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Heavy Metal Phytoremediation: Plant Hyperaccumulators and Clean Strategies for the Environment

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ABSTRACT

Increasing urbanization and industrialization have led to serious heavy metal pollution problems, detrimental to the environment and human health. Phytoremediation, which utilizes hyperaccumulator plants such as Indian mustard and water hyacinth, presents an efficient and sustainable alternative. Despite having the advantages of low cost and utilization of renewable natural resources, phytoremediation also carries risks, such as contamination of consumable plant parts and limited efficiency. Therefore, selecting the right hyperaccumulator plants and having an in-depth understanding of phytoremediation mechanisms are the keys to increasing their success. Phytoremediation mechanisms, such as phytoextraction, hemofiltration, and phytostabilization, can be implemented by considering environmental conditions and contaminants. Factors such as the nature of the medium, root zone, and environmental conditions play a crucial role in determining the effectiveness of phytoremediation. Although challenges still exist, phytoremediation remains a promising approach to treating heavy metal pollution in an economical and environmentally friendly manner.

1. Introduction

The swift advancement of urbanization and industrialization has led to a growing and significant issue: the escalation of heavy metal pollution [1], [2]. Certain rocks now contain more metal than they did before because of human activities, even though heavy metals are naturally found in rocks. Heavy metals are found in soil due to improper usage of sewage sludge, manure, agricultural chemicals, wastewater, and biosolids [3]. Heavy metal deposition in the soil poses major health risks to humans, animals, and plants [4], [5].

There are two types of heavy metals: essential and non-essential. Excessive consumption of cobalt (Co), copper (Cu), chromium (Cr), iron (Fe), nickel (Ni), manganese (Mn), and zinc (Zn) might have negative effects even though crucial heavy metals are vital micronutrients. Living things are severely harmed by non-essential heavy metals like lead (Pb), mercury (Hg), and cadmium (Cd) [6]. Methods currently used to remove heavy metals include solvent extraction [7], ion exchange [8], membrane separation [9] reverse osmosis [10]. Chemical precipitation [11] and electrodialysis [12], Expensive and the potential generation of toxic sludge pose additional significant challenges. The constraints associated with physical and chemical processing technology can be addressed through the implementation of phytoremediation.

Heavy metals present a grave environmental threat and can have hazardous consequences on human health. While several methods have been devised for heavy metal removal, their cost is comparatively higher when compared to plant-based industrial techniques for the detoxification of metals [13].The issue of heavy metal contamination is getting worse in developing nations. Much research has been done on plant-based adsorbents that are less expensive and environmentally benign than other methods of extracting heavy metals [14]. Industries that discharge waste without cleaning it up harm land and water. Heavy metals found in this trash are currently being removed via plant-based methods called phytoremediation [15]. Heavy metal-filled wastewater Aquatic life is seriously endangered by heavy metal contamination. Long-term use, low cost, and environmental friendliness characterize phytoremediation as an emerging technology. When it comes to eliminating heavy metal pollutants, aquatic plants are incredibly effective. A few other plants, including duckweed (Lemna minor), have a high metal accumulator efficiency [16].

