

Plant Growth-Promoting Rhizobacteria (PGPR) as Biofertilizers in Cactus Fruit Crops: Current Advances and Future Perspectives

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1. Introduction

Dragon fruit (*Hylocereus/Selenicereus* spp.) has emerged as a high-value horticultural crop due to its appealing taste, health benefits and adaptability to marginal environments (Karunakaran et al., 2026). Global demand is rising, and cultivation now spans tropical and subtropical regions. However, intensive dragon fruit farming often suffers from poor soil fertility and harsh abiotic conditions. In arid agroecosystems, maintaining soil health and crop productivity without excessive chemical inputs is a major challenge (Basu et al., 2021)

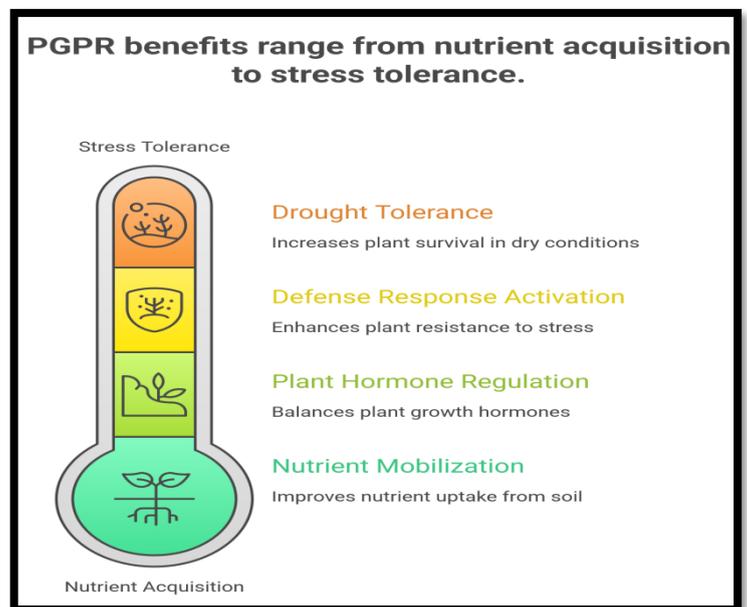


Fig 1: PGPR Benefits

PGPR are beneficial soil bacteria that colonize plant roots and enhance growth through diverse mechanisms. They can improve nutrient acquisition, modulate plant hormones, and trigger defense responses. For example, inoculating crops with PGPR-based biostimulants has been shown to increase biomass and stress tolerance, reducing reliance on synthetic fertilizers and agrochemicals (Backer et al., 2018). In desert farming systems, the plant rhizosphere often becomes enriched with PGPR that confer drought resilience. Marasco et al., (2012) found that *Capsicum annum* grown under desert conditions recruited *Bacillus*-dominated communities that boosted photosynthesis and biomass by up to 40% under water deficit. Similar strategies are promising for dragon fruit.

2. PGPR Diversity

PGPR encompass many genera of soil bacteria, including *Azospirillum*, *Azotobacter*, *Bacillus*, *Pseudomonas*, *Rhizobium* and *Burkholderia* (Basu et al., 2021). These microbes inhabit the rhizosphere

and the endosphere, forming intimate associations with plants. Through this alliance, they perform valuable ecological services.

3. Mechanisms of Plant Growth Promotion

PGPR enhance cactus growth through multiple biochemical routes:

