Advances in Phosphate-Solubilizing Microorganisms for Remediation of Heavy Metal-Contaminated Soils: A Postprint

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Date: 2018-05-29T00:00:00+00:00

Abstract

Soil heavy metal pollution is becoming increasingly severe, characterized by universality, concealment, surface accumulation, and irreversibility, and has become a prominent and challenging issue in environmental pollution control. Phosphate-solubilizing microorganisms can convert insoluble phosphorus in soil into plant-available phosphorus through their metabolic products or synergistic interactions with other organisms, exhibiting multiple plant growth-promoting functions and heavy metal detoxification capacities. Under heavy metal toxicity levels, they can promote plant growth, enhance plant disease resistance, mitigate the adverse effects of heavy metals on plant growth, thereby strengthening the survival competitiveness of heavy metal remediation plants. This review begins with the current research status of phosphate-solubilizing microorganisms, introduces their remediation capacity for soil heavy metal pollution, summarizes their mechanisms of action in soil heavy metal pollution remediation, analyzes existing challenges in the application of phosphate-solubilizing microorganisms in heavy metal remediation, and proposes future research directions, offering new insights for the remediation of heavy metal-contaminated soils.

Full Text

Research Advances in Heavy Metal Contaminated Soil Remediation by Phosphate-Solubilizing Microorganisms

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Abstract

Soil heavy metal contamination has become an increasingly severe environmental issue, characterized by its ubiquity and irreversibility, making it a critical focus in environmental pollution control. Phosphate-solubilizing microorganisms (PSMs) can transform insoluble phosphorus in soil into plant-available forms through their metabolic products or synergistic interactions with other organisms. These microorganisms possess multiple plant growth-promoting functions and heavy metal detoxification capabilities, enabling them to enhance plant growth, improve disease resistance, and strengthen the competitive survival of phytoremediation plants under heavy metal stress. This paper reviews the current research status of PSMs, summarizes their remediation mechanisms for heavy metal contaminated soils, analyzes existing challenges in their application, and proposes future research directions, offering new insights for heavy metal soil remediation.

Keywords: phosphate-solubilizing microorganisms; soil; remediation; heavy metal; pollution

Introduction

With rapid socioeconomic development, soil pollution has become increasingly prominent in China, particularly heavy metal contamination from both natural weathering of mineral parent materials and anthropogenic discharge of wastewater and waste residues. According to the first national soil pollution survey (2005), the exceedance rates for eight heavy metals were: Pb (7.0%), Cr (1.6%), Zn (2.7%), Ni (2.1%), Cd (1.5%), Hg (1.1%), As (0.9%), and Cu (4.8%). Heavy metal pollution has emerged as one of the most pressing environmental problems, attracting significant scientific attention as both a research hotspot and challenge.

Phytoremediation of heavy metal contaminated soils represents a promising and ecologically benign approach that has gained widespread attention in recent years. However, remediation plants typically exhibit low biomass, and their physiological activities are inhibited when heavy metal concentrations are excessively high, weakening their resistance mechanisms and making them vulnerable to pathogen attack, thereby substantially reducing remediation efficiency. As an important component of soil microbiota, phosphate-solubilizing microorganisms can convert recalcitrant inorganic and organic phosphorus into bioavailable forms through their metabolic products or cooperative interactions. This not only significantly improves soil phosphorus utilization and plant phosphorus nutrition to promote growth but also alters heavy metal speciation and enhances remediation efficiency.

Current research on PSMs for heavy metal soil remediation primarily focuses on isolation of PSMs from contaminated soils, their remediation capacity, mechanisms, and enhancement techniques. However, few studies have investigated the differential expression of phosphate-solubilizing functional genes and heavy metal resistance genes under heavy metal stress, or the influence patterns of PSMs on heavy metal speciation and immobilization—factors that critically constrain remediation efficiency. This paper synthesizes and prospects current research from these perspectives to provide theoretical and practical value for improving remediation efficiency, enhancing soil environmental quality, and safeguarding soil ecological security.

