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Combination of Phytoremediation and Phytomining Treatment as an Alternative Solution to Overcoming Heavy Metal Contamination in Soil

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ABSTRACT

Contamination by heavy metals has affected numerous facets of human life over the past few decades. These pollutants originate from diverse human activities, including agriculture, industry, mining, transportation, energy production, and even routine domestic practices. Heavy metal pollution exerts detrimental effects not only on humans but also on animals, plants, and microorganisms. Exposure to heavy metals can inhibit plant growth, leading to suboptimal yields. Moreover, the accumulation of heavy metals within plant tissues poses significant risks to animals and humans who consume them. Consequently, effective strategies are necessary to mitigate the environmental impacts of heavy metal pollution. This article explores phytoremediation and phytomining as sustainable approaches to address heavy metal contamination. In-situ phytoremediation offers a more cost-effective option compared to conventional remediation methods, enabling large-scale application. For economic feasibility, phytoremediation efforts can be integrated with phytomining, which provides an environmentally friendly and low-cost method for extracting valuable metals. Plants chosen for phytoremediation and phytomining should exhibit traits such as high stress tolerance, rapid growth rates, and substantial biomass production.

Keywords: In-situ, waste, agriculture, remediation

Introduction

Over the past two centuries, beginning with the Industrial Revolution, land and water resources have undergone severe pollution, unprecedented in earlier human history. Direct consumption of river water has become unsafe, and agricultural products such as fruits and vegetables are now often contaminated with heavy metals due to unsustainable cultivation practices. Today, nearly every aspect of human life faces the persistent threat of heavy metal contamination. As defined by Handayanto et al. (2017), heavy metals are metallic elements that can be toxic to plants and animals even at very low concentrations. According to Budovich (2021), heavy metals are recognized as the principal pollutants in industrial waste. In recent years, increasing attention has been directed toward soil contamination by heavy metals, primarily due to their detrimental effects on living organisms through the food chain, resulting from the contamination of soil and water by elements such as Mn, Co, Ni, Cu, Zn, Cd, Hg, and Pb (Brummer, 1986). Although heavy metals naturally occur in soils, both geological processes and anthropogenic activities have significantly elevated their concentrations. Major contributing activities include mining and smelting operations, fossil fuel combustion, the application of fertilizers and pesticides in agriculture, industrial manufacturing of batteries and metal products, as well as the disposal of sewage sludge and municipal waste (Sperdouli, 2022). Furthermore, rapid population growth, increased material production, heightened agricultural demands, and

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the use of compost and industrial byproducts are also considered critical factors exacerbating heavy metal pollution (Budovich, 2021).

The scarcity of clean water resources has led to the utilization of alternative water supplies for agricultural irrigation, including industrial effluents discharged into rivers that are contaminated with heavy metals such as Fe, Cr, Pb, Ni, Co, and Mn. The use of untreated industrial wastewater for agricultural purposes poses substantial threats to environmental integrity, public health, and economic stability. Consumption of contaminated vegetables has resulted in a range of health issues within affected communities, consequently diminishing overall quality of life. As a result, all three pillars of sustainability—environmental, social, and economic—are severely compromised by the ongoing use of polluted water in agricultural practices (Ullah et al., 2022).

Soil contamination with heavy metals can adversely impact health and ecosystems through several pathways: (a) direct contact with contaminated soil, (b) bioaccumulation through the food chain (soil-plant-human or soil-plant-animal-human), (c) consumption of contaminated groundwater, (d) reduction in food quality, and (e) decreased land productivity for agricultural use (Handayanto et al., 2017). Therefore, effective remediation strategies are essential to mitigate or eliminate heavy metal contamination in soils. Over the past decades, a range of in-situ and ex-situ remediation techniques have been developed, including surface capping, soil flushing, electrokinetic extraction, compaction, vitrification, and phytoremediation (Liu et al., 2018). This article aims to examine the sources and impacts of heavy metal contamination on plants and human health, and to explore the integration of phytoremediation and phytomining as viable strategies to address environmental contamination by heavy metals.

