Indian Journal of Modern Research and Reviews

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

Online ISSN:2584-184X

Review Article

Role of Hyperaccumulator Plants in The Phytoremediation of Contaminated Environments: A Review

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DOI: https://doi.org/10.5281/zenodo.22125200

Abstract

Contamination of soil and water by heavy metals and metalloids is one of the most persistent environmental problems of the modern industrial era. Because metals cannot be biologically degraded, remediation strategies must either remove or immobilise them. Conventional engineering methods—excavation, soil washing and chemical stabilisation—are effective but costly, energy-intensive and destructive to soil structure. Against this background, phytoremediation, the use of green plants to clean polluted media, has emerged as a low-cost, solar-driven and ecologically acceptable alternative. Central to this approach are *hyperaccumulator plants*—a remarkable group of species capable of concentrating metals in their above-ground tissues to levels hundreds or thousands of times greater than ordinary vegetation, without suffering toxicity. This review synthesises the concept, history and physiological basis of hyperaccumulation, surveys the global diversity of these plants (currently around 700 documented species), examines the molecular mechanisms of uptake, translocation and sequestration, and evaluates the principal phytoremediation strategies—phytoextraction, phytostabilisation, phytovolatilisation and rhizofiltration. Record-holding species such as *Pycnandra acuminata*, *Pteris vittata* and *Noccaea caerulescens* are discussed alongside emerging phytomining and agromining applications, before the advantages, limitations and future prospects of the technology are appraised.

Manuscript Information

- **ISSN No:** 2584-184X
- **Received:** 12-07-2026
- **Accepted:** 22-08-2026
- **Published:** 27-08-2026
- **MRR:**4(8); 2026: 283-288
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- **Plagiarism Checked:** Yes
- **Peer Review Process:** Yes

How to Cite this Article

Sharma L. Role of Hyperaccumulator Plants in The Phytoremediation of Contaminated Environments: A Review. Indian J Mod Res Rev. 2026;4(8):283-288.

Access this Article Online

www.mrrjournal.in

Keywords: hyperaccumulator; phytoremediation; heavy metals; phytoextraction; phytomining; nickel; serpentine soils; metal tolerance.

1. INTRODUCTION

Ellora Soil and water pollution by potentially toxic elements has accelerated sharply over the past two centuries as a consequence of mining, smelting, metallurgy, electroplating, tanning, battery manufacture, the burning of fossil fuels and the intensive use of agrochemicals. The eight elements most commonly listed as priority soil pollutants—arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc—are all non-biodegradable and, once released, may persist in the environment for decades or centuries, entering the food chain through bioaccumulation and posing chronic risks to human and ecosystem health.

The scale of the problem is enormous. Older global estimates suggested that roughly five million polluted sites, covering on the order of 500 million hectares, had been contaminated by heavy metals or metalloids, with an annual economic cost exceeding US$10 billion. More recent and rigorous mapping has reinforced this picture: a large 2025 assessment published in science, drawing on nearly 800,000 soil samples from more than 1,400 regional studies, estimated that between 14% and 17% of the world's cropland—approximately 242 million hectares—exceeds safe thresholds for at least one toxic metal, and that as many as 1.4 billion people live in affected high-risk zones. Cadmium was identified as the single most widespread pollutant, with a heavily contaminated belt stretching across low-latitude Eurasia, including South Asia. India, with its dense population, extensive mining and rapidly industrialising economy, sits squarely within the regions most exposed to this threat.

Because heavy metals resist chemical breakdown, remediation must rely on removal, extraction or immobilisation rather than degradation. Physico-chemical techniques—excavation and landfilling, soil flushing, electrokinetic separation, vitrification and chemical stabilisation—can be rapid and effective, but they are expensive, disruptive, and frequently leave the treated soil biologically dead. It is this combination of cost and collateral damage that has driven interest in phytoremediation: the deliberate use of plants and their associated microorganisms to extract, contain, degrade or detoxify pollutants in soil, sediment and water. Phytoremediation is solar-powered, comparatively inexpensive, aesthetically acceptable, and—crucially—it conserves and often improves the physical, chemical and biological quality of the soil. Cost analyses have repeatedly shown it to be an order of magnitude cheaper than excavation for suitable sites.

