

BIO-INOCULANTS FOR SUSTAINABLE FLORICULTURE

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ABSTRACT

Floriculture, a globally significant horticultural sector valued at over USD 55 billion, remains heavily dependent on synthetic fertilizers, fungicides, and pesticides that compromise soil health, water quality, and biodiversity. The urgent need for sustainable alternatives has directed attention toward microbial bio-inoculants—plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), biocontrol agents, endophytes, cyanobacteria, and microbial consortia—as transformative inputs in ornamental crop production. This review critically evaluates their mechanisms of action, including nutrient mobilization, phytohormone regulation, disease suppression, and abiotic stress tolerance. Empirical evidence across major floricultural species (rose, chrysanthemum, marigold, gladiolus, gerbera, carnation, orchid, jasmine, tuberose, lily, and petunia) demonstrates their potential to enhance yield, quality, and post-harvest longevity under both open-field and protected cultivation. Integration of bio-inoculants within organic farming, integrated nutrient management (INM), and climate-smart production frameworks is examined alongside advances in formulation strategies and application methodologies. Persistent challenges—such as inconsistent field efficacy, short shelf life, limited farmer adoption, and fragmented regulatory oversight—are critically analyzed. Emerging innovations, including nano-bioinoculants, synthetic microbial consortia, omics-guided strain selection, and AI-enabled precision floriculture, are highlighted as promising avenues to bridge the gap between controlled-environment success and commercial reliability. By identifying key research gaps and recommending priority areas for translational research, policy support, and commercialization, this review underscores the pivotal role of bio-inoculants in accelerating the transition toward biologically intensive, resilient, and environmentally responsible floriculture.

KEYWORDS: bio-inoculants, floriculture, PGPR, mycorrhizae, sustainable horticulture, ornamental crops, plant growth promotion, biocontrol.

INTRODUCTION

Floriculture is a specialized branch of horticulture that encompasses the cultivation of ornamental plants, including cut flowers, potted plants, bedding plants, and garden ornamentals (Titisari, 2025). Flowers have been integral to human culture for millennia, serving aesthetic, ceremonial, and economic purposes across diverse societies. In many communities, ornamental species are central to both daily life and spiritual practice; they are extensively used in wreaths, garlands, floral arrangements, home décor, religious ceremonies, and various social events, functioning as symbols of beauty and emotional expression (Deguenon et al., 2024).

The global floriculture industry has experienced remarkable growth over the past few decades, emerging as a major agricultural sector with significant economic implications. More than 140 countries are currently engaged in commercial flower production, reflecting the universal demand for ornamental plants and flowers (Kumar et al., 2020). According to recent estimates, the global area under flower cultivation spans approximately 702,383 hectares, with Asia accounting for the largest share, followed by South America, Europe, and North America (Chauhan et al., 2022). This geographic distribution underscores both the climatic diversity suitable for floriculture and the expanding market demand across different regions.

Market analyses project substantial growth in the global floriculture sector, with estimates suggesting the market will reach approximately USD 113.38 billion by 2032 (Pereira et al., 2021). This growth trajectory is driven by multiple factors, including increased urbanization, rising disposable incomes, growing consumer preference for ornamental and decorative products, expanding use of flowers in corporate and social events, and the development of sophisticated retail and online distribution channels (Gabbellini & Scaramuzzi, 2022).

India has emerged as one of the major floriculture-producing nations globally, with cultivation reported on approximately 285,000 hectares of land (Anumala & Kumar, 2021). The Indian floriculture sector has witnessed rapid expansion, propelled by targeted government initiatives, technological advancements in cultivation practices, and favorable agro-climatic conditions across different regions. In 2023-2024, the sector produced approximately 2.28 million metric tons of loose flowers and 0.95 million metric tons of cut flowers, demonstrating its substantial scale and commercial potential (Kumar et al., 2021).

Roses, carnations, orchids, gerberas, anthuriums, chrysanthemums, gladiolus, marigold, tuberose, and jasmine are among the most popular and commercially important flowers produced in India (Deguenon et al., 2024). The market for potted plants and bulbous ornamentals, particularly lilies, has also expanded considerably in recent years, solidifying their position in both domestic and export markets (Sharma et al., 2023). Beyond traditional ornamental uses, there is growing interest in utilizing flowers for natural dye extraction in textiles, food coloring applications, and the production of essential oils and fragrances for the perfume industry (Bhosale & Gobade, 2025).

While numerous studies have documented the economic growth of floriculture and the widespread use of pesticides, limited attention has been given to sustainable alternatives and their integration into commercial production systems (Zhang et al., 2024). This gap necessitates a comprehensive review of pesticide overuse, its environmental impacts, and potential eco-friendly strategies for sustainable floriculture (Pereira et al., 2024).

Scope and Hypothesis

This analysis rigorously evaluates the function of bioinoculants in enhancing sustainable floriculture by integrating recent developments in plant-microbe interactions, microbial processes, crop-specific uses, and innovative technology. Plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), phosphate-solubilizing microorganisms, potassium-solubilizing microorganisms, nitrogen-fixing bacteria, mycorrhizal fungi (PPFM), and helpful fungi are among the main categories of bioinoculants included in this review. Nutrient mobilization, phytohormone production, siderophore secretion, ACC deaminase activity, biological control of infections, and improvement of abiotic stress tolerance are among the mechanisms of action that are discussed (dos Reis et al., 2024; Díaz-Rodríguez et al., 2025).

With a focus on plant growth, flower yield, quality, soil health, and environmental sustainability, the review also assesses the use of bioinoculants in important ornamental crops like rose, chrysanthemum, gerbera, carnation, jasmine, marigold, tuberose, gladiolus, lily, petunia, and orchids. For the creation of next-generation bioinoculants, it also emphasizes formulation technologies, commercialization difficulties, farmer adoption, regulatory concerns, and cutting-edge tools like microbiome engineering, metagenomics, multi-omics techniques, and artificial intelligence (Monica et al., 2025). This study identifies research gaps and suggests future options for improving the sustainability and resilience of floriculture production systems by incorporating the most recent scientific findings.

The idea behind this review is that bioinoculants can be sustainable substitutes for chemical pesticides and fertilizers in floriculture, improving crop quality and yield while reducing environmental harm. It is predicated on the idea that, when carefully managed, plant-microbe interactions can enhance nutrient availability, bolster plant resistance to biotic and abiotic stressors, and promote long-term soil health.

Pesticide Overuse And Environmental Impacts

In contrast to food crops, flowers are frequently cultivated in protected environments such as greenhouses and polyhouses, which create favorable conditions for rapid pest and disease proliferation, consequently necessitating frequent and intensive pesticide applications. Numerous studies have documented that flower crops are among the agricultural commodities with the highest pesticide application rates globally. Cut flower production systems can have pesticide application rates exceeding 22-24 kg ha⁻¹, which is approximately 9-33 times higher than application rates for staple field crops such as wheat and maize (Yin et al., 2023).

Analytical investigations of harvested ornamental flowers, including roses, gerberas, and chrysanthemums, have detected over 100 different active pesticide ingredients, including acephate, methomyl, monocrotophos, chlorothalonil, and deltamethrin (Yin et al., 2023). A substantial proportion of these applied pesticides do not reach their intended targets and instead persist in the environment. Studies indicate that approximately 25% of pesticides used in greenhouse floriculture can accumulate in surface soils, where they may persist for extended periods due to strong adsorption and slow degradation rates (Pathak et al., 2022).

Such accumulation interferes with critical soil biological processes, resulting in decreased microbial activity, loss of soil biodiversity, impaired nutrient cycling, and ultimately a decline in soil fertility and productivity. The extensive and often inefficient use of pesticides has also led to significant environmental emissions, primarily through runoff into surface waters and leaching into groundwater systems (Mohammad & El-Refaey, 2023). These processes result in the contamination of soil and aquatic ecosystems, causing unintended exposure and toxicity to non-target organisms, including beneficial insects, pollinators, and aquatic fauna such as fish and amphibians (Sánchez-Bayo, 2021).

Specific pesticide classes have been demonstrated to have particularly severe ecological impacts. For instance, the herbicide atrazine has been shown to disrupt sexual development in amphibians, while neonicotinoid insecticides such as clothianidin can compromise the immune systems of pollinators, particularly honeybees and wild bee species (Alberoni et al., 2021).

Chemical Fertilizer Overuse And Soil Degradation

In addition to pesticides, floriculture systems employ substantial quantities of chemical fertilizers to enhance flower size, color intensity, stem strength, and overall yield. Production systems typically involve high inputs of nitrogen (N), phosphorus (P), potassium (K), and various micronutrients, often exceeding the actual nutrient uptake capacity of plants (Khambalkar et al., 2025). Such unbalanced and excessive nutrient application, particularly under the intensive irrigation regimes commonly employed in greenhouse cultivation, leads to significant nutrient losses through leaching, resulting in soil acidification, secondary salinization, and groundwater contamination (Bhatt et al., 2025).

Conventional fertilizer broadcasting techniques, which involve manual distribution of nutrients over the soil surface without precise control over application rates or timing, exacerbate nutrient inefficiency. This approach has been reported to significantly increase production costs, reduce crop nutrient use efficiency, lower yields, and contribute to greenhouse gas emissions, particularly nitrous oxide (N₂O), a potent greenhouse gas (Hosen et al., 2026).

Human Health Risks

The health implications of pesticide exposure in floriculture extend beyond environmental concerns to direct human health risks. Evidence demonstrates that florists and flower farm workers are directly exposed to pesticide residues during routine activities such as handling treated cut flowers, preparing bouquets, and working in pesticide-treated greenhouses. Dermal absorption represents a primary route of exposure for these workers. Biomonitoring studies assessing agricultural and greenhouse workers routinely detect multiple pesticide residues and their metabolites in urine, indicating significant occupational absorbed doses that lead to systemic oxidative damage and potential health risks (Costa et al., 2022; Toumi et al., 2020).

