Spotlight

Advances in Plant Science and Environment

Plant Growth-Promoting Rhizobacteria: Multifunctional Biological Tool for Sustainable Agriculture

Karim M. Hassan

https://doi.org/xx.xxxxx/xxxxx

Plant growth-promoting rhizobacteria (PGPR) are beneficial soil microorganisms that enhance plant growth and stress resilience through diverse physiological, biochemical, and molecular mechanisms. These bacteria facilitate nutrient acquisition via biological nitrogen fixation, phosphate solubilization, siderophore-mediated iron sequestration, and phytohormone biosynthesis, while modulating plant ethylene levels through 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity. Beyond their established role as biofertilizers, PGPR confer tolerance to abiotic stresses, including drought, salinity, temperature extremes, and heavy metal toxicity by reinforcing antioxidant defense systems and improving osmotic homeostasis. They also suppress phytopathogens through antibiosis and activation of induced systemic resistance (ISR). Recent advances in nano-enabled formulations further enhance microbial stability, colonization efficiency, and field performance. This spotlight highlights the multifunctional role of PGPR as a sustainable biological tool for improving crop productivity and resilience under changing environmental conditions.

Plant Growth-Promoting Rhizobacteria

Plant growth-promoting rhizobacteria constitute a diverse group of beneficial soil bacteria that colonize the rhizosphere, rhizoplane, or endophytic compartments and enhance plant growth through coordinated physiological and molecular processes (Neemisha et al. 2022). Over recent decades, PGPR have gained considerable recognition as effective biostimulants, with consistent yield improvements reported in crops such as potato, sugar beet, maize, wheat, chickpea, tomato, and cucumber under both controlled and field conditions. Nevertheless, variable performance across agroecosystems underscores the need for a deeper understanding of plant–microbe–soil interactions (Chandran et al., 2021).

PGPR influence plant growth by modifying rhizospheric physicochemical properties and enhancing nutrient bioavailability. Principal mechanisms include biological nitrogen fixation, inorganic phosphate solubilization, siderophore production, phytohormone biosynthesis, and modulation of stress ethylene via ACC deaminase activity (Wang et al. 2023). Certain strains also emit volatile organic compounds, including 2,3-butanediol and acetoin, which stimulate plant growth and systemic responses. Additionally, PGPR contribute to pollutant biodegradation and pathogen suppression through antibiotic production and secretion of hydrolytic enzymes (Backer et al. 2018). Their effectiveness is strongly influenced by soil nutrient status, with more pronounced growth responses often observed under nutrient-limited conditions. Combined applications with organic amendments frequently result in synergistic improvements in plant growth, yield, and nodulation (Elnahal et al. 2022). Several strains also confer heavy metal detoxification, salinity tolerance, and biological pest control, reinforcing their ecological and agronomic significance.

Role of PGPR as Biofertilizer

PGPR are widely recognized as sustainable biofertilizers due to their capacity to enhance soil fertility and nutrient use efficiency through biologically mediated processes. Unlike chemical fertilizers, which directly supply nutrients, biofertilizers increase nutrient availability and uptake efficiency (Aloo et al. 2022). A primary function of PGPR is biological nitrogen fixation. Symbiotic genera such as *Rhizobium*, *Bradyrhizobium*, and *Frankia* establish specialized associations with legumes, converting atmospheric nitrogen into plant-assimilable forms. Associative and free-living genera—including *Azospirillum*, *Azotobacter*, *Herbaspirillum*, and *Gluconacetobacter*—contribute to nitrogen nutrition in non-leguminous crops, thereby reducing dependence on synthetic nitrogen fertilizers (Rochlani et al. 2022).

PGPR also enhance phosphorus bioavailability by solubilizing insoluble phosphates and mineralizing organic phosphorus through organic acid secretion and phosphatase activity. Micronutrient acquisition, particularly of iron and zinc, is improved through siderophore production and rhizospheric pH modification (Vejan et al., 2016). Furthermore, phytohormone-mediated modulation of root architecture increases root surface area and nutrient absorption capacity. Collectively, these processes improve soil structure, stimulate microbial diversity, and promote long-term nutrient cycling and soil sustainability.

Role of PGPR in Abiotic Stress Tolerance

Abiotic stresses, including drought, salinity, temperature extremes, flooding, heavy metal toxicity, and nutrient deficiency, pose major constraints to global agricultural productivity. PGPR enhance stress tolerance by modulating plant physiological, biochemical, and molecular responses (Kumawat et al. 2023). A central mechanism involves ACC deaminase activity, which lowers stress-induced ethylene accumulation that otherwise restricts root growth. PGPR-mediated regulation of phytohormonal balance influences stomatal behavior, osmotic adjustment, and stress responsive signaling pathways (Bhat et al., 2022). Enhanced root system development further improves water and nutrient uptake under limiting conditions.

PGPR also strengthen antioxidant defense systems by increasing the activity of enzymes such as superoxide dismutase, catalase, and peroxidases, thereby mitigating oxidative damage caused by reactive oxygen species. Accumulation of compatible solutes, including proline and soluble sugars, contributes to cellular osmoprotectant under drought and salinity stress. In metal-contaminated soils, PGPR alleviate toxicity through metal immobilization, chelation, and transformation, while enhancing phytoremediation efficiency via improved metal sequestration (Gupta et al. 2021).

