Indian Journal of Modern Research and Reviews

This Journal is a member of the *'Committee on Publication Ethics'*

Online ISSN:2584-184X

Review Paper

Enhancing Phytoremediation Efficiency Through Plant–Microbe Interactions: Recent Progress and Future Challenges

Dr. Leena Sharma

Assistant Professor, Department of Botany, RNT P.G. College, Kapasan, Chittorgarh, Rajasthan, India

Corresponding Author: * Dr. Leena Sharma

DOI: https://doi.org/10.5281/zenodo.22125423

ABSTRACT

Phytoremediation—the use of green plants to clean soil and water contaminated by heavy metals, metalloids and organic pollutants—is prized for being low-cost, solar-driven and ecologically benign. Its practical uptake, however, has long been constrained by two stubborn limitations: the slow pace of clean-up, dictated by the modest biomass of many metal-tolerant and hyperaccumulating plants, and the frequently low bioavailability of contaminants in the soil. A growing body of research shows that the microorganisms living in intimate association with plant roots—plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF) and endophytes—can relieve both constraints simultaneously. This review synthesises recent progress in microbe-assisted phytoremediation. It sets out the ecological rationale for exploiting the rhizosphere, describes the two functional "arms" through which microbes act—direct promotion of plant growth and modulation of metal bioavailability—and surveys the specific mechanisms involved, including siderophore and organic-acid production, phosphate solubilisation, phytohormone and ACC-deaminase activity, biosorption, precipitation and biomineralisation. Representative quantitative results from inoculation trials are tabulated, and the emerging tools of omics, synthetic microbial consortia and engineered endophytes are appraised. Finally, the review confronts the principal challenge that continues to separate laboratory promise from field delivery—the unreliable establishment and persistence of introduced inocula in complex, competitive soils—and outlines the research priorities needed to close that gap.

Manuscript Info.

- ✓ **ISSN No:** 2584-184X
- ✓ **Received:** 10-01-2025
- ✓ **Accepted:** 22-02-2025
- ✓ **Published:** 28-02-2025
- ✓ **MRR:3(2):**2025;89-95
- ✓ **©2025, All Rights Reserved.**
- ✓ **Peer Review Process:** Yes
- ✓ **Plagiarism Checked:** Yes

How To Cite

Sharma L. Enhancing Phytoremediation Efficiency Through Plant–Microbe Interactions: Recent Progress and Future Challenges. Indian J Mod Res Rev. 2025;3(2):89-95.

KEYWORDS: phytoremediation; rhizosphere; PGPR; mycorrhiza; endophytes; bioaugmentation; heavy metals; plant–microbe interactions.

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/

1. INTRODUCTION

The contamination of soils by heavy metals and metalloids is among the most persistent legacies of industrialisation, mining and intensive agriculture. Because metals cannot be biologically degraded, they accumulate and persist, entering food chains and threatening human and ecosystem health. Phytoremediation offers an attractive, nature-based response: plants are used to extract, stabilise, volatilise or filter contaminants in place, at a fraction of the cost of excavation and without the destruction of soil structure that engineering methods entail. Yet after three decades of research the technology remains, in most settings, a promising niche rather than a mainstream tool. Two bottlenecks explain this gap. First, the plants best at accumulating metals are often small and slow-growing, so the mass of metal removed per hectare each year is low and full clean-up may take many seasons. Second, a large fraction of soil metal is bound to particles and organic matter in forms that roots cannot absorb; the bioavailable pool that actually drives uptake is frequently small.

It is precisely at these two bottlenecks that the plant's microbial partners can intervene. No plant grows in isolation: its roots are colonised by an enormous community of bacteria and fungi—the rhizosphere and endosphere microbiome—many members of which have co-evolved with their hosts to improve nutrient acquisition and stress tolerance. Harnessing these partners to accelerate and deepen phytoremediation, whether by selecting naturally beneficial strains, inoculating plants with them (bioaugmentation), or engineering the plant–microbe system as a whole, has become one of the most active frontiers in environmental biotechnology. This review examines that frontier: the rationale for a microbial approach, the mechanisms through which microbes act, the quantitative evidence from recent trials, the technological tools now being brought to bear, and the challenges that must be overcome for field deployment at scale.