Epidemiological studies have consistently linked long-term occupational pesticide exposure to various adverse health outcomes, including neurological disorders, respiratory problems, reproductive abnormalities, endocrine disruption, and genotoxic effects (Ahmad et al., 2024; Shekhar et al., 2024).

2. BIOINOCULANTS

According to Backer et al. (2018), and Kumar et al. (2020), bio-inoculants are prepared preparations that contain live microorganisms, such as bacteria, fungi, or their consortia, that colonize the rhizosphere, rhizoplane, or internal plant tissues and improve plant growth, nutrition, and health through one or more biological mechanisms. They differ from bio-stimulants (which may include non-microbial formulations) and biopesticides (though some include biocontrol qualities). Biofertilizers (microbes that fix nitrogen and solubilize phosphate), plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), biocontrol agents, cyanobacteria, endophytes, and multispecies consortium formulations are the main categories (Basu et al., 2021).

Over the past ten years, the global bioinoculant (microbial fertilizer) market has grown steadily due to rising demand for environmentally friendly substitutes for synthetic fertilizers and sustainable agricultural inputs. The global microbial fertilizer market grew from USD 2.8 billion in 2022 to roughly USD 3.1 billion in 2023 and is expected to reach USD 5.2 billion by 2028, showing the sector's ongoing rise, according to recent industry analyses compiled by Atum and Akay (2025). According to other market projections included in the analysis, the global market was estimated to be worth USD 1.41 billion by Precedence Research and USD 1.38 billion by Grand View Research, both of which projected a compound annual growth rate (CAGR) of between 12.8–13% over the next ten years.

2.1 Major categories of bio-inoculants

2.2.1 Biofertilizers

Beneficial live microorganisms that colonize the rhizosphere or plant tissues and improve nutrient availability and uptake are found in biofertilizer formulations. In contrast to chemical fertilizers, they increase soil fertility by phytohormone production, siderophore synthesis, nutrient solubilization, biological nitrogen fixation, and rhizosphere microbial activity stimulation. As a result, biofertilizers limit environmental contamination, enhance nutrient-use efficiency, lessen reliance on synthetic fertilizers, and promote sustainable crop production (Kumar et al., 2022).

Free-living, associative, and symbiotic diazotrophs such as *Azotobacter*, *Azospirillum*, *Rhizobium*, *Bradyrhizobium*, and *Herbaspirillum* make up nitrogen-fixing biofertilizers. Through biological nitrogen fixation, these microbes transform atmospheric nitrogen (N_2) into ammonia that plants may use. *Azotobacter*, *Azospirillum*, and *Herbaspirillum* improve nitrogen availability in cereals, horticultural, and ornamental crops, while *Rhizobium* and *Bradyrhizobium* create symbiotic root nodules in legumes (Fasusi et al., 2021).

By secreting organic acids and phosphatases that solubilize inorganic phosphates and mineralize organic phosphorus, phosphate-solubilizing microorganisms (PSM), such as *Bacillus megaterium*, *Pseudomonas striata*, and *Aspergillus niger*, improve the availability of phosphorus. Enhanced phosphorus nutrition enhances root development, blooming, and overall crop output while reducing the requirement for artificial phosphorus fertilizers (Nosheen et al., 2021).

By producing organic acids and chelating chemicals, potassium-solubilizing bacteria (KSB) such *Bacillus mucilaginosus* and *Frateruria aurantia* mobilize potassium from insoluble minerals like feldspar and mica. This enhances crop yield and quality, stress tolerance, photosynthetic efficiency, and nutritional balance (Kumar et al., 2022; Nosheen et al., 2021).

Beyond nutrient mobilization, biofertilizers enhance soil biological health by stimulating beneficial microbial populations, increasing enzyme activities, improving nutrient cycling and organic matter turnover, and maintaining long-term soil fertility. Their application reduces fertilizer input costs while improving productivity, making biofertilizers an environmentally sustainable and economically viable component of modern agriculture and floriculture (Olaniyan et al., 2022).

2.2.2 Plant Growth-Promoting Rhizobacteria (Pgpr)

High aesthetic quality and a long postharvest life are requirements of the floriculture industry, which are often satisfied by significant synthetic fertilizer and pesticide inputs. The industry is moving more and more toward biologically based crop management due to growing pesticide prices and the pressing need for environmental sustainability. Plant growth-promoting rhizobacteria (PGPR) have become one of these tactics' most successful bioinoculants, improving growth, maximizing nutrient use, and reducing illness (South et al., 2021).

Through a synergistic combination of direct and indirect methods, PGPR colonize the rhizosphere and root surfaces, promoting plant health (Basu et al., 2021). By fixing biological nitrogen, solubilizing phosphates, generating phytohormones like indole-3-acetic acid (IAA), and improving root system architecture to optimize vital mineral intake, these bacteria directly support growth. By generating antibiotics, siderophores, hydrogen cyanide, lytic enzymes, and volatile organic compounds (VOCs), PGPR indirectly shields plants from diseases. Additionally, they cause induced systemic resistance (ISR), which strengthens the plant's natural defenses against a variety of biotic stressors.

PGPR are potent biostimulants that can partially replace synthetic nutrients in ornamental horticulture, especially in greenhouse systems, without compromising floral performance. For instance, even with lower fertilizer regimens, inoculating *Petunia hybrida* with particular PGPR strains greatly enhanced shoot biomass and flower bud output (South et al., 2021). PGPR is essential for managing biological diseases in addition to growth promotion. *Pseudomonas fluorescens* and *Bacillus subtilis* bio-fungicides successfully suppressed white rust (*Puccinia horiana*) in chrysanthemum cultivation, lowering disease incidence while producing more marketable flowers and financial returns than traditional chemical methods (Hanudin et al., 2017).

2.2.3 Arbuscular Mycorrhizal Fungi (Amf)

About 80% of terrestrial plants, including the majority of floricultural products, have obligatory mutualistic relationships with arbuscular mycorrhizal fungi (AMF), which belong to the phylum Glomeromycota. AMF greatly increases the absorptive surface area of the root system by creating large extraradical hyphal networks. This enables plants to forage for water and relatively immobile nutrients, especially phosphorus, zinc, and copper, well beyond the root depletion zone (Begum et al., 2019; Diagne et al., 2020). This improved nutrient uptake and phytohormone pathway regulation results in strong vegetative development, greater photosynthetic efficiency, and superior flowering features, including more high-quality flowers, in ornamental plants (Parihar et al., 2020).

AMF offers vital resilience against environmental problems typical in extensive greenhouse systems, in addition to growth promotion. They release glomalin-related proteins that stabilize soil structure, modify rhizosphere microbial communities to inhibit soil-borne diseases, and improve drought and salinity tolerance through better water relations (Begum et al., 2019; Jiang et al., 2021). Acknowledging these multipurpose advantages, commercial AMF bioinoculants with broad-host species such as *Rhizophagus irregularis* and *Funneliformis mosseae* are becoming more and more important in sustainable floriculture. These inoculants are essential instruments for lowering reliance on synthetic fertilizers while preserving good crop quality and enhancing natural disease resistance when applied during seedling establishment (Kuyper & Jansa, 2023).

2.2.4 Cyanobacteria

Cyanobacteria (blue-green algae) are photosynthetic prokaryotes that serve as highly effective biofertilizers, particularly for sustainable open-field floriculture. By utilizing sunlight and carbon dioxide, heterocyst-forming genera like *Anabaena* and *Nostoc* naturally convert atmospheric nitrogen into plant-available forms, significantly reducing the need for synthetic fertilizers (Gonçalves, 2021). Additionally, these microorganisms improve physical soil properties by secreting extracellular polymeric substances (EPS) and forming biological soil crusts. This enhances soil aggregation, water-holding capacity, and erosion resistance, creating an optimal environment for healthy root development and sustained flower production (Muñoz-Rojas et al., 2018).

Beyond improving soil fertility and structure, cyanobacteria act as powerful bio-stimulants by synthesizing a diverse array of growth-promoting compounds, including phytohormones (such as IAA), amino acids, and vitamins. These metabolites directly enhance vegetative growth, nutrient uptake, and flowering characteristics (Muñoz-Rojas et al., 2018). Furthermore, they support overall plant health by producing antimicrobial substances that suppress soil-borne pathogens like *Fusarium* and *Rhizoctonia* while simultaneously boosting plant tolerance to abiotic stresses such as drought and salinity. Collectively, these attributes make cyanobacteria invaluable, multifunctional bioinoculants for environmentally sustainable agriculture (Alvarez et al., 2021).

2.2.5 Endophytes

Endophytic microorganisms, encompassing diverse bacteria and fungi, colonize the interior of plant tissues including the xylem, cortex, and mesophyll without eliciting disease symptoms or hypersensitive responses. In sustainable floriculture, their internal colonization enables long-term association with host plants, allowing continuous exchange of metabolites and sustained plant growth-promoting effects, allowing for stable symbiotic relationships that directly enhance the vegetative growth, stress resilience, and aesthetic longevity of ornamental crops. The root endophytic fungus *Piriformospora indica* (syn. *Serendipita indica*) is particularly notable for promoting host growth and abiotic stress tolerance. Recent evaluations indicate that *P. indica* significantly increases the survival rates and physiological resilience of vital floriculture crops such as *Rosa chinensis* (rose) and *Jasminum sambac* under severe drought stress by mitigating oxidative damage and preserving chlorophyll content (Ji et al., 2024). In addition to fungal endophytes, specific diazotrophic (nitrogen-fixing) endophytic bacteria play a critical role in the nutrient acquisition of non-leguminous ornamental crops. For instance, strains such as *Herbaspirillum frisingense*, when inoculated into the roots and leaves of *Cymbidium* orchids, have been shown to substantially increase internal nitrogen and phosphorus contents, thereby accelerating vegetative dry matter accumulation highlighting their potential to improve nutrient-use efficiency and reduce fertilizer inputs (Gontijo et al., 2018).

