



## The Dynamics of Phytoremediation as Green Initiative Technology for Restoring Soil Contaminated by Heavy Metals: A Systematic Review of Literature

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### ABSTRACT

Heavy metal (HM) pollution of soil has become a major global environmental concern due to increased industrialization and agricultural activities. In order to restore soil contaminated by heavy metals (HMs), this research conducts a systematic assessment of phytoremediation as a green initiative technology. Heavy metals, their impacts on soil, and phytoremediation were all examined using an explanatory research methodology and a qualitative research method. The sources of heavy metals (HMs) in the soil, their effects on living things, phytoremediation of HMs in the soil, plant species used for phytoremediation, their effects on the soil, their benefits, and how to dispose of plants used for phytoremediation, among other things, were all conceptualized in the paper. The limits of these methods and strategies for improving them were also discussed in the paper. Based on the systematic review, the paper was able to conclude that phytoremediation stands at the forefront of innovative environmental restoration, promising significant advancements in cleaner and healthier ecosystems, and that it may be used as an affordable, efficient, environmentally and eco-friendly method related to the use of metal-accumulating plants as an alternative method for HM cleanup.

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## **INTRODUCTION**

The universe and everything in it belong to the Lord, yet he also granted man authority over everything and bestowed upon him the "green world," an environment rich in vegetation. After realizing that plants and soil are the primary sources of human survival, God gave the order for man to conquer and cultivate the land. Man has made himself, plants, and animals endangered species as a result of progress and his desire to improve his lot, and the soil has suffered as a result. The focus is on how human actions, such as industrialization and agricultural practices, have severely damaged the biosphere. Although they are intended to improve human life, they have also been linked to widespread pollution and contamination. Heavy metal (HM) pollution of soil has become a major global environmental concern due to increased industrialization and agricultural practices (Chaoua et al., 2019). As previously mentioned, HMs are incredibly stable entities with half-lives exceeding 20 years (Hadia-e-Fatima, 2018). The particular mobility of various metals in the environment is mostly determined by the entry of contaminants and heavy metals (HMs) into the environment, which is influenced by the extraction of minerals and related varied handling practices. Heavy metal contamination has become a serious problem that requires an efficient remedy to lessen its impacts because of the growth of industrialization and the unsettling influence of the biological cycle. Heavy metals are basically big, non-biodegradable metals that build up in the ecosystem and endanger human and environmental health by contaminating soil and water, according to Priya et al. (2015). For example, in a live organism, these elements travel from a lower to a higher trophic level with an increasing concentration—a process called biomagnification—and accumulate in the bodily tissue through a process called bioaccumulation.

On the other hand, soil alone serves as both the foundation and the focal point of all human activity. As a result, it is a vital part of the earthly environment and is crucial to the development of horticulture and biological sustainability (Zhao et al., 2021; Beiyuan et al., 2021). Unfortunately, excessive mining operations, quickly growing modern activities, waste collection, and irresponsible use of pesticides and artificial composts have rendered potentially toxic elements (PTEs) a major global natural problem (Zeng et al., 2020). Phytoremediation, a plant-based technology, is one of the many methods being used to improve the situation in an effort to protect human, plant, and environmental life. Therefore, the use of plant technology (phytoremediation) to remove heavy-metal contaminated soils is the main topic of this paper. It also discusses the potential of plant species that have the ability to accumulate contaminants (hyperaccumulators), the tools and techniques needed for phytoremediation, the significance of identifying plant species and genetic traits that effectively remove heavy metals from the soil, and more. The limits of this strategy and the disposal of the plants employed in this remediation are also examined in the paper.

## LITERATURE REVIEW

The objectives of this paper are:

- To describe the types of phytoremediation and heavy metals;
- To identify the sources of heavy metals and how they affect living things;
- To describe how phytoremediation can be used to remediate soil contaminated by heavy metals;
- To identify plant species that can be utilized in phytoremediation;
- To determine the benefits, constraints, and strategies for improving the effectiveness of phytoremediation
- To determine how to dispose of hazardous plant debris following phytoremediation.

## METHODOLOGY

In order to investigate heavy metals, their effects on soil, and phytoremediation, this work employed a conceptual and qualitative research methodology using the explanatory research technique. To facilitate the writing of this paper, a systematic review of related literature was conducted. With particular attention to the nature of the topic under review, the researcher used various search engines and databases, including Google Search, Microsoft Edge, AcademiaEdu, ResearchGate, and other helpful websites, to obtain both retrospective and current literature on the topic. Key terms like "Heavy Metals," "Effect of Heavy Metals on Soil," "Phytoremediation and Uses," "Advantages and limitations," and others were used in the search approach. This methodological approach was used for a while to collect pertinent literature and articles. The researchers carefully reviewed and included the information about phytoremediation and heavy metal-contaminated soil into the paper after compiling papers and other literature from databases, search engines, and websites. Due to its multidisciplinary nature and strong dedication to thorough research, the full work took a long time to finish. Additionally, ethical considerations were meticulously upheld throughout the article, making sure that the results were presented consistently and that the authors included in the publication were properly cited.

## RESULT AND DISCUSSION

### The Heavy Metals

One of the biggest threats to food safety and human health globally is the presence of heavy metals in agricultural soil-crop systems. Through a variety of routes, these non-biodegradable substances penetrate agricultural fields, build up in the soil, and ultimately find their way into the food chain. For the purpose of creating efficient preventative measures and safeguarding the health of crops and human consumers, it is essential to comprehend the sources of these toxins. Because they linger in the environment forever, heavy metals, including cadmium, lead, arsenic, mercury, and chromium, are especially dangerous. These substances can eventually build up to hazardous amounts after being added to agricultural systems. Heavy metal accumulation in agricultural soils disrupts normal cellular and metabolic processes in plants, which negatively

impacts crop health and productivity (Food Safety Institute, 2025). The implication is that heavy metals are naturally occurring elements in our soil that become hazardous due to human activity, posing serious threats to human health and the ecosystem. They are described as elements with comparatively large atomic weights and densities.

