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Role of Plant Growth-Promoting Rhizobacteria (PGPR) in Soil Detoxification and Crop Productivity

Chethan, M. N[1] and **Ruchitha, M**[2]

[1]*Department of Agronomy, College of Agriculture, V. C. Farm, Mandya, Karnataka, India*
[2]*Department of Soil Science and Agricultural Chemistry, College of Agriculture, V. C. Farm, Mandya, Karnataka, India*

**Corresponding author - chetanmn474@gmail.com*

Abstract

Soils across the world are under mounting pressure from industrial effluents, mining waste, pesticide residues and heavy-metal contamination, all of which threaten crop productivity and food security. Plant Growth-Promoting Rhizobacteria (PGPR) - beneficial bacteria that colonize plant roots and the surrounding rhizosphere have emerged as a low-cost, eco-friendly tool that addresses both problems at once. On one hand, PGPR promote plant growth directly through nitrogen fixation, phosphate solubilization, siderophore production and phytohormone synthesis; on the other, many strains detoxify polluted soils through biosorption, bioaccumulation, biotransformation and metal-chelation mechanisms that lower the toxicity and bioavailability of contaminants. This chapter presents the biological concept behind PGPR-mediated soil detoxification, explains the major mechanisms in plain language, and surveys real-world applications ranging from heavy-metal phytoremediation to salinity-tolerant rice biofertilizers. The aim is to make an actively growing area of soil microbiology accessible to students, farmers and policymakers alike, while pointing towards the practical and regulatory hurdles that still stand between laboratory promise and field-scale adoption.

Introduction

Soil is often called the “Skin of the Earth” because it is very important for life. More than 95% of the world’s food depends on soil, so healthy soil is essential for producing enough food for people (Kaushal and Patil, 2025). Yet decades of intensive agriculture, unchecked industrial discharge, mining activity and indiscriminate pesticide use have left large tracts of farmland contaminated with heavy metals such as arsenic, lead, cadmium and chromium, along with a cocktail of organic pollutants. These contaminants are rarely destroyed by natural processes, heavy metals in particular are non-degradable and simply accumulate, moving up the food chain and eventually threatening human health.

Traditional clean-up methods like soil washing, excavation, chemical immobilization or incineration are often expensive, disruptive to soil structure and impractical for the vast areas of agricultural land that need remediation. Phytoremediation, the use of living plants to extract, stabilize or degrade contaminants, offers a gentler and more economical alternative, but it has its own limitations: many high-biomass crop plants are sensitive to metal toxicity, have shallow root systems and grow too slowly to make a meaningful dent in heavily polluted sites (Qin *et al*., 2024).

This is where Plant Growth-Promoting Rhizobacteria enter the picture. PGPR are naturally occurring soil bacteria that live in close association with plant roots and actively improve plant growth, either by supplying nutrients and hormones or by protecting the plant from stress and disease. In the past 30 years, interest in PGPR has increased greatly. Research shows that PGPR can both improve crop growth and reduce the harmful effects of soil pollution, making them useful for sustainable agriculture and soil restoration (Qin *et al*., 2024).

Overview of PGPR

PGPR are free-living, root-colonizing or endophytic bacteria that establish themselves in the rhizosphere - the thin zone of soil immediately surrounding plant roots that is enriched by root exudates such as sugars, amino acids and organic acids. PGPR genera include *Bacillus, Pseudomonas, Azospirillum, Serratia, Enterobacter, Rhizobium, Arthrobacter* and *Ochrobactrum*, among many others (Kaushal and Patil, 2025). The relationship is broadly mutualistic as the plant leaks a share of its photosynthetic sugars into the rhizosphere as food and in return the bacteria return the favour through nutrient acquisition, hormone signalling, stress protection and pathogen suppression.

PGPR act through direct and indirect mechanisms. Direct mechanisms are those where the bacterium physically supplies the plant with something it needs, such as fixed nitrogen or soluble phosphate. Indirect mechanisms are those where the bacterium improves the plant's growing conditions without directly feeding it for example, by out competing disease causing fungi or by lowering the internal stress signals a plant produces when it is exposed to a toxic environment.