1. Overview of Phosphate-Solubilizing Microorganisms

PSMs comprise diverse and complex taxa, including phosphate-solubilizing bacteria, actinomycetes, and fungi. In phosphate-solubilizing communities, bacteria account for 1-50% while fungi represent only 0.1-0.5%. Common PSMs are listed in Table 1 . Some scholars categorize PSMs based on substrate specificity into organic phosphorus-mineralizing and inorganic phosphorus-solubilizing microorganisms, though this distinction is often ambiguous as some strains can degrade both types. Over 30 genera and thousands of phosphate-solubilizing strains have been reported, with *Pseudomonas* being the most extensively studied as a plant growth-promoting bacterium, biocontrol agent, and phosphate-solubilizing inoculant. Azziz et al. isolated *Burkholderia cepacia* from no-till soil, identifying 8 phosphate-solubilizing strains—3 *Acinetobacter* and 5 *Pseudomonas*—through TP-RAPD fingerprinting. The vast diversity of PSMs provides ample biological resources for soil phosphorus transformation.

2. Phosphate-Solubilizing Capacity of PSMs

The phosphate-solubilizing capacity of PSMs directly correlates with heavy metal remediation efficacy—stronger phosphate solubilization enhances phosphate release, which can both reduce heavy metal mobility and promote plant growth for phytoremediation. The ratio of phosphate-solubilizing halo diameter (D) to colony diameter (d) is commonly used to characterize relative phosphate-solubilizing ability. Chen et al. isolated a strain from Shanxi mining soil identified as *Pantoea* sp., achieving high D/d values and solubilization rates of 12.61%, 1.21%, and 3.07% for calcium phosphate degradation. However, judging solubilizing capacity solely by halo-to-colony ratio may underestimate some strains by ignoring phosphorus absorbed by biomass, while measuring only soluble phosphorus in culture medium cannot accurately reflect true capacity. Zhao et al. employed fumigation-digestion methods to measure phosphorus released during sand culture, providing accurate quantification. Tian et al. isolated *Stenotrophomonas maltophilia* and *Burkholderia gladioli* from lead-zinc mining soil, achieving maximum solubilization of 402.9 mg/L and 589.9 mg/L with rates of 19.7% and 28.8%, respectively, demonstrating both strong phosphate-solubilizing capacity and lead resistance. *Enterobacter aerogenes* could solubilize 6.46 mmol/L phosphate with 17.5% efficiency. Given significant interspecies variation in phosphate-solubilizing capacity, screening highly efficient strains is crucial.

3. Heavy Metal Resistance of PSMs

High heavy metal concentrations represent the most important limiting factor in remediation. The metal tolerance of PSMs typically correlates with their isolation environment. For instance, Tian et al. isolated two phosphate-solubilizing bacteria from lead-zinc mining topsoil that exhibited strong phosphate solubilization and high resistance to Pb, Cd, Cu, Zn, Ni, and Cr (maximum tolerance concentrations of 2000, 2000, 1000, 400, 50, and 20 mg/L, respectively). Jiang et al. isolated *Burkholderia* from heavy metal contaminated soil with similar high tolerance. Heavy metal contaminated areas thus serve as important sources for resistant PSMs. Misra et al. isolated zinc-tolerant phosphate-solubilizing bacteria from *Osmanthus* rhizosphere, while plant rhizosphere soils generally harbor high microbial densities.

Metal resistance in PSMs operates through resistance genes. Mercury resistance genes are among the most studied, including mercuric reductase (*merA*), organomercurial lyase (*merB*), and transporter genes (*merC*, *merT*). Phosphate-solubilizing *Achromobacter* and *Pseudomonas* can oxidize arsenite to arsenate, reducing arsenic toxicity. The *ars* gene cluster controls arsenic detoxification, with *arsC* and *arsR* regulating reduction of As(V) to more toxic As(III) and its release from the cytoplasm. *Pseudomonas syringae* and *E. coli* contain cadmium resistance genes, while *Bacillus* carries copper resistance genes (*cop*), *Pseudomonas aeruginosa* has zinc resistance genes (*czc*), and other bacteria contain nickel resistance genes (*czr*). However, most studies report either heavy metal resistance genes or phosphate-solubilizing functional genes separately, with few integrating both, limiting mechanistic understanding of PSM-mediated heavy metal remediation.