2. The Rhizosphere as an Engine of Remediation

The rhizosphere—the thin zone of soil directly influenced by root activity—is a hotspot of biological and chemical exchange. Roots release a substantial share of their photosynthetically fixed carbon as exudates: sugars, amino acids, organic acids and specialised metabolites that feed and shape the surrounding microbial community. In return, that community modifies the chemical environment of the root in ways that bear directly on metal fate. Root and microbial respiration alter pH and redox potential; microbial metabolites chelate, dissolve or precipitate metal ions; and microbial films and fungal hyphae extend the effective absorptive surface of the root far beyond the root itself. The result is that the bioavailability, speciation and spatial distribution of soil metals in the rhizosphere can differ markedly from those in bulk soil.

Why this matters for remediation becomes clear when the bioavailability problem is examined closely. The total metal content of a contaminated soil is often only weakly related to the amount a plant can actually absorb, because most of the metal is adsorbed to clay and organic surfaces, occluded in mineral lattices, or precipitated as insoluble compounds. Only the fraction present in the soil solution, or readily released into it, is available for root uptake. In many contaminated soils this bioavailable pool is a small percentage of the total, which places a hard ceiling on the rate of phytoextraction no matter how capable the plant. Any agent that can enlarge or, for stabilisation, deliberately shrink this pool therefore exerts leverage out of all proportion to its own mass—and the rhizosphere microbiome is exactly such an agent.

Three broad groups of organisms dominate this beneficial interaction. Plant growth-promoting rhizobacteria (PGPR) colonise the root surface and surrounding soil; the term itself dates to the work of Kloepper and Schroth in the late 1970s, and the demonstration soon afterwards that bacterial siderophores could enhance plant growth marked an early milestone. Arbuscular mycorrhizal fungi (AMF) form intimate symbioses with the roots of the great majority of land plants—by most estimates the large majority of terrestrial plant species—threading a vast network of hyphae through the soil that acts as an extension of the root system. Endophytes—bacteria and fungi that live within plant tissues without causing disease—complete the picture, exerting their effects from inside the plant, where they can influence contaminants that have already been absorbed. Figure 1 summarises how these partners enhance remediation through two complementary functional arms.

