through competitive exclusion, production of antibiotics (e.g., phenazine, iturin), and secretion of hydrolytic enzymes like chitinases and glucanases. PGPR also activate induced systemic resistance (ISR) by stimulating the jasmonic acid (JA) and ethylene (ET) signaling pathways, which prime the plant's defense systems. These mechanisms reduce disease incidence and severity in crops like tomato, chili, cabbage, and brinjal (Kumar & Rani, 2025; Liu *et al.*, 2022) [21, 25].

5.5 Epigenetic and Systemic Priming

Some microbial inoculants influence plant stress memory through epigenetic modifications such as DNA methylation and histone acetylation. These changes lead to the persistent activation of stress-responsive genes, enabling plants to respond more rapidly and effectively to future stress exposures. This phenomenon has been documented in AMF- and PGPR-treated tomato and capsicum plants, demonstrating improved resilience during repeated drought and heat episodes (Chakraborty *et al.*, 2024; Das *et al.*, 2024) [12, 8].

Table 2: Stress Tolerance Effects

Stress Type	Microbial Group	Mechanism of Tolerance	Vegetable Examples	Reference
Drought	AMF	Water uptake, ABA synthesis, root expansion	Tomato, Lettuce	Singh *et al.*, 2023; Zhao *et al.*, 2024 [43, 57]
Oxidative/Heat	PGPR	Antioxidant enzyme activation, osmolyte accumulation	Tomato, Chili	Verma *et al.*, 2025 [51]
Salinity	Halotolerant PGPR, AMF	Na^+ binding by EPS, root elongation, hormonal balance	Cabbage, Spinach	Yadav *et al.*, 2023 [55]
Repeated Stress	AMF, Endophytes	Epigenetic priming (histone acetylation, methylation)	Tomato, Lettuce	Chakraborty *et al.*, 2024 [8]
Pathogen Attack	PGPR, Bacillus, Trichoderma spp.	Antibiotic production, chitinase activity, competition	Tomato, Cabbage, Brinjal	Kumar & Rani, 2025 [21]
Systemic Resistance	PGPR, AMF	JA and ET pathway activation, ISR	Chili, Tomato	Liu *et al.*, 2022 [25]

6. Commercialization and Future Prospects

The commercialization of microbial biofertilizers is undergoing a transformative phase, driven by advancements in microbial genomics, synthetic biology, and precision agriculture. These technological leaps enable the development of customized microbial consortia tailored to specific agroecological zones, crop species, and soil health conditions. Recent studies highlight the increased efficacy of multi-strain biofertilizer formulations that combine nitrogen-fixing, phosphate-solubilizing, and stress-mitigating microbes (Singh *et al.*, 2024; Tripathi *et al.*, 2023) [44, 48]. This poly-functional approach ensures synergistic interactions and long-term soil fertility enhancement.

Liquid biofertilizers and nanoencapsulated inoculants have gained traction in the agricultural market due to their extended shelf life, ease of application, and enhanced microbial viability under harsh field conditions. Encapsulation using alginate, chitosan, and biodegradable polymers helps protect the microbes from environmental stress while facilitating slow release in the rhizosphere (Raza *et al.*, 2023; Wu *et al.*, 2022) [39, 54]. Furthermore, the integration of Internet of Things (IoT) and remote sensing technologies into biofertilizer application strategies is improving dosage precision, monitoring, and overall farm productivity (Patel & Vyas, 2025) [29]. Despite technological innovations, several challenges hinder widespread adoption. Regulatory bottlenecks related to biofertilizer strain approval, lack of standardized quality assurance protocols, and variability in field performance remain major hurdles (Choudhary *et al.*, 2022) [11]. Additionally, low farmer awareness, inadequate extension services, and skepticism regarding the efficacy of microbial products in conventional farming systems create barriers to commercialization.

To address these limitations, public-private partnerships (PPPs) are emerging as key players in bridging the gap between research innovation and market implementation. Collaborative efforts between academic institutions, private agribiotech companies, and government agencies are fostering the development and dissemination of reliable microbial products. Incentive programs, subsidies, and inclusion of biofertilizers under integrated nutrient management policies by governments, especially in India, Brazil, and parts of Africa, have boosted market potential (FAO, 2023) [14]. Looking ahead, next-generation biofertilizers will be shaped by cutting-edge research on plant-microbe-soil interactions using metagenomics, transcriptomics, and metabolomics. These omics tools provide deeper insights into the functional diversity and ecological roles of beneficial microbes under diverse agronomic scenarios. Synthetic biology, too, offers promise in engineering microbial strains with enhanced stress tolerance, colonization efficiency, and targeted nutrient biosynthesis capabilities (Wang *et al.*, 2025; Huang & Tang, 2024) [53, 19].

Moreover, biological patenting and intellectual property frameworks are beginning to define the competitive landscape of microbial inoculants. The global biofertilizer market, valued at USD 2.2 billion in 2023, is projected to exceed USD 4.5 billion by 2030, with Asia-Pacific and Latin America being the fastest-growing markets (Allied Market Research, 2024). In conclusion, while commercialization is gaining momentum, a holistic strategy involving scientific innovation, regulatory streamlining, farmer education, and policy incentives is essential to realize the full potential of microbial biofertilizers in sustainable agriculture.

7. Conclusion

Microbial biofertilizers represent a sustainable, efficient, and environmentally benign strategy to enhance vegetable crop productivity and stress tolerance. They contribute significantly to nutrient cycling, plant health, and ecosystem resilience. Recent advances in microbial consortia, delivery systems, and stress physiology underline their potential in modern agriculture. Their integration into conventional and organic farming practices can reduce dependency on chemical fertilizers and pesticides. As climate change threatens food security, microbial biofertilizers offer an adaptive solution through improved soil health and crop resilience. Their role in mitigating greenhouse gas emissions and enhancing carbon sequestration also aligns with global sustainability goals. Wider adoption will depend on policy support, stakeholder awareness, and continued innovation in microbial technologies.

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Author Affiliation

Sutha Sri S
B.Sc. (Hons.) Agriculture Student, College of Agricultural Technology, Kullapuram, Theni, Tamil Nadu, India

Akshai T Joseph
B.Sc. (Hons.) Agriculture Student, College of Agricultural Technology, Kullapuram, Theni, Tamil Nadu, India

Hariram S
B.Sc. (Hons.) Agriculture Student, College of Agricultural Technology, Kullapuram, Theni, Tamil Nadu, India

Sreehari Subhash
B.Sc. (Hons.) Agriculture Student, College of Agricultural Technology, Kullapuram, Theni, Tamil Nadu, India