The Role of Plant Growth-Promoting Bacteria (PGPB) in Soil Fertility Restoration in Chemical-Contaminated Areas

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Abstract

Soil contamination by chemicals is a severe environmental problem that harms ecosystem health and agricultural output. Chemically-damaged soils must be restored to produce food and sustainable land usage. One potential strategy is applying Plant Growth-Promoting Bacteria (PGPB) to improve soil fertility and plant development. This article examines the research on using PGPB to restore soil fertility in chemically-polluted regions, including its methods of action, effectiveness, and prospective uses for long-term soil management.

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1. Introduction

Environmental and public health are seriously threatened by soil contamination from chemical pollutants such as heavy metals, pesticides, and industrial waste. These contaminants may cause nutrient depletion, soil deterioration, and decreased agricultural yields (Alengebawy et al., 2021). The procedures used in conventional soil remediation are frequently expensive and harmful to the environment. A viable alternative for environmentally benign and long-lasting soil fertility restoration is by using PGPB strains (Poria et al., 2022). Soil metal contamination is a major concern worldwide due to its detrimental environmental and human health effects. Conventional reclamation methods are often expensive and impractical, leading to microbe-aided phytoremediation as an environmentally friendly and cost-effective alternative (Alves et al., 2022).

Heavy metal contamination of soil reduces agricultural yield and negatively impacts ecosystem health. Metal-tolerant plants have been used in “green technology” to clean up contaminated soils. However, environmental factors are worsened by global warming, which inhibits the development and metal-accumulating ability of remediating plants. Through activities such as nitrogen fixation, phosphate solubilization, phytohormone synthesis, and biological disease control, PGPBs have been developed to increase the effectiveness of phytoremediation (Wang et al., 2022).

Bacteria that promote plant growth are known as PGPB and populate the rhizosphere region of the plant. They develop symbiotic partnerships with plants and help them get nutrients, produce hormones, and resist illness. Numerous PGPB taxa, including predominantly *Bacillus* and *Pseudomonas*, have undergone significant research to determine whether they have the ability to reduce the harmful impacts of chemical pollutants in the soil (Poria et al., 2022; Sorour et al., 2022).

2. Mechanisms of PGPB-Mediated Soil Fertility Restoration

2.1. Nutrient Solubilization

In polluted soils, PGPB can create organic acids and enzymes that solubilize insoluble nutrients, releasing them for plant absorption. This mechanism plays an essential role in regions where chemical contaminants have prevented plants from accessing vital nutrients (Ajijah et al., 2023; de Andrade et al., 2023; Olanrewaju et al., 2017).

2.2. Phytohormone Production

Auxins, cytokinins, and gibberellins, which control various plant development processes, are just a few examples of the phytohormones that PGPB may produce. These hormones encourage the growth of roots, improve nutrient absorption, and boost a plant's resistance to external stresses, including chemical toxicity (Egamberdieva et al., 2017; Orozco-Mosqueda et al., 2023).

2.3. Induced Systemic Resistance (ISR)

To protect themselves from pathogens and abiotic stress, plants' ISR is triggered by PGPB. This improved resistance benefits soil health and helps plants withstand the damaging impacts of biological and chemical contaminants (Choudhary et al., 2007; Saeed et al., 2021).

2.4. Metal Sequestration and Detoxification

Some PGPBs have enzymes and proteins that help with metal detoxification and sequestration. These bacteria help restore soil fertility by lowering the toxicity of metals in the soil (Wang et al., 2022).

2.5. Efficacy of PGPB in Chemical-Contaminated Areas

Numerous case studies have shown how well PGPB works to restore soil fertility in chemically polluted areas.

PGPBs can potentially enhance the phytoremediation of metal-polluted soils through mechanisms that promote plant growth and help to remove or immobilize metals in the soil. Microbes can also mediate metal removal and detoxification through processes such as adsorption of metals, chelation of heavy metals, transformation, and precipitation processes. PGPB can facilitate the plant's acquisition of nutrients, supply and regulate phytohormones in plants, and strive for control over antagonistic microorganisms. Understanding the relationship between plants and microbes in metal-polluted soils is crucial for boosting phytoremediation (Alves et al., 2022).