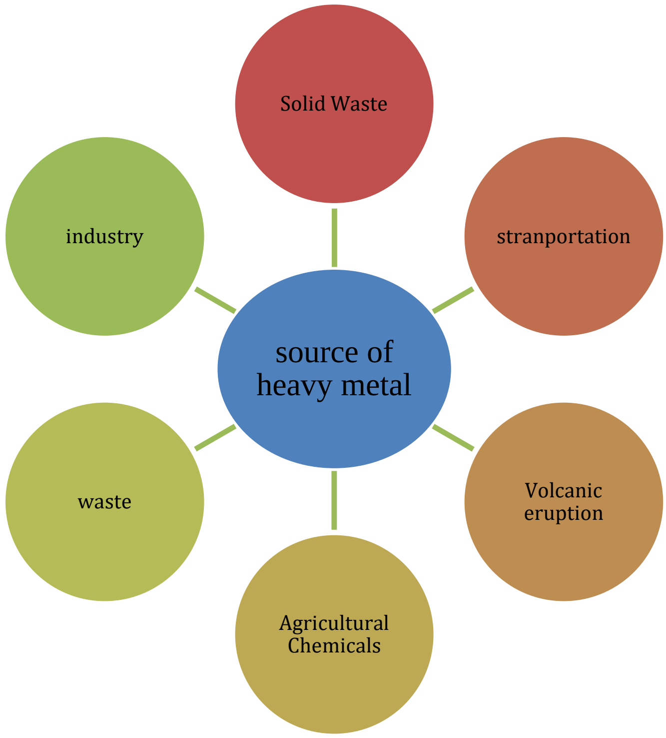

Fig 1. Various sources cause HM accumulation in water and soil [17]

2. Hypeacumulator plant

A plant that can flourish in high metal concentration soil or water is known as a hyperaccumulator plant. These plants are appropriate for phytoremediation, which uses plants to remove excessive metal concentrations from an area. This is because the plants have the capacity to absorb and store extraordinarily high quantities of metals in their tissues. Hyperaccumulator plants can be used to help manage and clean up heavy metal-contaminated soils, which can support environmental remediation initiatives [18].

Hyperaccumulator plants eliminate heavy metals from the soil through a blend of mechanisms, encompassing absorption, translocation, and detoxification. These plants possess the capability to absorb and amass heavy metals predominantly in the upper soil layers, particularly in the leaves, reaching concentrations 10-500 times higher than those found in other plant species [18]. Tolerance to heavy metals is achieved through segmented metal absorption and sequestration in distinct cell compartments, most notably the vacuole, which is located distant from the cytosol. This configuration shields delicate areas from the damaging effects of heavy metals and stops the cytoplasm's metabolic functions from being suppressed. There has been evidence of a notable concentration of proline and other amino acids, as well as organic solutes, which help plants thrive in contaminated settings. These solutes bind to heavy metals, which hinders their transit to sensitive plant parts. Phytoremediation, which uses a range of hyperaccumulator plants known as macrophytes, is thought to be an efficient and environmentally friendly approach. With the use of this method, heavy metal pollutants in water can be eliminated by rhizofiltration, phytoextraction, phytovolatilization, and phytostabilization [20].

Table 1. Phytoremediation experiments with hyperaccumulator plants to remove heavy metals

No	Hyperaccumulator plants	Phytoremediation mechanisms	Target heavy metal	Phytoremediation and time Experimental conditions	Ref
1	*Indian mustard (Brassica juncea)*	Phytoextraction	Cd, Pb	90 days. There were eighty plots in the field study. Each plot contains thirty plants, weeds removed by harrowing, and no fertilizer.	[21]
2	*Vetiver grass (Chrysopogon zizanioides)*	Phytostabilization, phytoextraction	Cr, Ni	28 days. The plant was grown on stock solutions and planted in soil with metal concentrations of 50, 150, and 300 parts per milligram.	[22]
3	*Water hyacinth (Eichornia crassipes)*	Rhizofiltration	As, Cd, Cu, Pb, Zn	30 days. In a 30 L foam container, 100 g of the plant was planted, and on the tenth, twentieth, and thirty days, the heavy metal content was measured.	[23]
4	*Water lettuce (Pistia stratiotes)*	Rhizofiltration	Cd, Cu, Fe, Pb, Zn	40 days. Plants were exposed to 0, 25, 50, 75, and 100% concentrations of paper mill effluent during a natural day-night cycle in order to prevent sedimentation and coagulation.	[24]
5	*Stonecrop (Sedum alfredii)*	Phytoextraction, hemofiltration	Cd	150 days. In root bags containing 0.47, 6.66, and 22.01 mg/kg of spike, two-week-old seedlings were planted.	[25]

Table 2. Utilizing Hyperaccumulators for Soil Phytoremediation in Heavy Metal Detoxification