At the heart of metal phytoremediation lies a botanical curiosity of the first order: the hyperaccumulator plant. First formally defined in the 1970s, hyperaccumulators are species that accumulate specific metals or metalloids in their living above-ground tissues to concentrations that would be lethal to most plants, yet do so while remaining healthy and reproductively viable. This review examines the biology of these plants and their application to the remediation of contaminated environments. It addresses, in turn, the concept and history of hyperaccumulation, the global diversity and distribution of hyperaccumulators, the molecular and physiological mechanisms that underpin the phenomenon, the principal phytoremediation strategies, notable species and field applications, the economic dimension of phytomining, and the advantages, limitations and future prospects of the technology.

2. The Concept and History of Hyperaccumulation

The scientific story of hyperaccumulation begins on the nickel-rich ultramafic (serpentine) soils of New Caledonia. Although unusually high plant nickel concentrations had been noted as early as 1948 in the Italian species *Alyssum bertolonii*, it was the discovery in 1976 of a New Caledonian rainforest tree with a startling blue-green latex that transformed the field. Jaffré and colleagues, reporting in science, showed that this tree—then named *Sebertia acuminata* and now reclassified as *Pycnandra acuminata*—contained around 25% nickel by dry weight in its latex, coloured blue-green by nickel complexes. The following year, Brooks and co-workers coined the term "hyperaccumulator" to denote a plant containing more than 1,000 mg of nickel per kilogram of dry above-ground tissue—roughly a hundred to a thousand times the level found in ordinary plants growing on the same soils.

The definition was subsequently broadened to cover a range of elements, each with its own threshold reflecting its normal abundance in plant tissue. Following the widely adopted criteria refined by van der Ent and colleagues in 2013, a plant is considered a hyperaccumulator if its dry-weight foliar concentration exceeds 100 mg/kg for cadmium, selenium or thallium; 300 mg/kg for cobalt, copper or chromium; 1,000 mg/kg for nickel, lead or arsenic; 3,000 mg/kg for zinc; and 10,000 mg/kg for manganese. Two further attributes distinguish true hyperaccumulators from mere metal-tolerant plants: a translocation factor greater than one (metal concentration in shoots exceeding that in roots), and a bioconcentration factor greater than one (shoot concentration exceeding that in the soil). Together these criteria capture the defining paradox of hyperaccumulation—the active pumping of a normally toxic element into the very tissues most vital to the plant.

3. Global Diversity and Distribution

The number of recognised hyperaccumulators has grown steadily as analytical screening has spread to poorly studied floras. The Global Hyperaccumulator Database, curated at the University of Queensland and formalised by Reeves and colleagues in 2018, documented 721 species as of mid-2017. The taxonomic and elemental distribution of these plants is strikingly uneven. Nickel dominates overwhelmingly, accounting for over 500 of the known species; the remainder comprise, in round figures, some 53 copper, 42 cobalt, 42 manganese, 41 selenium, 20 zinc, 8 lead, 7 cadmium, 5 arsenic, 2 thallium and a single chromium hyperaccumulator, with a small and growing number of rare-earth-element accumulators.

This dominance of nickel is partly real and partly an artefact of detection: a simple, nickel-specific colour test based on dimethylglyoxime made early field screening for nickel far easier than for any other element. The plants themselves are phylogenetically clustered. A large share belong to only a handful of families—notably the Brassicaceae (which contain many of the best-studied zinc, cadmium and nickel accumulators), the Phyllanthaceae, Cunoniaceae, Euphorbiaceae and Sapotaceae. Geographically, hyperaccumulators are concentrated on naturally metal-enriched substrates: the serpentine and ultramafic soils of Cuba (with roughly 130 nickel hyperaccumulators), the Mediterranean and Asia Minor, Southeast Asia and New Caledonia (about 65 species), and the copper–cobalt outcrops of the Katangan Copperbelt in the Democratic Republic of the Congo. Zinc and cadmium hyperaccumulators occur mainly on the calamine soils of Europe and on contaminated ground in China.

