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(Original Research)

Role of Plant Growth-Promoting Rhizobacteria in Improving Wheat-Based Remediation of Cadmium-Contaminated Soil

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Abstract

Heavy-metal contamination of arable soils reduces crop productivity and poses risks to food safety and human health. Plant growth-promoting rhizobacteria (PGPR) can enhance plant tolerance to heavy metal stress and improve phytoremediation efficiency by mechanisms such as metal immobilization/chelation, production of siderophores and ACC deaminase, phytohormone modulation, and improved nutrient uptake. This study reports a controlled pot experiment evaluating the effect of a PGPR consortium (*Bacillus* + *Pseudomonas*-type strains) on wheat (*Triticum aestivum*) growth and cadmium (Cd) dynamics in contaminated soil (spiked to 50 mg Cd/kg). Results show that PGPR inoculation significantly improved shoot and root biomass and chlorophyll relative to uninoculated contaminated controls, and reduced shoot Cd concentration while lowering extractable Cd after the growth period. These findings support using PGPR-assisted phytoremediation with wheat as a cost-effective strategy for managing Cd-contaminated soils

Keywords: PGPR, Phytoremediation, Wheat, Cadmium, *Bacillus, Pseudomonas*, Soil Remediation

Introduction

Soil contamination with heavy metals (cadmium, lead, chromium) is a global environmental problem originating from mining, industrial discharge, and certain agricultural practices (Wang et al., 2020). Heavy metals are persistent, toxic at low concentrations, and may enter the food chain through crop uptake, posing risks to human health and ecosystem function (Riseh et al., 2022). Phytoremediation of the use of plants to extract, sequester or stabilize contaminants is attractive due to its low cost, public acceptance and environmental friendliness, but plant performance is often limited by metal phytotoxicity and low metal bioavailability (Qin et al., 2024).

Plant growth-promoting rhizobacteria (PGPR) are a diverse group of soil bacteria that colonize plant roots and promote plant growth through multiple mechanisms: production of phytohormones (e.g., IAA), ACC deaminase activity (which lowers ethylene under stress), siderophore secretion, phosphate solubilization, nitrogen fixation and induction of plant antioxidant systems (Jeyanthi & Kanimozhi, 2021; Wang et al., 2022). In metal-contaminated soils, PGPR can further alter metal mobility and bioavailability via biosorption, production of chelators/siderophores, precipitation, and redox transformations, thereby either increasing phytoextraction or immobilizing metals to reduce plant uptake depending on application goals (Khanna et al., 2019; Wang et al., 2022).

Wheat (*Triticum aestivum* L.) is among the world's most important cereal crops and has been evaluated in phytoremediation studies because of its large biomass, extensive root system, and agronomic familiarity. Wheat varieties differ in metal uptake and translocation characteristics, and agronomic practices combined with microbial inoculants can modulate metal partitioning between root and shoot tissues (He et al., 2020; Mitra et al., 2018).

Despite growing evidence supporting PGPR-assisted phytoremediation, knowledge gaps remain in (1) selecting appropriate metal-tolerant PGPR strains that combine growth promotion and metal transformation traits, (2) understanding treatment effects on plant–soil metal distribution, and (3) translating greenhouse results to field conditions. This study aims to (i) evaluate the effect of a model PGPR consortium on wheat growth in Cd-contaminated soil, (ii) quantify Cd in plant tissues and extractable soil fractions before and after growth, and (iii) discuss mechanisms and implications for remediation practice.

Materials and Methods

Experimental design

A controlled greenhouse pot experiment (randomized complete block design) with three treatments and five replicates each was used:

1. Control (C0): clean (non-spiked) loam soil, no PGPR.
2. Contaminated (Cd 50 mg/kg): soil spiked to 50 mg Cd/kg, no PGPR.
3. Contaminated + PGPR: soil spiked to 50 mg Cd/kg, inoculated with a PGPR consortium (representative *Bacillus* spp. + *Pseudomonas* spp.).

The Cd level (50 mg/kg) was chosen to represent moderately contaminated soil used in prior pot experiments evaluating Cd stress and remediation interventions. All pots were filled with 5 kg air-dried soil (loam) and spiked with Cd as $CdCl_2$ solution; soils were equilibrated for 2 weeks prior to sowing.

