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REVIEW ARTICLE

Eco-renaissance in floriculture: unlocking the power of plant growth-promoting bacteria

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Abstract

The conventional floriculture industry heavily relies on chemical fertilizers and pesticides to meet global demand, which can have detrimental environmental impacts. To promote sustainable flower cultivation, Plant Growth-Promoting Bacteria (PGPB) has emerged as eco-friendly tools to enhance the productivity of major commercial flower crops. This review summarizes the current knowledge on diverse PGPB genera associated with ornamentals like rose, gerbera, carnation, chrysanthemum and orchids. It examines the abilities of PGPB to improve yield, quality and stress tolerance of flowers through mechanisms such as biological nitrogen fixation, nutrient solubilization, phytohormone synthesis, induced systemic resistance and antagonism against pathogens. The potential of developing microbial consortia and bioformulations as PGPB-based biofertilizers, bio stimulants and biopesticides for sustainable floriculture is discussed. By identifying research gaps and prospects, this review highlights the role of PGPB in driving sustainable intensification of commercial flower production with reduced environmental footprint.

Keywords

Plant growth promoting bacteria; floriculture; sustainable flower production; phytohormones

Introduction

Floriculture, defined as the cultivation of flowering and ornamental plants for gardens and floristry, is an economically important sector of commercial agriculture. According to a report from Floriculture magazine, the global market for flowers and ornamental plants is projected to increase by 6.3 % in the next 5 years, reaching $57.4 billion in 2024, up from $42.4 billion in 2019 (1). Flower cultivation and trade play a vital role in the agriculture of many developing countries like Kenya, Colombia and Ethiopia. Production and export of cut flowers, potted flowering plants, cut foliage, flower seeds, bulbs and tubers provide employment and generate foreign exchange revenue. India ranks second in flower production after China but hold only the 14th position in exports (2). The Indian floriculture sector has experienced substantial growth, with loose and cut flower production increasing at CAGRs of 9.92 % and 26.66 %, respectively (3). However, India's share in global floriculture exports remains low at 0.6 % (4).

The major flower crops grown for commercial purposes include Rose, Chrysanthemum, Gerbera, Carnation, Lily, Tulip, Orchids, Anthurium, Gladiolus, Iris, Marigold, Petunia, Pansy, Impatiens, Poinsettia, Zinnia and Sunflower. Flowers are cultivated for their aesthetic appeal as decorative items or as raw materials for extractives used in perfumes, cosmetics and food products. The key objectives in floriculture are to maximize flower productivity in terms of earliness, number and size while maintaining quality. However, several challenges are encountered in intensive flower farming which hamper growth and productivity. Nutrient deficiencies, salinity stress, drought stress, high temperatures, light stress and fungal diseases affect the flowering behaviour and vase life of flowers leading to economic losses. Excessive reliance on agrochemicals for enhancing production can cause environmental hazards. Sustainable solutions are needed to increase the productivity and quality of flower crops.

In recent years, scientists are exploring the use of bacteria and other microorganisms as a sustainable way to enhance flower production and quality. Plant Growth Promoting Bacteria (PGPB) are beneficial soil bacteria that can enhance growth, flowering and postharvest attributes in diverse flower crops through mechanisms like phytohormone production, nitrogen fixation, phosphorus solubilization, induced systemic tolerance against stresses and disease control (5). PGPB-based bio stimulants and bio-inoculants provide a biological alternative to agrochemicals for enhancing productivity in floriculture. This review overviews major studies where plant growth-promoting bacteria (PGPB) sustainably enhanced growth, flowering, yield and vase life of major ornamental crops. It examines the eco-friendly mechanisms by which PGPB improves flower productivity and quality, such as biological nitrogen fixation and induced systemic resistance, offering sustainable alternatives to agrochemicals. The potential of developing PGPB-based bioproducts like biofertilizers and biopesticides for sustainable floriculture is discussed. Limitations in transitioning PGPB technologies from lab to field for reducing the environmental impacts of commercial flower farming are also identified.

2. Plant Growth Promoting Bacteria (PGPB)

Plant growth-promoting bacteria (PGPB) can help plants grow by either direct method such as providing nutrients (like nitrogen) or adjusting hormone levels in plants or indirectly by protecting plants from harmful bacteria and pests (acting as biocontrols). These PGPB can exist in different forms: free-living, symbiotic (like Rhizobia and Frankia), or within plant tissues (endophytes). Despite their diversity, they all use the same methods to promote plant growth (6) (Fig. 1).