Cadmium (Cd), zinc (Zn), chromium (Cr), nickel (Ni), and lead (Pb) are examples of heavy metals (HMs), which are metals or metalloids having a higher elemental density. They are classified by their density, weight, or atomic number, and they are usually distinguished by a density of more than 5 g/cm<sup>3</sup> and a thickness higher than a specific threshold (Kumar et al., 2017; Ali and Khan, 2018; Ali et al., 2019). They are regarded as universal pollutants as they are persistent in the soil and do not biodegrade (Saif and Khan, 2017). Long-term exposure to elevated quantities is required because of the limited incidence of heavy metals (HMs) in natural settings.

### **Classification of Heavy Metals**

For clarity, heavy metals are categorized into two primary classes: essential and non-essential. These divisions are based on the roles that these metals play in the ecosystem. It is important to note that critical HMs can be hazardous if present in excessive concentrations, even though they are necessary in small amounts and are crucial for physiological and biochemical functions throughout the life cycle of plants. Copper, iron, nickel, zinc, and other metals are examples of them. Non-essential HMs, on the other hand, are extremely poisonous metals that have no recognized roles in living things and can be extremely harmful if they build up in plant cells. Lead, arsenic, cadmium, mercury, and other elements are among them.

### **Sources of Heavy Metals in the Environment**

HM pollution has garnered attention worldwide due to the possibility of bioaccumulation and harm to living things (Kanwar et al., 2020). As previously mentioned, biological systems in both terrestrial and marine ecosystems are greatly impacted by the effects of HM contamination in the environment. Nevertheless, these metals enter the soil in a number of ways. Chemical fertilizers, insecticides, and air deposition are examples of agricultural sources; additional sources include mining, smelting, and manufacturing. Even though the information that is now available indicates that they can occur naturally in the environment, human activities like oil extraction, wastewater discharge, ore mining, and the burning of fossil fuels have been identified as important contributors to heavy metal pollution (Hadia-e-Fatima 2018).

For the sake of clarification, both natural and man-made sources can contaminate soil with heavy metals. Parent soil, also known as a lithogenic source, is the usual source of heavy metals in contaminated soil (Priya et al., 2023). Nejad et al. (2018) claim that many heavy metals are synthetic constructs that are easily and immediately absorbed by living cells and tissues rather than existing as separate substances. The most prevalent heavy metals in soil are Zn, Hg, Cd, Pb, Cu, Ni, As, and Cr. Increased concentrations of other heavy metals, including aluminum (Al), barium (Ba), cobalt (Co), manganese (Mn), selenium (Se), and silver (Ag), can also be found in soil and cause health and environmental problems. Heavy metals can be found in soil due to a variety of

natural processes, including rock weathering, forest fires, wind-borne soil particles, volcanic emissions, and ocean salt sprays. According to Yan et al. (2020), heavy metals can also enter the soil through biogenic processes such as the decomposition of organic substances.

As was previously indicated, anthropogenic activities, including mining, agriculture, and industrial processes, also raise the concentration of heavy metals in soil much above natural levels, which may pose health and environmental risks. For example, hazardous heavy metals, including As, Cd, Cr, Cu, Hg, and Pb, can be found in paints, sewage, mine wastes, alloys, and electronics. According to Ene et al. (2010), these substances can readily seep into soil and build up over time, polluting the soil. Accidental spills or leaks from transportation or industrial locations can occasionally result in heavy metal contamination. The main point is that although there are many different causes of heavy metal pollution in soils, they often result from either natural or human activity (Vhahangwele et al., 2015). All of these activities have been found to have the potential to release large levels of heavy metals into the environment, which can contaminate the air, water, and soil (Bhat et al., 2022).

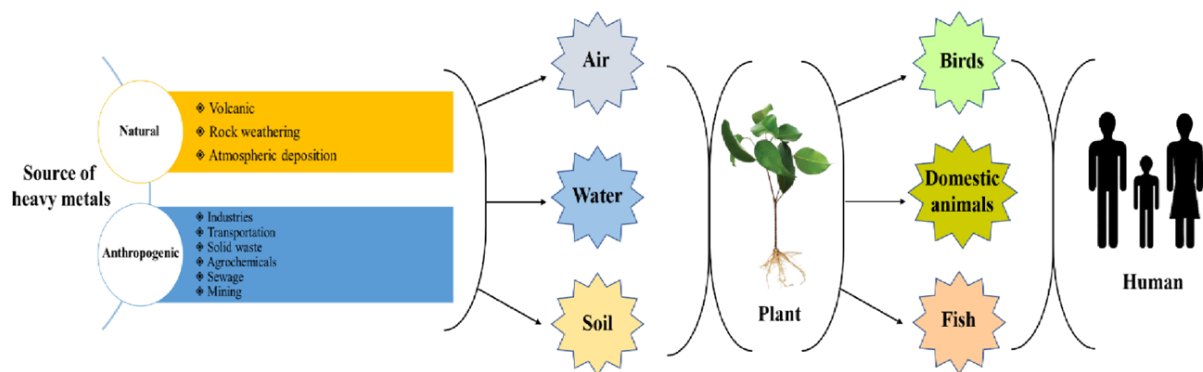


Figure 1. Various Sources of Heavy Metals and Their Environmental Pathways

### Effects of HMs on Living Organisms

According to Sandeep et al. (2019), heavy metal contamination is a pervasive problem that affects millions of hectares of land worldwide and adversely affects plant biochemistry and physiology, resulting in decreased productivity and possible health hazards. Thus, exposure to heavy metals has significant detrimental impacts on humans, plants, and the ecosystem as a whole.

According to Gu et al. (2018) and Fang et al. (2019), excessive exposure to heavy metals on plant development and physiological cycles may, first, reduce seed germination, limit plant growth, disrupt nutrient uptake, stifle photosynthesis, and alter enzyme activities. Additionally, heavy metals can build up in the food chain and cause health issues in humans and animals who eat contaminated food.