Material and Methods

This study employs a qualitative methodology based on an extensive literature review. A literature review serves as a comprehensive synthesis of existing research on a particular subject, aimed at informing readers about established knowledge and identifying gaps that warrant further investigation. The data utilized in this study are secondary sources, comprising peer-reviewed journals, scholarly books, and credible internet-based references. To collect relevant literature, the researcher systematically searched online databases and platforms, including ProQuest, PubMed, ResearchGate, SagePub, and Google Scholar, using targeted keywords such as "phytoremediation," "phytomining," "heavy metal," and "soil contamination." The structured process of conducting the literature review is illustrated in the following Figure 1:

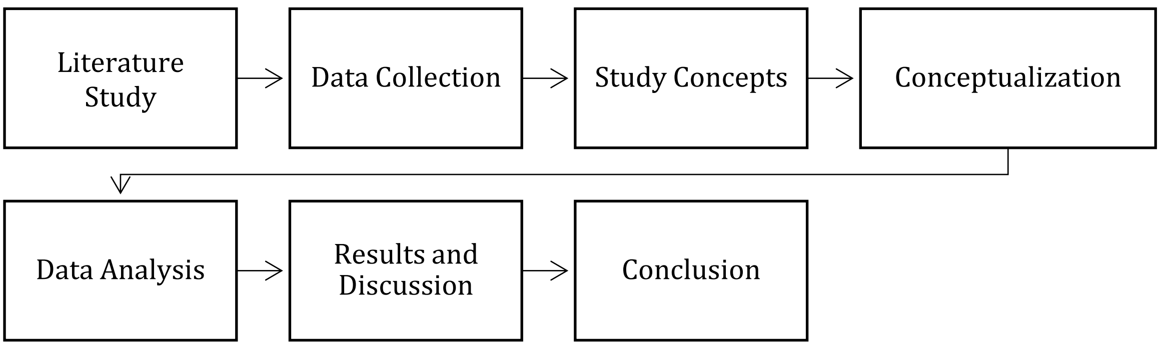

Figure 1. The steps in writing a literature review

Results and Discussion

Sources of heavy metal contamination

Heavy metals are inherently present within soil matrices, primarily as a consequence of the natural weathering of parent rocks. Additional geogenic sources include volcanic emissions, atmospheric dust, and the disintegration of mineralized rocks. However, anthropogenic activities have increasingly contributed to elevated heavy metal concentrations in terrestrial ecosystems. Major anthropogenic inputs arise from industrial manufacturing, mining operations, metallurgical processes, waste disposal practices, vehicular emissions, petroleum spills, and coal combustion by-products. Agricultural practices, particularly the excessive application of phosphate fertilizers, biosolids (such as animal manure, compost, and municipal sewage sludge), and pesticide formulations containing copper compounds (e.g., Bordeaux mixture, copper oxychloride, and lead arsenate), further exacerbate soil contamination. Moreover, irrigation using untreated industrial effluents and deposition from atmospheric sources, including emissions from road traffic, tire abrasion, and brake pad wear, intensifies the burden of heavy metals within soil systems. Other notable contributors include fly ash from coal-fired power plants, polyvinyl chloride (PVC) products, synthetic colorants, and rechargeable nickel-cadmium batteries (Rizvi et al., 2020). The principal pathways for heavy metal introduction into the environment are summarized in Figure 2.