- **Nitrogen Fixation:** Some rhizobacteria (e.g. *Azospirillum*, associative *Rhizobium*) convert atmospheric N₂ into ammonia. In arid soils where nitrogen is limiting, inoculation with N-fixing PGPR can significantly boost plant nitrogen uptake and vegetative growth (de Andrade et al., 2023)
- **Phosphate Solubilization:** In alkaline, calcareous soils common in drylands, phosphorus is often locked in insoluble forms. Phosphate-solubilizing bacteria (PSB) secrete organic acids (gluconic, oxalic) and phosphatases that free bound P, thereby improving phosphorus nutrition and fruit quality (Sun et al., 2024; Alori et al., 2017).
- **Phytohormone Production:** PGPR frequently synthesize indole-3-acetic acid (IAA) and gibberellins, which enhance root elongation and branching. For cactus crops facing drought stress, increased root surface area can improve water acquisition. Additionally, microbial cytokinins can delay leaf senescence and improve nutrient mobilization during fruit development (de Andrade et al. 2023).
- **ACC Deaminase Activity:** Many PGPR produce 1-aminocyclopropane-1-carboxylate (ACC) deaminase, an enzyme that lowers stress ethylene levels in plants. High ethylene under stress causes growth inhibition; ACC deaminase cleaves ACC, the ethylene precursor, thereby alleviating growth arrest. For example, under salinity or drought, ACC deaminase-producing *Bacillus* and *Pseudomonas* strains help plants maintain growth (Ha-Tran et al., 2021).
- **Siderophore Production:** Iron is often limited in alkaline soils. PGPR-generated siderophores chelate Fe³⁺ and facilitate its uptake by plants. This not only improves nutrition but can also suppress pathogens (many soil-borne fungi are sensitive to iron limitation) (Backer et al., 2018)
- **Stress-Adaptation Factors:** PGPR can produce exopolysaccharides (EPS) that improve soil aggregation and moisture retention around roots. They also induce host antioxidant systems: treated plants often show higher levels of proline and antioxidant enzymes (superoxide dismutase, catalase) under drought or salt stress. In one study, two drought-tolerant *Bacillus* strains from arid soil produced elevated IAA, gibberellins, siderophores, EPS and antioxidants under simulated drought; their co-inoculation increased seed germination rate and seedling vigor by over 40% (100% germination with inoculated mix vs. much lower in controls) (Ashry et al., 2022).

- **Induced Systemic Resistance (ISR):** Root-colonizing PGPR can trigger ISR, a whole-plant defensive state mediated by jasmonic acid/ethylene signaling. ISR can protect cactus plants from future biotic and abiotic stresses by enhancing stress-responsive gene expression.