Role of PGPR in Biotic Stress Management

Biotic stresses caused by pathogens, nematodes, insects, and weeds significantly reduce crop productivity worldwide. Overreliance on chemical pesticides has contributed to environmental contamination and pathogen resistance, necessitating sustainable alternatives (Gupta et al. 2021). PGPR suppress phytopathogens through direct antagonistic mechanisms, including antibiotic production, hydrogen cyanide release, siderophore mediated competition for iron, and secretion of lytic enzymes such as chitinases and glucanases. In addition, PGPR activate induced systemic resistance in host plants via jasmonic acid and ethylene-dependent signaling pathways, resulting

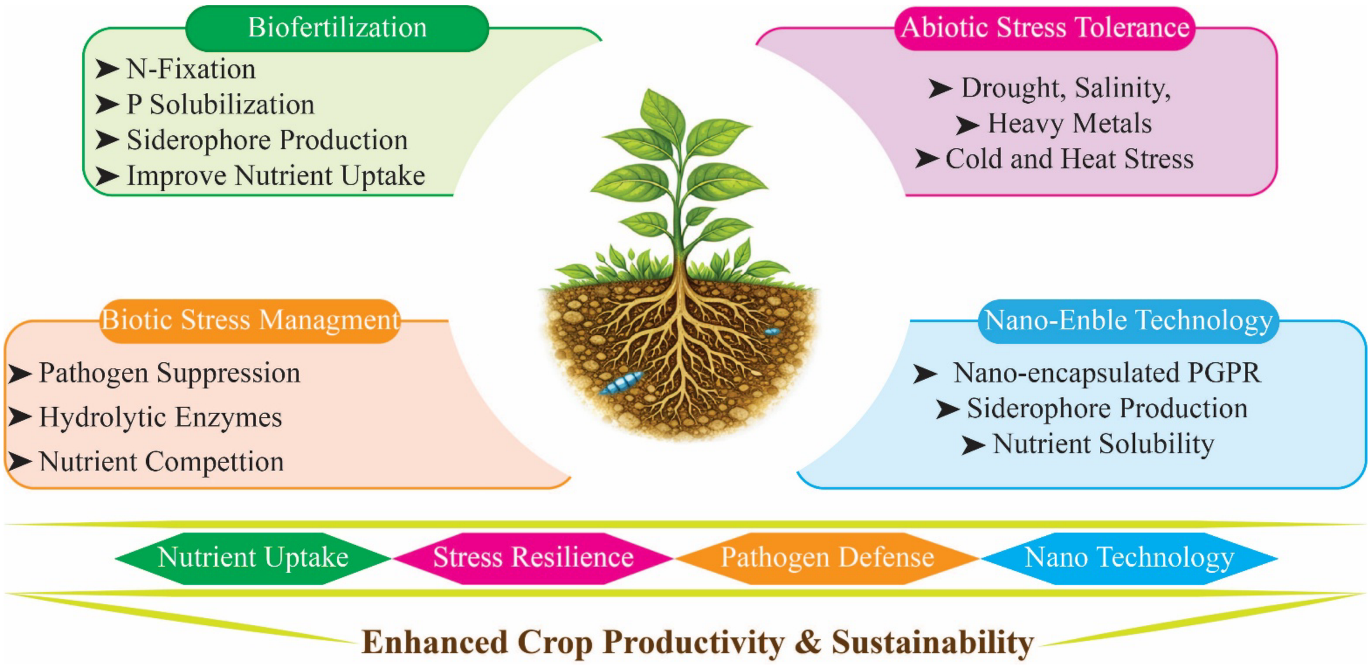

Fig. 1. Plant growth promoting rhizobacteria: versatile biological tools for sustainable agriculture.

in enhanced defense gene expression and reduced disease severity (Jha and Mohamed, 2023). Improved nutrient acquisition and root development further enhance plant vigor, enabling crops to better withstand pathogen pressure. Synergistic interactions between PGPR and other beneficial microorganisms, particularly arbuscular mycorrhizal fungi, further strengthen disease suppression and crop resilience (Bhat et al. 2022).

PGPR in Nano-Enabled Agriculture

Melatonin Nanotechnology offers innovative strategies to enhance the stability and field performance of PGPR based inoculants. Although PGPR demonstrate significant potential, their field efficacy is often constrained by limited survival and inconsistent rhizosphere colonization. Nano enabled delivery systems provide protective carriers that improve microbial viability, controlled release, and persistence (Mohan et al., 2023). Nanobiofertilizers involve the association of beneficial bacteria with nanoparticles such as silica, zinc oxide, iron oxide, and titanium dioxide. These nanomaterials enhance bacterial adhesion to roots and protect cells from environmental stresses, thereby improving colonization efficiency (Goyal et al. 2023). Moreover, nanoparticles may enhance PGPR mediated traits, including phytohormone production, siderophore synthesis, and nutrient solubilization. However, nanoparticle microbe interactions depend on particle characteristics and concentration, necessitating careful optimization and environmental risk assessment (Garg et al., 2023). Nano enabled PGPR thus represent a promising approach for developing next-generation biofertilizers with improved consistency and sustainability.