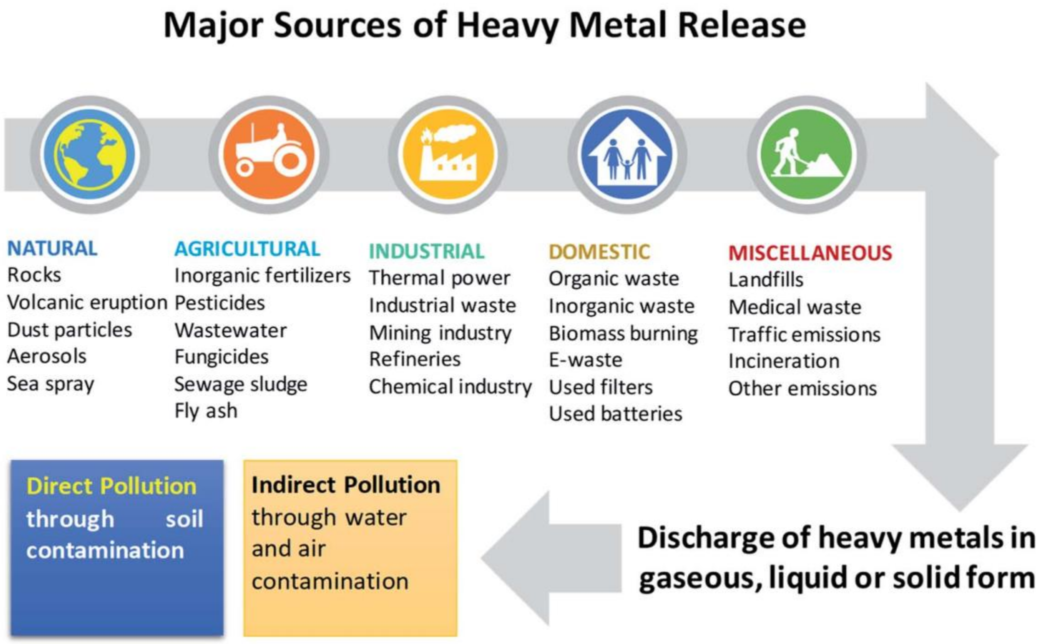

Figure 2. Sources of heavy metal contamination in the environment (Rizvi et al., 2020)

D'Amore et al. (2005) emphasized four critical reasons why soils are highly susceptible to heavy metal contamination: (a) anthropogenic accumulation rates surpass natural biogeochemical cycling, (b) unregulated dispersal from mining sites enhances environmental exposure risks, (c) waste streams often contain metals at concentrations significantly higher than those found naturally, and (d) certain chemical forms enhance the bioavailability of heavy metals under environmental conditions. Handayanto et al. (2017) also noted that anthropogenic emissions of specific metals into the atmosphere are estimated to be one to three times greater than those from natural cycles. Furthermore, heavy metals derived from anthropogenic activities exhibit greater mobility and bioavailability compared to those originating from pedogenic or lithogenic processes. Major anthropogenic sources include agrochemical inputs, municipal biosolids, industrial effluents, mining tailings, and airborne particulates.

Impact of heavy metal contamination on plants

The intensification of industrial, mining, and heavy metal processing activities has severely disrupted the self-purification capacity of terrestrial and aquatic ecosystems (Budovich, 2021). Phytotoxicity symptoms induced by heavy metals include nutrient uptake inhibition, impaired translocation processes, chlorophyll degradation, disruption of electron transport chains, suppression of carbon dioxide fixation, chloroplast ultrastructural damage, and increased formation of reactive oxygen species (ROS), which subsequently inhibits antioxidant enzymatic activities, induces cellular redox imbalance, and leads to oxidative damage of DNA and proteins (Sperdouli, 2022).

The bioaccumulation of heavy metals in plant tissues is significantly influenced by environmental conditions, plant species, and post-harvest handling, including drying, storage, and transport procedures (Budovich, 2021). Heavy metal-induced stress alters primary and secondary metabolic pathways, ultimately impacting the yield and phytochemical quality of agricultural products. Presently, contamination of soil and water resources with heavy metals is recognized as a critical threat to food security and ecosystem health.

Heavy metals are generally defined as elements with a density exceeding 5 g cm^{-3} (Chen et al., 2020). Several of these elements—such as Fe, Mo, Mn, Zn, Ni, Cu, V, Co, W, and Cr—function as essential micronutrients under normal concentrations. However, when present at elevated levels, they exert toxic effects on plant physiology (Zhan et al., 2016).

At toxic concentrations, heavy metals compromise plant vitality through several mechanisms, including: (i) alteration of membrane permeability, (ii) inhibition of key enzymatic activities, (iii) disruption of photosystem integrity, and (iv) impairment of mineral nutrient metabolism. Additionally, heavy metal toxicity induces oxidative stress, pigment degradation, protein dysfunction, and overall metabolic imbalance. Critical physiological processes such as seed germination, seedling establishment, photosynthetic efficiency, and plant immune responses are notably impaired under heavy metal stress conditions (Rizvi et al., 2020). A summary of heavy metal effects on plant systems is provided in Table 1.