4. Effects of Environmental Factors on PSM Remediation Capacity

Numerous root exudates, organic degradation products, and microorganisms in soil solution, along with soil properties such as temperature, pH, Eh, and heavy metal concentrations, affect PSM remediation capacity. In contaminated areas, carbohydrate and amino acid content correlate positively with the comprehensive pollution index. Organic matter can activate PSM metabolism while influencing heavy metal bioavailability. Available phosphorus content affects PSM population abundance, and pH is a critical factor for lead phosphate precipitation formation. PSMs can also promote weathering dissolution of primary mineral heavy metals. *Bacillus* species secrete organic acids that lower pH, increase soluble phosphorus, and immobilize lead and zinc. Increased soil available phosphorus can temporarily promote heavy metal mobilization while reducing toxicity to PSMs. Total organic acid content, particularly oxalic and malonic acids, can elevate pH in the rhizosphere of *Elsholtzia haichowensis*. Arbuscular mycorrhizal fungi (AMF) can reduce soil pH, with optimal solubilization of selenium and arsenic phosphates occurring at pH 7.0.

5. Methylation of Heavy Metals by PSMs

Certain PSMs can convert cobalamin to methylcobalamin, which acts as a methyl donor under specific reductant conditions, methylating metal ions to form methylmercury—a process to be avoided in bioremediation. Pseudomonas species play important roles in metal/metalloid methylation, though some methylated metal ions can enhance microbial methylation rates of arsenic.

6. Redox Reactions of Heavy Metals by PSMs

PSMs can alter heavy metal valence states through metabolism for detoxification. They deposit iron and manganese oxides/hydroxides extracellularly and regulate redox reactions of Fe^{2} and other metals. Metals such as Hg, Pb, Sn, and metalloids can be detoxified through microbial redox transformations. *Pseudomonas aeruginosa* strain PSB10 can reduce heavy metal toxicity while enhancing plant hormone secretion and growth. Inoculation with *P. aeruginosa* in contaminated soil reduced heavy metal uptake in chickpea roots and seeds by 36%, 38%, and 40%. Phosphate-solubilizing yeast *Pichia farinosa* can oxidize Ni(NO) to less available Ni (PO) .

7. Dissolution of Heavy Metals by PSMs

PSMs dissolve heavy metals directly or indirectly through metabolic activities that produce low-molecular-weight organic acids such as succinic and lactic acids. These acids dissociate into protons and anions, causing pH and redox potential changes that promote mineral weathering. PSMs can solubilize recalcitrant heavy metal minerals, increasing bioavailability. Inoculation with *Bacillus megaterium* increased plant extraction efficiency several-fold. Studies on phosphate-solubilizing bacteria dissolving various phosphate rocks revealed that fungi can reduce rhizosphere pH, increase available copper, and promote plant uptake. Some associated metal elements in phosphate rock dissolve along with phosphorus release, with solubility varying based on their location in the mineral matrix.

8. Complexation and Chelation of Heavy Metals by PSMs

Bacterial surface carboxyl and phosphate groups can coordinate with heavy metal ions to form inner-sphere complexes. Low-molecular-weight organic acid anions exhibit strong affinity for heavy metals, forming organometallic complexes through chelation. Competition between organic anions and solid particles for heavy metal binding facilitates metal mobility. Mycorrhizal fungi secrete citric and malic acids that chelate metals, while siderophores bind heavy metal ions to form complexes that increase metal bioavailability in the rhizosphere. A siderophore-overproducing mutant of *Enterobacter* not only increased plant growth but also enhanced nickel and chromium uptake in mustard.

9. Adsorption and Accumulation of Heavy Metals by PSMs

Microorganisms resist heavy metals through surface adsorption and intracellular accumulation. The cell wall, rich in carboxylate and phosphate anions, provides anionic surface properties for metal binding. *Bacillus* and *P. aeruginosa* can adsorb lead through interactions with surface functional groups, reducing metal mobility. Bioaccumulation depends on microbial metabolism—*Bacillus cereus* and *B. subtilis* cultured in heavy metal media accumulate metals at concentrations far exceeding those in the medium, with *Bacillus* biomass reaching significant enrichment levels.