Additionally, contaminated food crops have the capacity to bioaccumulate heavy metals (HMs), which might potentially affect humans and other living things by biomagnifying throughout the higher trophic levels in the

order (Priya and Nagan 2015). Kanwar et al. (2020) state that HM development in the body can result in unanticipated serious issues like itai sickness from diligent disc openness, kidney damage and illness from zinc, mucosa disintegration, hepatic structure disappointment, central tactile framework damage from copper, and skin irritation and tangible framework entrapments from nickel. According to Priya et al. (2023), these heavy metals have toxicological effects that can lower the quantity and productivity of living organisms in the soil in which they are present.

Furthermore, if food crops are grown in pesticide-polluted soils, there is a chance that the contaminants will find their way into the food chain and endanger people and animals who eat the contaminated foods. If pesticides are regularly administered or are not broken down by natural processes, they may remain in the soil for extended periods of time. According to Hadia-e-Fatima (2018), in such a scenario, the pesticides may then be absorbed by the roots of food crops and build up in the edible portions of plants, including grains, fruits, and vegetables. There is no need in reiterating the obvious, which is that the global environment may suffer more if the threat posed by HMs contamination is not addressed because the outcome could be disastrous. In light of this, steps are being taken to improve the circumstances, which is where phytoremediation comes into play. What exactly is phytoremediation?

#### **Phytoremediation: Conceptual Overview**

The word "phyto," which comes from the Ancient Greek word "phyton," which means plant, is the root of the compound word "phytoremediation," whereas remediation is an action intended to stop or reverse environmental damage. It is sufficient to explain that phytoremediation is the use of plants to prevent environmental harm, and in this work, it refers to the use of plants to treat soil contaminated by heavy metals. This suggests that phytoremediation is a plant-based method of cleaning up soil contaminated with heavy metals. Clearly, using plants to collect and eliminate heavy metals (HMs) from contaminated soil is an environmentally benign technique that has gained popularity. In this instance, even in soils with low HMs, plants can absorb these elements through their roots, aiding in soil repair. By using this method, plants can also create a complex underground rhizosphere ecosystem that boosts the absorption of heavy metals, encourages biological metabolism, revitalizes the soil, and cultivates beneficial microbes (Sabreena et al., 2022). It is important to note that plants with strong phytoremediation capacities frequently have deep roots, rapid development, high biomass, and effective uptake and transport of heavy metals or other pollutants to their above-ground portions. Thus, the question is how heavy metal-contaminated soil may be restored through phytoremediation.

#### **Phytoremediation of Heavy Metal Contaminated Soil**

Plants contain heavy metals in a variety of forms and amounts. For example, cadmium (Cd) is primarily found as gelatin and protein in tea plants, *Panicularia paniculata*, and *impatiens resin*, but lead (Pb) is mostly found in striped seaweed as soluble inorganic and amino acid salts (Yang et al. 2018). Heavy metal phosphate and oxalate, which are insoluble in water, grain roots, gelatin, and protein binding in barley malt, are other forms of cadmium. In

order to choose the best removal methods, it is crucial to identify the various types of heavy metals in plants (Zhang et al. 2020).

Nevertheless, depending on the particular metals present, their speciation, and the level of contamination, a variety of methods were previously used to stop HMs from entering the soil, the atmosphere, and aquatic ecosystems as well as to recover already polluted soil. Soil incineration, garbage disposal, and electrokinetic remediation were some of the mechanical and chemical methods used in the past (Kapoor and Singh 2021). The type of soil, the type of contaminants, and the intended use of the remediated soil were the only variables that determined how efficient these treatments were. However, there are several drawbacks to these chemical approaches, such as their high cost, limited ability to regulate contaminants, residual chemical persistence, irreversible changes in soil composition and soil cover, and the possibility of secondary contamination. For the effective cleanup of HM-contaminated areas, it is imperative to find economical and environmentally sound approaches (Priya & Nagan, 2015). In light of this, the plant-based technology known as phytoremediation emerged recently.

As previously mentioned, phytoremediation is a soil remediation method that has drawn interest from a variety of professionals because of its effectiveness, affordability, and environmental friendliness. It entails employing plants to eliminate or break down pollutants in the soil (Awa and Hadibarata 2020). The claim is that because of their physiological ability to tolerate and accumulate heavy metals as well as their adaptability to different environmental circumstances, plants are good candidates for phytoremediation. However, because different plant species have varied capacities to accumulate particular heavy metals, the use of particular plant species for phytoremediation depends on the type of heavy metal contamination (Eid et al., 2020).

According to Muthusaravanan et al. (2018), phytoremediation restores damaged natural sources, including soil and water, by using metal-accumulating plants. As previously said, employing phytoremediation technology to remove heavy metals from polluted soil requires several different approaches, and choosing the right approaches is essential to the technique's effective application. Phytoextraction, phytofiltration, phytostabilization, phytodegradation, and phytovolatilization are some of the techniques that have been emphasized and acknowledged in scientific research (Tangahu et al., 2011). It is important to note that the type of contamination, the plant species employed, and additional ecological elements like temperature, pH, nutrient availability, and soil types, among others, all affect how these techniques are applied.

### **Phytoextraction**

Phytoextraction is the process by which pollutants are absorbed by plant roots and then accumulate in plant tissues above ground, such as shoots or other sections that can be harvested. This method makes use of plants' innate capacity to draw pollutants—mostly heavy metals—from the soil. As a result, plants capable of accumulating heavy metals are grown on contaminated sites,

and the metal-enriched biomass above the ground is gathered, which eliminates some of the soil pollutant. According to Yryszhan et al. (2024), this method has been successfully applied to soil that has been contaminated with elements including Pb, Cd, and Zn. Some plants, referred to as hyperaccumulators, have the unusual capacity to take up pollutants through their roots, transfer them, and store them in their above-ground components, such as leaves, stems, and fruits, where they are broken down or changed into less dangerous compounds. About 450–500 distinct plants have been identified as hyperaccumulators, according to Chaudhary et al. (2018). According to Suman et al. (2018), these plant species must possess the following qualities to be suitable for phytoextraction: they must be able to produce large amounts of biomass, be metal-tolerant to hazardous metals, and have a high capacity for active accumulation of heavy metals in parts that are easily harvested. The basic principle of phytoextraction, according to Sharma et al. (2023), is to cultivate suitable plant species on the site, gather the metal-enriched biomass, and then treat it to decrease its bulk and size. This can be accomplished by composting, compressing, dehydrating, and thermal decomposition.