Table 1. Effect of heavy metals on plants (Handayanto et al., 2017)

Heavy Metals	**Plants**	**Effect on Plants**
As	Rice *(Oryza sativa)*	Decreased seed germination; decreased seedling height, decreased leaf area and dry weight of plants
	Tomato *(Lycopersicon esculentum)*	Decreased fruit yield; decreased fresh leaf weight
	Canola *(Brassica napus)*	Stunted growth; chlorosis; wilt
Cd	Wheat *(Triticum sp.)*	Decreased seed germination; decreased plant nutrient content; decreased shoot and root length
	Garlic *(Allium sativum)*	Reduced root growth; Cd accumulation
	Corn *(Zea mays)*	Inhibited shoot and root growth
Co	Tomato *(Lycopersicon esculentum)*	Decreased plant nutrient content
	Bean *(Vigna radiata)*	Decreased antioxidant enzyme activity; reducing sugar, amino acid, and protein content in plants
	Radis *(Raphanus sativus)*	Decreased shoot length, root length, and total leaf area; decreased chlorophyll content; decreased plant nutrient content and antioxidant enzyme activity; decreased sugar, amino acid, and protein content in plants
Cr	Wheat *(Triticum sp.)*	Decreased shoot and root growth
	Tomato *(Lycopersicon esculentum)*	Decreased plant nutrient absorption capacity
	Shallot *(Allium cepa)*	Inhibition of the germination process; decreased plant biomass

To be continued…

Cu	Bean *(Phaseolus vulgaris)*	Accumulation of Cu in plant roots; decreased root formation
	Black bindweed (polygonum convovulus)	Plant death; decreased biomass and seed production
	Rhodes grass (Chloris gayana)	Decreased root growth
Hg	Rice *(Oryza sativa)*	Decreased plant height; decreased tiller and grain formation; decreased yield; bioaccumulation in shoot and seedling roots
	Tomato *(Lycopersicon esculentum)*	Decreased germination percentage; decreased plant height; decreased flowering and fruit weight; chlorosis
Ni	*Pigeon pea (Cajanus cajan)*	Decreases chlorophyll content and stomatal activity; decreases enzyme activity affecting the Calvin cycle and CO2 fixation
	Rye Grass *(Lolium perenne)*	Decreases plant nutrient uptake; decreases shoot yield, chlorosis
	Wheat *(Triticum sp.)*	Decreases plant nutrient uptake
	Rice *(Oryza sativa)*	Inhibits root growth
Pb	Corn *(Zea mays)*	Decreases germination percentage; inhibits growth; decreases plant biomass; decreases plant protein content
	Portia Tree *(Thespesia populnea)*	Decreases number of leaves and leaf area; decreases plant height; decreases plant biomass
	Oat *(Avena sativa)*	Inhibits enzyme activity affecting CO2 fixation
Zn	Cluster Bean *(Cyamopsis tetragonoloba)*	Decreases germination percentage; decreases plant height; reduce chlorophyll, carotenoid, sugar, and amino acid content
	Pea *(Pisum sativum)*	Reduce chlorophyll content; changes in chloroplast structure; reduce photosystem activity; inhibit plant growth
	Rye grass *(Lolium perenne)*	Accumulation of Zn in plant leaves; inhibit growth; reduce plant nutrient content; reduce photosynthetic energy conversion efficiency

Impact of heavy metal contamination on health

In the agricultural sector, heavy metal contamination represents an escalating concern, primarily resulting from the utilization of wastewater-laden soils and the intensive application of chemical fertilizers. The intrinsic biological persistence and long-term stability of heavy metals within soil matrices facilitate their bioaccumulation across the food chain, posing significant risks to human health. A critical issue associated with heavy metals is their inability to undergo metabolic degradation upon entry into biological systems. Rather than being rapidly excreted, these metals accumulate within various tissues—including adipose, muscular, osseous, and articular tissues—where they can induce a spectrum of pathological conditions. Moreover, heavy metals often substitute essential minerals within the body; for instance, cadmium can replace zinc during periods of dietary deficiency, exacerbating toxicological outcomes.

