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Heavy metal pollution and phytoremediation- a review

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Abstract

Heavy metal pollution is a critical environmental issue driven by industrialization and urbanization. These pollutants persist in the environment, posing risks to soil, plants, and human health due to their toxicity, non-biodegradability, and bioaccumulation potential. Metals like lead, cadmium, arsenic, and mercury disrupt soil microbial activity, impair nutrient cycling, and cause physiological damage to plants, including stunted growth, chlorosis, and reduced photosynthesis. In humans, heavy metal exposure leads to serious health issues, such as organ damage, developmental disorders, and increased cancer risks. Traditional remediation techniques are often costly and disruptive, emphasizing the need for sustainable alternatives. Phytoremediation, an innovative and eco-friendly approach, uses plants to absorb, store, and neutralize heavy metals from contaminated soil, water, and air. Various techniques, including phytoextraction, rhizofiltration, phytostabilization, and phytovolatilization, use plants to remove or control contaminants, providing natural solutions for cleaning and protecting the environment. Hyperaccumulator plants such as *Thlaspi caerulescens*, *Alyssum murale*, *Pteris vittata* etc play a major role in efficiently absorbing and neutralizing toxic metals to restore contaminated environments. Despite challenges like slow remediation rates, plant toxicity, and the variability of metal uptake across species, advancements in biotechnology and the identification of resilient plant species help to increase the effectiveness of phytoremediation. Therefore, phytoremediation as a sustainable and cost-effective method has great potential for mitigating heavy metal pollution and restoring contaminated environments.

Keywords: Environmental pollutants, Heavy metals, Hyperaccumulator, Plants

1. Introduction

Heavy metal pollution is one of the world's most pressing environmental issues, caused by rapid industrialization and urbanization. Its detrimental effects make it a serious threat to the environment and human health. The consumption and production growth of global heavy metals has grown rapidly in parallel with economic activity, resulting in widespread pollution (Hembron et al., 2019). Due to their toxicity, long environmental and biological half-lives, inability to decompose biologically, and propensity to build up in food chains, heavy metals are especially problematic (Herath et al., 2018). Natural elements having an atomic number higher than 20 and a density higher than 5 g/cm³ are known as heavy metals (HMs). Copper (Cu), cadmium (Cd), chromium (Cr), cobalt (Co), zinc (Zn), iron (Fe), nickel (Ni), mercury (Hg), lead (Pb), arsenic (As), silver (Ag), and platinum group metals are some examples of heavy metals. Cadmium, arsenic, mercury, and lead have no biological function in the body, making them unnecessary and highly toxic even at very low concentrations. These elements can cause serious health problems and are classified as priority pollutants by many environmental protection agencies around the world (Sarwar et al., 2017). Soils serve as the primary reservoir for heavy metals released by human activities. Heavy metals, unlike organic pollutants, cannot be chemically or biologically degraded. As a result, their concentrations in soil remain elevated for extended periods (Adriano, 2001; Wuana & Okieimen, 2011).

This causes soil and water pollution, as well as toxic, genetic, developmental, and mutational effects in living organisms (Sarwar et al., 2017; Ali & Khan, 2018).

Pneumatic fracturing, soil flushing, solidification, vitrification, electrophoresis, chemical reduction, soil washing, acid leaching, ozonation, pyrometallurgical separation and excavation are among the most commonly used technologies for in situ and ex-situ remediation of heavy metal (HM)-contaminated soil. Most widely used traditional methods for remediation of contaminated water and soil, also known as "pump and treat" and "dig and dump" techniques (ex-situ remediation), are limited in their applicability to small areas and have their limitations (Mulligan et al., 2001). Over the last decade, a rapidly emerging, low-cost, environmentally friendly, non-intrusive, and aesthetically pleasing remediation technology alternative to traditional remediation techniques has gained popularity worldwide. This technique is phytoremediation which uses plants to clean up the environment. Plants can absorb, accumulate, and detoxify contaminants from their substrates (soil, water, and air) through physical, chemical, biological, or biochemical means (Hooda, 2007; Lee, 2013; Chandra et al., 2015).

This review aims to provide a comprehensive analysis of heavy metal contamination, with a focus on its sources, effects on soil, plants, and human health, as well as the techniques and potential of phytoremediation as an effective, environmentally friendly, and long-term solution to heavy metal pollution. The paper also discusses the characteristics of ideal phytoremediation plants, notable plant species used in phytoremediation, and the challenges and prospects for this technique.

