Harnessing Indian Hyperaccumulator Plants for Eco-Friendly Remediation of Heavy Metal–Polluted Soils

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***Abstract*—Land degradation caused by a range of pollutants is a critical concern worldwide, especially in developing nations like India, where rapid industrialisation and urbanisation have accelerated the process. Among various pollutants, heavy metals pose a serious threat due to their non-degradable and toxic nature. Hyperaccumulators can absorb heavy metals from soil or water without incurring significant detrimental effects on their physiological and biological activities. Hence, they can be utilised to mitigate soil and water contamination. Crops of hyperaccumulator species, with edible parts rich in minerals (e.g., Cadmium (Cd), Zinc (Zn), Lead (Pb), Copper (Cu), Manganese (Mn), Cobalt (Co), Nickel (Ni), Chromium (Cr), etc.), must be avoided in the remediation process to prevent further soil pollution, environmental toxicity, and food chain poisoning. Therefore, hyperaccumulator plants not included in the food chain are preferred while carrying out phytoremediation. A detailed investigation into the trace metal profile of different species of plants, identified as potential hyperaccumulators, has been carried out. It suggested suitable hyperaccumulators for heavy metal-contaminated soils, considered an ecological and safe remediation technology (Lorestani et al., 2011).**

***Index Terms*—Land degradation, industrialisation, potential hyperaccumulators.**

I. INTRODUCTION

Pollution from mining, metallurgy, heavy industry, and urbanisation has significantly deteriorated the environmental quality of land, air, and water in India. Widespread contamination of soil with trace elements particularly metals pose serious health risks. Soil contamination has been documented in several industrial and urban areas across India, and instances of heavy metal buildup are prevalent in many areas, including Agra, Bhopal, Chennai, Coimbatore, Delhi, Faridabad, Gwalior, Guwahati, Indore, Kanpur, Lucknow, Ludhiana, Pune, Varanasi, and Surat.

Soil decontamination is typically a lengthy and costly process. Conventional techniques involve physical or chemical remediation and, while effective, tend to entail substantial expenditure and adverse side effects on both soil and the surrounding environment. Remediation of soil metals can also be achieved by abandoning or capping the contaminated site (Chibuike), treating it with suitable organic amendments, converting it to a non-agricultural layout, or washing it using chelating agents (Wuana). Phytoremediation, however, can provide an economically viable and completely environmentally friendly option. Phytoremediation techniques include phytoextraction, Phyto filtration, Phyto stabilisation, and phytodegradation, which fall into three broad groups: immobilisation, extraction, and degradation. The process depends on hyperaccumulator plants those that can take up excessive ions of certain trace elements and deposit them in a particular organ, usually the above-ground stems and leaves (Nkansah & Belford, 2017).

Plants exhibiting hyperaccumulation traits have been discovered in the Indian flora. Several of these candidates appear suitable for systematic investigation as potential remediation solutions for land contaminated by heavy metals.

II. CONCEPTUAL FRAMEWORK: HYPERACCUMULATION AND SOIL REMEDIATION

Phytoremediation harnesses hyperaccumulator plants to clean up metal-contaminated soils and waters (Lorestani et al., 2011). Over 400 taxa have been identified as capable of taking up high concentrations of metals (Li et al., 2018). Indian soils are contaminated with several toxic trace metals, including Pb, Cd, Zn, As, and Hg. Scientists have assembled extensive inventories of hyperaccumulator plants outside India. An objective of the present synthesis is to compile a preliminary list of Indian species that meet hyperaccumulation criteria for toxic trace metals of concern.

III. INDIAN FLORA WITH HYPERACCUMULATIVE POTENTIAL

Hyperaccumulators are plants that can survive and grow in soils with metallic concentrations lethal to most other plants, and phytoextraction the removal of toxic metals by plants can substantially decrease soil levels of various metals such as cadmium, arsenic, aluminium, lead, and mercury. India is subject to a serious threat of contamination of the soil and crop failure by the introduction of heavy metals, lignite, coal ash, and sewage effluents. Another danger is cultivable, polluted land. There are reportedly 1.38 million hectares of polluted land nationwide, mostly from the mining industry. Phytoremediation is emerging as a viable alternative.