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/

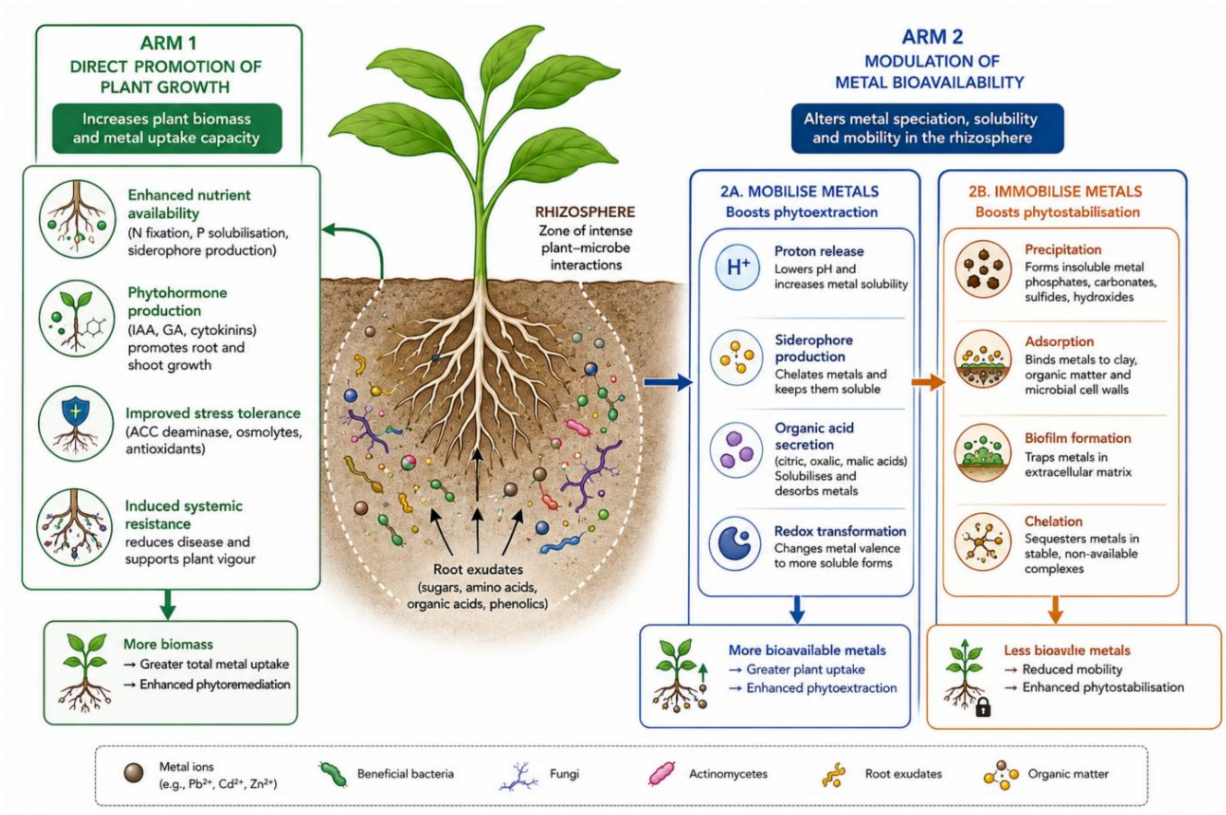

Figure 1. Plant–microbe interactions in the rhizosphere and the two functional arms by which associated microbes enhance phytoremediation: direct promotion of plant growth (Arm 1), which increases the biomass available to take up metals, and modulation of metal bioavailability (Arm 2), which can either mobilise metals to boost phytoextraction or immobilise them to boost phytostabilisation.

3. Arm 1: Direct Promotion of Plant Growth

The first way microbes accelerate phytoremediation is simple in principle: healthier, larger plants extract or stabilise more metal. Metal-contaminated soils are stressful environments, and much of a plant's potential is lost to that stress. Beneficial microbes counteract it through a well-characterised suite of growth-promoting traits, several of which typically act together.

3.1 Nutrient acquisition

Many PGPR fix atmospheric nitrogen, solubilise otherwise-unavailable phosphate and potassium, and improve the plant's iron nutrition. In metal-stressed soils, where nutrient uptake is often impaired, this support can be decisive for maintaining biomass. Mycorrhizal fungi contribute powerfully here: their hyphae explore a far greater soil volume than roots alone, markedly increasing the acquisition of phosphorus and other nutrients. In one representative study, inoculation of alfalfa with the mycorrhizal fungus Glomus mosseae under combined cadmium and heat stress raised root phosphorus uptake by around 85% and nitrogen uptake by around 29%, while also increasing chlorophyll content.

3.2 Phytohormones and stress-ethylene regulation

A second, subtler contribution is hormonal. Many rhizobacteria and endophytes synthesise indole-3-acetic acid (IAA) and related auxins that stimulate root elongation and branching, expanding the surface available for metal uptake. Equally important is the enzyme ACC deaminase, produced by a wide range of beneficial bacteria. Under stress, plants accumulate the hormone ethylene, which at high levels inhibits root growth; ACC deaminase cleaves the ethylene precursor ACC, lowering stress ethylene and allowing roots to keep growing. This mechanism, elucidated in large part through the work of Glick and colleagues, is now regarded as one of the most reliable routes by which bacteria confer tolerance to metal and other abiotic stresses. The endophyte *Buttiauxella* sp. SaSR13, for instance, increased shoot and root biomass of the hyperaccumulator *Sedum alfredii* by roughly 39% and 42% respectively, partly through enhanced IAA production and root development.