Furthermore, endophytic bacteria enhance the post-harvest quality of cut flowers. Flower senescence, driven largely by stress-induced ethylene production, is the primary cause of abbreviated vase life in ornamental markets. The introduction of endophyte consortia has been shown to modulate essential phytohormonal pathways including ethylene, auxins, and gibberellins in ornamental crops like French marigold (*Tagetes patula*), effectively sustaining plant vigor and preserving floral quality (Naveed et al., 2022). Beyond growth and hormonal regulation, endophytic fungi serve as an environmentally friendly alternative to chemical fungicides. These biocontrol agents reside within the host to form a biological shield, effectively inducing systemic resistance and decreasing the prevalence of destructive soil-borne phytopathogens such as *Fusarium* in agricultural systems (Grabka et al., 2022).

2.2.6 Biocontrol Agents

Microbial biocontrol agents (BCAs) are living organisms that suppress plant pathogens while acting as bio-stimulants, making them essential components of integrated disease management in sustainable floriculture (Kredics et al., 2024). By utilizing mechanisms such as mycoparasitism, antibiosis, nutrient competition, and induced systemic resistance (ISR), BCAs significantly reduce the reliance on synthetic agrochemicals. Among the most prominent fungal BCAs are *Trichoderma* species (*T. harzianum*, *T. viride*, *T. asperellum*). These robust rhizosphere colonizers actively detect and degrade the cell walls of pathogenic fungi using hydrolytic enzymes like chitinases. This makes them highly effective against devastating soil-borne diseases such as vascular wilts and root rots caused by *Fusarium*, *Rhizoctonia*, and *Pythium* while simultaneously enhancing nutrient uptake and plant vigor in high-value ornamental crops (Abdel-Wahed et al., 2024; Giovanardi et al., 2025).

Bacterial BCAs, particularly *Bacillus* and *Pseudomonas* species, offer distinct and highly effective defense mechanisms both in the soil and post-harvest. *Bacillus subtilis* and *B. amyloliquefaciens* produce environmentally resilient endospores and synthesize antimicrobial lipopeptides that severely disrupt pathogen membranes. They are especially valuable for forming protective biofilms on petals and stems to suppress post-harvest diseases like *Botrytis cinerea* (gray mold) (Doria et al., 2025). Meanwhile, *Pseudomonas fluorescens* employs competitive exclusion by secreting high-affinity siderophores (such as pyoverdine) that starve soil-borne pathogens of essential bioavailable iron. Furthermore, *Pseudomonas* emits volatile organic compounds and secondary metabolites that directly inhibit pathogens and prime the plant's innate immune system, fortifying ornamental crops against future infections (Giovanardi et al., 2025).

2.2.7 Consortium Inoculants

Consortium formulations combine two or more compatible microbial strains to exploit synergistic interactions—for example, PGPR that improve P availability may enhance AMF colonization efficiency, which in turn supports PGPR by improving root carbon exudation. Empirical evidence increasingly favors consortium over single-strain inoculants for consistent field performance, though compatibility screening and formulation stability remain technical challenges (Basu et al., 2021; Ngalimat et al., 2021).

3. MECHANISMS OF ACTION

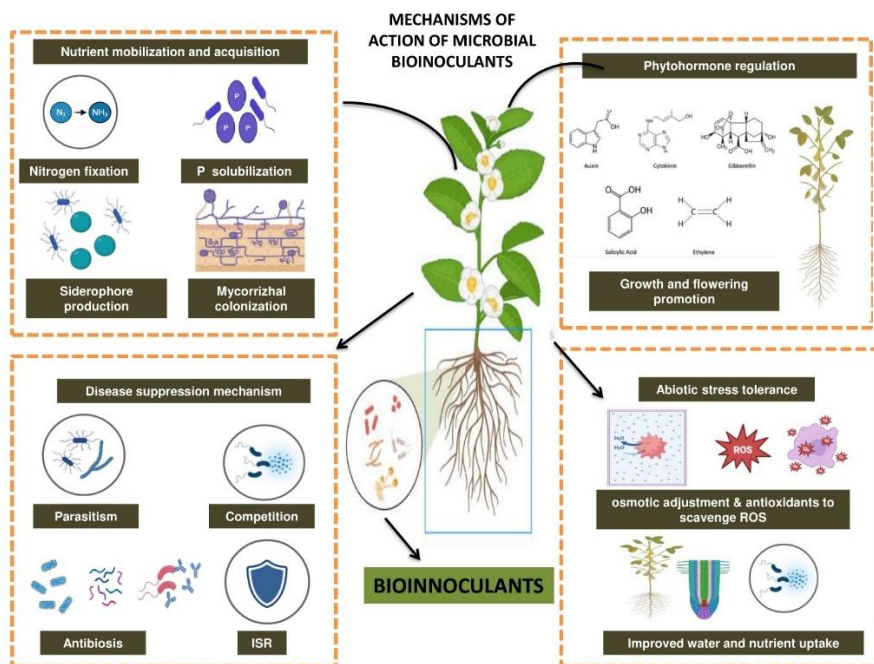


Figure 1. Schematic representation illustrating the diverse mechanisms by which microbial bioinoculants enhance plant health, encompassing nutrient mobilization, phytohormone regulation, disease suppression, and abiotic stress tolerance.

3.1 Nitrogen Fixation

Biological nitrogen fixation (BNF) is catalyzed by the nitrogenase enzyme complex (*nifH*, *nifD*, *nifK* gene products) in diazotrophic bacteria and converts atmospheric N₂ to ammonia (NH₃), which is subsequently assimilated into plant-available forms. Free-living diazotrophs such as *Azotobacter chroococcum* can fix 20–30 kg N ha⁻¹ year⁻¹ under optimal conditions, while associative diazotrophs (*Azospirillum*, *Herbaspirillum*) contribute an estimated 5–20 kg N ha⁻¹ in rhizospheric association with non-leguminous crops. Although floricultural crops are not typically nodule-forming, associative N-fixation in the rhizosphere of nitrogen-demanding species like rose and chrysanthemum can meaningfully supplement synthetic N inputs (Santi et al., 2013; Santi et al., 2013).

3.2 Phosphate And Potassium Solubilization

Soil phosphorus exists predominantly in insoluble inorganic (Ca, Fe, Al phosphates) and organic forms, of which only orthophosphate ions (H₂PO₄⁻, HPO₄²⁻) are plant-available (Sharma et al., 2013). PSM solubilize bound phosphates through production of low-molecular-weight organic acids (gluconic, oxalic, citric, malic acids), which acidify the rhizosphere and chelate cations bound to phosphate groups (Alori et al., 2022). Additionally, PSM produce phytase and phosphatase enzymes that mineralize organic P (Sharma et al., 2013). Given that floricultural soils particularly under

polyhouse cultivation commonly accumulate luxury P from intensive fertilization, PSM may redirect this P pool into plant-available forms while reducing the need for further P inputs (Alori et al., 2017).

Potassium-solubilizing bacteria (KSB) release K from K-bearing silicate minerals (feldspars, micas) through production of organic acids, capsular polysaccharides, and biofilm matrix that enhance mineral weathering rates (Sattar et al., 2019). Though the agronomic contribution of KSB remains more modest than PSM, their combination in consortium formulations can reduce reliance on synthetic K fertilizers, particularly in K-deficient or K-fixing soils used for gladiolus, tuberose, and lily bulb production (Olaniyan et al., 2022).

Auxin (predominantly indole-3-acetic acid, IAA) produced by PGPR is arguably the most critical growth-promoting metabolite in bio-inoculant action (Spaepen et al., 2007). Rhizobacterial IAA stimulates primary root elongation at low concentrations while promoting lateral root initiation and root hair proliferation effects that collectively expand the root surface area for nutrient and water absorption (Ali et al., 2009). IAA-producing *Pseudomonas* and *Bacillus* strains have demonstrated consistent improvements in root biomass and transplant establishment in potted ornamentals including gerbera, petunia, and chrysanthemum (Backer et al., 2018).

Cytokinin production by PGPR (*Bacillus subtilis*, *Arthrobacter* spp.) delays leaf senescence, prolongs flowering duration, and stimulates axillary bud development—traits of direct commercial relevance in floricultural systems where extended flowering period is a selection criterion (Ruzzi & Aroca, 2015). Gibberellin-producing PGPR (*Bacillus pumilus*, *Azospirillum brasilense*) have been associated with increased internode elongation and stem length in cut flower crops, potentially reducing the need for synthetic growth regulators (Kumar et al., 2020). Absciscic acid (ABA) modulation by rhizobacteria under drought stress is discussed separately in Section 5.

3.4 Siderophore Production

Iron is a critical micronutrient whose bioavailability is severely limited in calcareous and alkaline soils (pH > 7.0) commonly encountered in floriculture zones of India, Iran, and the Middle East (Saha et al., 2016). Siderophores—low-molecular-weight iron-chelating compounds—secreted by fluorescent pseudomonads (pyoverdins, pseudobactins) and *Bacillus* species (bacillibactin) solubilize Fe³⁺ and transport it to roots via cognate receptor systems, enhancing iron nutrition of crops like rose and gerbera (Ahmed & Holmström, 2014). Concurrently, the iron sequestration activity of siderophores creates a competitive disadvantage for iron-dependent phytopathogenic fungi and bacteria in the rhizosphere, constituting an important biocontrol mechanism.

3.5 ACC Deaminase Activity

1-Aminocyclopropane-1-carboxylic acid (ACC) is the immediate precursor of ethylene in plants. Under biotic and abiotic stresses, ethylene accumulates and triggers a cascade of growth inhibitory responses (Glick, 2014). ACC deaminase-producing bacteria (*Pseudomonas putida*, *Burkholderia phytofirmans*, *Variovorax paradoxus*) cleave ACC into α -ketobutyrate and ammonia, thereby reducing plant ethylene concentrations and alleviating stress-induced growth inhibition (Nascimento et al., 2014). In floricultural contexts, ACC deaminase activity has been linked to improved vase life by delaying petal senescence and to enhanced salinity and drought tolerance, making it a mechanistic target for inoculant strain selection (Gamalero & Glick, 2022).