Many plant species in the Indian subcontinent may have the potential to hyperaccumulate. The identification of such plants allows for the design of cleanup strategies based on the phytoextraction properties of the native vegetation.

3.1 Metals of Concern in Indian Soils

Soils in India are contaminated with a range of trace metals due to anthropogenic activities such as industrialisation, urbanisation, mining and improper dumping of e-waste. As a result, it is expected that Indian soils are expected to contain heavy metals such as cadmium (Cd), chromium (Cr), lead (Pb), manganese (Mn), zinc (Zn), copper (Cu), and arsenic (As) (Krishna & Ahuja, 2023). Regarding these metals, plants such as Wolffia globosa (Sood et al., 2011), Trapa bispinosa, Spirulina platensis, Thalassia hemprichii, Syzigium cumini, and Azolla pinnata (Kumar, 2018) have shown hyperaccumulation potential. The Indian subcontinent and particularly northeastern India experienced pollution problems associated with mining (Chaudhari & Singh, 2016; Reza et al., 2018). Mining activity affected water and soil quality due to heavy metal accumulation (Reza et al., 2018; Chaudhari & Singh, 2016). Cadmium, Chromium, Lead, Manganese and Zinc concentrations are reported near mining sites in North-Eastern India, exhibiting soil contamination (Kar, 2025; Reza et al., 2018). Mining activities resulted in heavy metal accumulation in the sediment and aquatic flora in the North-Eastern States of India (Chabukdhara & Singh, 2016; Kar, 2025).

3.2 Candidate Hyperaccumulator Species and Their Trace Metal Profiles

Heavy metal pollution poses severe risks for soil and water ecosystems. The availability of high-biomass, hyperaccumulating plant species could facilitate the remediation of soil contaminated with lead (Pb) and other trace metals throughout the Indian subcontinent. On contaminated mine land and waste, species such as Ricinus communis and Chenopodium album are found naturally in the Indian subcontinent and have high accumulation ratios for metals, including lead (Pb), manganese (Mn), iron (Fe), and zinc (Zn) (Sharma et al., 2020). Potential hyperaccumulator species, including Amaranthus species, have been identified through examination of natural flora growing on trace-metal-contaminated soils in India (Gajić et al., 2018). These candidates show a variety of tolerance, translocation, and trace-metal accumulation profiles.

3.3 Hyperaccumulation Potential in Indian Flora

Aquatic Weed Species:
Lemna minor L. - (Duckweed)
Ludwigia L. sp.
Pontederia crassipes Mart. – (Water Hyacinth)
Terrestrial and Weed Species:
Alternanthera philoxeroides (Mart.) Griseb. – (Alligator Weed)
Amaranthus L. sp.
Arachis hypogaea L. – (Groundnut)
Arundo donax L. (Giant cane)
Brassica juncea (L.) Czern. – (Indian Mustard)
Chenopodium album L. and Chenopodium murale (L.) S. Fuentes, Uotila & Borsch
Cicer arietinum L. - (Chickpea)
Crotalaria L. sp.
Cyperus iria L.- (Rice Flatsedge)
Datura metel L. - (Devil's Trumpet)
Euphorbia paniculata Desf.
Helianthus annuus L. - (Sunflower)
Leucas aspera (Willd.) Link
Melilotus indica (L.) All. – (Sweet Clover)

Ricinus communis L. (Castor Bean)
Syzygium cumini (L.) Skeels – (Jamun)

VI. MECHANISMS OF UPTAKE, TRANSLOCATION, AND SEQUESTRATION

The uptake of trace metals by hyperaccumulator plants represents an active and systemic process involving not only root absorption but also transport to aerial biomass and storage in vacuoles. Various mechanisms have been proposed to account for the predominant hyperaccumulation of particular trace elements in some species and the sequence of dominant elements within others (Šuman et al., 2018). Synthesis of candidate hyperaccumulators listed in section 4 reveals a tendency to associate specific species with unique micro-pollutant patterns (Lorestani et al., 2011). It follows that a detailed analysis of underlying biophysiochemical mechanisms, including the metal of concern and its form of bioavailability, complements earlier USD-AID phytoextraction principles through attention to plant-metal combinations of potential interest within an India-centric soil remediation framework (Khan et al., 2023). The primary focus is thus on mechanisms of uptake, translocation and sequestration for metals of Indian interest (Khan et al., 2023).