Conclusion and Future Perspectives

Plant growth-promoting rhizobacteria represent multifunctional biological agents capable of enhancing nutrient acquisition, stress tolerance, and plant health while reducing reliance on chemical inputs. Their integrated roles in biofertilization, abiotic stress mitigation, and biotic stress suppression underscore their importance in resilient agricultural systems. Despite extensive experimental evidence, inconsistent field performance remains a limitation. Future research should prioritize molecular characterization of plant–PGPR interactions, targeted strain selection, and development of stress-specific microbial consortia. Advances in nano-enabled formulations and precision agriculture integration will be critical for maximizing field efficacy and ensuring sustainable food production under evolving climatic conditions.

Reference

Aloo, B.N., Tripathi, V., et al., 2022. Plant growth-promoting rhizobacterial biofertilizers for crop production: The past, present, and future. Frontiers in Plant Science 13, 1002448. https://doi.org/10.3389/fpls.2022.1002448

Vejan, P., Abdullah, R., et al., 2016. Role of plant growth promoting rhizobacteria in agricultural sustainability—a review. Molecules 21, 573. https://doi.org/10.3390/molecules21050573

Backer, R., Rokem, J.S., et al., 2018. Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Frontiers in Plant Science 9, 1473. https://doi.org/10.3389/fpls.2018.01473

Bhat, B.A., Tariq, L., et al., 2022. The role of plant-associated rhizobacteria in plant growth, biocontrol and abiotic stress management. Journal of Applied Microbiology 133, 2717-2741. https://doi.org/10.1111/jam.15796

Chandran, H., Meena, M., et al., 2021. Plant growth-promoting rhizobacteria as a green alternative for sustainable agriculture. Sustainability 13, 10986. https://doi.org/10.3390/su131910986

Elnahal, A.S., El-Saadony, M.T., et al., 2022. The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review. European Journal of Plant Pathology 162, 759-792. https://doi.org/10.1007/s10658-021-02393-7

Garg, D., Sridhar, K., et al., 2023. Nano-biofertilizer formulations for agriculture: A systematic review on recent advances and prospective applications. Bioengineering 10, 1010. https://doi.org/10.3390/bioengineering10091010

Goyal, V., Rani, D., et al., 2023. Unlocking the potential of nano-enabled precision agriculture for efficient and sustainable farming. Plants 12, 3744. https://doi.org/10.3390/plants12213744

Gupta, A., Bano, A., et al., 2021. Plant Growth Promoting Rhizobacteria (PGPR): A sustainable agriculture to rescue the vegetation from the effect of biotic stress: Letters in Applied NanoBio Science 10, 2459-2465. https://doi.org/10.33263/lianbs103.24592465

Jha, Y., and Mohamed, H.I., 2023. Enhancement of disease resistance, growth potential, and biochemical markers in maize plants by inoculation with plant growth-promoting bacteria under biotic stress. Journal of Plant Pathology 105, 729-748. https://doi.org/10.1007/s42161-023-01338-9

Kumawat, K.C., Sharma, B., et al., 2023. Plant growth-promoting rhizobacteria: Salt stress alleviators to improve crop productivity for sustainable agriculture development. Frontiers in Plant Science 13, 1101862. https://doi.org/10.3389/fpls.2022.1101862

Neemisha, Kumar, A., et al., 2022. Harnessing rhizobacteria to fulfil inter-linked nutrient dependency on soil and alleviate stresses in plants. Journal of Applied Microbiology 133, 2694-2716. https://doi.org/10.1111/jam.15649

Rochlani, A., Dalwani, A., et al., 2022. Plant growth promoting rhizobacteria as biofertilizers: application in agricultural sustainability. Acta Scientific Microbiology 5, 12-21. https://doi.org/10.31080/asmi.2022.05.1028

Mohan, N., Ahlawat, J., et al., 2023. Engineered nanoparticles a novel approach in alleviating abiotic and biotic stress in millets: a complete study. Plant Stress 10, 100223. https://doi.org/10.1016/j.stress.2023.100223

Wang, D., Wang, C., et al., 2023. Developing plant-growth-promoting rhizobacteria: A crucial approach for achieving sustainable agriculture. Agronomy 13, 1835. https://doi.org/10.3390/agronomy13071835

Corresponding Author

Karim M. Hassan: Horticulture Department, Faculty of Agriculture, Ain Shams University, 68-Hadayek Shoubra, 11241 Cairo, Egypt
Email: kareem_hassan@agr.asu.edu.eg
ORCID: https://orcid.org/0000-0002-1241-2307

Author Contributions

The author contributed to all aspects of the manuscript.

Competing Interests

The author has no relevant financial or non-financial interests to disclose.

Data availability

No data was used for the research described in the article.

Article Info.
Received: 20 August 2024
Accepted: 25 September 2024
Published online: 6 December 2024

Additional Information

Publisher's note: BGA Press (https://bgapress.com/) remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.