3.6 Enhanced Nutrient Uptake Via Amf

The extraradical mycelium of AMF explores soil pores inaccessible to roots (diameter < 10 μ m), exploiting microsites depleted of P around roots (Kuyper & Jansa, 2023). Phosphate transporters (PT) at the arbuscule-periarbuscular membrane interface facilitate P flux into cortical cells at efficiencies exceeding non-mycorrhizal roots by 3–5-fold (Ezawa & Saito, 2018). AMF-mediated improvements in P nutrition in floricultural species have been extensively documented for gladiolus, lily, and rose, with consistent effects on root biomass, chlorophyll content, and flowering phenology (Begum et al., 2019).

3.7 Disease Suppression And Induced Systemic Resistance (Isr)

Biocontrol agents suppress plant pathogens through direct mechanisms competition for nutrients and space, antibiotic production (iturin, fengycin, surfactin in *Bacillus*; 2,4-diacetylphloroglucinol and phenazines in *Pseudomonas*), mycoparasitism (*Trichoderma*) and indirect mechanisms including ISR and systemic acquired resistance (SAR) (Lee et al., 2023). ISR, primed by non-pathogenic PGPR, prepares the plant for accelerated defense responses upon pathogen encounter without incurring constitutive defense costs (Pieterse et al., 2014). In roses, *Pseudomonas fluorescens*-induced ISR has been demonstrated to significantly reduce *Botrytis* infection under greenhouse conditions, while *Trichoderma harzianum* provides both direct antagonism of *Fusarium oxysporum* and ISR priming in carnation (Yadav et al., 2017).

3.8 Stress Tolerance Enhancement

Bio-inoculants enhance plant tolerance to abiotic stresses through multiple convergent pathways: upregulation of antioxidant enzymes (superoxide dismutase, catalase, peroxidase), accumulation of osmoprotectants (proline, glycine betaine, trehalose), modulation of aquaporin expression, maintenance of membrane integrity, and suppression of stress-inducible ethylene synthesis via ACC deaminase activity (Gamalero & Glick, 2022).

Table 1: Major Categories and Mechanisms of Bio-inoculants in Floriculture

Bio-inoculant Category	Key Microbial Genera/Species	Primary Mechanisms of Action	Primary Mechanisms of Action
Biofertilizers	<i>Azotobacter</i> , <i>Azospirillum</i> , <i>Rhizobium</i> , <i>Bacillus megaterium</i> , <i>Frateriuria aurantia</i>	Nitrogen fixation (BNF); phosphorus and potassium solubilization; phytohormone and siderophore synthesis.	Kumar et al., 2022; Fasusi et al., 2021; Nosheen et al., 2021
Plant Growth-	<i>Pseudomonas</i>	Direct: BNF, P solubilization, IAA	Backer et al., 2018; South et

Promoting Rhizobacteria (PGPR)	fluorescens, Bacillus subtilis	synthesis. Indirect: Pathogen suppression (antibiotics, HCN, enzymes) and Induced Systemic Resistance (ISR).	al., 2021; Hanudin et al., 2017
Arbuscular Mycorrhizal Fungi (AMF)	Rhizophagus irregularis, Funneliformis mosseae, Glomus fasciculatum, Acaulospora laevis	Hyphal network expansion for enhanced nutrient (P, Zn, Cu) and water uptake; glomalin production for soil aggregation.	Smith & Read, 2008; Rouphael et al., 2015; Asrar et al., 2012; Kuyper & Jansa, 2023
Cyanobacteria	Anabaena, Nostoc, Oscillatoria	Photosynthetic BNF; EPS synthesis for soil structure/moisture; production of phytohormones and antimicrobials.	Gonçalves, 2021; Alvarez et al., 2021; Muñoz-Rojas et al., 2018; Chiaiese et al., 2018
Biocontrol Agents	Trichoderma harzianum, Bacillus amyloliquefaciens, Pseudomonas fluorescens	Mycoparasitism (lytic enzymes) and antibiosis (lipopeptides); competitive exclusion (siderophores); ISR priming (VOCs).	Kredics et al., 2024; Abdel-Wahed et al., 2024; Giovanardi et al., 2025; Doria et al., 2025
Endophytes	Piriformospora indica, Herbaspirillum frisingense	Asymptomatic internal colonization; phytohormone modulation to delay senescence; oxidative stress mitigation.	Ji et al., 2024; Gontijo et al., 2018; Naveed et al., 2022; Grabka et al., 2022
Consortium Inoculants	Multi-strain combinations (e.g., Bacillus or Pseudomonas spp. co-inoculated with Funneliformis mosseae)	Synergistic root colonization; broad-spectrum pathogen defense; ACC deaminase-mediated stress alleviation.	Fasusi et al., 2021; Santoyo et al., 2021; Basu et al., 2021

4. ROLE OF BIO-INOCULANTS IN FLORICULTURAL CROPS

The following section synthesizes crop-specific research, critically comparing outcomes and highlighting inconsistencies where they exist. The reviewed literature spans field trials, greenhouse experiments, and protected cultivation systems.

4.1 Rose (*Rosa Hybrida*, *Rosa Damascena*)

Rose species such as *Rosa hybrida* and *Rosa damascena* are economically important crops worldwide, valued for the cut flower trade and as oil bearing flowers rich in antioxidant compounds (Önder, 2023). Among the most studied strategies to sustainably improve crop yield and resilience is the application of microbial biostimulants, e.g., Arbuscular Mycorrhizal Fungi (AMF), that help plants acquire nutrients and provide them with protection against environmental stresses (Sun & Shahrajabian, 2023).

The use of certain bacterial strains, such as *Pseudomonas fluorescens*, in the rose industry is more complicated. Some applications and environmental interactions of *P. fluorescens* have been reported to positively promote the vase life of cut rose flowers (Li et al., 2021). In contrast, *P. fluorescens* has also been demonstrated as having antagonistic activity, having been isolated directly from cut stem vasculature where it causes vascular blockage and deleterious bent-neck symptoms in *Rosa hybrida* (Lee & Kim, 2018). This highlights the significance of highly specific strain selection and application strategies in the development of bioinoculants for floriculture.

4.2 Chrysanthemum (*Chrysanthemum Morifolium*)

Chrysanthemum is a major pot plant and cut flower crop with a good market presence worldwide. One of the key goals of sustainable floriculture is to decrease reliance on synthetic fertilizers without sacrificing aesthetic quality. The dual inoculation of root systems with nitrogen fixing bacteria (like *Azospirillum*) and Arbuscular Mycorrhizal Fungi (AMF) has been found to result in a remarkable increase in nutrient uptake. These organisms are complementary rather than overlapping. AMF mainly extends the physical reach of the root system for phosphorus scavenging, while PGPRs fix atmospheric nitrogen and secrete root-stimulating phytohormones (Barea et al., 2005).

A notable mechanism for improving post-harvest quality through sustainable practices is the enhanced mineral nutrition provided by these bio-inoculants. Increased calcium and potassium uptake facilitated by microbial symbionts directly translates into improved cell wall rigidity and stomatal regulation, which are critical for extending vase life and delaying petal senescence (Rouphael & Colla, 2018). Furthermore, microbial communities are increasingly utilized in protected polyhouse cultivation to sustainably manage pathogens, reducing the need for chemical fungicides.

4.3 Marigold (*Tagetes Erecta*, *Tagetes Patula*)

Marigold is among the most cultivated loose flower crops, grown extensively for religious markets, dye extraction, and essential oil production. Intensive marigold cultivation traditionally requires heavy NPK fertilization; however, sustainable floriculture models emphasize the use of microbial consortia to offset these chemical inputs. The integration of phosphate-solubilizing bacteria (PSB) and nitrogen-fixing strains like *Azotobacter* can significantly reduce the required chemical fertilizer doses while maintaining flower dry weight, carotenoid content, and essential oil yields

(Lugtenberg & Kamilova, 2009). This practice directly benefits smallholder farmers by lowering input costs and reducing nutrient runoff.

Additionally, marigold is widely recognized for its root exudation of nematicidal allelochemicals, such as α -terthienyl. Incorporating marigold into crop rotations is a cornerstone of sustainable nematode management. Emerging research in rhizosphere dynamics suggests that vigorous root colonization by PGPRs can enhance root biomass and, by extension, the volume of nematicidal compounds released into the soil profile, reinforcing the crop's utility in sustainable agricultural systems.

Among the bioinoculants tested for *Tagetes erecta* L., *Azotobacter chroococcum* strain HT-54 was found to be the most effective treatment, giving better results in plant biomass, shoot and root dry weights, height and flower count. The *Pseudomonas* sp. strain P-36 was in the second position for its good growth parameters and highest root fresh weight. Strain HT-54 was performed following its schedule, whereas PGPR isolate SD-25 was superior in inducing the earliest flower initiation. The results suggest that SD-25 is the best choice for early flowering, while HT-54 and P-36 are most effective in promoting total vegetative growth and floral yield (Kumar & Pathak, 2023).

4.4 Gladiolus (*Gladiolus Grandiflorus*)

Gladiolus is a corm-propagated crop where both vegetative quality (corm size, corm weight, cormlet production) and inflorescence quality (spike length, floret count) determine market value. In sustainable production systems, AMF colonization is particularly valuable for bulbous and corm-based crops, as the fungal network acts as a powerful sink for photosynthates, ultimately driving greater biomass accumulation in the daughter corms (Barea et al., 2005).