In this sense, once the plants have gathered significant levels of toxins, they are harvested and disposed of securely, which lowers the concentration of contaminants in the soil (Nedjimi 2021). As long as the accumulated toxins remain safe, the metal-enriched biomass can be used for a variety of applications, including the manufacture of biofuel or animal feed. Re-extraction of trace elements can also be done with the collected biomass. Metals like nickel, cobalt, and zinc are extracted from the enriched plant material using a technique known as phytomining. Since projections are considerably easier to gather than roots and are the most efficient phytoremediation technique for eliminating heavy metals and metalloids, metal exchange to shoots is an important physiological interaction in phytoextraction.

According to a study by De Souza et al. (2019), the North American duckweed species *Lemna valdiviana* is well-known for its capacity to absorb heavy metals and metalloids, including arsenic, in its tissues. It can even extract up to 82% of arsenic from contaminated sources. Other plants with strong phytoremediation capability for heavy metals, especially lead and chromium, are *Zea mays* L. and *Bixa orellana*. The phytoextraction process can be improved by increasing the solubility and availability of heavy metals in soil by adding chelating agents like ethylenediaminetetraacetic acid (EDTA) (Kumar et al., 2022).

### **Phytostabilization**

A phytoremediation method called phytostabilization uses plants to immobilize heavy metals in the soil and stop them from being dispersed by runoff or wind. The potential for exposure to humans and the environment is decreased as a result of the immobilized heavy metals becoming less mobile and bioavailable (Gerhardt et al., 2017). According to Marques et al. (2009), plants with deep root systems that can maintain and penetrate the soil can accomplish this, preventing heavy metals from leaking into the environment. Heavy metal complexation or precipitation in the rhizosphere, heavy metal

uptake and accumulation in root tissues, and adsorption onto root cell walls are some of the mechanisms that might cause this. In areas where heavy metals are present, the phytostabilization process aids in maintaining soil health. Because contaminated biomass does not need to be removed, this method is more favorable than phytoextraction highlight Arantza et al. (2022). However, a study by Ely and Smets (2017) found that suitable plant species with dense root systems that can generate a substantial amount of biomass and are tolerant to heavy metal environments must be chosen in order to accomplish efficient phytostabilization. Soil additives can also improve the physicochemical and biological characteristics of soil, modify metal speciation, and lower metal solubility and bioavailability. These additions, which can be either organic or inorganic, improve plant colonization and water-holding capacity by raising the soil's organic matter content and vital nutrients.

### **Phytovolatilization**

The process of using plants to absorb heavy metal pollution and change them into volatile, less dangerous chemical species through transpiration is known as phytovolatilization (Kumar et al., 2023). Certain heavy metals, such as mercury and selenium, can be found in the environment as gaseous species (Chandra et al., 2015). It has been demonstrated that a few naturally occurring or genetically modified plants, including *Arabidopsis thaliana*, Indian mustard (*Brassica juncea*), and muskgrass (*Chara canescens*), can absorb heavy metals and change them into gaseous forms inside the plant before releasing them into the environment (Ghosh and Singh, 2005). About 75% of the initial amount of arsenite can be volatilized by *Arundo donax* when combined with the microorganisms *Stenotrophomonas maltophilia* and *Agrobacterium*, which promote plant growth. Only around 0.15% accumulated in the plant, and about 25% stayed in the sand (Guarino et al., 2020). Because selenium has a lengthy half-life of about 327,000 years, soil contamination poses a serious risk to the environment. Phytovolatilization is a procedure that can eliminate it (Sharma et al., 2015). There are five distinct oxidative states of selenium found in nature: -2, 0, +2, +4, and +6. Selenate (+6) is the most prevalent form of selenium found in nature, and soil plants absorb it through sulfate transporters. Inorganic Se is transformed into volatile  $(\text{CH}_3)_2\text{Se}$  in the plant via a number of biochemical mechanisms and enzymes (Sharma et al., 2015). Additionally, plants release methaneselenol ( $\text{CH}_3\text{Se}$ ), dimethyl diselenide [ $(\text{CH}_3)_2\text{Se}$ ], dimethyl selenone [ $(\text{CH}_3)_2\text{SeO}_2$ ], and dimethyl selenylsulfide [ $(\text{CH}_3)_2\text{SeS}$ ] from the soil (Chen et al., 2019). Mercury (Hg), a heavy element that causes neurodegeneration, is similarly eliminated via the phytovolatilization process. Because of its biological amplification throughout the food chain, the methylated form of mercury poses a serious hazard to humanity (Kumar et al., 2017). The phytoremediation process involves plants that absorb mercury from the soil through their roots, move it to the aerial portion of the plant via their vascular system, and then transpire it. The plant's enzymes convert mercury into a volatile form (Sharma et al., 2015).

The type of metal present, the plant species used, and the natural conditions all affect the efficacy of this method, which removes contaminants

from soil without needing the removal or treatment of the land. For example, when mercury is phytovolatilized, the vaporized mercury may recondense and redeposit in the environment, contaminating soil and water. In order to minimize any ecological harm, phytovolatilization must be used carefully and ecological variables, such as wind direction and speed, must be evaluated (Bortoloti et al., 2022). Although phytovolatilization is effective in reducing some environmental contaminants, it is not widely used due to some drawbacks. The main drawback is the possibility that airborne pollutants will pollute nearby places. As a result, this approach must be used carefully and only in places where there are constraints on air pollution or low population densities (Awa et al., 2020).