This distribution carries an important conservation message. Because so many hyperaccumulators are endemic to small areas of metalliferous soil, they are acutely vulnerable to habitat destruction from the very mining activities that expose the metals they thrive on. Several nickel and copper–cobalt hyperaccumulators of central Africa are now threatened, meaning that the loss of a mineralised hillside can extinguish a species of direct value to remediation science before it has even been characterised.

4. Mechanisms of Metal Hyperaccumulation

The ability to hyperaccumulate rests on the enhancement of processes that all plants possess, coordinated into an unusually efficient pathway. Four steps can be distinguished: mobilisation and root uptake; xylem loading and root-to-shoot translocation; distribution and vacuolar sequestration in the shoot; and biochemical detoxification. Figure 1 summarises this internal pathway alongside the four remediation strategies it makes possible.

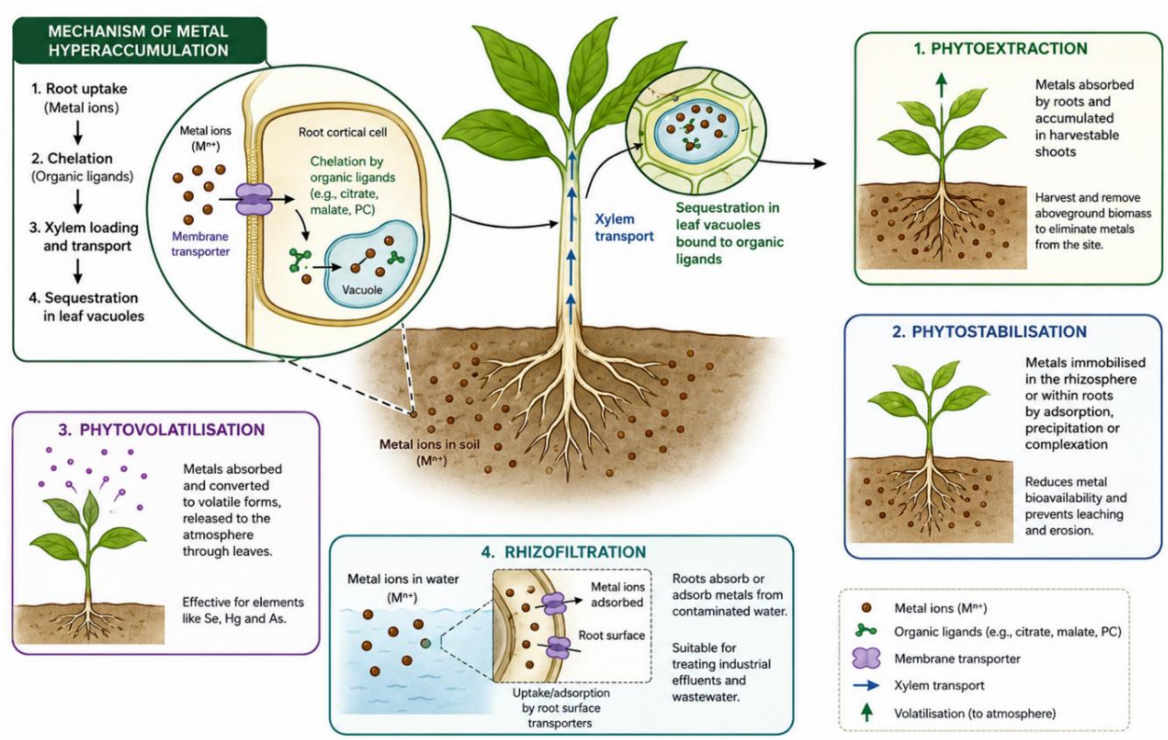

Figure 1. Schematic overview of the mechanisms of metal hyperaccumulation and the four principal phytoremediation strategies—phytoextraction, phytostabilisation, phytovolatilisation and rhizofiltration. Metal ions are taken up at the root by membrane transporters, chelated and loaded into the xylem for transport to the shoot, and finally sequestered in leaf vacuoles bound to organic ligands.