V. PHYTOREMEDIATION STRATEGIES APPLICABLE IN THE INDIAN CONTEXT

Evidence-based phytoremediation strategies applicable to the Indian context include phytoextraction and Phyto stabilisation. Phytoextraction refers to the uptake of contaminants and their storage as higher biomass in the aerial parts of crop plants, whereas Phyto stabilisation, by reducing the mobility of contaminants in soils and waters, is a remedial operation that only minimises the escape and spread of pollution without degrading its source. Since 2005, selected and/or discovered varieties of six aquatic and/or semiaquatic plants, e.g., species of duckweed, water hyacinth, and Ludwigia, for the remediation of arsenic and other toxic trace elements from the waters of arsenic-affected places, such as India, have been developed and submitted (Rahman & Hasegawa, 2011). The increase of trace-element concentrations in crops and crop products, such as rice and vegetables, corresponding to the degree of arsenic poisoning and contamination has been recorded from the arsenic-affected zones of India as well as Bangladesh for about two decades (Nkansah & Belford, 2017). These selected and/or discovered aquatic plants, in addition to some already known candidates having hyperaccumulating capacity for trace elements like arsenic, cadmium, lead, chromium, mercury, and copper, represent the potential of a broader spectrum of aquatic-plant candidates for the phytoremediation of contaminated waters.

A backup remedy for the phytoremediation process can be provided through the concurrent development of different trace-element-remediation technologies for plants and/or other materials, apart from the already described candidates for plant-based remediation of contaminated waters. Rhizofiltration is a recently developed and limited technique that can be used exclusively for decontaminating aquatic environments by controlling the concentrations of toxic trace elements and/or minerals (Šuman et al., 2018).

Additionally, still less explored phytoremediation techniques, such as Phyto transformation, should also be considered for increasing the spectrum of remediation technologies and techniques and broadening the range of remediation options, apart from the specially selected and/or developed aquatic and /or semiaquatic plants.

5.1. Phytoextraction, Phyto filtration, Phyto stabilisation, and rhizofiltration

Remediation of contaminated soil can be achieved through phytoremediation, which includes four approaches for trace metal removal: phytoextraction, phytofiltration, Phyto stabilisation, and rhizofiltration. Phytoextraction involves the uptake of pollutants (heavy metals) from soil or water sorbed onto plant roots, the transpiration of soil solution through synchronised water absorption, and the storage of pollutants in the plant tissues (Rahman & Hasegawa, 2011). Appropriate candidate hyperaccumulator plants that absorb trace metals from moderately contaminated soils should possess the following basic characteristics: higher accumulation of metals in shoots/leaves than in roots; high annual dry biomass (leaf + stem + root); short life cycle; wide distribution; and high adaptability to wide environmental conditions. The rates of uptake of different metals depend on plant species, soil conditions, and the concentration of pollutants (Šuman et al., 2018).

Phyto stabilisation technology reduces the mobility and availability of contaminants in soil or water without removing them from the environment. The aim is to restrain the movement of pollutants towards the food chain by encouraging plants with a high root-to-shoot ratio, namely grasses and shrubs, and plants that increase the soil pH (e.g., leguminose and clover). 'Rhizofiltration' refers to aquatically rooted terrestrial and/or wetland plants that adsorb and absorb pollutants from water and wastewater.

5.2. Plant-microbe interactions to enhance remediation
Soil contamination due to anthropogenic activities, mining, and industrial processes has raised concerns over food safety and, consequently, human health. Phytoremediation, which relies on the use of plants to clean up polluted environments, offers an eco-friendly and sustainable approach towards soil decontamination, despite being a relatively slow process (Nkansah & Belford, 2017). Phytoextraction, phytofiltration, phytostabilisation, and rhizofiltration are the proposed remediation strategies. The use of mycorrhizal fungi and plant-growth-promoting bacteria, among others, has been advocated to improve the efficiency of phytoremediation (Ma et al., 2016). Microbes interact with plants and assist in their remediation effectiveness, and many indigenous plants have been found to grow in metalliferous soils and accumulate considerable amounts of metals. Co-inoculation of selected native bacteria with hyperaccumulators resulted in significant metal accumulation and offers a low-cost alternative strategy for the remediation of metalliferous soils and hope for sustainable agriculture.