PGPR and Soil Detoxification

The contamination problem

Heavy metals such as cadmium, lead, chromium and arsenic enter agricultural soils through mining tailings, industrial wastewater, vehicle emissions and phosphate fertilizers themselves. Unlike organic pollutants, metals cannot be broken down into harmless by-products - they can only be transformed into less bioavailable, less mobile or less toxic chemical forms, or physically removed from the site. Elevated metal concentrations disturb chlorophyll synthesis, generate reactive oxygen species inside plant cells and stunt root and shoot growth, which is why contaminated fields typically show poor and uneven crop stands (Rao *et al*., 2025)

How PGPR detoxify soil

PGPR reduce plant exposure to contaminants through different mechanisms that make harmful substances less available around the plant roots.

• *Biosorption and bioaccumulation*: bacterial cell walls, capsules and exopolysaccharides carry negatively charged functional groups that passively bind metal cations, trapping them outside the plant root and away from sensitive tissues.

• *Chelation via siderophores and organic acids*: iron-scavenging siderophores and small organic acids can bind toxic metal ions in soluble complexes, which either keeps the metal away from the root or when phytoremediation is the goal, makes it easier for the plant to take the metal up in a controlled form.

• *Biotransformation and redox conversion*: some PGPR enzymatically convert metals between oxidation states (for example, more mobile and more toxic chromium(Cr^{4+}) into the far less mobile and less toxic chromium(Cr^{3+}), which is one of the more powerful detoxification routes because it changes the chemistry of the pollutant itself.

• *Precipitation and biomineralization*: bacterial metabolic by-products, such as phosphate or sulfide ions, can react with metals to form stable, insoluble mineral precipitates that are locked out of the soil-water system.

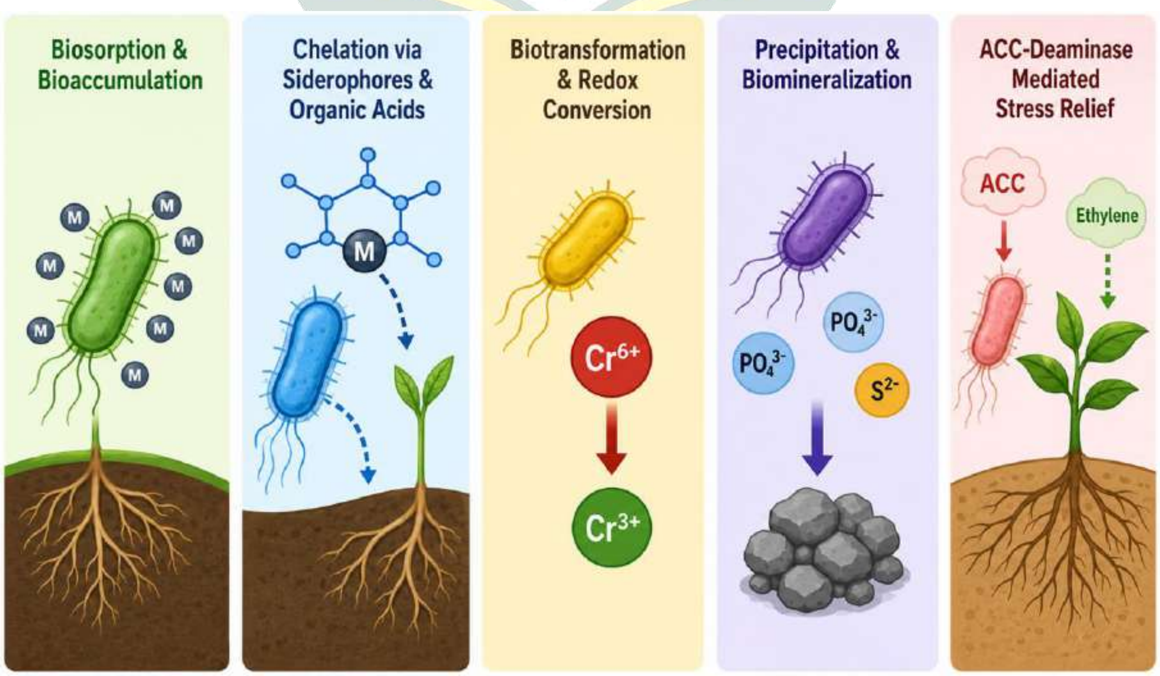
• *ACC-deaminase-mediated stress relief*: by lowering the ethylene surge that heavy-metal stress normally triggers in roots, PGPR allow the plant to keep growing roots and shoots even while contaminants are present, buying time for other detoxification processes to work.