No	Hyperaccumulator	Heavy metal	Ref
1	*Arabidopsis helleri*	Zn	[26]
2	*Achillea millefolium*	Hg	[27]
3	*Alyssum morale*	Ni	[28]
4	*Brassica juncea L.*	Cu, Zn, Pb	[29]
5	*Cardaminopsis halleri*	Zn, Pb, Cd, Cu	[30]
6	*Cicer aeritinum L.*	Cd, Pb, Cr, Cu	[31]
7	*Eleocharis acicularis*	Us	[32]
8	*aumaniastrum katangense*	Cu	[33]
9	*Lavadula vera L.*	PB	[34]
10	*Lepidium sativum L.*	As, Cd, Pb	[35]
11	*Noccaea Caerulescens*	PB	[36]
12	*Pteris vittata*	Hg	[37]
13	*Salvia sclarea L.*	Pb, Cd, Zn	[38]

The following possible dangers are connected to the use of hyperaccumulator plants in phytoremediation: Pollution of harvested plant material: The consumption of hyperaccumulator plant parts that are above ground raises questions about human health since it may lead to the buildup of heavy metals in the body. Using non-consumable hyperaccumulator plants for phytoremediation is crucial to lowering this danger. Low level of efficiency the short lifespans, limited biomass production, and sluggish growth rates of many hyperaccumulator plants can reduce the effectiveness of phytoextraction [39]. This risk can be reduced with the use of efficient hyperaccumulator plants and appropriate procedures. pH and soil quality: Soil pH and quality can affect how well hyperaccumulator plants work in phytoremediation [40].

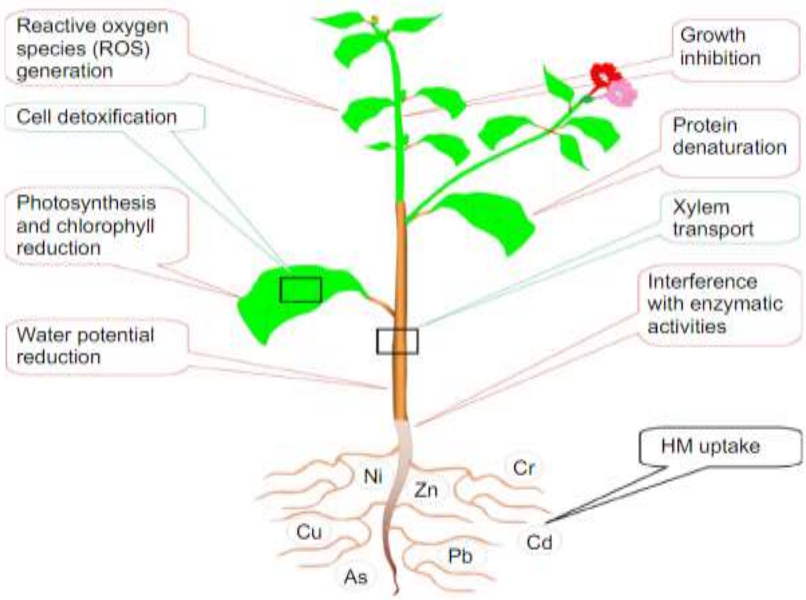

Fig 2. Heavy metal toxicity in plants and tolerance strategies [42]

Plants exposed to heavy metals (HMs) have evolved a number of detoxification strategies to counteract the detrimental effects of HMs and maintain regular development and metabolic processes. Plants defend their organs from harmful heavy metals (HMs) using two basic tactics [41]. Figure 2 shows the toxicity of heavy metals in plants and tolerance strategies.

3. Phytoremediation Process

Because it's inexpensive and simple to use, phytoremediation has become more popular than physical and chemical treatments like compaction, leaching, and soil replacement. Numerous research has been carried out on phytoremediation technique since its inception in 1983, demonstrating its practicality and environmental benefits in the removal of heavy metals from soil. Bello and associates, for instance, studied how well Phragmites australis phytoremediation removed cadmium, lead, and nickel, among other heavy metals, from contaminated water [43].