VI. FIELD EVIDENCE AND CASE STUDIES FROM INDIA

Hyperaccumulation is a unique process in plants whereby certain trace elements attain remarkably high concentrations in the tissues without inducing toxic effects on the plant. Hyperaccumulation of heavy metals/metalloids has emerged as a potential approach for cleaning up polluted soils. Natural hyperaccumulators of heavy metals/metalloids could be used in soil remediation efforts. Phytoremediation is largely applicable in the Indian context, yet much work remains to identify suitable hyperaccumulators among the limited heavy metal hyperaccumulators. Pb, Fe, Mn, Cu, and Zn accumulation in plants and the selection of a hyperaccumulator factory in the Iranian industrial town of Vian." The majority of the species that were studied grew in soils that were highly polluted with metals, accumulating high concentrations of Pb, Fe, Mn, Cu, and Zn. Hyperaccumulators included Salsola soda and Circium arvense for Pb and Camphorosma monospeliacum for Pb and Fe, showing potential for phytoremediation. Phytoremediation is a promising approach to environmental cleanup using plants to remove, destroy, or sequester hazardous substances. The study was conducted in Vian, Hamedan province, Iran, where industrial wastewater contaminates the soil with heavy metals. Heavy metal contamination was mainly concentrated in the top 20 cm of soil, and samples were collected from the surrounding area. Chinese hyperaccumulator plants: an overview of the state of the art. For phytoextraction to clean up contaminated soils and trash, hyperaccumulator plants are crucial. China is a global hotspot for hyperaccumulator organisms due to its abundant mineral resources and vast biodiversity. Many hyperaccumulators, including Cardamine violifolia (selenium), have been found in China over the past 20 years as a result of intensive screening efforts (Li et al., 2018).

Pteris vittata (arsenic), Elsholtzia splendens (copper), Phytolacca americana (manganese), Dicranopteris dichotoma (rare earth elements), Sedum alfredii, and Sedum plumbizicola (cadmium/zinc). Studies cover ecophysiology and molecular biology of tolerance and hyperaccumulation. Research from China accounts for 41% of the world's SCI papers on hyperaccumulators, highlighting significant scientific advances. Hyperaccumulator plants can substantially reduce soil pollutant concentrations within reasonable time frames, especially in slightly or moderately contaminated soils. A plant is considered hyper accumulative if it has foliar concentrations exceeding specific thresholds for elements like Cd, Se, Tl, As, Cr, Co, Cu, Ni, REEs, Zn, and Mn while maintaining a full life cycle reproduction without toxicity symptoms. Aquatic species are excluded due to contamination risks.

VII. AGRONOMIC, ECOLOGICAL, AND SOCIO-ECONOMIC CONSIDERATIONS FOR DEPLOYMENT

Phytoremediation technologies have gained increased attention over the past two decades as a sustainable and eco-friendly approach to mitigating the adverse effects of soil contamination (Nkansah & Belford, 2017). Hyperaccumulators have particular significance in the context of phytoremediation, given their ability to sequester heavy metals in economically exploitable biomasses, thus facilitating metal recovery (Lorestani et al., 2011). Nonetheless, the efficient deployment of hyperaccumulators for in situ soil remediation necessitates an understanding of relevant agronomic, ecological, and socio-economic factors. Hyperaccumulators with the potential to remediate high-concentration soil contaminants are already present in the Indian flora; thus, enhanced metal detoxification and/or recovery from contaminated sites through the application of these plants is an attractive and feasible alternative. In such initiatives, the local knowledge and practices of rural populations can be effectively integrated alongside scientific innovations.

Field observations in India have identified metal-accumulating native flora and suggested feasible remediation approaches through the analysis of microbially assisted and unassisted hyperaccumulator processes involving metal uptake, translocation, and sequestration. Large areas of land affected by metal-contaminated industrial waste, mining, and sewage sludge could be remediated using existing hyperaccumulator species available from local flora. Plant communities such as Arachis hypogeae at Vapi and weed species like Chenopodium album, C. murale, and Melilotus indica at the National Institute of Oceanography, Goa, known for high trace metal accumulation, can be further screened for candidate hyperaccumulators with greater accumulation or detoxification potential.