2. Sources of heavy metals

Heavy metals occur naturally in the earth's crust and are also released as a result of human activities. They then become persistent environmental pollutants because they cannot be degraded or destroyed. In the developing world, uncontrolled and rapid urbanization and industrialization have increased levels of contamination in ecosystems. Anthropogenic activities such as the use of fertilizers, pesticides, various industries, waste used to fertilize soil, municipal waste, dumping sites, mining, smelting, waste management, transportation, and agricultural activities primarily cause ecosystem contamination and human exposure to heavy metals (Fulekar et al., 2009; Angon et al., 2024). Heavy metals are produced industrially through coal combustion in power plants, pharmaceuticals, metal processing in refineries, textiles, petroleum combustion, high tension lines and nuclear power plants, microelectronics, plastics, paper processing plants, wood preservation, batteries and paint industries etc. So, heavy metals are often found in high concentrations around industrial sites (Ali et al., 2013). Heavy metals enter the environment through a variety of natural processes, including ocean vaporization, volcanic eruptions, rock degradation, metal corrosion, soil erosion of metal ions, sediment resuspension, crustal erosions, dust outbreaks and heavy metal leaching, forest fires, and soil formation (Bradl, 2005; Alloway, 2012). Table 1 shows the anthropogenic sources of different heavy metals in the environment.

3. Impacts of heavy metal

3.1 Impacts of heavy metal in soil

Human activities, driven by technological advancements, have introduced significant

Table 1. Anthropogenic sources of different heavy metals (Ali et al., 2013)

HM	Sources
As	Pesticides and wood preservatives
Cd	Paints and pigments, plastic stabilizers, electroplating, incineration of cadmium-containing plastics, phosphate fertilizers
Cr	Tanneries, steel industries, fly ash
Cu	Pesticides, fertilizers
Hg	Release from Au–Ag mining and coal combustion, medical waste
Ni	Industrial effluents, kitchen appliances, surgical instruments, steel alloys, automobile batteries
Pb	Aerial emission from combustion of leaded petrol, battery manufacture, herbicides and insecticides

amounts of heavy metals (HMs) into the soil. Heavy metals can exist in soil in two states: solid and dissolved. They are stable, immobile, and non-toxic in the solid phase, but become mobile and harmful when dissolved. Heavy metals in the solid state bind to organic and inorganic soil particles or form solid precipitates. Changes in soil conditions, such as pH, cation concentration, or oxidation-reduction potential, can cause these metals to be released and become available in dissolved form (Ogundiran & Osibanjo, 2009). Soil contains heavy metals in six geochemical forms (Ramos et al., 1994; Abollino et al., 2006; Ogundiran & Osibanjo, 2009; Li et al., 2018): water-soluble, exchangeable, carbonate-bound, Fe-Mn oxide-bound, organic matter-bound, and residual. Residual forms are the most stable and pose little threat to the environment or organisms. For example, lead (Pb) in the form of lead phosphates (e.g., Pb3(PO4)2 and PbHPO4), mixed lead chloride phosphate (Pb5(PO4)3Cl), PbS, and PbSO4 is primarily present in residual form and causes little environmental harm. However, more soluble forms of lead, such as lead nitrate [Pb(NO3)2], lead acetate (PbCOOCH3), and, to some extent, lead chloride (PbCl2), are extremely mobile. These forms may be absorbed by living organisms or leach into groundwater (Ogundiran & Osibanjo, 2009). In addition to affecting plant quality and yield, heavy metal pollution disrupts soil microbial communities by changing their size, structure, and activity. Chromium (VI) is a highly toxic and powerful oxidizing agent. It is known to disrupt the structure and organization of soil microbial communities (Kandeler et al., 1996; Zhang et al., 2016; Jaiswal et al., 2018) (Table 2). Soil contamination by heavy metals such as Pb, Cd, Cu, As, Cr, Zn, Hg, and Ni is a significant environmental issue, primarily caused by industrial, mining, and agricultural practices. These metals accumulate in the soil, increasing its toxicity and making it less conducive to plant growth (Alloway, 2012). In addition, soil pH plays a crucial role in metal solubility, with acidic soils enhancing the mobility and bioavailability of metals like Pb, Cd, and Cu, making them more accessible to plants (Kicińska et al., 2022; Naz et al., 2022).

Contamination from Pb, Cd, As, and Cu inhibits important nutrient cycling processes, such as nitrogen fixation, phosphorus cycling, and the availability of other essential nutrients. For example, arsenic contamination in soil is known to reduce the availability of phosphorus, a key nutrient for plant growth (Khan et al., 2010; Shahid et al., 2015). Heavy metals like Cd, Pb, Zn, and Ni inhibit the decomposition of organic material, resulting in a decrease in organic carbon content and an altered carbon-nitrogen ratio. The decomposition of plant residues in soil contaminated with Cd is slower compared to non-contaminated soil, leading to a reduction in soil organic carbon and affecting the soil's nutrient balance (Li et al., 2018). Soil enzymes are also affected by different metals. Lead (Pb) is less toxic to enzymes than cadmium because it has lower mobility and binds more strongly to soil colloids. It inhibits â-glucosidase activity more than cellulase activity. Pb also significantly reduces the activities of catalase, urease, acid phosphatase, and invertase. Arsenic, on the other hand, inhibits sulfatase and phosphatase but does not affect urease (Wang et al., 2007; Aponte et al., 2020). Heavy metals lead to toxicity not only for plants but also for soil fauna (earthworms, etc.), which can affect soil health and ecosystem functioning. Reproduction in earthworms is also reduced up to 90 % by soil heavy metal (Spurgeon et al., 2006).