4.1 Mobilisation and root uptake

Metals must be in a bioavailable form before a plant can absorb them. Hyperaccumulators actively promote this bioavailability: their roots release protons that lower rhizosphere pH, and secrete organic acids and other exudates that solubilise metal ions bound to soil particles. Root-associated bacteria and mycorrhizal fungi further modify metal speciation. Once mobilised, ions cross the root-cell plasma membrane through a suite of metal transporter proteins. Members of the ZIP family carry zinc, iron and other divalent cations; NRAMP proteins transport manganese, iron, cadmium and nickel; and in the arsenic fern the transporter PvACR3 handles arsenite. A hallmark of hyperaccumulators is that several of these transporter genes are constitutively expressed at much higher levels than in related non-accumulating species.

4.2 Xylem loading and translocation

The trait that most sharply separates hyperaccumulators from metal-excluding plants is their capacity to move metals rapidly out of the root and into the shoot. This requires efficient loading of metals into the xylem, driven in large part by heavy-metal-transporting ATPases, of which HMA4 is the best characterised in the Brassicaceae. Within the transpiration stream, metals do not travel as free ions but are chelated by small ligands—histidine is central to nickel transport, while citrate, malate and nicotianamine complex a range of metals. This chelation both protects sensitive cellular machinery and keeps the metals soluble during their journey upward. In *Pycnandra acuminata*, for example, nickel is carried and stored largely as nickel–citrate complexes.

4.3 Sequestration and detoxification

Arriving in the leaf, metals must be kept away from the chloroplasts and cytoplasm where they would otherwise poison photosynthesis and respiration. Hyperaccumulators achieve this by compartmentalising metals into the vacuole and, frequently, into the epidermis, trichomes and cell walls—metabolically fewer active sites. Detoxification is completed by binding the metals to thiol-rich peptides such as phytochelatins and metallothioneins, and to organic acids. The result is that extraordinarily high total metal concentrations coexist with very low concentrations of free, reactive metal ions in the sensitive tissues. This spatial and biochemical management, rather than any single "super gene," is what allows the plant to tolerate its own metal burden.

Why plants should have evolved such an expensive habit remains debated. The leading hypothesis is elemental defence: high tissue metal concentrations deter and poison leaf-chewing insects and pathogens, a proposition supported by feeding experiments showing that hyperaccumulated nickel is toxic to many herbivores. Competing or complementary explanations include drought tolerance, protection against oxidative stress, and inadvertent uptake as a by-product of efficient micronutrient acquisition.

5. Phytoremediation Strategies

Hyperaccumulators and other useful plants are deployed through several distinct strategies, each suited to particular contaminants and site conditions.

Phytoextraction is the flagship application and the one most dependent on true hyperaccumulators. Plants absorb metals through their roots, translocate them to the shoots, and are then harvested; the metal-laden biomass is removed, dried and reduced in volume by ashing, and either disposed of safely or processed to recover the metal. Repeated cropping progressively lowers the soil metal burden. Effectiveness depends on the product of two factors—shoot metal concentration and harvestable biomass—which explains the enduring search for species that combine high accumulation with vigorous growth.

Phytostabilisation does not remove metals but immobilises them, using metal-tolerant plants to reduce the mobility and bioavailability of contaminants. Dense root systems and the surrounding rhizosphere bind and precipitate metals, limit leaching to groundwater, and stabilise the surface against wind and water erosion. It is well suited to large, heavily contaminated sites such as mine tailings where full extraction would be impractical.

Phytovolatilisation exploits the ability of certain plants to convert elements into volatile forms that are released to the atmosphere through the leaves. It applies chiefly to selenium and mercury; selenium hyperaccumulators such as *Astragalus* species can transform selenium into comparatively benign volatile compounds such as dimethylselenide. Because the contaminant is dispersed rather than contained, this strategy is used selectively and with regulatory care.