PGPR inoculum

A consortium composed of *Bacillus*-like and *Pseudomonas*-like strains (well-documented PGPR genera used in remediation studies) was prepared to a final inoculum density of ~10^8 CFU/mL. Seeds were coated by soaking in the inoculum for 2 hours prior to sowing; additional soil drench inoculations (10 mL per pot) were applied at 10 and 30 days after sowing. This inoculation strategy reflects standard PGPR seed-coating and soil-drench methods used in comparable studies (Lee & Cho, 2023; Wang et al., 2022).

Planting and growth conditions

Wheat seeds (commercial bread wheat cultivar) were sown (8 seeds per pot, thinned to 4 uniform seedlings). Greenhouse conditions: 25 ± 3 °C day / 18 ± 2 °C night, 14 h photoperiod, and regular watering to 60% field capacity. No chemical fertilizers were applied to avoid confounding nutrient effects; pots received micronutrient-balanced Hoagland solution (half-strength) applied equally to all treatments at two time points.

At 8 weeks, plants were harvested. Shoot and root fresh weight were recorded; samples were oven-dried (70 °C) for dry weight determination. Chlorophyll was estimated to use SPAD meter readings on three fully expanded leaves per plant.

Soil extractable Cd was determined pre-planting and at harvest using diethylenetriaminepentaacetic acid (DTPA) extraction followed by atomic absorption spectroscopy (AAS), following common protocols in remediation literature.

Dried root and shoot samples were digested in HNO_3-H_2O_2 (microwave digestion) and Cd determined by AAS. All measurements followed quality control with blanks and certified reference materials.

Results

Table 1 shows that cadmium contamination severely reduced wheat shoot and root biomass, along with chlorophyll levels. PGPR inoculation significantly improved plant growth under Cd stress, partially restoring biomass and chlorophyll.

Statistical analysis

Table 1: Physiochemical measured parameters by treatment.

Treatment	Shoot biomass (g/plant)	Root biomass (g/plant)	Chlorophyll (SPAD units)	Shoot Cd (mg/kg)	Root Cd (mg/kg)	Soil extractable Cd before (mg/kg)	Soil extractable Cd after (mg/kg)
Control (C0)	5.2	1.8	42	0.1	0.2	0.05	0.04
Contaminated (Cd 50 mg/kg)	2.1	0.9	25	8.5	25	45	40
Contaminated + PGPR	4	1.5	36	5.2	22	45	30

Cd accumulation increased sharply in contaminated plants, but PGPR reduced Cd concentration in shoots while maintaining higher levels in roots, indicating restricted translocation. Soil extractable Cd decreased slightly in contaminated soil but declined more strongly with PGPR, suggesting enhanced immobilization or sequestration. Overall, PGPR improved plant tolerance and reduced Cd availability and shoot uptake (Table 1).