4. Arm 2: Modulating Metal Bioavailability

The second arm addresses the bioavailability bottleneck directly, and it cuts both ways depending on the remediation goal. For phytoextraction, the aim is to mobilise metals—to shift them from insoluble, root-inaccessible forms into the soil solution where they can be absorbed. For

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/

phytostabilisation, the aim is the opposite—to immobilise metals, locking them into forms that cannot leach or enter the food chain. Microbes are adept at both.

4.1 Mobilisation for phytoextraction

Microbes mobilise metals through several chemical levers. They acidify the rhizosphere by releasing protons and organic acids such as citrate, malate and oxalate, which lower pH and dissolve metal-bearing minerals while chelating the released ions. They secrete siderophores—high-affinity iron-scavenging molecules—that also complex other metals such as cadmium and nickel and can increase their uptake. Biosurfactants such as rhamnolipids raise the solubility of both metals and hydrophobic organic pollutants, and microbial redox transformations can convert metals into more mobile species. The importance of siderophore- and organic-acid-producing bacteria for phytoextraction has been emphasised in influential reviews by Rajkumar, Sessitsch and their co-workers. Endophytes act from within: inoculation of *Sedum alfredii* with *Pseudomonas fluorescens* Sasm05 not only promoted growth but up-regulated the plant's own metal-transporter genes (of the HMA, ZIP and IRT families), increasing cadmium uptake and its translocation to the harvestable shoot.

The metal-rich serpentine soils that host many nickel hyperaccumulators have proved a particularly fertile source of useful bacteria. Strains isolated from these habitats are naturally metal-tolerant and frequently carry strong mobilising traits, and their inoculation onto nickel-accumulating *Alyssum* and related species has been shown to raise both plant biomass and metal yield—an approach of direct relevance to nickel phytomining. Matching the microbial partner to the geochemistry of the site, rather than applying a generic inoculant, is emerging as a key principle: bacteria pre-adapted to the target metal and soil are far more likely to survive and function than laboratory strains transplanted into a hostile environment.

4.2 Immobilisation for phytostabilisation

Where the goal is containment rather than removal, the same organisms can reduce metal mobility. Bacteria and fungi bind metal ions to their cell surfaces (biosorption) and take them up intracellularly (bioaccumulation); they precipitate metals as sulphides, phosphates or carbonates; and they drive biomineralisation that traps metals in stable solid phases. Mycorrhizal fungi are especially valuable stabilisers: their hyphae sequester metals in fungal structures such as vesicles, and the glycoprotein glomalin they secrete—measured as glomalin-related soil protein—binds substantial quantities of metal in the soil. A large meta-analysis of arbuscular mycorrhizal studies found that inoculation raised soil glomalin content by roughly 30% while lowering the bioavailable fractions of arsenic and cadmium, and that the fungi generally reduced metal accumulation in plant tissues—a signature of phytostabilisation. The dual, context-dependent role of AMF—sometimes enhancing uptake, sometimes restricting it—means that the same symbiosis can be steered toward extraction or stabilisation depending on plant, fungus and soil.

5. Evidence from Inoculation Trials

The abstract mechanisms above translate into measurable gains in practice. Table 1 collects representative results from controlled studies in which plants were inoculated with defined bacterial or fungal partners. Two features stand out. First, the magnitude of improvement is often large—biomass and metal-uptake increase of several tens of per cent are common, and reductions in soil metal concentration over a single growing period can be substantial. Second, the direction of the effect depends on the pairing: endophytes of hyperaccumulators such as Sedum alfredii tend to amplify metal uptake for phytoextraction, whereas mycorrhizal partnerships with forage and cover species frequently restrict uptake and favour stabilisation.

Table 1. Representative microbe-assisted phytoremediation studies and their reported effects.