Rhizofiltration applies the same uptake principles to water rather than soil. The roots of plants grown hydroponically or in constructed wetlands adsorb and absorb metals from contaminated water and wastewater, which are then harvested with the biomass. Related approaches—phytodegradation and rhizodegradation—target organic pollutants rather than metals and fall outside the scope of this review.

6. Notable Hyperaccumulator Species and Field Performance

A handful of species have become models for the whole field. *Pycnandra acuminata* remains the most spectacular: its blue-green latex, containing up to about 25.7% nickel by dry weight (some 250,000 mg/kg), represents the highest metal concentration recorded in any living organism, with foliar tissues reaching around 16,900 mg/kg. *Pteris vittata*, the Chinese brake fern identified by Ma and colleagues in 2001 as the first known arsenic-hyperaccumulating fern, can concentrate more than 22,000 mg/kg of arsenic in its fronds, and far higher still under heavy dosing. In the Brassicaceae, *Noccaea caerulescens* (formerly *Thlaspi caerulescens*) is the classic zinc–cadmium model, accumulating zinc to 40,000 mg/kg and cadmium to 2,000 mg/kg, while *Odontarrhena chalcidica* (formerly *Alyssum murale*) has become the agronomic workhorse of nickel phytomining. Table 1 summarises the accumulation capacities of these and other important species.

Table 1. Representative hyperaccumulator species and their reported metal accumulation.

Species	Target element	Family	Reported shoot / tissue concentration
Pycnandra acuminata	Nickel (Ni)	Sapotaceae	Up to 25.7% Ni (≈250,000 mg/kg) in latex — highest recorded in any organism
Odontarrhena chalcidica (syn. Alyssum murale)	Nickel (Ni)	Brassicaceae	≈ 20,000–25,000 mg/kg; workhorse of Ni phytomining
Noccaea caerulescens (syn. Thlaspi caerulescens)	Zn / Cd / Ni	Brassicaceae	Zn up to 40,000 mg/kg; Cd up to 2,000 mg/kg; Ni up to 10,000 mg/kg
Pteris vittata	Arsenic (As)	Pteridaceae	Up to ≈22,600 mg/kg in fronds; >60,000 mg/kg under heavy As dosing
Sedum plumbizincicola	Zn / Cd	Crassulaceae	High Zn and Cd accumulation; used in Chinese field phytoextraction
Astragalus bisulcatus	Selenium (Se)	Fabaceae	Several thousand mg/kg Se; enables phytovolatilization

Values are indicative maxima drawn from the cited literature; actual concentrations vary with genotype, soil metal availability and growth conditions.

Field performance is necessarily more modest than these laboratory maxima, because remediation depends on the metal removed per hectare per year rather than on peak tissue concentration. Long-term field trials give a realistic sense of the scale. In arsenic phytoextraction with *Pteris vittata*, a four-year study on moderately contaminated soil achieved a best rate of about 5 kg of arsenic per hectare per year in compost-amended plots, while an eight-year Japanese field trial removed roughly

2.8 kg of arsenic per hectare and, importantly, brought water-soluble arsenic down to the regulatory standard. For zinc, *Noccaea caerulescens* has been reported to extract on the order of 30 kg of zinc per hectare in a single season. These figures underline both the promise of the technology and its principal constraint—time.

7. From Clean-up to Profit: Phytomining and Agromining

A natural extension of phytoextraction is to treat the metal-rich harvest not as hazardous waste but as an ore. In phytomining—also called agromining when practised as a farming system—nickel hyperaccumulators are cropped on naturally metal-rich or contaminated land, harvested, and incinerated to yield a "bio-ore" ash from which the metal is recovered. Nickel is the prime candidate because of its high value, the abundance of vigorous nickel hyperaccumulators, and the extent of sub-economic ultramafic land worldwide.