2.1. Role of PGPB in improving Flower Crops

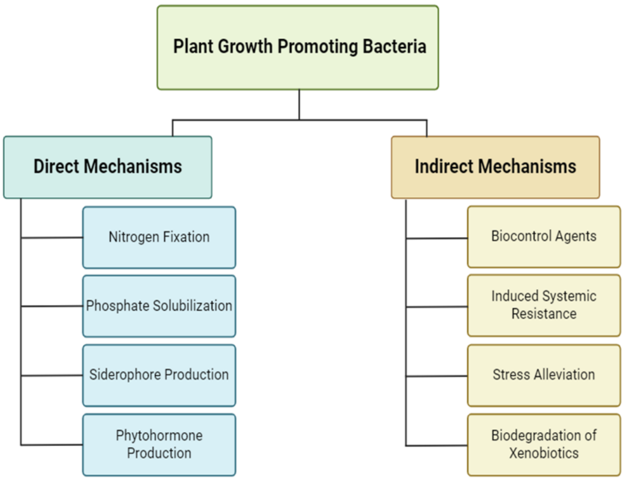

Fig. 1. PGPB classification based on its role in plant growth. (Figure created with Biorender.com)

PGPB augment plant growth through diverse mechanisms such as atmospheric nitrogen fixation, phosphorus solubilization, iron chelation, phytohormone synthesis, 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity, volatile organic compound (VOC) emission, improved nutrient uptake and disease suppression (7-9). Several of these traits are relevant for improving flowering behaviour, flower productivity and quality in ornamental plants. Recent studies have revealed intricate molecular interactions between PGPB and ornamental plants. For instance, research on *Chrysanthemum morifolium* showed that *Bacillus subtilis* CBR05 inoculation upregulates genes involved in jasmonic acid and ethylene signaling pathways, enhancing both growth and stress tolerance (10). Additionally, bacterial volatile organic compounds like 2,3-butanediol and acetoin produced by *Bacillus subtilis* GB03 have been found to promote growth and flower production in *Pelargonium peltatum* by modulating auxin transport and gibberellin biosynthesis (11). These advancements in understanding PGPB mechanisms offer new possibilities for sustainable ornamental plant production and stress management (Fig. 2).

2.1.1. Phytohormone Production

Many PGPB belonging to genera *Azospirillum, Azotobacter, Bacillus, Burkholderia, Enterobacter, Klebsiella, Pantoea, Pseudomonas, Rhizobium, Serratia* and *Stenotrophomonas* have the ability to synthesize phytohormones including auxin, cytokinin, gibberellin and ethylene (12-14). Of these, auxin (primarily indole-3-acetic acid) and cytokinin are well known for their role in plant growth and organ development. Auxin stimulates root elongation while cytokinin promote shoot proliferation. The relative levels of these 2 hormone types determine

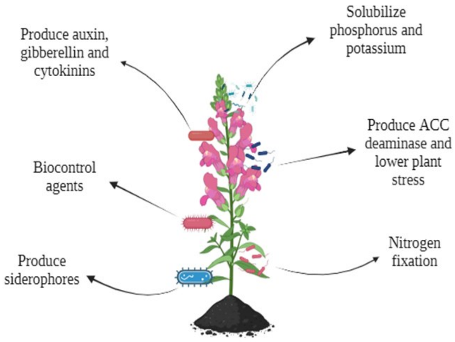

Fig. 2. Mechanisms which PGPB use to promote the growth of horticultural plants. (Figure created with Biorender.com)

plant morphology.

PGPB-synthesized phytohormones, particularly auxins and cytokinins, play crucial roles in modulating various aspects of plant reproductive development. These bacterial-derived hormones influence multiple stages of floral ontogeny, including the initiation of flowering, the emergence and differentiation of floral primordia and the subsequent development and maturation of floral organs (15, 16). Since floral transition and blooming involve complex interactions between different phytohormones, strategic modulation of hormone levels by PGPB inoculations can stimulate early flowering and enhance flower productivity in ornamentals (17, 18). Specific PGPB strains can finetune the auxin: cytokinin balance to achieve desired effects on flowering time and yield in target flower crops.

PGPB are also sources of gibberellin which stimulate internodal and stem elongation, flowering and flower development. For instance, significant increase in endogenous gibberellin content leading to improved flowering was noted in rose inoculated with *Bacillus pumilus* (19). Ethylene is involved in initiation of corolla wilting and senescence. Many PGPB induce ACC deaminase which degrades the immediate precursor of ethylene biosynthesis thereby delaying senescence of flowers (20). Thus, PGPB have potential for prolonging the display life of cut flowers by lowering ethylene production.