PGPR can perform several beneficial functions at the same time. They improve nutrient availability and plant growth while also reducing the harmful effects of soil contaminants, helping plants develop better roots and produce more biomass. In phytoremediation, this greater plant growth can also increase the amount of contaminants taken up from the soil (Bhattacharyya *et al*., 2012).

Applications in the field

Biofertilizers for Sustainable Agriculture

The most widespread commercial use of PGPR



today is as a biofertilizer - a living inoculant applied to seeds, roots or soil in place of chemical fertilizer. Because PGPR-based inoculants reduce the need for synthetic nitrogen and phosphorus inputs, they cut both cost and environmental pollution while maintaining or improving yields. A recent field study on rice demonstrated the point concretely: salt-tolerant PGPR isolates, screened for indole acetic acid production, nitrogen fixation, phosphate and potassium solubilization, ACC-deaminase activity and siderophore output, improved rice seedling growth in both normal and saline pot conditions, with strains such as *Mesorhizobium* and *Enterobacter* successfully colonizing rice roots across a range of salinity levels (Sarinet *et al*., 2025).

Assisted phytoremediation of contaminated land

In heavy metal-contaminated soils, PGPR can work together with plants to improve phytoremediation. They colonize the plant roots and help plants tolerate the toxic effects of heavy metals. PGPR produce useful substances such as ACC-deaminase, siderophores and organic acids. These substances can reduce metal-induced stress and improve nutrient availability to plants. PGPR can also change the availability and mobility of heavy metals in the soil. This helps plants maintain better root growth even under contaminated conditions. Healthy roots allow plants to absorb more water and nutrients from the soil. Improved plant growth results in greater biomass production and better plant survival. Greater biomass can increase the total amount of heavy metals removed from contaminated soil. Therefore, PGPR-assisted phytoremediation is a promising approach for reducing contamination by arsenic, lead, cadmium and chromium (Sahoo *et al*., 2024).

Abiotic stress tolerance

Beyond chemical contamination, PGPR help crops cope with drought, flooding, high temperature and soil salinity stresses that are becoming more frequent under a changing climate. ACC-deaminase producing strains have, for instance, been reported to help tomato plants tolerate combined drought and salinity stress and comparable deaminase activity has been linked to improved plant tolerance of flooding, temperature extremes and UV exposure across a range of crop species (Ehinmitan *et al*., 2024). This stress-buffering role is particularly valuable in marginal or contaminated soils, where physical and chemical stress is often compounded rather than singular.

Integration with organic amendments and new technologies

Recent studies have shown that PGPR perform more effectively when combined with complementary soil amendments such as compost, rock phosphate and biochar. Increasingly, nanotechnology based carriers are also being explored to develop integrated approaches that improve soil fertility, detoxifies heavy metals and supports climate-resilient crop production together, rather than as separate interventions. Molecular tools such as metagenomics and meta-transcriptomics are now being used to identify which PGPR genes involved in nitrogen fixation, phosphate solubilization, siderophore production and ACC-deaminase activity are active under field conditions. This helps researchers select and develop effective PGPR strains based on their actual functions rather than relying mainly on trial and error (Wang and Xu, 2026).

Practical constraints

Despite their potential, using PGPR successfully in farmer's fields is not always easy. The performance of a PGPR strain can vary depending on the crop, soil type and climatic conditions. A strain that performs well in one location may not give the same results in another location. Therefore, using native PGPR strains that are already adapted to the local soil and environment is often recommended (Melo *et al*., 2016). Other challenges also limit the widespread use of PGPR. These include maintaining the quality and stability of the inoculant during storage and transport, ensuring that the bacteria survive after application to the field and dealing with competition from naturally occurring soil microorganisms. In addition, regulatory approval for using PGPR as biofertilizers or bioremediation agents can also be a major challenge for their commercial adoption (Ehinmitan *et al*., 2024).

Conclusion

Plant Growth-Promoting Rhizobacteria (PGPR) have great potential to support both agricultural production and environmental restoration. They promote plant growth by improving nutrient availability and producing beneficial compounds, while some strains can also reduce the harmful effects of heavy metals and other soil pollutants. This makes PGPR useful as both biofertilizers and bioremediation agents. Their combined role can improve plant growth, soil health and the recovery of contaminated soils. However, successful field application depends on selecting suitable strains, developing effective microbial consortia, improving formulation and storage, and conducting proper field validation. Overall, PGPR offer a promising approach for achieving healthier soils, better crop productivity and reduced soil toxicity through sustainable agricultural practices.

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