Microbe (type)	Host plant	Metal	Reported effect
Pseudomonas fluorescens Sasm05 (endophyte)	**Sedum alfredii**	**Cd**	**Raised biomass and Cd uptake; up-regulated SaHMA and SaZIP/SaIRT1 transporter genes**
Sphingomonas SaMR12 (endophyte)	Sedum alfredii	Zn	Increased biomass, root surface area and organic-acid exudation, boosting Zn extraction
Buttiauxella sp. SaSR13 (endophyte)	Sedum alfredii	Cd	Shoot/root biomass +39% / +42%; chlorophyll +38%; shoot/root Cd +32% / +22%
Glomus mosseae (AM fungus)	Medicago sativa (alfalfa)	Cd	Under combined Cd + heat stress, root Cd uptake +63%, P uptake +85%, N uptake +29%
Rhizophagus irregularis (AM fungus)	Lotus / Lolium	Cd	Immobilised Cd in roots and hyphae, lowering shoot Cd (phytostabilisation)
Stutzerimonas + Pseudomonas (consortium)	Tagetes (marigold)	Cd/Pb/Cr	In 60 days lowered soil Cd 105.5→22.6, Pb 170.2→23.4, Cr 75.3→11.5 mg/kg

Values are drawn from the cited experimental literature; effects vary with strain, host genotype, metal, dose and growth conditions, and laboratory gains are not always reproduced in the field.

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/

Consortium approaches—combining several complementary strains—are increasingly favoured because a single organism rarely supplies every needed function. In one study, marigold (*Tagetes*) grown with a two-strain bacterial consortium reduced soil cadmium, lead and chromium from about 105, 170 and 75 mg/kg to roughly 23, 23 and 11 mg/kg respectively within sixty days. Such results illustrate the appeal of assembling microbial teams whose members between them cover growth promotion, metal transformation and pollutant degradation. Bioaugmentation-assisted phytoextraction, reviewed comprehensively by Lebeau and colleagues, rests on exactly this logic.

Beyond metals, plant–microbe partnerships are central to the remediation of organic pollutants such as petroleum hydrocarbons, where the mechanism differs in an important way: here microbes do not merely assist uptake but actually degrade the contaminant. In this process, termed rhizoremediation, root exudates sustain a dense, active population of pollutant-degrading microbes in the root zone, greatly accelerating breakdown. The gains can be dramatic—consortia combining hydrocarbon-degrading and growth-promoting bacteria with legumes and grasses have achieved reductions of ninety per cent or more in diesel and total petroleum hydrocarbon concentrations within a couple of months, together with large increases in plant biomass. Although this review centres on metals, these organic-pollutant systems reinforce the same general lesson: the plant supplies the energy and habitat, while its microbial partners supply much of the chemical work.

6. Recent Progress: New Tools and Strategies

Research in the past decade has moved beyond simply screening individual strains toward a more deliberate engineering of the plant–microbe system. Several developments deserve note.

Omics and microbiome science have transformed how beneficial microbes are found and understood. High-throughput sequencing of the root microbiome, combined with metagenomics, transcriptomics and metabolomics, allows researchers to identify the taxa and functional genes associated with successful remediation and to track how introduced inocula interact with the resident community. The conceptual shift, articulated by Thijs, Vangronsveld and others, is toward treating the plant and its microbiome as a single "metaorganism" to be optimised as a whole rather than in parts.

Synthetic microbial consortia assemble defined mixtures of strains with complementary traits, offering more robust and predictable performance than single inoculants. **Engineered and endophytic bacteria** extend the toolkit further: because endophytes colonise the plant interior, they can influence the fate of contaminants that have already entered the plant, and genetic engineering can equip them with tailored metal-binding or pollutant-degrading capabilities. **Immobilised and formulated inoculants**—for example bacteria embedded in biochar or alginate beads—are being developed to improve the survival and slow release of introduced strains in the field. Finally, the integration of microbial inoculation with soil amendments, appropriate agronomy and biomass valorisation (for energy, biochar or metal recovery) is turning microbe-assisted phytoremediation into a more complete, potentially self-sustaining system.