To eliminate contaminated colors from soil or water sources, phytoremediation employs live plants [44]. There are various methods for carrying out phytoremediation, including as phytodegradation, phytoextraction, Phyto filtration, and phytoremediation. Volatilization [45]. Hyperaccumulators are short-lived, fast-growing plants that can readily harvest, create more biomass, and absorb more heavy metals into their bodily tissues [46].

Table 3. Wastewater phytoremediation: advantages and disadvantages [49]

Advantages	Disadvantages
• Low capital requirements • Low energy requirements • Environmental friendliness • Utilize natural and renewable resources • Produces less secondary waste • Less carbon footprint • Wastewater and nutrient reclamation • Recovery • Manufacture of raw materials for various applications • The capacity to harvest plants to recover absorbed and accumulated pollutants, such as hazardous heavy metals, for recycling at a reasonable cost	• Limited to superficial contaminants • Phyto-contaminant toxicity • Slower than standard techniques • Unknown consequences of items that degrade • possibility of pollutants making their way into the food chain Plant mats serve as a haven for harmful insects like mosquitoes.

The harvesting of metal-rich plant tissue through this process holds considerable commercial value. Phytoremediation proves to be an efficient and versatile method, capable of removing various elements, both inorganic and organic pollutants, from solid, liquid, and gaseous substrates. Its application extends to the in-situ recovery of extensive soil, water, and air areas from pollutants over extended periods. In contrast to substantial investments required for physical and chemical remediation methods, which may lead to the generation of secondary pollutants and significant alterations in soil properties and microflora, phytoremediation stands out as an environmentally friendly and effective land management strategy. It not only aids in reducing soil erosion but also enhances soil quality and organic content [47].

Green plants are used in phytoremediation, an environmentally and economically advantageous method of removing pollutants from contaminated soil and water through retention, absorption, or detoxification [48] The advantages and disadvantages of phytoremediation in wastewater are listed in Table 3.

3.1 The mechanisms of heavy metal phytoremediation

Using plants that can absorb metals, phytoremediation cleans up contaminated primary sources, such as water and land. [24]. In the phytoremediation of contaminated soil, the absorption of heavy metals occurs through various mechanical processes. The primary mechanisms of phytoremediation encompass phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration[50]. The schematic representation of the phytoremediation mechanism is depicted in Figure 3.

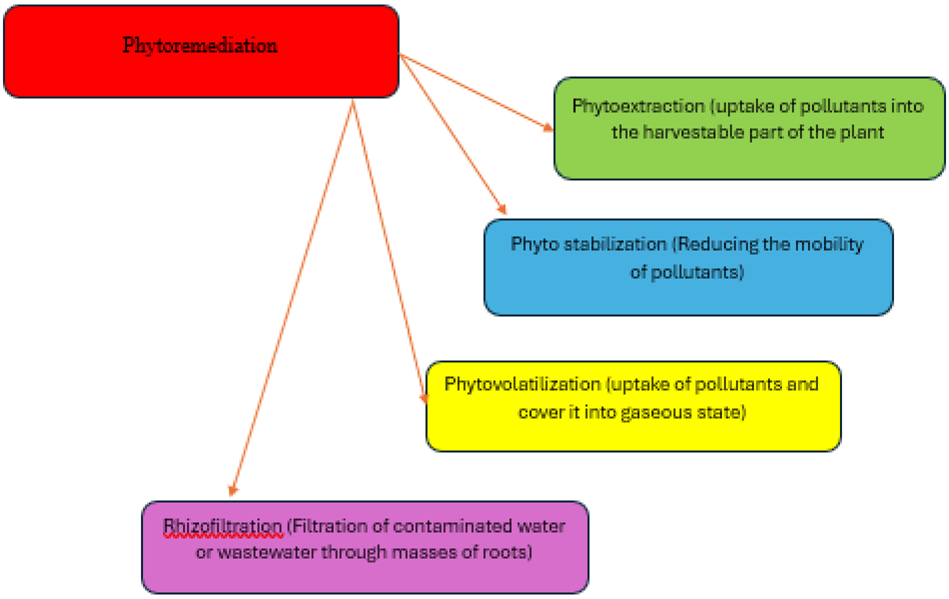

Fig 3. Mechanism of heavy metal absorption in phytoremediation [50]