### **Rhizofiltration**

One phytoremediation method for eliminating impurities from water or liquid waste is rhizofiltration, also known as hydraulic control. This technique relies on the ability of plant roots to absorb and store metal contaminants from water. According to Singh and Santal (2015), this phytoremediation method can remove radionuclides including uranium, cesium, and strontium as well as metals like Cd, Cr, Cu, Ni, Pb, and V. Rhizofiltration works best on plants with high surface areas and fibrous root systems (Kanwar et al., 2020). Large volumes of water are drawn from the subterranean water table by the fibrous-rooted plants, which function as pumps (Muthusaravanan et al., 2018). As a result, throughout this process, pollutants in the water table are absorbed along with the water. Citric acid and malic acid are examples of root exudates that can improve pollutant absorption, adsorption, or sedimentation (Banerjee and Roychoudhury, 2022). Benavides et al. (2018) found that *Z. mays* L. had a 12% decrease in Hg, a 32% decrease in Pb, and a 30% decrease in Cr. The aquatic plant *Typha angustifolia* demonstrates the tremendous potential of rhizofiltration. It can absorb 4,941.1–14,109.4 mg of Cd and 14,039.3–59,360.8 mg of Zn per plant, respectively. While bean species (*Phaseolus vulgaris*) have been shown to effectively extract uranium and cesium from groundwater, *Typha latifolia* also successfully eliminates methyl parathion from hydromorphic soils. *Eichhornia crassipes*, *Salvinia molesta*, and *Pistia stratiotes* have been found to be viable choices for heavy metal removal from industrial sludge, while *Arundo donax* is successful at rhizofiltrating copper from artificial wetlands (Guarino et al., 2020). Three popular aquatic plants have distinct phytoremediation qualities: *Eichhornia* (water hyacinth), *Pistia* (water lettuce), and *Azolla* (water fern). While *Eichhornia* and *Azolla* efficiently absorb Ni and Cu from the contaminated water, *Pistia* has a good ability to phytoextract and phytostabilize As, Pb, and F. Compared to other phytoremediation techniques, rhizofiltration is more economical and ecologically benign. However, it might take longer than other approaches to drastically lower pollutant levels (Yan et al., 2020).

### **Rhizodegradation**

Plant roots, microbes, and pollutants interact during the natural yet complicated process of rhizodegradation (Latif et al., 2023). It's a kind of phytoremediation where contaminants in soil are broken down by plants and the microorganisms that live in their root zones. The area of soil that surrounds

a plant's roots and has a high concentration of microorganisms that can interact with the plant and pollutants is known as the rhizosphere (Priya 2023). Because different plants release varying kinds and amounts of exudates, which can affect the microbial community and their capacity to break down pollutants, choosing the right plant species is also essential to rhizodegradation. Compared to conventional remediation techniques, rhizodegradation offers a number of benefits, such as low cost, minimal environmental impact, and the possibility of long-term efficacy (Cristaldi et al., 2017). However, a number of variables, like the kind of toxins in the soil, the kind of plants utilized, and the environmental circumstances, affect how effective the procedure is. Choosing the right plants and microbes for a certain location can affect how well rhizodegradation works. According to Ely and Smets (2017), many plant species and the root-zone microbes that are linked with them can both survive and flourish in a variety of environmental circumstances and breakdown a variety of contaminants.

### Phytodesalination

A phytoremediation method called phytodesalination uses halophytic plants to extract salt from salt-impacted soils (Zorrig et al., 2012). Plants that have evolved to thrive in extremely salty conditions are known as halophytes. Compared to glycophytic plants, which thrive in non-saline habitats, they are more successful in heavy metal situations (Sakai et al., 2012). In just four months, halophytic plants like Suaeda maritima and Sesuvium portulacastrum may remove 504 kg and 474 kg of salt from a one-hectare field affected by salt, according to studies (Ravindran et al., 2020).

These plants have the ability to absorb sodium chloride from extremely saline soils, which enhances crop quality and yield. Additionally, by lowering the salt of the soil, this technique promotes the natural growth of glycophytic crops like *Hordeum vulgare*. In general, halophytic plants can be used in phytoremediation to improve crop output, remediate salt-impacted soils, and lessen the detrimental effects of salinity on plant growth (Devi and Kumar, 2020).