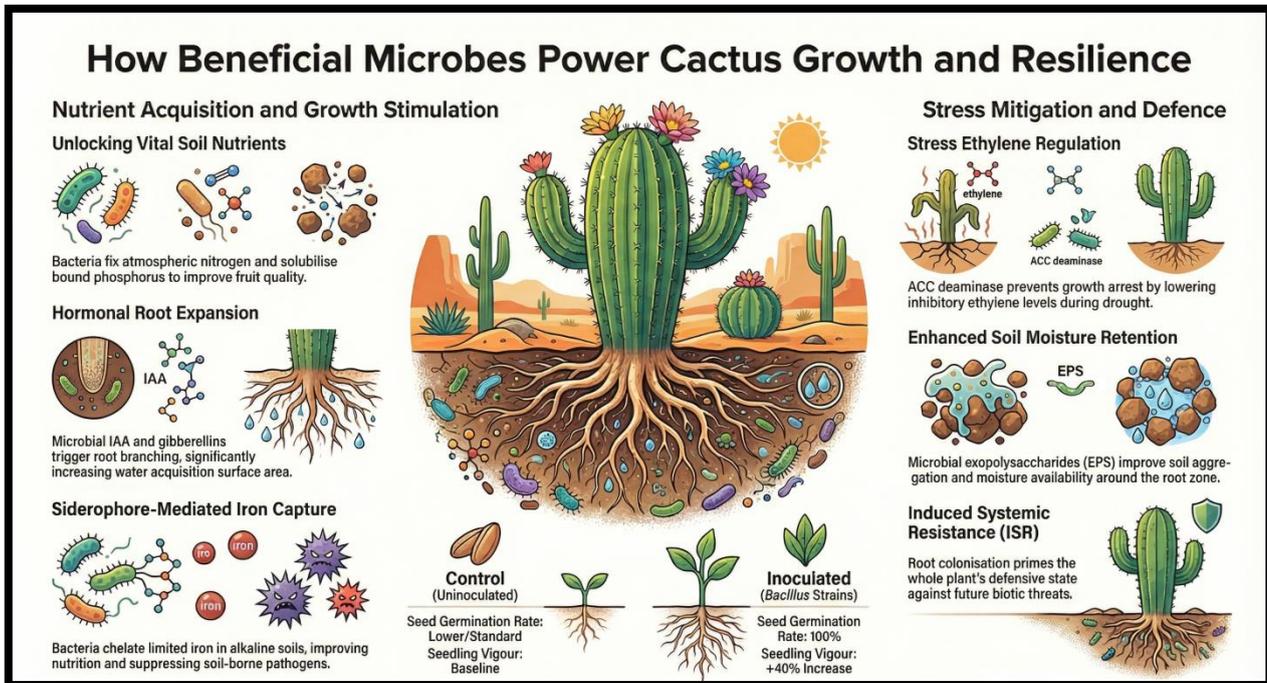


Figure 2: Functions of PGPR

4. Applications in Cactus Fruit Crops

Research specifically on dragon fruit has begun to demonstrate PGPR benefits. Although direct field trials are still limited, preliminary studies and analogous systems suggest promising results. For example, in dragon fruit stem propagation, combining vermicompost with the PGPR *Bacillus amyloliquefaciens* led to 100% cutting emergence and vigorous growth in seedlings, illustrating synergistic effects of microbial inoculants and organic amendments (Karunakaran et al., 2026).

In arid-adapted crops related to cactus (such as certain cucurbits and pepper), native rhizobacteria were found to enhance drought resilience by up to 40% in biomass compared to non-inoculated plants (Marasco et al., 2012). Given the similar challenges in dragon fruit cultivation, analogous outcomes are expected: local *Bacillus* and *Pseudomonas* strains isolated from cactus rhizospheres often possess multiple PGP traits (hormone production, N fixation, stress tolerance) and thus likely improve pitaya yields and quality.