Clinically, exposure to heavy metals has been implicated in the etiology of multiple disorders, including but not limited to neurodegenerative diseases (e.g., Parkinson's disease, Alzheimer's disease), psychiatric conditions (e.g., depression, schizophrenia), oncogenic processes, endocrine dysfunctions, obesity, spontaneous abortion, respiratory and cardiovascular impairments, immunosuppression, premature genomic alterations, dermatological conditions, cognitive decline, anorexia, arthritic disorders, alopecia, osteoporosis, and in severe cases, mortality (Budovich, 2021).

Ullah et al. (2022) further elucidated that the persistent use of water contaminated with industrial effluents containing heavy metals not only compromises agricultural productivity but also imposes extensive ecological and public health challenges. The gradual accumulation of toxic metals in agricultural soils enhances the likelihood of their uptake into edible plant parts, thereby increasing human exposure. Vegetables, fruits, and cereal crops, which are vital sources of carbohydrates, proteins, minerals, and vitamins, are particularly susceptible to contamination when cultivated in heavy metal-laden environments.

The predominant heavy metals detected in industrial wastewater include arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), nickel (Ni), manganese (Mn), lead (Pb), and iron (Fe). Although trace elements such as cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), vanadium (Vd), and zinc (Zn) are essential cofactors for various biochemical and physiological processes, their excessive accumulation exerts toxic effects on humans, animals, and plants, thereby instigating diverse pathological conditions.

Handayanto et al. (2017) emphasized that heavy metal toxicity is closely associated with the induction of oxidative stress through the generation of reactive oxygen species (ROS). Oxidative stress is characterized by an imbalance between ROS production and the cellular antioxidant defense systems, ultimately leading to oxidative damage of biomolecules and potential cell death. A detailed overview of the specific health effects linked to various heavy metals is summarized in Table 2.

Table 2. Adverse effects of heavy metals on human health (Ali et al., 2013)

Heavy Metals	Effect on Human Health
As	Disrupts important cellular processes such as oxidative phosphorylation and ATP synthesis
Cd	Disrupts calcium regulation in biological systems; causes kidney failure and chronic anemia
Cr	Causes hair loss
Cu	Causes brain disorders, kidney damage, liver cirrhosis, chronic anemia of the stomach, and intestinal irritation
Hg	Causes anxiety, autoimmune disease, depression, difficulty with balance, drowsiness, fatigue, hair loss, insomnia, irritability, memory loss, recurrent infections, restlessness, visual disturbances, tremors, angry outbursts, ulcers, damage to the brain, kidneys, and lungs
Ni	Nickel inhalation can cause lung, nose, and sinus cancers; throat and stomach cancers have also been linked to inhalation, causing hair loss
Pb	Causes problems in children such as developmental disorders, reduced intelligence, short-term memory loss, learning disabilities; causes kidney failure
Zn	Excessive doses of Zn cause dizziness and fatigue

Solutions to overcome heavy metal contamination

Various in-situ and ex-situ remediation technologies have been developed to mitigate heavy metal contamination in soils, including surface capping, encapsulation, landfilling, soil flushing, soil washing, electrokinetic extraction, stabilization, compaction, vitrification, phytoremediation, and bioremediation. These remediation strategies employ diverse mechanisms such as containment, extraction, and immobilization to attenuate contaminant effects through physical, chemical, biological, electrical, and thermal processes. Generally, in-situ remediation approaches are considered more cost-effective compared to ex-situ methods, with contaminant extraction or removal offering superior benefits relative to immobilization or containment techniques (Liu et al., 2018).

The selection of a suitable remediation technique for heavy metal-contaminated soils depends on multiple factors, including site-specific geographical conditions, the nature and extent of contamination, targeted remediation outcomes, cost-effectiveness, available financial resources, technical feasibility, time constraints, and community acceptance (USEPA, 2017). Among the available methods, phytoremediation emerges as a promising option for large-scale applications due to its relatively low cost and environmental compatibility. Furthermore, phytoremediation practices can be synergistically integrated with phytomining to derive economic value from the recovered metals.