A major constraint in gladiolus production is *Fusarium* corm rot (*Fusarium oxysporum* f. sp. *gladioli*). Conventional production relies heavily on chemical fungicide dips, which pose environmental and resistance risks. Sustainable floriculture increasingly utilizes robust biocontrol agents, particularly *Trichoderma harzianum*. *Trichoderma* species act as opportunistic, avirulent plant symbionts that colonize the corm surface and rhizosphere, outcompeting pathogenic *Fusarium* for nutrients and space while inducing systemic resistance within the plant (Harman et al., 2004). Applying *Trichoderma* as a pre-plant corm treatment offers a viable, eco-friendly alternative to chemical disease management.

4.5 Gerbera (*Gerbera Jamesonii*)

Gerbera jamesonii is one of the most commercially important cut flower crops in the world, heavily reliant on the floriculture trade and is mainly produced under protected cultivation. While plant nutrition management is important, researchers are increasingly using biological treatments to improve growth and vase life of flowers. For example, inoculation of *Gerbera* seedlings with Arbuscular Mycorrhizal Fungi (AMF) has been reported to significantly improve flower yield by up to 44% and increase post-harvest vase life by as much as 28%, particularly with the mitigation of environmental stressors such as soil salinity (Othman et al., 2022).

Vascular integrity of the cut stem is an important factor in post-harvest longevity of *Gerbera*. The xylem occlusion caused by the proliferation of bacteria in the vase water and stem adversely affects the water balance and rapidly deteriorates the aesthetic quality of the flower (Chen et al., 2023). Thus, it is required to adjust the cell water status and structure by interventions. For example, specific pre-treatments with gibberellin A3 and calcium chloride lead to the inhibition of flower stem bending and a significant increase in vase life (Tonooka et al., 2023). The best way to improve the quality of *Gerbera* is to combine early-stage bio-inoculants for strong physiological development with post-harvest treatments to control bacterial succession.

4.6 Carnation (*Dianthus Caryophyllus*)

Carnation production is severely constrained by *Fusarium* wilt (*Fusarium oxysporum* f. sp. *dianthi*), which remains one of the most destructive soilborne diseases in global floriculture. Traditional management has heavily relied on systemic chemical fungicides, but repeated monoculture in protected greenhouse systems often leads to pathogen resistance, chemical toxicity, and "soil fatigue." In the context of sustainable floriculture, the application of microbial bioinoculants presents a highly effective and ecologically sound alternative for both disease suppression and plant growth promotion.

Research demonstrates that pre-plant applications of antagonistic fungi and bacteria can dramatically reduce wilt incidence. Arici et al. (2019) evaluated various biological preparations against *Fusarium* wilt in carnation and found that *Trichoderma harzianum* and *Bacillus subtilis* treatments could suppress the disease by up to 96% under controlled conditions, vastly outperforming untreated controls where plants experienced complete mortality. These biocontrol agents work through multifaceted mechanisms: *Trichoderma* strains utilize competitive saprophytic ability, mycoparasitism, and the secretion of volatile inhibitory compounds to directly hinder fungal mycelial growth (Zandyavari et al., 2024).

Because carnations are susceptible to multiple soilborne pathogens including *Pythium* and *Rhizoctonia* in addition to *Fusarium*—they are ideal candidates for multi-pathogen consortium biocontrol strategies. Combining fungal mycoparasites like *Trichoderma* with the antibiosis and biofilm-forming properties of *Bacillus subtilis* creates additive biocontrol efficacy. These bioinoculants not only manage disease pressure through the release of antimicrobial lipopeptides but also actively promote root biomass and prime induced systemic resistance (ISR) within the plant offering physiological benefits that traditional fungicide treatments lack (Ongena & Jacques, 2008).

4.7 Orchid (Various Genera: *Dendrobium*, *Phalaenopsis*, *Cymbidium*)

Orchids occupy a unique niche in bio-inoculant research due to their natural obligate dependence on Orchid Mycorrhizal Fungi (OMF) for seed germination. Because orchid seeds lack an endosperm, they are entirely mycoheterotrophic during early development, relying heavily on basidiomycete fungi predominantly from the *Rhizoctonia* aggregate, including the genera *Tulasnella* and *Ceratobasidium* for carbon and nutrient provisioning (Dearnaley et al., 2019). This inherent evolutionary dependence makes orchids highly responsive to mycobiome management within sustainable floriculture systems.

In commercial orchid production, tissue culture is the standard propagation method, but ex-vitro acclimatization (hardening) is often constrained by high transplant mortality, making it a major cost driver. The application of root-colonizing endophytic fungi, particularly *Serendipita indica* (formerly *Piriformospora indica*), has emerged as a transformative bio-inoculant strategy. Research demonstrates that *S. indica* colonization significantly accelerates protocorm development, increases root biomass, and drastically improves the survival rates of tissue-culture-raised plantlets during greenhouse transfer. For example, inoculating *Cymbidium* plantlets with *S. indica* not only enhances nutrient acquisition but also mitigates the severe abiotic shock of the ex-vitro transition, leading to vigorous growth and higher survival without chemical interventions (Shah et al., 2019).

Furthermore, the integration of these endophytes offers an avenue for sustainable disease management. While the long-term durability of *S. indica* against specific orchid pathogens like *Phytophthora* and *Fusarium* across multiple production cycles requires further commercial-scale investigation, the endophyte is widely documented to induce systemic resistance (ISR). Colonization primes the plant's defense pathways and upregulates antioxidant enzyme activity, providing a biological buffer against both abiotic stress and complex pathogenic infections (Varma et al., 1999).

4.8 Jasmine (*Jasminum Sambac*, *Jasminum Grandiflorum*)

Intensive jasmine production often leads to soil fertility depletion and heightened susceptibility to insect pests, making the crop a prime candidate for microbial intervention (Murugan & Ravi, 2020; Rajiv et al., 2025). The application of biofertilizers, such as Azophos, in conjunction with organic amendments significantly improves soil nutrient mobilization, which translates into increased vegetative growth and higher overall flower yields. Furthermore, these microbial inoculants accelerate early flower bud initiation by enhancing the transport of growth-promoting substances, such as cytokinins, to the axillary buds (Rajiv et al., 2025).

In addition to growth promotion, bioinoculants serve a critical role in managing severe jasmine pests, including budworms (*Hendecasis duplifascialis*), whiteflies (*Aleuro clava jasmini*), and red spider mites (*Tetranychus* sp.). Biological control strategies utilizing biopesticides like *Trichoderma viride*, *Bacillus thuringiensis*, and *Paecilomyces lilacinus* successfully suppress these populations. Studies also indicate that combining these biopesticides with rhizosphere bacteria like *Azospirillum* and *Phosphobacterium* further reduces pest incidence compared to untreated crops (Murugan & Ravi, 2020). Integrating these diverse microbial consortia provides a robust framework for high-yielding, ecologically sound jasmine cultivation without relying heavily on chemical inputs (Murugan & Ravi, 2020; Rajiv et al., 2025).

4.9 Tuberose (*Polianthes Tuberosa*)

Tuberose (*Polianthes tuberosa*) is an important high value crop for smallholder growers and a highly prized commercial floriculture crop because of its intensely fragrant spikes. The transition of this bulbous ornamental to sustainable cultivation is increasingly reliant on integrated nutrient management and microbial inoculants to enhance floral yield and bulb multiplication while minimizing the dependency on chemical fertilizers. The use of biofertilizers like *Azotobacter* and phosphate-solubilizing bacteria (PSB) in combination with organic amendments has been found to significantly improve spike quality, floret number and bulb production (Lal et al., 2010).

The success of these treatments depends on rhizosphere dynamics. Beneficial plant growth promoting microorganisms colonizing early roots contribute to enhanced reproductive performance and improved long-term nutrient acquisition efficiency mechanisms that are critical to maximizing crop biomass (Backer et al., 2018; Naamala & Smith, 2020). In addition to bacterial inoculation, symbiotic associations with arbuscular mycorrhizal fungi (AMF) and the use of biostimulants have been shown to optimize physiological performance, enhance robust spike development and greatly improve water-deficit tolerance during field cultivation (Saravani et al., 2025). These microbial strategies should be integrated with organic inputs for maximizing the reproductive traits such as mother bulb weight and bulblet diameter for sustainable propagation and commercial viability (Jamja et al., 2024).

4.10 Other Ornamentals

Petunia hybrida has been adopted as a model ornamental for PGPR studies due to its fast growth cycle, easy cultivation and sensitivity to environmental stresses (Ruzzi & Aroca, 2015). AMF inoculation has been shown to provide significant benefits to lily (*Lilium longiflorum* and Asiatic hybrids) in terms of improved nutrient uptake, growth and bulb development, largely attributed to the ability of mycorrhizal hyphae to compensate for the relatively limited absorptive capacity of monocot root systems (Begum et al., 2022; Kuyper & Jansa, 2023). Research on *Anthurium*, *Heliconia*, *Alstroemeria* and *Protea* under bio-inoculant treatments in the field of ornamental horticulture is relatively limited and mostly restricted to greenhouse and pot-scale studies, indicating the need for more rigorous field studies (Backer et al., 2018; Scagliola et al., 2021).

Table 2: Empirical Crop-Specific Responses to Bio-inoculant Applications

Crop	Inoculant	Observed Agronomic and Physiological Effects	References
Rose (<i>Rosa hybrida</i>)	AMF, <i>Pseudomonas fluorescens</i>	AMF helps plants acquire nutrients and provides protection against environmental stresses. P. fluorescens can positively promote vase life though some strains may cause vascular blockage	(Sun & Shahrajabian, 2023). (Li et al., 2021), (Lee & Kim, 2018).