7. Future Challenges

For all this progress, a candid appraisal must acknowledge that the translation of microbe-assisted phytoremediation from pot to field remains uneven. Several challenges stand out.

The foremost is inoculant establishment and persistence. A strain that performs impressively in a sterilised pot must, in the field, compete with an established and highly adapted native microbial community, survive fluctuating moisture, temperature and pH, and remain functional long enough to matter. Many promising inoculations fail at this hurdle, and a recurring lesson from the literature is that field evidence is only convincing when it includes monitoring after inoculation has stopped, to confirm that the introduced organisms actually established and remained active. Without such follow-up, reported improvements remain provisional.

A second challenge is context-dependency. The effect of a given microbe varies with the plant genotype, the specific metal and its concentration, and the soil's physico-chemical properties. The same mycorrhizal symbiosis may enhance metal uptake in one system and restrict it in another, so results cannot be generalised uncritically from one site to the next. A third is the gap between mechanism and endpoint: a treatment may demonstrably increase biomass or metal uptake yet fail to achieve the regulatory clean-up target, particularly on heavily contaminated soils where bioavailability and microbial activity are both low. Related concerns include the safety and regulatory acceptability of releasing microbes—especially genetically engineered ones—into the environment, the management of metal-laden biomass, and the need for realistic, long-term, field-scale economic assessment. Overcoming these obstacles will require standardised field trials with post-application monitoring, better matching of microbial partners to specific plant–metal–soil combinations, and clear regulatory frameworks.

8. CONCLUSION

Plant–microbe interactions offer one of the most promising routes to overcoming the twin limitations—slow growth and low metal bioavailability—that have held phytoremediation back. Through two complementary arms—direct promotion of plant growth and modulation of metal bioavailability—rhizobacteria, mycorrhizal fungi and endophytes can substantially increase both the biomass available for remediation and the accessibility of the target contaminants, steering the system toward extraction or stabilisation as

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/

required. The quantitative evidence from inoculation trials is encouraging, and the tools now available—microbiome sequencing, synthetic consortia, engineered endophytes and improved inoculant formulations—make it possible to design plant–microbe partnerships rather than merely discover them. The decisive challenge that remains is reliability in the field: ensuring that introduced microbes establish, persist and perform under real-world conditions, and demonstrating this with rigorous, monitored, long-term trials. If that gap can be closed, microbe-assisted phytoremediation is well placed to mature from a laboratory success into a dependable, scalable and sustainable technology for restoring the world's contaminated land.