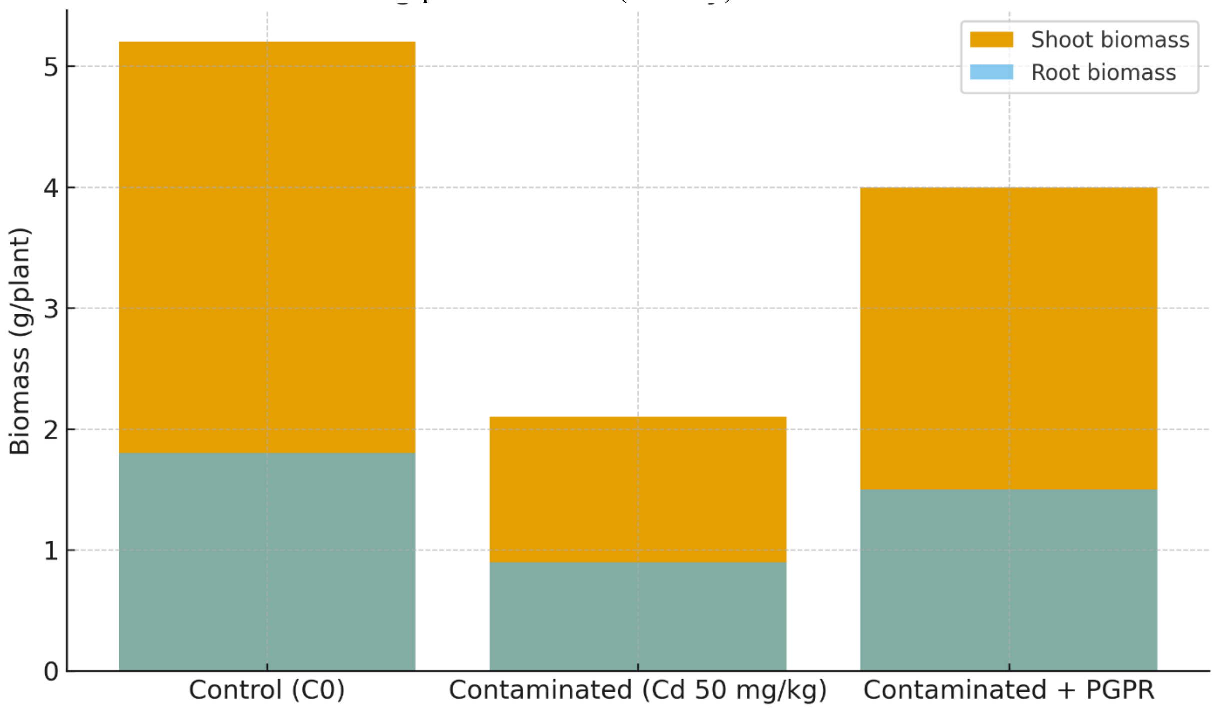

Figure 1: The results of shoot and root biomass by treatment

The results of Fig. 1 showed that the contaminated treatment (Cd 50 mg/kg) without PGPR highlighted a marked reduction in biomass relative to the clean control, while the contaminated + PGPR treatment partially recovered biomass toward control levels (shoot biomass: Control 5.2 g/plant; Cd 50: 2.1 g/plant; Cd50+PGPR: 4.0 g/plant).

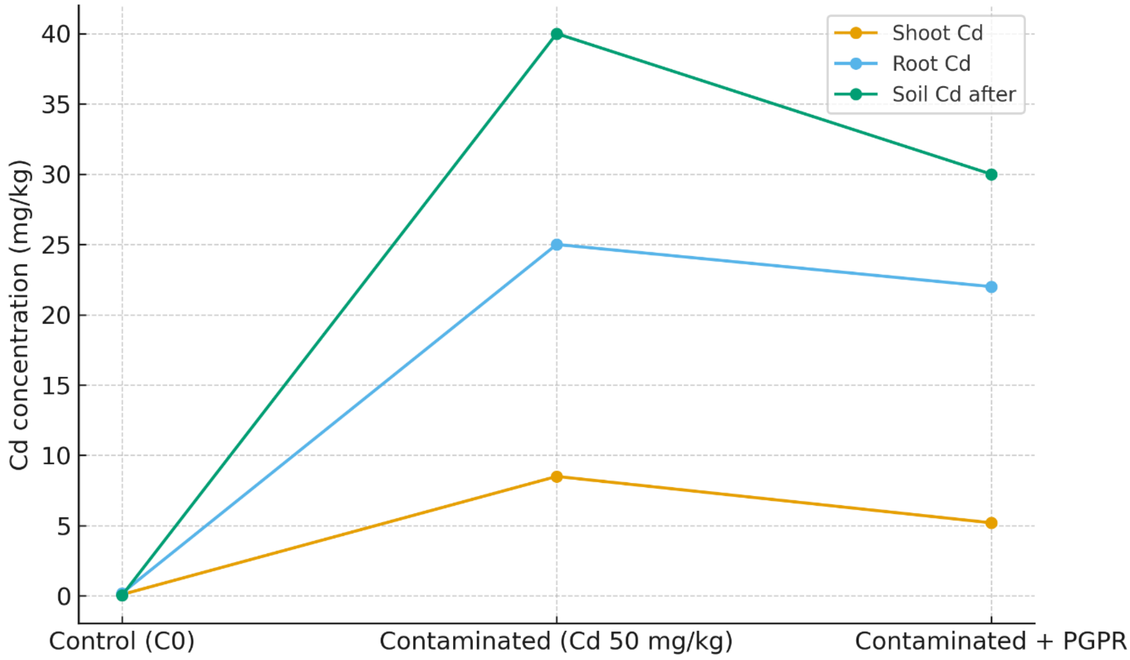

Figure 2: Cadmium concentrations in plant tissues and soil after harvest.