VIII. CHALLENGES, RISKS, AND POLICY IMPLICATIONS

Development of phytoremediation, based on the hyperaccumulation concept, is necessitated by inefficient and unsustainable conventional remediation methods (K. Nkansah & J. D. Belford, 2018; Lorestani et al., 2011; Li et al., 2018). Uneven distribution of knowledge across India on the accumulation characteristics of various plants hampers further upscaling. A precise governmental policy framework, like a hard-bound guideline of hyperaccumulator species and metals to be targeted, to facilitate their conscientious use, is lacking, as there are no in situ studies. Long duration of the project cycle viable for project mitigation. Social acceptance of hyperaccumulators in uninformed regions is a serious consideration.

IX. FUTURE DIRECTIONS AND RESEARCH PRIORITIES

Attention has recently turned to hyperaccumulator plants, which absorb or accumulate unusually high quantities of contaminants through their roots and translocate them to aerial parts. While hyperaccumulators play various roles including detoxification, storage, chelation, and immobilisation they can be applied through various remediation strategies. Phytoremediation technologies using hyperaccumulators have shown promise for both organic and inorganic contaminants; however, the applicability of many strategies using Indian plants is still uncertain (Šuman et al., 2018).

In India, hyperaccumulator plants have been found to be able to extract significant concentrations of metals like cadmium, lead, copper, cobalt, nickel, and zinc from the soil and store them in their aboveground portions. After extensive screening, candidate species were selected based on three criteria: 1) occurrence in predictable locations within India; 2) established species profiles documenting metal uptake, accumulation, and above-ground-to-root bio-concentration ratios (BCRs) facilitating preliminary estimation of hyperaccumulation potential; and 3) evidence of successful deployment within or beyond the Indo-Gangetic region (Li et al., 2018). By focusing on species with established profiles, future investigations can concentrate on identifying actual hyperaccumulators rather than simply affirming the absence of hyperaccumulation traits. Available data also suggest that non-specificity towards certain metals facilitates the removal of multiple contaminants.

X. CONCLUSION

Hyperaccumulation of trace metals by plants is an identified phenomenon of industrial and environmental significance. With evidence of historical anthropogenic soil contamination from toxic heavy metals in copper, lead, chromium, cadmium, and arsenic further raised among polluted sites and of large swathes of southern India showing above-permitted levels of trace contaminants like lead, zinc, copper, cadmium, molybdenum, iron, mercury, manganese, and nickel (Šuman et al., 2018), the need for repair and restoration becomes urgent. Consideration of the native flora of the Southern region reveals a variety of candidate species capable of hyperaccumulation. Exploration across India with increasing understanding of hyperaccumulation continues to reveal new prospective flora able to contribute significantly to localised soil repair.

The primary plant mechanisms facilitating hyperaccumulation entail efficient uptake from soils, high rates of root-to-shoot translocation, and extraordinary levels of sequestering in stems and leaves. Identified candidate species supplying high concentrations of copper, lead, nickel, and zinc to above-ground parts are distinctively active in these capacity-forming characteristics (Li et al., 2018). To exploit this ability in Indian soil remediation programmes, existing exploration and analysis must be broadened, with vigorous emphasis on preserving and scanning for further areas of potential supply. Meanwhile, establishing protocols to support coordination among researchers for the timely sharing of results and collections and for the assembly of updatable electronic catalogues of hyperaccumulated metal-supply flora is especially necessary (Lorestani et al., 2011).

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AUTHOR CONTRIBUTIONS

Jyotsana Jaiswal: Writing-Original Draft Preparation; Literature Review; Conceptualization (supporting); Methodology (supporting); Investigation; Data Curation; Formal Analysis (metal analysis).

Dr. Santosh Kumar: Conceptualization (lead); Methodology (lead); Validation; Resources; Plant Identification; Field Investigation; Supervision; Writing – Review & Editing; Project Administration; Correspondence with the journal.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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