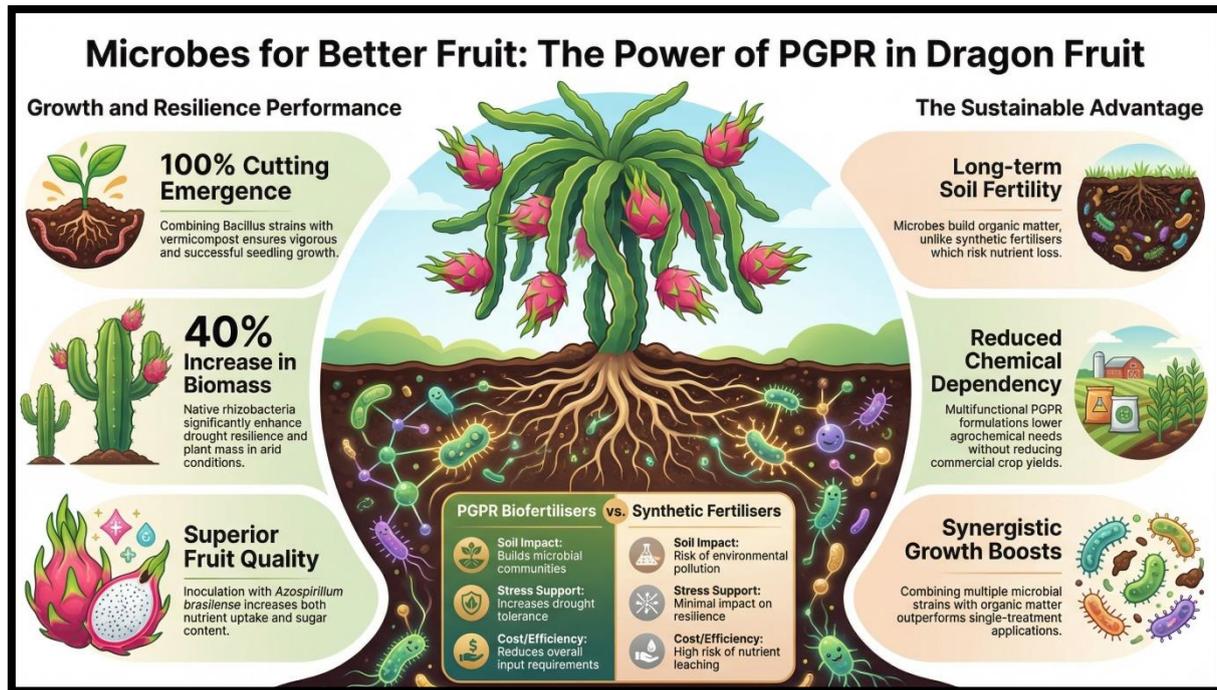


Figure 3: Application of PGPR in Dragon Fruit

To date, specific reports include greenhouse trials where *Azospirillum brasilense* increased nutrient uptake and sugar content in pitaya vines and consortia of rhizobacteria improved drought tolerance in cacti by maintaining root hydraulic conductivity (Marasco et al., 2012). There is also evidence that combining PGPR with other biofertilizers or organic inputs amplifies effects. A co-inoculation of *Bacillus* and *Azotobacter* with vermicompost, for instance, significantly boosted vegetative growth of dragon fruit compared to either treatment alone.

However, responses can be context-dependent. Soil type, climate, and cactus variety influence PGPR effectiveness. Field validation remains sparse. This underscores the need for on-farm trials. Yet, the body of research strongly indicates that introducing beneficial rhizobacteria is a viable strategy to enhance dragon fruit production sustainably, improving nutrient efficiency, yield and stress resilience.

5. Advantages over Chemical Fertilizers

PGPR biofertilizers offer several advantages relative to conventional inputs. They improve soil health and fertility over the long term by building microbial communities and organic matter. In contrast to synthetic N-P-K fertilizers, PGPR inoculants reduce nutrient losses and environmental pollution. For example, deploying PGPR has been linked to lower fertilizer requirements without yield penalties. Moreover, inoculated plants often show stronger growth under adverse conditions, potentially reducing crop losses in drought or saline soils. As one review notes, the advent of multifunctional PGPR

formulations can “minimize the use of synthetic fertilizers and agrochemicals” in agriculture (Backer et al., 2018). Thus, integrating PGPR into dragon fruit cultivation aligns with sustainable agriculture goals, lowering costs and environmental impact.

6. Challenges in Field Application

Despite the promise, practical challenges remain. Many PGPR formulations suffer from limited shelf life and inconsistent colonization under field conditions. Harsh environments in cactus orchards (high UV, extreme heat, salinity) can reduce bacterial survival. Selecting strains that are both highly effective and robust is crucial. Standardizing inoculation methods (seed vs. soil vs. cutting dips) is also an issue. Moreover, benefits seen in controlled trials do not always translate directly to farmers’ fields due to local soil microbiomes or agronomic practices. Overcoming these challenges will require rigorous formulation (e.g., encapsulation techniques, carrier materials) and quality control. Additionally, farmer awareness and extension support are needed, since adoption of biofertilizers is still low in many arid regions.