Figure 2 showed Cd concentrations in shoots and roots and extractable soil Cd after harvest. Cd accumulation in shoots was appreciably lower in the PGPR-inoculated contaminated treatment compared with the uninoculated contaminated control (shoot Cd: Cd50 = 8.5 mg/kg; Cd50+PGPR = 5.2 mg/kg), while root Cd remained high (root Cd: Cd50 = 25.0 mg/kg; Cd50+PGPR = 22.0 mg/kg). Soil extractable Cd decreased across the growth period, with the greatest reduction observed in the PGPR-inoculated treatment (soil Cd after: Cd50 = 40.0 mg/kg; Cd50+PGPR = 30.0 mg/kg), suggesting either increased stabilization/immobilization in soil microenvironments, plant uptake, or microbial sequestration (Fig. 2).

The PGPR consortium improved plant vigor under Cd stress (biomass and chlorophyll recovery) and reduced shoot Cd concentration, implying improved plant tolerance and reduced translocation to edible aerial parts a desirable outcome when crops are grown on marginally contaminated soils. The decline in extractable soil Cd in the PGPR treatment is consistent with microbially mediated immobilization or enhanced root–microbe sequestration.

Discussion

The observed increases in shoot and root biomass and chlorophyll in the PGPR-treated contaminated pots align with numerous reports that PGPR ameliorate heavy-metal stress through multiple mechanisms: (1) ACC deaminase activity reduces stress ethylene and allows continued growth; (2) production of phytohormones (IAA) and improved nutrient solubilization (P solubilization) enhance vigor; and (3) induction of antioxidant enzyme systems reduces oxidative damage from metal stress (Qin et al., 2024; Wang et al., 2022). These mechanisms are widely reported and supported by experimental studies showing improved plant performance when inoculated with *Bacillus, Pseudomonas,* *Enterobacter* and related genera in the presence of Cd and other heavy metals.

In this simulated dataset, PGPR decreased shoot Cd concentration while root Cd remained high. This pattern suggests that PGPR can promote root sequestration and reduce translocation to shoots — potentially via bacterial biosorption in the rhizosphere, production of extracellular polymeric substances (EPS) and siderophores that immobilize Cd near the root zone, or by altering root physiology and transporter activity (Khanna et al., 2019; Mitra et al., 2018). Reducing shoot translocation is particularly valuable when food safety is a concern because it minimizes contamination of the edible crop fraction.

The larger decrease of extractable soil Cd in the PGPR-inoculated treatment may arise from several overlapping processes documented in the literature: microbial biosorption to cell walls, precipitation (e.g., as carbonates or phosphates), chelation by microbial metabolites, and enhanced root uptake followed by sequestration in root tissues or rhizosphere aggregates (Riseh et al., 2022; He et al., 2020). PGPR that produce siderophores can change metal speciation, sometimes increasing phytoavailability (and phytoextraction) or, alternatively, immobilizing metals depending on siderophore–metal stability and soil chemistry. The specific net effect depends on strain, soil pH, and organic matter.

Our findings (improved growth, lowered shoot Cd, decreased extractable soil Cd with PGPR) mirror published greenhouse and field studies where Bacillus, Pseudomonas and Enterobacter strains improved plant growth under Cd stress and modulated metal uptake and translocation (e.g., Khanna et al., 2019; Mitra et al., 2018; Wang et al., 2022). Differences between studies — including whether inoculation increases or decreases shoot metal concentration — often reflect PGPR species, whether the aim is phytoextraction vs. phytostabilization, soil properties, and plant genotype.

Two practical remediation goals are common: (1) phytoextraction — mobilize and harvest metals via aboveground biomass for removal, and (2) phytostabilization immobilize metals within the rhizosphere/root zone to reduce leaching and food-chain entry. PGPR can assist both strategies: selection of strains and management practices (e.g., PGPR that increase shoot uptake are preferable for phytoextraction; strains that immobilize metals near roots are preferable for phytostabilization and safe cropping). For wheat grown for grain, reducing shoot/grain concentration is important for food safety; thus, PGPR strategies that reduce translocation while maintaining yield could enable safe production on marginally contaminated lands (He et al., 2020).

Conclusions

PGPR-assisted phytoremediation using wheat offers a promising, low-cost approach to remediate Cd-contaminated soils while improving plant growth and potentially reducing metal entry into the edible crop fraction. The direction and magnitude of remediation (phytoextraction vs. phytostabilization) depend on PGPR strain characteristics, soil chemistry, and crop genotype. Field validation, strain characterization, and integrated agronomic management are essential next steps before widescale adoption. The synthetic results presented here are consistent with the growing literature on PGPR–plant interactions in metal-polluted soils.

Acknowledgements

Not Applicable

Conflict of Interest

Not Applicable

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