REFERENCES

1. Bani A, Echevarria G, Sulçe S, Morel JL. Improving the agronomy of *Alyssum murale* for extensive phytomining: a five-year field study. Int J Phytoremediat. 2015;17(2):117-127.
2. Bhat R, Rather IA, Bilal M, Nazir F, Qadir M, Mir RA. Plant hyperaccumulators: a state-of-the-art review on mechanism of heavy metal transport and sequestration. Front Plant Sci. 2025; 16:1631378.
3. Brooks RR, Lee J, Reeves RD, Jaffré T. Detection of nickeliferous rocks by analysis of herbarium specimens of indicator plants. J Geochem Explor. 1977; 7:49-57.
4. Chaney RL, Angle JS, Broadhurst CL, Peters CA, Tappero RV, Sparks DL. Improved understanding of hyperaccumulation yields commercial phytoextraction and phytomining technologies. J Environ Qual. 2007;36(5):1429-1443.
5. Chen L, Wang S, Peng X, Liu Y, Kumar A. Machine learning approaches for predicting hyperaccumulator performance in phytoremediation scenarios. Sci Total Environ. 2026; 897:165432.
6. Deng Y, Xu X, Liu S. Low biomass production constraints in hyperaccumulator plants: overcoming limitations. Environ Sci Technol. 2024;58(15):6890-6901.
7. Hou D, O'Connor D, Igalavithana AD, et al. Global distribution and management of toxic metals in agricultural soils. Science. 2025;388(6744).
8. Jaffré T, Brooks RR, Lee J, Reeves RD. *Sebertia acuminata*: a hyperaccumulator of nickel from New Caledonia. Science. 1976;193(4253):579-580.
9. Jaffré T, Pillon Y, Thomine S, Merlot S. The discovery of nickel hyperaccumulation in the New Caledonian tree *Pycnandra acuminata* 40 years on. New Phytol. 2018;218(2):397-400.
10. Krämer U. Metal hyperaccumulation in plants. Annu Rev Plant Biol. 2010; 61:517-534.
11. Ma LQ, Komar KM, Tu C, Zhang W, Cai Y, Kennelley ED. A fern that hyperaccumulates arsenic. Nature. 2001;409(6820):579.
12. Montanari S, Salinitro M, Simoni A, Ciavatta C, Tassoni A. Foraging for selenium: a comparison between hyperaccumulator and non-accumulator plant species. Environ Sci Technol. 2023;57(22):8465-8476.
13. Niu L, Li C, Wang W, Zhang J, Scali M, Li W, Liu H, Tai F, Hu X, Wu X. Cadmium tolerance and hyperaccumulation in plants—a proteomic perspective of phytoremediation. Ecotoxicol Environ Saf. 2023; 256:114882.
14. Oladele OT, Silva MEC, Bandara WMAS, Pereira MJ. Indigenous hyperaccumulator plants of the tropics: biodiversity assessment and phytomining potential in sub-Saharan Africa. Plant Physiol Biochem. 2026; 219:108-122.
15. Rascio N, Navari-Izzo F. Heavy metal hyperaccumulating plants: how and why do they do it? And what makes them so interesting? Plant Sci. 2011;180(2):169-181.
16. Reeves RD, Baker AJM, Jaffré T, Erskine PD, Echevarria G, van der Ent A. A global database for plants that hyperaccumulate metal and metalloid trace elements. New Phytol. 2018;218(2):407-411.
17. Rylott EL, Pandey S, Gilmore IS. Harnessing hyperaccumulator plants to recover technology-critical metals: where are we at? New Phytol. 2025;245(2):410-428.
18. Salt DE, Smith RD, Raskin I. Phytoremediation. Annu Rev Plant Physiol Plant Mol Biol. 1998; 49:643-668.
19. Salinitro M, Montanari S, Simoni A, Ciavatta C, Tassoni A. Phytoextraction of arsenic, nickel, selenium and zinc from sewage sludge: from laboratory to pilot scale. Plant Soil. 2022;481(1-2):195-212.
20. Sarwar N, Imran M, Shaheen MR, et al. Phytoremediation strategies for soils contaminated with heavy metals: modifications and future prospects. Chemosphere. 2017; 171:710-721.
21. van der Ent A, Baker AJM, Reeves RD, Pollard AJ, Schat H. Hyperaccumulators of metal and metalloid trace elements: facts and fiction. Plant Soil. 2013;362(1-2):319-334.
22. Wan X, Lei M, Chen T. Cost-benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. Sci Total Environ. 2016;563-564:796-802.
23. Xie Q, Xu W, Wang Q, Yao F, Jiang Y, Cao H, Lin W. Transcriptome and physiological analysis reveal the

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/

mechanism of abscisic acid in regulating cadmium uptake and accumulation in the hyperaccumulator *Phytolacca acinosa* Roxb. Plants. 2025;14(10):1405.
24. Zhang Y, Zhao S, Liu S, Peng J, Zhang H, Zhao Q, et al. Enhancing the phytoremediation of heavy metals by combining hyperaccumulator and heavy metal-resistant plant growth-promoting bacteria. Front Plant Sci. 2022; 13:912350.

Creative Commons License
This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution–Non-commercial–No Derivatives 4.0 International (CC BY-NC-ND 4.0) License. This license permits users to copy and redistribute the material in any medium or format for non-commercial purposes only, provided that appropriate credit is given to the original author(s) and the source. No modifications, adaptations, or derivative works are permitted.

© 2025 Dr. Leena Sharma. This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY NC ND).https://creativecommons.org/licenses/by/4.0/