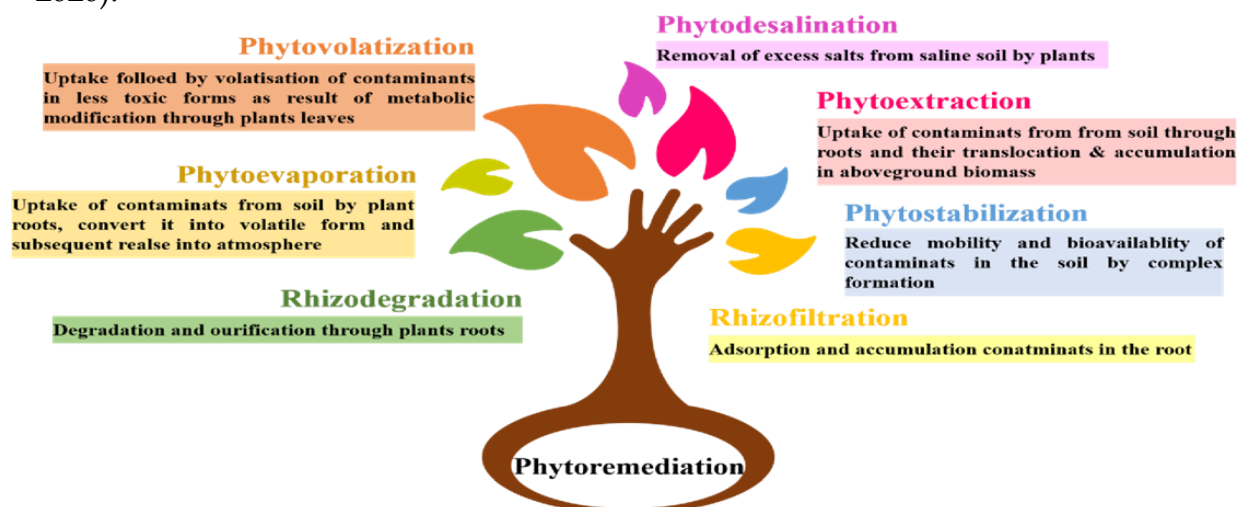


Figure 2. Image Representation of Types of Phytoremediation

### **Plants Species Used for Phytoremediation**

A key component of effective phytoremediation of HM-contaminated soil is plant selection. Phytoavailability, or the biological availability of plants, is one of the requirements. Water-soluble HMs can avoid the plant root system without substantial buildup, and HMs can be tightly bonded to soil organic matter and remain non-bioavailable to plants for an extended period of time (Yryszhan et al., 2024). Because of this, it is essential to choose plant species that have anatomical, structural, physiological, and biochemical adaptations that provide resilience to unfavorable climatic conditions. Many plant species that grow in contaminated places may acquire heavy metals (HMs), however they may not be able to tolerate adverse environmental circumstances such as salinization, high temperatures, and little rainfall. Therefore, when selecting a phytoremediation strategy, it is crucial to take into account both the plants' capacity to retain moisture and their capacity to adapt to the local climate (Wei et al., 2021). Fast growth, big biomass, deep roots, and effective uptake and transport of heavy metals or other contaminants to their above-ground portions are common characteristics of plants with significant phytoremediation capabilities.

Because they require little upkeep and are well suited to the local climate, native plant species are frequently used for phytoremediation. Plants known as metallophytes are able to thrive on soils that are high in heavy metals. Zaghoul (2020) classifies them into three groups, namely:

- (a) Metal indicators that accumulate heavy metals (HMs) in their aerial parts;
- (b) Metal excluders that accumulate HMs primarily in roots
- (c) Metal accumulators that accumulate high HM concentrations primarily in the above-ground plant parts, such as shoots and leaves.

These metallophytes include *N. caerulescens*, which accumulates significant amounts of zinc and cadmium, and *Alyssum bertolonii*, which hyperaccumulates nickel. Lead and copper-rich conditions are also ideal for *Armeria maritima*. The potential of these plants for phytoremediation makes them valuable. Additionally, hyperaccumulators can grow and accumulate heavy metals (HMs) in soils with high HM concentrations. While some of these are capable of accumulating several HMs, others are specialized in the accumulation of just one. About 75% of known hyperaccumulator plants are Ni, which is mostly linked to significant hyperaccumulation (Seregin et al., 2022).

In desert and semi-desert regions, soil restoration is greatly aided by the adoption of halophytic hyperaccumulator plant kinds (halophytes are plants that flourish in saltwater settings) that are resistant to unfavorable environmental circumstances. These regions are also home to xerophytic flora. Thus, it is crucial to find and investigate hyperaccumulators in xerophytic and halophytic plant species (Manousaki et al., 2011). For example, the halophyte *Salsola kali* is known to accumulate heavy metals, and the xerophytic species *Atriplex canescens* can also absorb heavy metals from contaminated soils. By accumulating pollutants, these species not only withstand harsh environments

but also aid in their recovery (Ouaini et al., 2023). According to Lone et al. (2008), halophytes have a great phytoremediation potential because of their capacity to flourish in saltwater settings and efficiently absorb large levels of heavy metals, providing a long-term option for enhancing soil quality in damaged areas. According to a report by Yryszhan et al. (2024), both halophytic and xerophytic hyperaccumulator species are essential for safeguarding soil ecological functions and have been acknowledged for their capacity to fight global problems like desertification and soil contamination by accumulating heavy metals, thereby promoting ecological restoration and soil stability. In desert and semi-desert regions, hyperaccumulator plants serve a variety of purposes beyond soil decontamination, such as absorbing heavy metals (HMs) into roots, stems, and leaves; increasing soil fertility; improving food and human and animal safety; fostering environmental biodiversity; lowering carbon dioxide and dust emissions; establishing a microclimate in dry conditions; and reducing global warming.

The buildup of Pb, Cd, Hg, and As in the soil is caused by anthropogenic activities like mining, agriculture, and industrial operations, necessitating the use of efficient remediation techniques. Vetiver grass is a perfect choice for phytoremediation because of its exceptional ability to stabilize soil and absorb pollutants. Its deep root system can reach up to three meters. The effectiveness of vetiver grass on HM buildup from Pb and Zn mining waste was shown by Wei et al. (2011), who also highlighted the substantial HM sequestration in the roots. This grass is being used more and more in a variety of projects to protect groundwater supplies, improve agricultural productivity, and restore contaminated land. Zeng et al. (2019) investigated *P. vittata*'s capacity for phytoextraction when it was planted in soil contaminated with As, Cd, Pb, and Zn alongside trees like *Morus alba* or *Broussonetia papyrifera*. These results showed that intercropping improves overall phytoextraction and lessens the harmful effects of metals on plant growth, indicating a viable method for cleaning up metal-contaminated soil. Additionally, vetiver grass's extensive root structure fosters the development of arbuscular mycorrhizal fungi, which are essential to the phytoremediation process. These fungi work in symbiosis with plant roots to improve plant development, nutrient uptake, and resistance to pollutants and environmental stressors. These plants also increase the activity of beneficial soil microbes and produce biomass, which boosts the effectiveness of phytoremediation. Arbuscular mycorrhizal fungi's overall contribution to plant productivity is still clear, even though their efficacy in phytoremediation may differ based on the particular pollutants, plant species involved, and local environmental factors (Ma et al. 2022). As a result, certain plant species are better suited for phytoremediation than others. Nevertheless, the evaluation of a plant's capacity for phytoremediation is typically based on two main aspects. These are the translocation factor (TF) and bioconcentration factor (BCF).