Two PGPBs, *Acinetobacter* sp. and *Pseudomonas putida*, were examined in a study to see how they affected the phytoextraction of copper (Cu) in the Maize plant. The strains were chosen because of their capacity to synthesize siderophores, solubilize phosphorus, synthesize indole compounds, improve soil conductivity, and enhance the amount of extractable copper in the soil. These active bacterial isolates can also liberate copper from the soil and considerably improve soil conductivity compared to the control. PGPBs help in phytoextraction of polluted soil by boosting plant development and mineral availability to plants from the soil (Rojas-Tapias et al., 2014).

In industrially contaminated soil, *Bacillus pumilus* and ethylenediaminetetraacetic acid synergy for enhanced plant growth and Cd-uptake potential of *Zea mays* (Hayat et al., 2020).

3. Potential Applications and Future Directions

Sustainable agriculture and environmental rehabilitation are greatly enhanced by using PGPB to restore soil fertility in chemically damaged areas. However, several problems and areas for further study should be addressed (Glick, 2012; Poria et al., 2022).

PGPBs enhance crop yield and nutritional content and suppress plant pathogens. Furthermore, they promote soil health and decrease the need for chemical fertilizers. However, long-term research on their impacts on the organization of the current microbial population in and around plants is lacking. Most PGPBs are resistant to some antibiotics, which can be harmful if spread to other bacteria. The development of PGPB strains that are not resistant to antibiotics might increase agricultural output without a detrimental environmental impact. Large-scale antimicrobial resistance screening of PGPB is required, as are long-term investigations into how biofertilizers affect the natural microbial populations of the soil (Ramakrishna et al., 2019).

3.1. Field-Specific Formulations

The effectiveness of PGPB can be influenced by specific soil conditions and types of contaminants. Developing tailor-made PGPB formulations for different chemical-contaminated sites will optimize their impact.

The two metal-resistant PGPB strains, *Pseudomonas* sp. and *Pseudomonas jessenii*, can utilize 1-aminocyclopropane-1-carboxylic acid as a nitrogen source, solubilize phosphate, and produce indole-3-acetic acid. *Ricinus communis* grown in a pot with nickel, copper, zinc, and PGPB strains reported more biomass from the PGPB-inoculated pot than their control counterparts. These strains help in the accumulation of Zn in more plant parts than other metals. The metal-resistant PGPB has the potential to be an efficient bioinoculant by sequestering metal and encouraging the growth of plants under metal-stressed soil (Rajkumar and Freitas, 2008).

3.2. Interaction with Indigenous Microbiota

Understanding the interactions between introduced PGPB strains and indigenous soil microorganisms is vital to ensure the stability and long-term success of soil fertility restoration programs.

3.3. Risk Assessment

Thorough risk assessment studies are necessary to evaluate the potential ecological problems associated with releasing genetically modified PGPB strains into the environment.

Genetically modified PGPB strains can improve soil fertility and plant health and lower chemical input use. However, concerns exist regarding the possible dangers connected to their usage. Numerous PGPBs include antibiotic resistance genes (ARGs), which raises the possibility that they may spread to local microbial communities in the soil and other environmental reservoirs, including animals, water bodies, and people. The widespread inoculation of crops with bacteria that produce ARGs has the potential to exacerbate the spread and development of antibiotic resistance, as well as the detrimental effects on ecosystems and public health (Mahdi et al., 2022).

3.4. Scaling up

Developing large-scale application strategies for PGPB-based biofertilizers is essential to make them economically viable for widespread adoption in contaminated areas.

Conclusion

Plant Growth-Promoting Bacteria offer a promising and eco-friendly solution for soil fertility restoration in chemical-contaminated areas. Through various mechanisms, including nutrient solubilization, phytohormone production, and metal detoxification, PGPB enhances plant growth and resilience, promoting sustainable agriculture in polluted soils. Further research and field trials will continue to advance our understanding of PGPB's potential applications, contributing to a greener and healthier future.

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