Chrysanthemum (Chrysanthemum morifolium)	Nitrogen-fixing bacteria (e.g., Azospirillum), AMF	Dual inoculation results in a remarkable complementary increase in overall nutrient uptake. Microbes increase calcium and potassium uptake, improving cell wall rigidity and stomatal regulation to extend vase life.	(Barea et al., 2005) (Rouphael & Colla, 2018).
Marigold (Tagetes erecta)	Phosphate-solubilizing bacteria (PSB), Azotobacter	Integration significantly reduces the required chemical fertilizer doses while maintaining flower dry weight, carotenoid content, and essential oil yields. Vigorous root colonization enhances root biomass, reinforcing the release of nematicidal compounds into the soil profile.	(Lugtenberg & Kamilova, 2009).
Gerbera (Gerbera jamesonii)	AMF	Inoculation significantly improves flower yield by up to 44% and increases post-harvest vase life by as much as 28%. Mitigates environmental stressors, particularly soil salinity	(Othman et al., 2022).
Carnation (Dianthus caryophyllus)	Trichoderma harzianum, Bacillus subtilis	Suppresses Fusarium wilt disease by up to 96% under controlled conditions. Manages disease pressure through antimicrobial lipopeptides while promoting root biomass and priming ISR	(Arici et al., 2019). (Ongena & Jacques, 2008).
Gladiolus (Gladiolus grandiflorus)	AMF, Trichoderma harzianum	Fungal networks act as a powerful sink for photosynthates, driving greater biomass accumulation in daughter corms. Trichoderma outcompetes pathogenic Fusarium for nutrients and space while inducing systemic resistance.	(Barea et al., 2005). (Harman et al., 2004).
Orchid (Cymbidium, etc.)	Serendipita indica	Accelerates protocorm development and significantly increases root biomass. Drastically improves the survival rates of tissue-culture-raised plantlets during ex-vitro acclimatization without chemical interventions	(Shah et al., 2019).

5. BIO-INOCULANTS UNDER ABIOTIC STRESS CONDITIONS

5.1 Drought Stress

Water deficit is increasingly recognized as a major limitation in floricultural production systems, especially in semi-arid regions and urban areas with irregular irrigation scheduling. Bio-inoculants mitigate drought stress via multiple, non-mutually exclusive pathways: AMF extraradical hyphae improve hydraulic conductance and delay turgor loss (Augé, 2001; Wu & Zou, 2017); PGPR with ACC deaminase activity reduce stress ethylene accumulation (Glick, 2014); Bacillus species induce accumulation of proline, trehalose and glycine betaine as osmotic adjustment solutes (Kaushal & Wani, 2016); and certain PGPR volatiles (like 2,3-butanediol and acetoin) activate stomatal regulation pathways that conserve water under deficit conditions (Cho et al., 2008).

Repeated investigations with *Rosa hybrida* and *Tagetes erecta* (Asrar & Elhindi, 2011) under controlled drought stress conditions (like 50% field capacity) have shown that bio-inoculant treated plants have better relative water content (RWC), lower leaf water potential deficit and superior chlorophyll content than uninoculated stressed controls. However, most studies have been conducted under pot or greenhouse conditions and large-scale field validation of drought-protection efficacy under variable irrigation conditions remains limited, a critical gap for climate adaptation planning (Backer et al., 2018).

5.2 Salinity Stress

Salinity stress severely impairs floricultural production by inducing ionic toxicity (Na^+ , Cl^-) and osmotic stress, which combine to suppress seed germination, root elongation, and photosynthesis (Gupta et al., 2022). Beneficial plant growth-promoting rhizobacteria (PGPR) producing 1-aminocyclopropane-1-carboxylate (ACC) deaminase, like *Pseudomonas*

spp. and *Achromobacter piechaudii*, alleviate these effects by reducing the stress-induced ethylene levels in the host plant (Shahid et al., 2023; Shilev, 2020). In ornamental horticulture, inoculation of crops with *Pseudomonas* species has shown improvement in plant quality, biomass and resilience under abiotic stress conditions (Nordstedt et al., 2020). For instance, ACC deaminase-producing *Pseudomonas* strains have been reported to effectively retard flower senescence and preserve postharvest quality of ornamental crops, for example carnations (*Dianthus caryophyllus*), under stress conditions (Goswami et al., 2016).

Arbuscular mycorrhizal fungi (AMF) play a crucial role in alleviating salinity stress in flower crops by maintaining ionic homeostasis. AMF symbiosis enhances the capacity of plants to exclude toxic Na^+ and promotes preferential K^+ accumulation, helping to maintain a favorable Na^+/K^+ ratio (Evelin et al., 2019). A vital mechanism for this Na^+ exclusion and K^+ transport across plant cell membranes during salt stress is the action of high-affinity potassium transporters (HKT) (Waters et al., 2013). Furthermore, AMF mitigate oxidative stress, reducing lipid peroxidation and helping to maintain the structural integrity of plant cell membranes (Evelin et al., 2019). Plant adaptation to salinity also inherently relies on structural membrane lipid remodeling, such as adjustments in phosphatidylcholine, to preserve membrane fluidity and permeability (Guo et al., 2019). In major floricultural crops like *Chrysanthemum morifolium*, AMF colonization under moderate to severe salt stress significantly improves root nitrogen uptake and total dry plant biomass, providing a vital biological buffer against saline soils (Wang et al., 2018).

5.3 Heat Stress

Global warming is progressively threatening the quality of temperature-sensitive floricultural crops—particularly cut roses grown at high altitudes (e.g., East Africa, the Andes) and heat-sensitive ornamentals in temperate greenhouse systems. A rising global surface temperature increases the frequency of acute heat stress, which reduces plant biomass, induces premature flower senescence, and impairs floral development (Hasanuzzaman et al., 2013).

However, microbe-mediated thermotolerance offers a promising adaptation strategy. Plant growth-promoting rhizobacteria (PGPR) have been shown to mitigate heat damage by preserving physiological functions. For instance, the well-characterized endophyte *Paraburkholderia phytofirmans* PsJN enhances plant resilience to temperature extremes by modulating cellular homeostasis and resource mobilization (Esmaeel et al., 2018). Under heat stress, PGPR-inoculated plants consistently demonstrate lower electrolyte leakage—indicating protected cellular membranes and maintain superior photosystem II quantum efficiency compared to uninoculated controls (Dastogeer et al., 2022).

The mechanism behind this resilience involves PGPR-mediated upregulation of heat shock transcription factors (HSFs) and their downstream chaperone targets, such as heat shock protein 70 (HSP70) (Ahmad et al., 2022). These molecular chaperones prevent protein denaturation and aggregation during temperature spikes, representing a vital form of induced thermotolerance. While these mechanisms are well documented in model crops and increasingly studied in ornamentals like *Tagetes erecta* (African marigold), current evidence often relies on controlled greenhouse gradients. Robust field validation in commercial cut-flower environments remains urgently needed to integrate microbial inoculants into standard climate adaptation practices.

5.4 Nutrient-Deficient Soils

In nutrient-poor sandy soils or heavily weathered laterite soils common to tropical floriculture regions, bio-inoculants provide disproportionately larger benefits compared to fertile soils. Because the baseline nutrient availability in these environments is so low, the micro-scale mobilization of bound minerals by microbial inoculants constitutes a substantial proportional increase in plant nutrient uptake.

Consortium inoculants specifically those combining phosphate-solubilizing bacteria (PSB), potassium-solubilizing bacteria (KSB), nitrogen fixers (like *Azotobacter* or *Azospirillum*), and arbuscular mycorrhizal fungi (AMF) significantly improve NPK use efficiency. In major cut-flower crops like carnation and gladiolus grown in degraded soils, researchers consistently find that integrating these microbial consortia allows growers to heavily reduce synthetic fertilizer application. Field trials demonstrate that applying bio-inoculants alongside just 75% of the recommended dose of chemical fertilizers (RDF) yields equivalent or superior stem length, flower diameter, and corm production compared to using 100% synthetic fertilizers alone (Bhalla et al., 2006; Kumar et al., 2011). This represents a highly practical 25% improvement in baseline nutrient use efficiency, making bio-inoculants an essential economic and ecological buffer for sustainable floriculture.

5.5 Climate Change Implications

The interaction of elevated atmospheric CO_2 , increasing temperature, and altered precipitation regimes is expected to substantially influence floricultural production systems and their associated microbial communities. Elevated CO_2 generally increases root biomass, rhizodeposition, and the release of carbohydrates and organic compounds into the rhizosphere, thereby stimulating microbial activity and potentially enhancing colonization by beneficial bio-inoculants such as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) (Dong et al., 2018; Drigo et al., 2013).

However, increasing temperatures may negatively affect microbial survival, AMF spore viability, rhizosphere colonization efficiency, and microbial competitiveness, leading to inconsistent bio-inoculant performance under field conditions (Gupta et al., 2015). In floricultural crops, heat stress already causes significant reductions in growth, flower quality, and physiological performance, as demonstrated in gerbera (*Gerbera jamesonii*), where exposure to 45°C induced chlorophyll degradation, membrane damage, and reduced ornamental value (Kim et al., 2016). Similar climate-related stresses are increasingly reported in rose (*Rosa hybrida*), chrysanthemum (*Chrysanthemum morifolium*), lily (*Lilium* spp.), petunia (*Petunia hybrida*), and marigold (*Tagetes* spp.), where elevated temperatures and irregular water availability compromise flowering, postharvest quality, and disease resistance. Consequently, the development of thermotolerant PGPR and AMF strains, combined with heat-stable carrier formulations, represents a promising climate-adaptation strategy for sustainable floriculture under future climate scenarios (Kumar et al., 2021; Gupta et al., 2015).

6. INTEGRATION WITH SUSTAINABLE FLORICULTURE PRACTICES

6.1 Organic Floriculture

Certified organic floriculture is a growing niche market especially for export to EU and North American markets where there is a strong demand for pesticide free flowers. Bio-inoculants are fully compatible with organic standards (USDA NOP, EU Regulation 2018/848) and constitute an important tool for fertility management in organic flower production. In marigold cultivation, the combination of compost-enriched substrates with specific PGPR and AMF inoculants has been shown to have productive performance comparable to conventional fertilized systems (Chaupoo & Kumar, 2022). Chrysanthemum and other ornamentals have shown significant improvements in growth, flowering, nutrient uptake and soil health, after AMF and biofertilizer inoculation in reduced chemical-input or organic production systems (Attia & Eid, 2005; Wahab et al., 2023). However, some ornamentals, like rose and gerbera, with high nutrient demands, are still difficult to grow under fully organic production systems. The variable nutrient content and slow-release nature of organic fertilizers often necessitate accurate management of substrates to sustain commercial yield and quality standards (Čepulienė et al., 2024).