Phytoremediation

Phytoremediation, as defined by Handayanto et al. (2017), involves the utilization of plants in association with soil microorganisms to reduce pollutant concentrations or mitigate their toxic effects within environmental matrices. This technique is applicable for remediating soils contaminated with heavy metals, radionuclides, and organic pollutants such as polycyclic aromatic hydrocarbons and pesticides. Phytoremediation, being an in-situ, eco-friendly, and cost-effective strategy, facilitates pollutant neutralization without impairing soil fertility. Phytoremediation techniques/strategies include phytoextraction, phytofiltration (rhizofiltration), phytostabilization, phytovolatilization, and phytodegradation (phytotransformation). According to Marmiroli and Monciardini (1999), phytoremediation encompasses various mechanisms by which plants restore contaminated environments, primarily through the uptake, degradation, or stabilization of pollutants. The principal phytoremediation strategies include:

1. Phytoextraction: Involves the absorption and translocation of heavy metals from the rhizosphere to the aerial parts of hyperaccumulator plants, which are subsequently harvested and processed (e.g., via incineration or composting) to recover accumulated metals. Repeated cropping cycles may be necessary to achieve contaminant levels below regulatory thresholds.
2. Rhizofiltration: Entails the adsorption or precipitation of heavy metals onto root surfaces or their uptake by roots from aqueous environments. Saturated plant biomass is harvested and treated accordingly.
3. Phytostabilization: Utilizes specific plant species to immobilize contaminants within the root zone, thereby reducing metal mobility, limiting leaching into groundwater, and preventing erosion and airborne dispersal.
4. Phytodegradation: Refers to the enzymatic breakdown of organic contaminants within plant tissues, rendering the pollutants into non-toxic metabolites incorporated into biomass.
5. Rhizodegradation: Enhances microbial degradation of organic contaminants in the rhizosphere through exudates (sugars, alcohols, organic acids) that stimulate microbial activity.
6. Phytovolatilization: Involves the uptake of contaminants by plants followed by their release into the atmosphere in a volatile, less harmful form during transpiration.

Phytomining

Phytomining, derived from the terms "phyto" (plant) and "mining", refers to the bio-assisted recovery of valuable metals from contaminated soils through cultivation of hyperaccumulator plant species. Following biomass harvest, the plant material is incinerated to yield bio-ore, from which metals are subsequently extracted (Handayanto et al., 2017). According to Sheoran et al. (2009), phytomining exploits the natural capacity of certain plants to concentrate metals in their aboveground tissues. After sufficient biomass accumulation, plants are harvested, dried, and subjected to thermal processing techniques such as roasting, sintering, or smelting, facilitating metal recovery analogous to conventional metallurgical operations.

Phytomining offers several advantages: (a) the economic feasibility of recovering metals from low-grade ores unviable for traditional mining; (b) minimal environmental disruption compared to conventional extraction methods; (c) compatibility with standard agricultural practices; (d) higher metal concentrations in bio-ore compared to raw ores; and (e) reduced risk of acid rain due to the low sulfur content of plant biomass. Certain types of plants can be used for the phytomining process, as listed in Table 3. Selection of appropriate plant species is critical for successful phytomining operations. As noted by Anderson et al. (2005), ideal candidates are indigenous or locally adapted species that exhibit tolerance to adverse edaphic conditions (e.g., extreme temperature, drought, salinity) and possess rapid growth rates with substantial biomass production. Increasing planting density may further compensate for reduced vegetative growth under metal stress and optimize total biomass yield per unit area.