2.1.2. Atmospheric Nitrogen Fixation

Biological Nitrogen Fixation (BNF) by soil and rhizosphere microorganisms converts atmospheric nitrogen into plant-available forms, enhancing nitrogen nutrition and reducing reliance on synthetic fertilizers. This process, primarily performed by diazotrophic bacteria and cyanobacteria, promotes growth and flowering in plants (21). Studies have demonstrated that nitrogen-fixing PGPB isolated from flower crop rhizospheres, when applied as inoculants, significantly increase plant nitrogen content and improve growth and flowering parameters. Beneficial effects have been observed in various ornamental plants, including orchids (*Herbaspirillum frisingense* and *Burkholderia* sp.) (22), roses (*Azospirillum amazonense*) (23), petunias and chrysanthemums (*Rhodopseudomonas* sp.) (24, 25) and gerberas and tuberoses (*Rhizobium* and *Azotobacter* spp.) (26, 27). The supplemental nitrogen provided by these PGPB enhances overall plant performance, particularly in terms of flowering quality and quantity.

2.1.3. Phosphorus Solubilization

Phosphorus is an essential macronutrient influencing many growth and metabolic processes in plants. Most soil phosphorus exists as insoluble phosphates, which plants cannot directly absorb (28, 29). Phosphate-solubilizing bacteria convert inorganic phosphates into plant-usable forms by secreting organic acids, which chelate cations and lower pH, making phosphates soluble.

Phosphate-solubilizing PGPB have been identified in the rhizosphere of various ornamental plants, including species from genera such as Bacillus and Pseudomonas (30-33). By enhancing phosphorus nutrition, these PGPB improve growth and flowering attributes in ornamentals, leading to benefits like early blooming and increased flower production. These positive effects are directly linked to the increase in soil available phosphorus facilitated by the bacterial activity.

2.1.4. 1, 3-Propanediol and Volatile Organic Compounds

Some PGPB like *Bacillus subtilis* and *B. amyloliquefaciens* produce 1, 3-propanediol (1, 3-PD) which elicits induced systemic tolerance against abiotic stresses in plants (34). 1, 3-PD can penetrate plant cell walls and activate stress defence responses. This helps protect flowers against environmental stresses like high temperature and drought.

Several *Bacillus* and *Pseudomonas* spp. also emit Volatile Organic Compounds (VOCs) such as acetoin, 2, 3-butanediol, 2-methyl-n-1-tridecene and lipopeptides which trigger growth promoting effects in plants (11, 35). The VOCs may activate phytohormone signalling pathways leading to enhanced flowering and flower development in commercial flower crops as observed in crops treated with VOC-producing strains.

2.1.5. Induction of Systemic Tolerance

PGPB are known to induce systemic tolerance against biotic and abiotic stresses in plants through priming of various cellular defence responses (36). This mechanism of induced systemic resistance (ISR) operates through pathways mediated by growth regulators such as jasmonic acid, ethylene and salicylic acid. Exposure to beneficial PGPB confers stress resilience in plants.

In flower crops, PGPB treatments have been shown to elicit key protective responses, including the activation of antioxidant enzymes, upregulation of stress-responsive genes and accumulation of compatible solutes (37). These metabolic changes enhance the ability of flowers to withstand environmental fluctuations, thereby extending their longevity and display life. By inducing systemic tolerance, PGPB can thus improve floral traits related to shelf life and postharvest quality.

2.1.6. Antagonism against Pathogens

Fungal diseases represent a significant threat in flower cultivation, leading to substantial economic losses. Pathogens such as *Fusarium*, *Rhizoctonia*, *Phytophthora*, *Botrytis* and powdery mildews adversely impact the productivity and vase life of flower crops. PGPB suppress these pathogenic microbes through various mechanisms *viz.* production of antibiotics, cell wall degrading enzymes, siderophores and induction of systemic resistance in plants (38, 39).