6.2 Integrated Nutrient Management (Inm)

Integrated Nutrient Management (INM) strategies in floriculture involve the use of organic manures, biofertilizers and reduced doses of chemical fertilizers to optimize nutrient use efficiency and maintain yield and quality. Recent INM trials have evidenced that biofertilizers + 50% of recommended NPK consistently gave equal or even higher yields than 100% chemical NPK treatments (Ali et al., 2024; Kumar et al., 2024). Furthermore, these integrated approaches are also very effective in enhancing the soil health parameters such as soil organic carbon and microbial biomass carbon to a large extent which are important indicators of sustainable soil fertility (Bargali, 2024).

6.3 Integrated Disease Management (Idm)

Bio-inoculant based biocontrol can be integrated within IDM regimes with reduced dose chemical fungicides, the use of resistant cultivars and cultural practices (solarization and crop rotation). The synergistic use of microbial biocontrol agents (e.g., *Trichoderma* spp. and *Bacillus subtilis*) and compatible synthetic chemicals can provide more effective and sustainable disease control, significantly reducing the reliance on full-dose chemical fungicides (Fenta & Mekonnen, 2024). However, critical compatibility screening is needed prior to application of tank-mix or sequential application protocols. *Trichoderma* is highly compatible with some contact fungicides and insecticides, however the systemic fungicides such as tebuconazole, propiconazole and hexaconazole have been reported to either completely inhibit or severely suppress the populations of *Trichoderma* even at the recommended field doses (Madhavi et al., 2011).

6.4 Protected Cultivation And Precision Floriculture

In protected cultivation environments (polyhouses, climate-controlled greenhouses), bio-inoculants perform best because temperature extremes are buffered, UV-mediated inoculant degradation on leaf surfaces is minimized, and precise application is possible through drip fertigation systems, a practice that is increasingly being referred to as “biofertigation” (Mejía et al., 2022). The major commercial application of bio-inoculants in high-value floriculture is production of Gerbera, carnation and rose under protected conditions where management of the root-zone biology is crucial for yield. Precision floriculture technologies such as sensor-based soil moisture monitoring, EC/pH feedback fertigation systems and machine learning-based disease prediction models can complement the bio-inoculant programs by optimizing the microclimate and nutrient scheduling to maximize optimal rhizosphere colonization conditions (Escamilla-García et al., 2020).

6.5 Urban And Rooftop Floriculture

Urban floriculture including rooftop gardens, vertical farms, and community growing spaces—presents unique opportunities for bio-inoculant application in non-pathogen-pressured, substrate-based systems. In soilless or semi-soilless substrates (e.g., cocopeat, perlite mixes) frequently used in these setups, arbuscular mycorrhizal fungi (AMF) inoculation is particularly valuable because native soil microbial populations are naturally absent (Rouphael et al., 2015). Furthermore, PGPR inoculants deployed in urban systems must be selected for their tolerance to the abiotic stresses characteristic of rooftop environments, such as elevated temperatures and fluctuating moisture levels, to successfully confer stress resistance to the host plants (Etesami & Maheshwari, 2018). Urban floriculture also facilitates closed-loop nutrient cycling; for instance, the integration of bio-inoculants into the composting of floral and green waste yields nutrient-enriched organic amendments, thereby strengthening circular economy linkages within urban agriculture (Singh et al., 2025).

7. COMMERCIAL FORMULATIONS AND APPLICATION METHODS

7.1 Formulation Types

The commercial viability of bio-inoculants is critically dependent on formulation quality, which determines shelf life, application convenience, and colonization efficacy. Carrier-based formulations using sterilized peat, lignite, or vermiculite remain the most widely used globally due to low cost and buffering capacity for microbial survival. However, peat shortage (particularly in Europe where peat extraction is being phased out) and variable quality control are driving interest in alternative carriers including biochar, kaolin clay, and biopolymer matrices (Herrmann & Lesueur, 2013; Saranya et al., 2011).

Liquid biofertilizers (aqueous suspensions, broth-based) have gained traction due to ease of use in drip fertigation and compatibility with precision application systems. Their limitation often lies in shorter shelf life and high sensitivity to temperature fluctuations during transport and storage (Herrmann & Lesueur, 2013). Wettable powder (WP) and water-dispersible granule (WDG) formulations offer improved shelf life (often 12–24 months) and ease of transport, but they

are generally limited to organisms with endospore or robust spore-forming capacity, such as *Trichoderma* and *Bacillus* species, which can survive the desiccation process (Jayaraj et al., 2005; Schisler et al., 2004).

7.2 Application Methods

The method of bio-inoculant application profoundly influences colonization efficiency and subsequent plant response. Seed treatment (pelletization, slurry coating) is not applicable to vegetatively propagated ornamentals (corm-based crops, cuttings), significantly limiting its utility in floriculture. Instead, root dipping of transplants or bare-root cuttings in concentrated bio-inoculant suspensions is among the most effective application methods, ensuring direct contact between microorganisms and the root zone during the critical establishment phase (Malusá et al., 2012). This method is particularly recommended for rose, chrysanthemum, and carnation transplants.

Soil incorporation (broadcast or band application) of granular bio-inoculants prior to planting remains highly suitable for bulb and corm crops such as gladiolus, lily, and tuberose. Furthermore, drip fertigation with liquid bio-inoculants (often termed "biofertigation") allows for repeated application throughout the growing season, maintaining active rhizosphere populations and supplementing the initial transplant inoculation (Basu et al., 2021). Foliar spray application of growth-promoting preparations—particularly those leveraging extracellular metabolites with cytokinin and siderophore activity—is utilized for specific growth stages and stress mitigation, though it is inherently less effective for establishing true root colonizers (Kour et al., 2020). Ultimately, the choice of application method should be guided by the functional target (root colonization vs. foliar activity) and the delivery infrastructure available on-farm.

8. CONSTRAINTS AND CHALLENGES

8.1 Variable Field Performance

The most frequently cited limitation of bio-inoculants across published literature and industry assessments is inconsistent field performance outcomes that are highly positive in controlled greenhouse or laboratory experiments but variable or negligible under commercial field conditions (Backer et al., 2018). This variability arises from multiple interacting factors: soil properties (pH, texture, organic matter content, and native microbial competitiveness), environmental conditions (temperature and moisture fluctuations), crop genotype-inoculant compatibility, application timing, and carrier formulation quality (Bashan et al., 2014). Critically, the vast majority of published bio-inoculant studies are single-site, single-season experiments with small replication, making it difficult to distinguish true treatment effects from site-specific environmental variation. Transitioning from lab to farm requires that multi-location, multi-season field trials become a scientific priority to establish reliable, scalable agronomic recommendations (Parnell et al., 2016).

8.2 Shelf Life And Quality Control

Regulatory standards for bio-inoculant quality (viable cell count, absence of contaminating pathogens, labelled strain identity) are inconsistently enforced across countries (Herrmann & Lesueur, 2013). However, studies have found that a substantial proportion of commercially available biofertilizers contain suboptimal viable cell counts well below this regulatory minimum at the point of retail sale, likely due to inadequate cold chain management, excessive storage temperatures, and extended distribution times (Brahmaprakash & Sahu, 2012; Mitter et al., 2021). This quality gap is a major contributor to inconsistent field performance, leading to farmer disappointment and significant adoption barriers. Minimum quality standards, mandatory cold chain requirements, and point-of-sale viability testing are regulatory interventions with high potential impact to restore farmer trust (Herrmann & Lesueur, 2013).

8.3 Compatibility With Agrochemicals

Many commonly used floriculture pesticides and fungicides are bactericidal or fungicidal at concentrations achieved in soils following recommended application. Broad-spectrum fungicides (such as mancozeb, carbendazim, and copper oxychloride) can severely suppress AMF colonization and reduce PGPR populations in the rhizosphere by disrupting non-target microbial metabolic pathways (Meena et al., 2020). Consequently, systematic compatibility testing between bio-inoculant strains and the specific agrochemical inputs typically used in target crop systems is necessary for integrated recommendation development (Goswami et al., 2016). The practice of tank-mixing bio-inoculants directly with systemic pesticides or potent bactericides/fungicides—still common among uninformed users trying to save labor represents a significant cause of biological product failure and microbial death prior to soil application (Brahmaprakash & Sahu, 2012; Madhavi et al., 2011).

8.4 Farmer Awareness And Adoption Barriers

Adoption of bio-inoculants by floricultural farmers is constrained by limited awareness of product options and application protocols, distrust of biological inputs due to formulation instability and past product quality failures, an absence of visible short-term effects compared to chemical fertilizers, and inadequate extension service infrastructure (Beleri, 2023; Ehinmitan et al., 2024). Demonstration trials on farmers' fields, farmer-to-farmer knowledge transfer, and transparent performance documentation through agri-extension networks are the most effective pathways for building adoption (Bhooshan et al., 2020). In India, initiatives like the ICAR All India Network Project on Soil Biodiversity-Biofertilizers have shown measurable impact on awareness across the country, though targeted national coverage for specialized sectors like floriculture remains incomplete.