10. Precipitation of Heavy Metals by PSMs

PSMs release phosphate from mineral or organic phosphorus that precipitates with heavy metals as phosphates, reducing mobility and bioavailability. Phosphate-solubilizing *Enterobacter cloacae* can dissolve soil phosphates and form lead phosphate complexes, immobilizing lead. Remediation not only fixes free heavy metals but also inhibits their translocation from roots to shoots. Inoculation with *Glomus mosseae* reduces zinc phytotoxicity and cadmium uptake. Gram-negative *Citrobacter* secretes phosphate ions that form minerals with heavy metals on cell surfaces, while acid-producing bacteria secrete phosphatases that hydrolyze glycerophosphate, releasing inorganic phosphate to precipitate metals and immobilize them in soil, concurrent with microbial enrichment.

11. Growth-Promoting Effects of PSMs on Heavy Metal Hyperaccumulators

PSMs abundantly present in soil and rhizospheres possess multiple plant growth-promoting functions. Under heavy metal stress, they improve mineral nutrition (P, N, S) and provide essential elements for plant survival, enhancing nutrient uptake while reducing heavy metal toxicity. PSMs can increase phosphorus content in plant tissues, forming low-solubility metal-phosphate complexes that reduce metal phytotoxicity. Pot experiments showed that inoculation significantly increased aboveground biomass of marigold, with metal uptake in shoots far exceeding root uptake, demonstrating potential for phytoextraction. Siderophores provide nutrients, particularly iron, to plants under heavy metal stress, alleviating toxicity and promoting uptake of K, Ca, Mg, Fe, and Zn. Many rhizosphere PSMs produce auxin (IAA), increasing plant hormone content and stimulating growth. However, research on siderophore-producing microbes for enhanced phytoremediation remains preliminary, and the precise mechanisms affecting heavy metal acquisition are unclear. Additionally, PSMs produce cell wall-degrading enzymes and antibiotics that resist plant pathogens, reducing disease damage. ACC deaminase-producing strains can lower ethylene levels, improving plant stress tolerance. A cadmium-resistant strain isolated from contaminated soil exhibited phosphate solubilization, siderophore production, IAA synthesis, and ACC deaminase activity. Endophytic bacteria from nickel hyperaccumulator *Alyssum serpyllifolium* showed high nickel tolerance and phosphate-solubilizing capacity, significantly promoting plant growth and nickel uptake.

12. Dual Role of PSMs in Heavy Metal Immobilization and Mobilization

PSMs exhibit bidirectional regulation of heavy metals, with two corresponding remediation mechanisms: (1) bioprecipitation, intracellular accumulation, and phytostabilization promotion; (2) enhanced bioavailability through organic acid secretion, facilitating metal translocation and accumulation in plant tissues. However, immobilization only changes metal speciation without reducing total quantity, and combined use of stabilizers may negatively affect soil physicochemical properties and microbial communities. PSM-plant combined remediation is an environmentally friendly, ecologically sustainable approach with broad application prospects. The mechanisms are illustrated in Figure 2 [Figure 2: see original paper], and common PSMs in heavy metal contaminated soils are listed in Table 2 .

13. Challenges and Future Perspectives

Soil heavy metal remediation remains a global challenge, and while PSMs play important roles, current research has limitations. Studies report both increased and decreased metal activity by PSMs, but few investigate microscale interactions between PSMs, their metabolites, and heavy metals. The effects of heavy metal concentrations, soil environmental factors, PSM metabolites, and functional genes on metal immobilization/mobilization and the bidirectional mechanisms remain unclear, hindering efficiency improvement. Limited research addresses PSM participation in chemical passivation remediation, raising concerns about long-term effectiveness. Future research should strengthen investigations into PSM application effects and mechanisms under varying soil conditions, deepen studies on metabolites and functional genes (including phosphate-solubilizing and heavy metal resistance genes), and explore metagenomic diversity of phosphate-solubilizing genes under heavy metal stress and their regulatory strategies. Additionally, research should examine soil microbial community changes following PSM inoculation, and how PSM-plant interactions affect indigenous microbial diversity and structure. Analyzing heavy metal speciation in rhizospheres and resistance gene dynamics will elucidate PSM bidirectional mechanisms from metabolite and functional gene perspectives, providing support for improving soil environmental quality and ecological security.

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