Biocontrol PGPB with antifungal properties have been isolated from rose (*Bacillus amyloliquefaciens*) (40), gerbera (*Bacillus subtilis*) (41), carnation (*Pseudomonas aeruginosa*, *P. fluorescens*) (42) and orchids (*Bacillus* sp., *Burkholderia* sp., *Pseudomonas* sp.) (43). Inoculations with these PGPB controlled common fungal diseases and improved flower quality in the respective crops. Exploiting such biocontrol traits of PGPB is a sustainable strategy for mitigating the biotic stresses in commercial flower

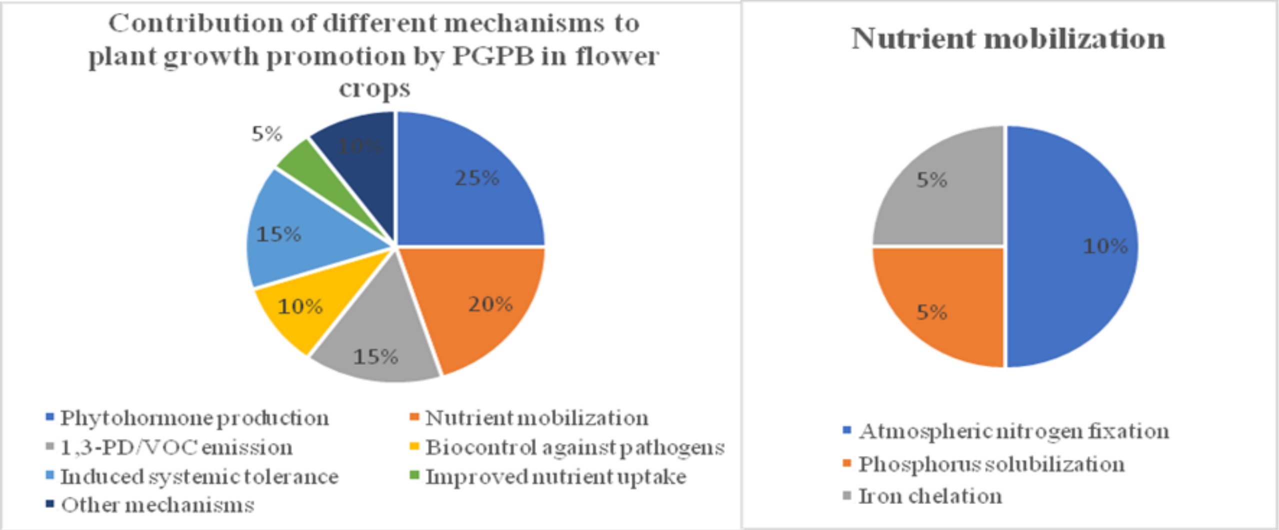

Fig. 3. Contribution of different mechanisms to plant growth promotion by PGPB in flower crops.

cultivation (Fig. 3)

3. PGPB in Major Flower Crops

Plant Growth-Promoting Bacteria (PGPB) have demonstrated significant benefits across various ornamental flower crops, including roses, chrysanthemums, gerberas, orchids and gladiolus. These beneficial bacteria enhance multiple aspects of flower production and quality through various mechanisms.

3.1. Roses

PGPB strains such as *Bacillus pumilus* INR7 (44), *Pseudomonas putida* PW15 (45), *Burkholderia phytofirmans* PsJN (46) and *Azospirillum amazonense* (23) have shown remarkable effects on rose cultivation. These bacteria improved flower yield, increased the number of flowers per plant, extended flowering duration and enhanced postharvest longevity. They also boosted nutrient uptake, chlorophyll content and induced systemic tolerance against stresses (23, 44-47).

3.2. Chrysanthemum

For chrysanthemums, PGPB strains including *Pseudomonas chlororaphis* HT66 (48), *Rhodopseudomonas* sp. CQ001 (25) and *Bacillus subtilis* AU195 (46) have proven effective. These bacteria increased flower diameter, prolonged vase life, enhanced flower numbers and yield and augmented plant biomass. They achieved these improvements through mechanisms such as induced systemic tolerance, improved nutrient fixation and solubilization and production of growth-promoting compounds (25, 48-50).

3.3. Gerbera

Gerbera cultivation benefited from PGPB strains like *Bacillus subtilis* RZ19 (31), *Azotobacter chroococcum* Az3 (26) and *Pseudomonas aeruginosa* EF121 (51). These bacteria increased flower numbers and size, reduced disease incidence and extended shelf life. They functioned through various mechanisms, including pathogen antagonism, nitrogen fixation and induction of systemic resistance (26, 31, 51, 52).