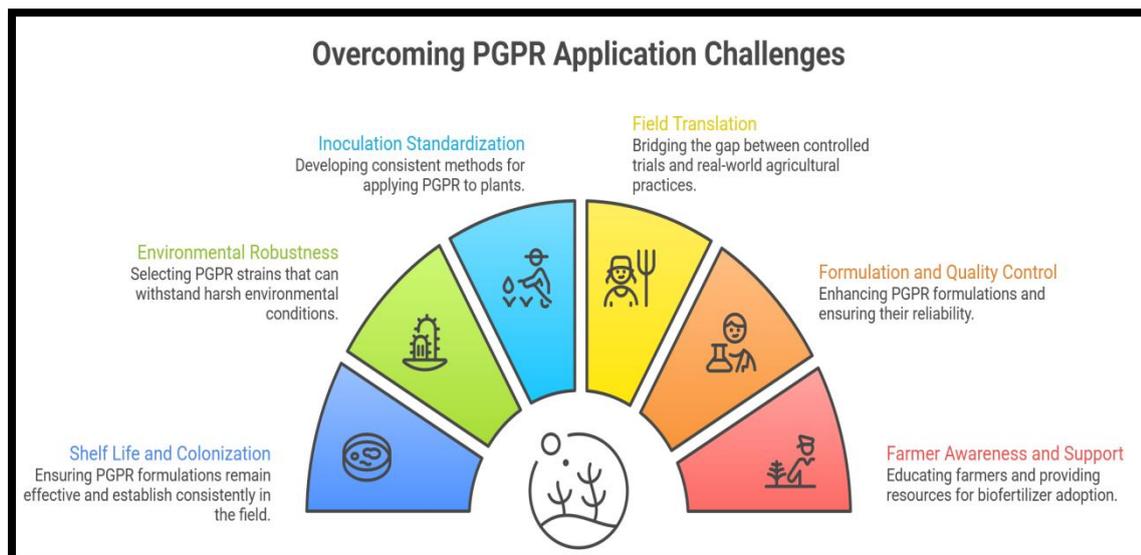


Figure 4: Challenges in Field Application and Solutions

7. Future Perspectives

To fully harness PGPR in cactus fruit systems, future work should focus on:

- **Isolation of Native Strains:** Surveying dragon fruit rhizospheres and endemic arid soils to find local PGPR adapted to specific conditions. Native isolates are more likely to survive and perform well in situ.
- **Multi-omics and Metagenomics:** Applying metagenomic and transcriptomic tools to characterize the microbial community under healthy vs. stressed cactus plants, and to identify key functional genes. This knowledge can guide selection of complementary consortia for inoculation.

- **Consortia Development:** Rather than single strains, developing tailored microbial consortia that combine nitrogen fixers, P solubilizers, ACC deaminase producers, etc., for synergistic effects. For instance, Ashry et al. (2022) showed that a combination of two *Bacillus* strains outperformed single-strain inoculants under drought.
- **Advanced Formulations:** Innovating carriers and delivery systems, such as biochar-based inoculants or nanoparticle encapsulation, to improve shelf stability and slow release of bacteria in the soil.
- **Field Trials:** Conducting multi-location trials in arid agroecosystems to validate PGPR efficacy under real farming conditions. Trials should measure not only plant growth but also fruit yield and quality parameters.
- **Integration with Organic Practices:** Studying the interactions between PGPR and organic amendments (manures, composts, biofertilizers) to develop integrated nutrient management packages. The synergistic use of PGPR with composts or vermicompost could enhance both fertility and microbial activity.
- **Rhizosphere Engineering:** Ultimately, an ‘omics’-guided approach may enable deliberate engineering of the cactus rhizosphere microbiome for optimal crop outcomes.

Addressing these areas will pave the way for reliable PGPR applications. Given the increasing challenges of climate change and soil degradation, PGPR offer a climate-smart tool: they can enhance drought resilience and nutrient use efficiency in dragon fruit, making cultivation more sustainable.

8. Conclusion

PGPR-based biofertilizers represent a promising strategy for sustainable cactus fruit production. Research to date indicates that beneficial rhizobacteria can enhance dragon fruit growth, nutrient uptake, and tolerance to drought or saline stress. Compared to chemical inputs, PGPR improve soil health and reduce environmental impact, aligning with eco-friendly agriculture goals. However, realizing this potential requires overcoming challenges of formulation and field variability. Ongoing research should emphasize isolating effective native strains, developing robust consortia, and validating them in situ. With targeted efforts, PGPR inoculation can become an integral component of dragon fruit cultivation, leading to higher yields and more resilient farming systems.

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