Table 3. Several plant species that can be used for phytomining valuable metals (Sheoran et al., 2009)

Metals	Plant Species
Cobalt	*Haumaniastrum katangense, Crepidorhopalon perennis, Acalypha cupricola, Anisopapus chinesis*
Manganese	*Macadamia neurophylla, Phytolacca acinose*
Nickel	*Thlaspi goesingense, Psyshotria douarrei, Sebertia acuminate, Alyssum narkgrafii, Alyssum murale, Phyllanthus species, Euphorbia helenae, Leucocroton flavicans, Leucocroton linearifolius*
Platinum	*Sinapis alba, Lolium perenne*
Silver	*Amanita strobiliformis*
Thallium	*Lolium perenne, Brassica napus, Phaseolus vulgaris, Zea mays, Brassica oleracea acephala, Iberis intermedia, Hirschfeldia incana, Diplotaxis catholica*

Hyperaccumulator plants

According to Handayanto et al. (2017), while all plants exhibit some capacity for metal uptake, certain taxa demonstrate hyperaccumulation traits, characterized by the ability to concentrate metals at exceptionally high levels in their root and shoot tissues without exhibiting phytotoxic symptoms or growth retardation. These "hyperaccumulator plants" possess specialized physiological and molecular mechanisms to facilitate efficient metal translocation and sequestration. Threshold values for hyperaccumulation and representative hyperaccumulator species are detailed in Tables 4 and 5.

Table 4. Lower limit for hyperaccumulation of various metals and, number of known hyperaccumulators with their families (Sheoran et al., 2009)

Element	Lower limit for hyperaccumulation	Number of hyperaccumulators	Families of hyperaccumulators
Arsenic	1000	5	*Pteridaceae*
Cadmium	100	2	*Brassicaceae, Asteraceae, Chenopodiaceae*
Cobalt	1000	30	*Lamiaceae, Scrophulariaceae*

To be continued…

Copper	1000	34	*Cyperaceae, Lamiaceae, Brassicaceae, Poacea, Scrophulariaceae*
Gold[a]	1	-	*Brassicaceae*
Lead[a]	1000	14	*Compositae, Brassicaceae*
Manganese	10,000	11	*Apocynaceae, Cunoniaceae, Proteaceae*
Nickel	1000	320	*Brassicaceae, Cunoniaceae, Flacortiaceae, Violaceae, Euphorbiaceae*
Selenium	100	20	*Fabaceae, Brassicaceae*
Silver[a]	1	-	*Brassicaceae*
Thallium	100	1	*Brassicaceae*
Uranium[a]	1000	-	*Brassicaceae*
Zinc	10,000	16	*Brassicaceae, Crassulaceae, Leguminosae*

[a] For induced hyperaccumulation

Table 5. Specific hyperaccumulator plants with certain metal concentrations and biomass (Sheoran et al., 2009)

Element	**Plant Species**	**Concentration mg/kg dry matter**	**Biomass kg/ha**
Cadmium	*Thlaspi caerulescens*	3000 (1)	4000
Cobalt	*Haumaniastrum robertii, Berkheya coddii*	10,200 (1)	4000
Copper	*Haumaniastrum katangense, Ipomea alpine*	8356	5000
Gold (induced-hyper-accumulation)	*Brassica juncea, Berkheya coddii, Chicory, C. linearis*	10 (.001)	20,000
Lead	*Thlaspi rotundifolium*	8200 (5)	4000
Manganese	*Macadamia neurophylla*	55,000 (400)	30,000
Nickel	*Alyssum bertolonii*	13,400 (2)	9000
	Berkheya coddii	17,000 (2)	18,000
Thallium	*Iberis intermedia, Biscutella laevigata*	4055 (1)	8000
Uranium	*Atriplex confertifolia*	100 (0.5)	10,000
Zinc	*Thlaspi calaminare*	10,000 (100)	4000

NB: values in parentheses are mean concentrations

Conclusion

Based on the findings from the conducted literature review, the integration of phytoremediation and phytomining presents a viable alternative for remediating soils contaminated with heavy metals. This approach offers several advantages, including low cost, simplicity, and environmental sustainability, ensuring that the process does not induce further contamination. Furthermore, the recovery of valuable metals through phytomining can generate significant economic benefits. Numerous plant species have been identified through research for their ability to perform both phytoremediation and phytomining. However, the selection of suitable plant species must consider specific characteristics, including tolerance to contaminated soils, rapid growth rate, and high biomass production.

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