Table 1. Shows the Potential Plant Species Which can be Used for Heavy Metal Remediation

S/N	Plant Species	Contaminants Removed
1	Brassica juncea L	Cd, Cu, Zn
2	Populus sp.	Cd
3	Helianthus annuus	Zn
4	Melica jacquemontii Poaceae	Fe
5	Medicago sativa, Brassica nigra	Pb
6	Eleocharis acicularis	Cu
7	Lemna minor	Pb, Cd, Ni, Cr
8	Brassica rapa L.	U
9	Alyssum murale, Berkheya coddii	Ni
10	Azolla filiculoides	Hg (II), Pb (II)
11	Jatropha curcas	Al, Cd, Fe, Cr, Pb, Zn, Ni, Cu
12	Viola bashanens	Zn
13	Aeollanthus subacaulis	Cu
14	Oryza sativa	Cd, Zn, Fe, Cu, Pb, Cr, Mn
15	Schima superba	

### Factors Affecting Phytoremediation of Heavy Metal Contaminated Soil

The chemical and physical characteristics of the soil, plant and microbial exudates, metal bioavailability, and the plants' capacity to "uptake, accumulate, translocate, sequester, and detoxify metals" are all factors that affect the effectiveness of phytoremediation (Wang et al., 2020b). The following highlights a few of these factors:

- Plant species: The capacity of various plant species to absorb and eliminate pollutants from soil varies. Plants that are hyperaccumulators are especially good at removing heavy metals from the soil.
- Type and concentration of contaminants: The type and concentration of contaminants determine how well plants can remove heavy metals from the soil. Certain heavy metals are simple to remove, while others are more challenging.
- The ability of plants to develop and absorb pollutants can be impacted by soil qualities, including pH, organic matter concentration, nutrient availability, oxygen level, and the type of microbes present.
- Climate and weather: Temperature, precipitation, and sunlight are examples of climate and weather factors that can affect how quickly plants develop and eliminate pollutants.
- Soil moisture: The amount of moisture in the soil has an impact on both the availability of pollutants for absorption and the growth and health of the plants.
- Plant growth stage: A plant's capacity to absorb pollutants and produce biomass for removal can both be impacted by its growth stage.

- Treatment duration: The efficacy of pollutant removal may be impacted by the length of phytoremediation treatment. Certain pollutants and soil types may require longer treatment times.
- Management techniques: Appropriate techniques, like fertilization and soil amendments, can enhance plant growth and phytoremediation efficacy.
- By affecting the accessibility and adaptability of heavy metals in soils, microorganisms in the rhizosphere of plants might enhance the effectiveness of phytoremediation (Chen et al. 2022).

Increasing the number of plants that can be employed for the phytoremediation of heavy metal-contaminated soil requires an understanding of the mechanisms by which plants tolerate a particular metal. Plant tolerance is provided by a variety of metal-binding proteins (MBPs) that are involved in the absorption, accumulation, translocation, and detoxification of heavy metals (Feki et al., 2021). Phytochelatin (PCs), metallothioneins (MTs), and transporter proteins [heavy-metal ATPase (HMA)] are among the MBPs (Mathur and Chauhan, 2020).

#### **Advantages of Phytoremediation Techniques**

It was believed that the first methods for cleaning up heavy metal-contaminated soil had several flaws, which led to the need for new methods. According to Priya and Nagan (2015), the situation necessitated the immediate development of economical and environmentally sound methods for the effective cleanup of HM-contaminated areas. In light of this, the plant-based technology known as phytoremediation emerged recently.

In the first case, phytoremediation was used to address the high expense of remediating soil contaminated with heavy metals. To put it another way, using phytoremediation to clean up contaminated locations can be both economical and environmentally beneficial (Kafle et al. 2022). The phytoremediation strategy has been found to have numerous benefits in ecological cleanup because of its special capacity to remove hazardous synthetic compounds by plant subterranean root growth, bioaccumulation, impurity debasement, or movement (Shen et al. 2022). For example, a study on the use of sunflower and canola crops for the phytoremediation of heavy-metal-contaminated soils found that the plants not only reduced heavy metal concentrations in the soil but also produced high yields of oil for use in biofuel production (Bortoloti and Baron 2022). This suggests that using phytoremediation for heavy metal removal from polluted soils allows for the cultivation of oil crops for biodiesel or bioenergy production. This implies that phytoremediation may be useful for producing sustainable energy and cleaning up the environment (Kurniawan et al., 2022). In conclusion, phytoremediation offers the following benefits:

- According to Corzo et al. (2020), it is an economical and environmentally sustainable remediation technique that can be used for both large-scale and small-scale initiatives to reduce HM concentrations.

- Ponds, rivers, and artificial wetlands can all be effectively cleaned up with it at a reduced cost of operation (Abdullahi, 2015).
- It requires less maintenance and lowers the danger of pollutant movement (Limmer and Burken, 2016).
- Additionally, it works well for airborne pollutants and helps lower environmental contamination levels overall. (Muthusaravanan and others, 2020).

### **Limitations of Phytoremediation**

Even while phytoremediation has been found to be beneficial for soils contaminated with heavy metals, there are drawbacks as well. According to Zhu and Rosen (2009), heavy metals (HMs) build up on soil surfaces all over the world, posing serious environmental contamination risks. HMs, including Pb, Cd, Hg, and As, have an impact on ecological stability in addition to human health. Despite its encouraging potential, phytoremediation has several drawbacks and restrictions that are determined by a number of variables, such as the availability of heavy metals, the state of the soil, plant growth, and long-term stability. The kind and concentration of contaminants, the properties of the soil, the current climate, and the selection of plant species for remediation all affect how effective the process is. Furthermore, phytoremediation operations usually take a long time to remove large amounts of contaminants, which might not be possible in circumstances where decontamination is required right away.

#### **Techniques for Enhancing Phytoremediation Efficiency**

It is impossible to claim that the issue of HMs-contaminated soil has been resolved using phytoremediation. It is far from it, since it has been noted that the method still has flaws of its own. Numerous methods have been proposed in this area to increase phytoremediation's effectiveness. According to Bortoloti and Baron (2022), one method is genetic engineering, which can be utilized to boost the potential for phytoremediation by either adding or altering genes that will improve plant metal uptake, transport, and detoxification. This is due to the fact that genetic engineering can improve plants' ability to accumulate metals, boost their resistance to harmful pollutants, and modify their root systems to better absorb and store pollutants (Latif et al. 2023).