3.4. Orchids

In orchid farming, PGPB strains such as *Bacillus subtilis* OH 131.1 (22), *Burkholderia* sp. F-390 (53) and *Pseudomonas oryzihabitans* (54) showed promising results. These bacteria increased spike length, boosted flower numbers and reduced disease incidence. They achieved these improvements through pathogen antagonism, enhanced nutrient uptake and production of growth-promoting compounds (22, 53-55).

3.5. Gladiolus

Gladiolus cultivation was enhanced by PGPB strains including *Pseudomonas fluorescens* PF-08 (56), *Bacillus* sp. EU-1 (57) and *Azotobacter chroococcum* (58). These bacteria increased spike length, number of florets, corm weight and cut flower longevity. Their beneficial effects were attributed to various plant growth-promoting traits such as nutrient solubilization, nitrogen fixation and phytohormone production (56-58).

3.6. Other Flower crops

Bacillus megaterium augmented growth, early flowering, number of flowers and phosphorus uptake in marigold (30). *Azospirillum lipoferum* and *B. coagulans* increased the growth and flower yield in tuberose (27). *Pseudomonas* sp. strain P45 and *Bacillus* sp. strain EPB10 enhanced growth, flower size and postharvest life of lilies (59, 60). *Pseudomonas putida* strain PW12 induced early flowering, increased flower size and shelf life in carnation (61). *Bacillus* sp. *strains* IN937b and WB800N stimulated growth and flowering in *Petunia* and *Gaillardia* (24, 62). *Klebsiella variicola* improved flowering behavior and flower quality traits in pansy (63). Thus, PGPB confer beneficial effects on productivity and quality across the diverse ornamentals.

In conclusion, across these diverse ornamental crops, PGPB consistently demonstrated the ability to enhance flower yield, quality and longevity while also improving plant health and stress tolerance. These findings highlight the significant potential of PGPB as a sustainable approach to improving ornamental flower

Table 1. Effect of PGPB inoculations on growth and flowering parameters in major ornamental plants.

Flower Crop	PGPB Strain	Key Effects	References
Rose	*Bacillus pumilus* INR7	↑ Flower yield by 29 % ↑ NPK uptake	(44)
Chrysanthemum	*Pseudomonas chlororaphis* HT66	↑ Flower diameter ↑ Vase life by 2.7 days	(48)
Gerbera	*Bacillus subtilis* RZ19	↑ Number of flowers by 37.5 % ↓ Disease incidence by 42 %	(34)
Orchids	*Bacillus subtilis* OH 131.1	↑ Spike length by 28 % ↑ Number of flowers by 42 %	(22)
Gladiolus	*Pseudomonas fluorescens* PF-08	↑ Spike length by 19 % ↑ Vase life by 2 days	(56)

production (Table 1).

4. Commercial products of PGPB in Floriculture

Research on PGPB has paved the way for developing microbial bio stimulant products and bioinoculants for application in floriculture. Some examples of commercially available PGPB-based formulations for flower crops are presented (Table 2 and 3).

5. Limitations in PGPB application

A critical analysis of current research on Plant Growth-Promoting Bacteria (PGPB) in floriculture reveals several limitations that must be addressed to successfully translate laboratory findings to field applications. Studies on various ornamental crops, including roses (44-46), chrysanthemums (48, 49), gerberas (31, 51), orchids (22, 53, 54) and gladiolus (56-58), often occur under controlled conditions, potentially misrepresenting field performance. Additionally, most experiments lack long-term efficacy assessments and fail to adequately address PGPB interactions with indigenous soil microorganisms. Optimization of formulations and concentrations for different flower crops remains a challenge, despite promising results with specific strains (23, 25). The lack of standardized protocols and quality regulations further

Table 2. Some of the commercial PGPB products used in floriculture sector (64, 65).

Product	Manufacturer	Composition	Application
Rhizoflow FP	Rizobacter, Argentina	*Bacillus amyloliquefaciens*	Improving growth and flowering in ornamentals
Blünger	Sourcon Padena, Germany	*Pseudomonas* sp., *Bacillus* sp.	Shelf-life enhancer for cut flowers
Quantum Vita	Anthurium Biotech, Mauritius	*Bacillus megaterium*	Biofertilizer for anthurium
Radix WP	New Bio-Products, South Africa	*Bacillus subtilis*	Biofungicide and growth promoter for ornamentals
NutriLife PB	Terramera, Canada	*Bacillus* sp.	Stimulate flowering and yield in flowers
EcoVita	Mapleton Agri Biotec, Australia	*Azospirillum brasilense*	Biofertilizer to improve growth and nitrogen uptake in ornamentals
PhosNfix	Novozymes, Denmark	*Penicillium bilaiae*	Enhance nutrient availability in flowering plants
Zhongkemairui	Guangdong VTR Bio-Tech Co., China	*Bacillus subtilis*, yeast extracts	Increase yield in chrysanthemum
IronMaxx	BioWorks, USA	*Pseudomonas putida*	Prevent iron deficiency in potted flowering plants
Serifel	BASF, Germany	*Serratia plymuthica*	Stimulate flowering in ornamentals and vegetables
Florgib	Valagro, Italy	Gibberellic acid producing bacteria	Increase size and number of flowers

Table 3. India based PGPB products (66-69).