A. Phytoextraction

The process of moving heavy metals from soil or water into plants, where they are absorbed into a range of plant tissues, including vacuoles, cell walls, membranes, and metabolically dormant sections, is known as phytoextraction. Other names for it include Phyto sequestration, photo absorption, and phytoaccumulation. Most importantly, this occurs without degrading the quality of the land. [51]. The mobilization of metal cations in the rhizosphere is the initial step in the multi-stage phytoextraction mechanism for heavy metals. In the end, this causes heavy metal ions to build up and separate within the plant tissues. Following that, they are absorbed and transferred from the roots to the aboveground plant shoots [52].

The ability of plant roots to draw toxins from the soil is a critical component of the phytoextraction process. Concerns have been raised about the employment of hyperaccumulators or phytoremediation techniques in the cleanup of contaminated areas. Environmental specialist's express concerns that some plant species used in phytoremediation may encroach into nearby natural regions, disrupting and changing the functions of ecosystems. This incursion may result in a decline in the natural biodiversity, which would be detrimental to the local economy and possibly dangerous for human health [53].

B. Phytostabilization

Heavy metals in contaminated soil can be made immobile by using plants that are tolerant of them, which reduces their bioavailability to the environment [54]. It has been discovered that immobilizing heavy metals in the rhizosphere zone not only reduces the likelihood that they will enter the food chain and hinder their mobility within the ecosystem, but it also reduces soil erosion, enhances rhizosphere aerobics, and feeds organic matter, all of which contribute to the stabilization of contaminants [55]. Fields with a range of soil properties, such as salinity, pH, and heavy metal concentrations, can use Phyto stabilization. For instance, Pseudomonas citronellol, SLP6, a PGPB that stimulates shoot and root development and raises antioxidant enzyme activity, was able to counteract the effects of Cu and salinity on H. annuus [56]. increasing the efficiency of Phyto stabilization is largely dependent on the choice of appropriate and productive plant species as well as the application of specialized soil amendments to contaminated sites. [57].

C. Rhizofiltration

Rhizofiltration is a method were plant roots extract pollutants from wastewater. Through the absorption of heavy metals (HMs), root exudates play a role in altering the pH of the rhizosphere [58]. The biogeochemical processes of root exudates, released by plant roots, lead to the deposition of contaminants on the roots or into water bodies. Subsequently, there is the adsorption of pollutants onto the roots or their translocation to the phyllo sphere (plant organs above the ground surface). The specific outcomes depend on the plant type, contaminant species, and concentration [59]

Because they are necessary components of many different enzymes and proteins, several heavy metals aid in the growth and development of plants. However, high levels of non-essential and critical heavy metals (HMs) cause phytotoxicity associated with heavy metals, which disrupts membrane integrity, inhibits functional groups, and deactivates enzymes. Hence, modifications to different physiological processes occurring at the molecular or cellular level affect how plants grow and develop. Enhanced oxygen radical production that disrupts electron transport functions is a prevalent instance of phytotoxicity associated with heavy metals [60].

D. Phytovolatilization

Phytovolatilization is one type of phytoremediation that uses plants to draw pollutants out of the soil. Using this strategy, the plants transform these hazardous compounds into less harmful volatile forms, which they subsequently transpire into the atmosphere, primarily through their foliage system or leaves. This method is employed to remove heavy metals like As, Hg, and Se as well as organic compounds from the body [61].