Thus far, applying fertilizer and biochar has improved soil quality and fertility, which has increased the availability of nutrients for plants. However, modifying soil pH, nutrient levels, and water availability can improve the phytoremediation process. As previously mentioned, these growth conditions can improve plant growth and metal uptake, boosting the effectiveness of phytoremediation (Mench et al., 2009).

The use of phytococktails, which combine various plant species to remediate numerous pollutants at once, is another strategy that has been proposed (Ali et al., 2019). Additionally, agronomic practices that can improve the effectiveness of phytoremediation of heavy metal contamination include the application of compost, water recommendations, and established culturing techniques (Samsuri et al. 2019). The fact that phytoremediation time can be shortened by using plant growth regulators and soil amendments is a benefit of

this strategy. This is because plant growth regulators can increase biomass output and encourage plant development, which increases plant uptake of metals (Zhang et al. 2019).

However, as Singh et al. (2022) point out, it is crucial to remember that some of these techniques, like genetic engineering and chelating chemicals, can have detrimental effects on human health and the environment if not utilized appropriately. Therefore, it is advised that before using these techniques in phytoremediation, their efficacy and possible dangers must be properly assessed and monitored.

### **Methods of Disposing Harmful Plant Waste after Phytoremediation**

Although phytoremediation is an economical and eco-friendly method that can be applied alone or in conjunction with other remediation strategies, it may ultimately produce polluted biomass. Therefore, a crucial element in the process to stop additional environmental pollution is the proper disposal of plant debris following phytoremediation. The clearance of the resulting polluted biomass, as well as the possible environmental effects of the phytoremediation process itself, must be taken into account. To prevent additional pollution, the plant biomass that accumulates heavy metals needs to be treated and disposed of properly. In this regard, experts in the field have discovered six standard methods that are appropriate for disposing of contaminated biomass. As highlighted and explained, they are:

- According to Al Chami et al. (2014), pyrolysis is a thermal degradation process that breaks down biomass into solid, liquid, and gas constituents. It is thought to be a useful technique for transforming and stabilizing heavy metals in biomass. In order to extract heavy metals from contaminated biomass like *Pteris vittata*, the pyrolysis temperature is particularly crucial because higher temperatures lead to more significant stability (Shen et al. 2022).
- The next technique is incineration, which can occasionally be used to recover any accumulated metals in the biomass, even though it is not always feasible or economical and may discharge contaminants into the air.
- Another option is the landfilling and direct disposal method, which allows the plant material to be deposited at separate hazardous waste sites or landfilled. However, biomass disposal in hazardous waste sites or landfills may cause long-term environmental contamination.
- Next is the composting process, which involves mixing and diluting plant biomass with other organic materials and letting it break down to create a soil amendment that is rich in nutrients. This method's benefit is that the compost produced can be utilized for landscaping, horticulture, or agriculture.
- The production of bioenergy is an additional method. According to Tatu et al. (2020), plant biomass can produce energy through a variety of processes, including pyrolysis, combustion, and anaerobic digestion. This strategy can offer a renewable energy source and lessen dependency on fossil fuels.

- The last technique is leaching, which depends on the soluble heavy metals' capacity to move through a medium. It should be noted that each of these techniques needs to be thoroughly considered before being applied.

## **CONCLUSIONS AND RECOMMENDATIONS**

One of the major threats to soil is heavy metals (HMs). Using inexpensive, eco-friendly methods appears to be a viable way to clean up these contaminants. Because of this, phytoremediation is one of the most widely used and successful plant-based methods for eliminating pollutants from contaminated regions with minimal harm to soil structure. Therefore, phytoremediation's relevance as a sustainable remedy for HM contamination in soil ecosystems is highlighted by economic factors, societal acceptance, and policy consequences. According to the report, phytoremediation is at the vanguard of creative environmental restoration, offering substantial improvements to healthier, cleaner ecosystems. Furthermore, research and applications have shown that phytoremediation needs to be intensified and accelerated due to the advantages it offers as an ecological process as well as the disadvantages of the length of time it takes to remove heavy metals (HMs) and the risks HM toxicity poses to soil and plant integrity.

One thing that stands out from the review is that phytoremediation is a multidisciplinary topic that involves several scientific disciplines with the goal of developing and improving phytoremediation technology. According to him, interdisciplinary research is essential for improving the effectiveness of phytoremediation and tackling the intricate environmental issues related to soil contamination, and librarians, who are widely knowledgeable, have a significant role to play when it comes to research in this area. In this sense, Devi and Kumar (2020) summarized several scientific fields that are involved in phytoremediation research, such as environmental engineering, botany, plant physiology, soil science, microbiology, chemistry, and aquatic science. The fear is that more successful phytoremediation techniques can be created by merging the knowledge and skills of specialists from many fields. For example, they stated that soil scientists can offer important insights into the physical and chemical characteristics of the soil, which can impact plant development and the absorption of pollutants. The design and execution of phytoremediation systems, including the selection of suitable plants and the optimization of environmental conditions, can be better understood by environmental engineers. Microbiologists can shed light on the function of soil microbes in promoting phytoremediation processes, while botanists and plant physiologists can offer knowledge on the uptake, transport, and detoxification of pollutants by plants. Aquatic biologists would assist in identifying appropriate plants and their effectiveness in hydric and underwater soils for the removal of particular pollutants. Additionally, interdisciplinary research can assist in identifying the constraints and difficulties related to phytoremediation and in creating solutions to these difficulties. For example, nanotechnology can improve the uptake and transport of toxins by plants, while molecular biology techniques

can be utilized to create genetically modified plants that are better able to absorb and detoxify contaminants.

In nutshell, the paper looked at phytoremediation as a plant technology suitable for remediating HMs contaminated soil, as well as identifying commonly utilized plants for phytoremediation. It further looked at some of the possibilities and strategies for enhancing phytoremediation more so, through different phytoremediation types and variables impacting phytoremediation. The underlying point is that phytoremediation may be utilized as an economical, effective, environmentally and ecologically friendly method related to the usage of metal-accumulating plants as an alternative method for HM cleanup.

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