Field results are encouraging. In the European LIFE-Agromine programme, cultivation of *Odontarrhena chalcidica* in Albania was optimised to produce up to about 10 tonnes of dry biomass per hectare, yielding as much as 150 kg of nickel per hectare—a return comparable to conventional low-grade mining. A controlled trial on Austrian serpentine soil recorded up to 55 kg of nickel per hectare from *O. chalcidica* and 36 kg per hectare from *Noccaea goesingensis*. Agromining thus offers a genuine dual benefit: it gradually strips excess metal from marginal or polluted soils while generating a saleable product that can offset remediation costs and, in the case of critical metals such as nickel and cobalt, contribute to secure supply chains.

8. Advantages, Limitations and Enhancement Strategies

The appeal of hyperaccumulator-based phytoremediation is easy to state. It is markedly cheaper than physico-chemical alternatives; it is powered by sunlight and requires little specialised infrastructure; it preserves and often enriches soil biology and structure; it is publicly acceptable and can improve the landscape; and, through phytomining, it can turn a liability into an asset. It is also applicable in situ, avoiding the disturbance and secondary pollution associated with excavation.

These strengths are balanced by real limitations. The foremost is slowness: because most hyperaccumulators are small and slow-growing, complete clean-up of a heavily contaminated site may take many growing seasons or longer. The classic trade-off is that the species with the highest tissue concentrations, such as *Noccaea caerulescens*, tend to produce little biomass, whereas high-biomass crops accumulate less. Most hyperaccumulators are also element-specific, treating only one or two metals and leaving co-contaminants untouched, and their action is confined to the rooting depth. Climatic and edaphic requirements limit where a given species can be grown, and the metal-laden biomass itself constitutes a waste stream that must be managed responsibly to prevent re-entry of metals into the food chain.

Considerable research effort is therefore directed at overcoming these constraints. **Chelate-assisted phytoextraction** uses soil amendments such as EDTA to increase metal solubility and uptake—effective but risky, because mobilised metals may leach into groundwater, so biodegradable chelators and organic acids are now preferred. **Microbe-assisted phytoremediation** harnesses plant-growth-promoting rhizobacteria and mycorrhizal fungi to improve both plant vigour and metal availability. Agronomic optimisation—fertilisation, planting density, crop rotation and harvest timing—has already lifted phytomining yields substantially. Finally, **genetic engineering** seeks to combine the accumulation genes of hyperaccumulators with the biomass and hardiness of crop plants; the transfer of the arsenic transporter PvACR3 from *Pteris vittata* into other plants is one proof-of-concept in this direction.

9. FUTURE PROSPECTS AND CONCLUSION

The trajectory of hyperaccumulator research points towards integration rather than isolation. The most promising future systems are likely to be combinations: hyperaccumulators grown together with metal-mobilising microbes, supported by optimised agronomy, and increasingly informed by the molecular understanding of transporters and chelators that could be transferred into fast-growing crops. Coupling phytoextraction with bioenergy or biochar production, and phytomining with the recovery of critical metals, offers routes to make remediation economically self-sustaining. Continued discovery—particularly of hyperaccumulators for under-served elements such as lead, arsenic and the rare-earth elements, and from botanically neglected regions—will widen the toolkit, while the conservation of endemic metallophyte floras must proceed in parallel, lest useful species be lost to mining before they are studied.

In conclusion, hyperaccumulator plants occupy a unique position at the meeting point of plant biology, geochemistry and environmental engineering. Their capacity to concentrate normally toxic metals to extraordinary levels—epitomised by the quarter-nickel latex of *Pycnandra acuminata*—is not merely a botanical marvel but a practical resource. Through phytoextraction, phytostabilisation, phytovolatilisation and rhizofiltration, and through the emerging economy of phytomining, these plants offer a low-cost, sustainable and soil-conserving means of addressing one of the most intractable pollution problems of our time. Their limitations—chiefly the slowness of clean-up and the element-specificity of most species—are real, but they are increasingly being met by advances in agronomy, microbiology and molecular biology. As the global burden of metal-contaminated land continues to grow, the quiet work of these remarkable plants is likely to become ever more valuable.

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