In India			
Product	**Manufacturer**	**Composition**	**Application**
Biotor Plus	Mapri Bioculture Pvt. Ltd.	*Azotobacter*, *Azospirillum*, *Pseudomonas*, *Bacillus*	Ornamental crops for plant growth, nutrient uptake, disease resistance
Bio-Vert	Bharat Biotech International Ltd.	*Bacillus subtilis*, *Bacillus licheniformis*, *Pseudomonas fluorescens*	Ornamental crops like roses, carnations, orchids for plant growth and biocontrol
BioPro	Growrich Biotechnologies Pvt. Ltd.	*Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Pseudomonas putida*	Ornamental plants for nutrient uptake, root development, plant vigor
Biomax	Multiplex Biotech Pvt. Ltd.	*Azotobacter*, *Azospirillum*, *Pseudomonas*	Ornamental crops for plant growth, nutrient availability, stress tolerance
Biogreen Plus	Novozymes South Asia Pvt. Ltd.	*Bacillus amyloliquefaciens*, *Trichoderma*	Ornamental plants like roses, chrysanthemums, gerberas for root growth, nutrient uptake, plant vigor

hinders result comparisons and product quality assurance.

To address these limitations, future research should prioritize long-term field trials under diverse conditions, PGPB-native microbiome interaction studies, development of PGPB consortia and exploration of site-specific strains. Standardization of PGPB formulation, application methods and quality control measures is crucial, as are economic viability studies in commercial settings. Advancing PGPB from laboratory to field applications in floriculture will require interdisciplinary collaboration, public-private partnerships and supportive policies. By addressing these challenges, the full potential of PGPB in enhancing flower crop production and quality can be realized, paving the way for more sustainable and efficient floriculture practices.

6. Future perspective

Advancing plant growth-promoting bacteria (PGPB) applications in floriculture requires focused research in key areas. These include identifying flower crop-specific PGPB strains, elucidating PGPB-ornamental plant molecular interactions and developing synergistic PGPB consortia. Integration with precision agriculture and microbiome engineering, assessment of long-term ecological impacts and optimization of field application and delivery systems are also crucial. Successful implementation will necessitate collaboration between researchers, industry stakeholders and policymakers. By concentrating on these critical aspects, the floriculture sector can leverage PGPB to enhance sustainability and efficiency in global commercial flower production.

Conclusion

Commercial flower cultivation is an economically important yet resource-intensive agricultural sector. Excessive reliance on agrochemical inputs in intensive floriculture can cause environmental degradation and pollution. Plant growth-promoting bacteria (PGPB) offer an eco-friendly and sustainable solution to enhance productivity, quality, and stress resilience of diverse flower crops. This review documented significant benefits of PGPB inoculations across major ornamentals like rose, chrysanthemum, gerbera, orchids and gladiolus. Key mechanisms employed by PGPB include nutrient mobilization, modulation of phytohormones, induction of systemic tolerance and biocontrol of diseases. Several PGPB-based commercial products are available as biofertilizers, bio stimulants and biopesticides for the floriculture industry. Future research should prioritize long-term field trials, PGPB-native microbiome interactions, development of crop-specific consortia, optimization of formulations and application methods, economic and environmental impact assessments and integration with precision agriculture techniques. Addressing these areas will facilitate the transition towards sustainable, environmentally responsible commercial flower production systems with minimized ecological impacts.

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Authors' contributions

MAM conducted literature search and data extraction, analysed and interpreted the compiled information. SK cconceptualized the review topic, provided guidance on the review process and approved the final manuscript. PIV and SU developed key ideas for the review, critically reviewed the manuscript and approved the final manuscript. RJ assisted in summarizing and revising the manuscript. MD contributed to manuscript editing, summarization and revision.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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During the preparation of this work the author(s) not used AI tools and the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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