8.5 Standardization And Regulatory Fragmentation

The regulatory landscape for bio-inoculants remains highly fragmented and inconsistent across different countries (Herrmann & Lesueur, 2013). In India, for example, biofertilizers are regulated under the Fertilizer Control Order (FCO) of 1985 (with subsequent amendments), which currently specifies quality standards and testing protocols for only a limited, strictly defined list of traditional organisms (Arjjumend & Koutouki, 2021; Brahmaprakash & Sahu, 2012). Consequently, novel plant growth-promoting rhizobacteria (PGPR) strains, endophytes, and multi-strain microbial consortium products often fall outside these existing regulatory categories. This regulatory lag creates significant

uncertainty for manufacturers, delays market entry, and ultimately constrains biological innovation (Mitter et al., 2021). Agronomic and policy literature suggests that harmonizing bio-inoculant regulations with international standards, developing science-based registration criteria tailored specifically to living organisms, and creating expedited regulatory pathways for complex microbial consortia are essential reforms to accelerate the sector's growth and global adoption (Herrmann & Lesueur, 2013; Mitter et al., 2021).

9. RECENT ADVANCES AND EMERGING TRENDS

9.1 Microbiome Engineering

The expanding availability of high-throughput sequencing technologies has enabled comprehensive characterization of rhizosphere and bulk soil microbiomes in floriculture systems. Microbiome engineering approaches—including the selective enrichment of beneficial taxa through prebiotics (specific root exudate compounds and organic amendments), synthetic community (SynCom) design, and targeted rhizosphere-competent strain introduction represent the frontier of bio-inoculant science (Mitter et al., 2021). For example, the characterization of the rose rhizosphere has revealed dramatic microbial shifts associated with Rose Replant Disease (RRD); studies have shown that specific bacterial genera, such as *Streptomyces*, *Rhizobium*, and *Lysobacter*, are actively enriched in diseased replant soils compared to healthy soils (Yim et al., 2020). Identifying these complex microbial successions and understanding which keystone taxa drive root health versus disease states provides the necessary targets for advanced microbiome manipulation strategies.

9.2 Synthetic Microbial Consortia

Top-down microbiome engineering through synthetic microbial communities (SynComs) assembled from well-characterized strains with complementary functional traits represents a precision alternative to undefined multi-species inoculants (de Souza et al., 2020). SynCom design principles explicitly consider functional redundancy (for ecological robustness), metabolic complementarity (for synergistic nutrient processing), and inter-strain compatibility (to prevent inhibitory or antagonistic interactions) (Shayanthan et al., 2022). Early results from SynCom applications in agricultural and horticultural systems suggest superior consistency and reliability compared to traditional, field-selected consortia. However, the high production costs associated with maintaining and scaling exact ratios of multiple strains, coupled with complex regulatory categorization obstacles for multi-species products, remain significant barriers to widespread commercialization (Mitter et al., 2021; Shayanthan et al., 2022).

9.3 Nano-Bioinoculants

Nano-bioinoculants microorganisms encapsulated in or co-formulated with nanoparticles (such as nano-clays, silica nanoparticles, carbon nanotubes, and chitosan nanoparticles) are emerging as a highly effective solution to historical shelf life and delivery challenges (Thirumurugan et al., 2024). Nano-encapsulation acts as a physical safeguard, protecting microbial cells from environmental stressors such as UV radiation, extreme pH levels, and desiccation, potentially extending product shelf life to 18–24 months under ambient conditions. Furthermore, early laboratory and greenhouse studies suggest that the controlled release of microbes and signaling molecules from nano-matrices can significantly improve rhizosphere colonization rates compared to conventional carriers (Mahapatra et al., 2022). However, rigorous eco-toxicological data regarding the long-term persistence, bioaccumulation, and potential non-target toxicity of nanomaterials in agricultural soils are urgently needed before widespread commercial deployment can be safely recommended (Mahapatra et al., 2022).

9.4 Omics Approaches In Inoculant Development

Genomics, transcriptomics, proteomics, and metabolomics approaches are revolutionizing the identification of superior bio-inoculant strains. Genome mining for functional gene clusters—such as *nif* genes for nitrogen fixation, *phl* genes for 2,4-DAPG production, *iaaM/iaaH* for IAA synthesis, and *acdS* for ACC deaminase enables the rapid in silico prediction of functional traits before phenotypic confirmation is required (Mitter et al., 2021). Furthermore, comparative rhizosphere transcriptomics in bio-inoculant-treated versus untreated plants has revealed host pathways consistently upregulated by successful inoculant colonization. These include the activation of jasmonyl-isoleucine (JA-Ile) conjugation to trigger Induced Systemic Resistance (ISR), as well as the upregulation of flavonoid and coumarin biosynthesis to shape root microbiome assembly (Pieterse et al., 2014). Understanding these omics-level responses provides critical mechanistic insights with significant implications for targeted strain-crop matching.

9.5 Ai And Precision Agriculture Integration

Machine learning algorithms trained on multi-environment agricultural datasets can predict soil-crop interaction outcomes and optimize input recommendations for site-specific conditions (Liakos et al., 2018). In the context of bio-inoculants and nutrient management, early applications include AI-based decision support systems that integrate soil test data, weather forecasting, and crop growth stage monitoring to prescribe precise application timing, dose, and formulation type (Sharma et al., 2020). Furthermore, the integration of robotic application systems in greenhouse floriculture allows for the delivery of exact bio-inoculant or fertilizer doses to individual plants at optimal growth stages. This precision automation significantly reduces input wastage and improves microbial colonization consistency within controlled environments (Shamshiri et al., 2018).

10. FUTURE PERSPECTIVES

10.1 Research Priorities

Critical research gaps identified from the synthesis of current literature include: (i) the need for multi-location, multi-season field trials in major floriculture crops under diverse soil and climate conditions to validate commercial efficacy (Backer et al., 2018); (ii) comprehensive post-harvest quality studies in bio-inoculant-treated cut flowers with rigorous experimental controls, as most current research focuses strictly on vegetative yield (iii) the elucidation of the

biochemical mechanisms driving bio-inoculant-mediated fragrance quality and essential oil improvement in aromatic floricultural crops such as jasmine, rose, and tuberose (Banchio et al., 2008); (iv) systematic compatibility studies between bio-inoculants and the common agrochemicals used in floriculture across diverse soil types (Meena et al., 2020); (v) long-term soil health monitoring in bio-inoculant-treated versus chemically managed floriculture systems (Mitter et al., 2021); and (vi) detailed techno-economic analyses of bio-inoculant adoption to determine financial viability across different production scales and market contexts.

10.2 Breeding For Microbe-Responsive Ornamentals

Plant genotype strongly influences rhizosphere microbiome composition and bio-inoculant colonization efficiency (Park et al., 2023). Breeding programs that incorporate microbe-responsiveness as a selection criterion—identifying genotypes with superior root architecture for AMF colonization, optimal exudate profiles for PGPR chemotaxis, and compatible signaling pathways for ISR priming—could significantly improve bio-inoculant efficacy across commercial cultivars (Trivedi et al., 2020). The development of rose rootstocks optimized for beneficial microbiome recruitment represents a promising future breeding direction. This possibility is supported by recent evidence showing that scion–rootstock interactions significantly influence rhizosphere microbiome assembly and microbial recruitment in commercial roses (Ramirez-Villacis et al., 2023).

10.3 Commercialization Opportunities

The global bio-inoculant market's growth trajectory creates substantial commercialization opportunities in floriculture-specific product lines (Fasusi et al., 2021). Most commercial bio-inoculant products have historically been developed for large-acreage field crops, with comparatively fewer products specifically designed for ornamental and floricultural systems (Parnell et al., 2016). Developing floriculture-specific bio-inoculant products featuring crop-specific strain selection, appropriate carrier matrices tailored specifically for protected soil or hydroponic delivery systems, and backed by robust performance data from ornamental crop trials could improve product performance, consistency, and commercial relevance in ornamental production systems compared with formulations originally developed for broad-acre crops (Malusá et al., 2012; Rouphael & Colla, 2020).

10.4 Policy Support And Sustainable Floriculture Roadmap

Accelerating bio-inoculant adoption in floriculture requires coordinated policy interventions. These include incentivizing biological inputs as part of sustainable agricultural transitions (Arjjumend & Koutouki, 2021), strengthening quality assurance frameworks and storage standards to ensure inoculant efficacy (Herrmann & Lesueur, 2013), developing centralized microbial resource and performance databases to support informed strain selection and regulatory oversight (Mitter et al., 2021), integrating bio-inoculant-based fertility management within existing organic certification frameworks, and fostering public-private partnerships to facilitate technology transfer, commercialization, and large-scale production of high-quality microbial products (Fasusi et al., 2021).

11. CONCLUSION

This review demonstrates that bio-inoculants represent a scientifically robust, mechanistically diverse, and agronomically versatile toolkit for sustainable floriculture. The evidence base—spanning PGPR, AMF, biocontrol agents, endophytes, cyanobacteria, and consortium formulations—confirms consistent improvements in vegetative growth, flower yield, quality parameters, post-harvest longevity, and disease resistance across the major floricultural crops when appropriate strains are applied under suitable conditions. Bio-inoculants have demonstrated meaningful performance under drought, salinity, heat, and nutrient-deficient conditions, positioning them as climate adaptation tools of increasing relevance as global floriculture faces escalating abiotic stress challenges.

Critical assessment reveals that the gap between laboratory promise and consistent field performance remains the central challenge in the field. This gap is bridgeable through investment in multi-environment trials, improved formulation technologies (including nano-encapsulation and SynCom design), rigorous quality control infrastructure, and farmer-centric extension programs. The emerging convergence of omics-guided strain selection, AI-assisted recommendation systems, and precision application technologies promises to transform bio-inoculant performance predictability in the coming decade.

Floriculture occupies a unique position in this transition: its high-value products, globally conscious consumer base, export market exposure, and preference for premium sustainability certifications create favorable socioeconomic conditions for bio-inoculant adoption beyond those present in commodity food crop production. The path to bio-inoculant-enabled sustainable floriculture is neither straight nor free of obstacles, but the scientific foundation is firm, the market incentives are growing, and the ecological imperative is clear. Coordinated investment in research, commercialization, regulation, and farmer engagement will determine how rapidly this potential is realized in practice.

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