Compared to other phytoremediation techniques, phytovolatilization has the advantage of not requiring the harvesting and disposal of plants since it disperses the heavy metal (metalloid) contaminants as gaseous molecules after removing them from the site. It's important to remember, though, that phytovolatilization is not a complete remediation technique; toxins still exist in the ecosystem. Through this process, pollutants are moved from the soil into the sky, where they can release volatile, hazardous chemicals that worsen air pollution. Moreover, these contaminants could degrade and end up back in the soil [62].

4. Factors influencing Phytoremediation.

Figure 4 below shows a few variables that may affect the phytoremediation process:

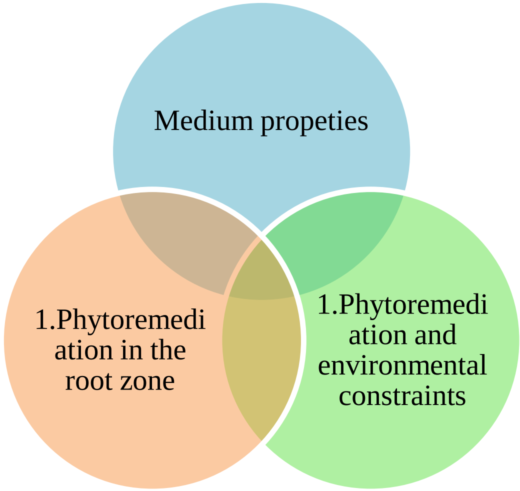

Fig 4. Factors that affect the phytoremediation process

4.1 Medium properties

Plants are chosen based on their potential for different remediation techniques. In comparison to annual plants, processes including phytodegradation, rhizofiltration, and Phyto stabilization primarily highlight quicker growth in terms of root depth plant mass per unit eloping period [63].

4.2 Phytoremediation in the root zone

Because it absorbs and metabolizes pollutants inside plant tissues or releases enzymes to break down toxins, the root zone is essential to phytoremediation. [64].

4.3 The limitations of the environment in phytoremediation

The most notable and obvious shortcoming in the use of phytoremediation is the local environment. Temperature affects how plants transpire, grow, and metabolize, which affects how pollutants are absorbed and disposed of [65].

According to [66]. Throughout the phytoremediation process, plant transpiration may be impacted by ambient temperature. Plants absorb water through their roots and expel it during transpiration through the stomata on their leaves. Transpiration is the primary method used in the phytoremediation process to remove pollutants. Plant transpiration rates can affect variables related to bioconcentration and pollutant transfer. Whereas the bioconcentration factor is the ratio of pollutant concentration in plant tissue to the surrounding environment, the translocation factor is the ratio of pollutant concentration in plant roots to that in plant leaves.

5. Conclusion

With increasing urbanization and industrialization, heavy metal pollution is becoming a serious problem that negatively affects the environment and human health. Industrial effluents, wastewater and excessive use of fertilizers can lead to heavy metal accumulation, harming humans, animals and plants. Phytoremediation, as an effective and environmentally friendly alternative, uses plants as heavy metal removal agents. Hyperaccumulator plants such as water hyacinth and Indian mustard have been successfully used in various phytoremediation processes, including phytoextraction, hemofiltration, and phytostabilization. Although phytoremediation has advantages such as low cost, environmental friendliness, and use of renewable natural resources, there are risks and constraints such as contamination of consumed plant parts, limited efficiency, and influence on soil quality. Therefore, proper selection of hyperaccumulator plants and an in-depth understanding of phytoremediation mechanisms are essential to minimize risks and increase effectiveness. Several phytoremediation mechanisms, such as phytoextraction, phytostabilization, rhizofiltration, and phytovolatilization, have their respective tasks in the phytoremediation process with advantages and disadvantages that depend on the nature of heavy metal pollution, location, and phytoremediation objectives. Factors such as media properties, rooting zone, and environmental conditions affect the effectiveness of phytoremediation. Despite the constraints, phytoremediation remains a promising approach to address heavy metal pollution in an economical and environmentally friendly manner.

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