3.2 Impacts of heavy metal in plant

Some heavy metals, including As, Cd, Hg, Pb, and Se, are not required for plant growth because they play no known physiological role in plants. Metals such as Co, Cu, Fe, Mn, Mo, Ni, and Zn are required for plant growth and metabolism, but their concentrations can be toxic if they exceed optimal levels (Rascio & Izzo, 2011). High concentrations of certain metals in soils can cause plant toxicity. These metals act as stressors, causing physiological changes or strains that can reduce plant vigour or, in extreme cases, completely halt growth. Sensitivity refers to the negative effects of stress that can cause plant injury or death (Sethy & Ghosh, 2013). Metal toxicity in plants is characterized by stunted root growth, suppressed shoot and leaf development, and chlorosis in young leaves (Smith & Bradshaw, 1979; Baker & Walker, 1989) (Table 2). Heavy metals affect a variety of plant enzymes, including alcohol dehydrogenase, nitrogenase, nitrate reductase, amylase, and hydrolytic (phosphatase and ribonuclease), as well as carboxylating enzymes (phosphoenolpyruvate carboxylase and ribulose-1,5-bisphosphate carboxylase) (Saxena et al., 2019). Heavy metals interfere with a variety of biochemical and physiological processes in plants, including seed germination, enzymatic activity, nitrogen metabolism, electron transport, transpiration, CO2 absorption, antioxidant defences, photosynthesis, photophosphorylation, cellular metabolism, nitrogen fixation, water regulation, mineral nutrition, and ionic balance, membrane structure which ultimately resulting in plant death. High levels of lead (Pb) in soils lower productivity, leading to plants developing dark green leaves, drooping older leaves, less foliage, and short, brown roots (Nagajyoti et al., 2010; Anjum et al., 2015; Lajayar et al., 2017; Raza et al., 2021; Hu et al., 2023) (Table 2). Nickel (Ni), Lead (Pb), Chromium (Cr) and Cadmium (Cd) are toxic to plants, affecting seed germination, root elongation, seedling development, and overall growth. Ni disrupts enzyme activities like amylase and protease, Pb impairs seed morphology and physiology, and Cd delays germination, damages membranes, and hinders food reserve mobilization (Sethy & Ghosh, 2013; Goyal et al., 2020).

3.3 Impacts of heavy metal on human health

The edible parts of plants are the primary source of heavy metal exposure for humans, and consumption can have long-term negative effects on human health. Several heavy metals are considered toxic due to their detrimental effects on human health when consumed in excess. Heavy metals (HMs) are major environmental pollutants that pose significant risks to human

Table 2. Impacts of heavy metals on plants

Impact	Heavy metals involved	Effects on plants	References
Reduced germination and growth	Pb, Cd, Zn, Cu, Ni, Cr	Exposure to heavy metals inhibits seed germination and early growth stages by disrupting cellular processes such as membrane integrity, enzyme activity, and nutrient uptake. These metals reduce the elongation of roots and shoots, leading to stunted growth and even seedling death.	Sethy & Ghosh, 2013; Goyal et al., 2020
Oxidative stress and cell damage	Pb, Cd, Cu, Cr, Hg, As	Heavy metals cause oxidative stress in plants by increasing the production of reactive oxygen species (ROS) like superoxide anion and hydrogen peroxide. These ROS damage cellular components such as lipids, proteins, and DNA, leading to membrane instability, loss of cellular function, and eventually cell death.	Raza et al., 2021; Goyal et al., 2020
Reduced photosynthesis	Cd, Pb, Ni, Cr	Heavy metals such as Cd, Ni, Cr and Pb reduce the efficiency of photosynthesis by disrupting chlorophyll synthesis, inhibiting electron transport, and causing damage to chloroplast membranes. This results in a decrease in photosynthetic rates, which ultimately reduces the overall growth and productivity of plants.	Sheoran & Singh, 1993; Hu et al., 2023
Nutrient imbalance	Cu, Pb, Cd, Zn	Heavy metals interfere with the uptake of essential nutrients (e.g., nitrogen, phosphorus, and potassium) in plants by disrupting ion channels and transport mechanisms. This nutrient imbalance affects various physiological processes, including growth, development, and stress tolerance.	Nagajyoti et al., 2010; Lajayar et al., 2017
Root damage and toxicity	Cd, Pb, Cu, Cr, Ni, Mn, Hg	Metal toxicity disrupts root growth and development by interfering with the integrity of root cell membranes and altering the expression of genes responsible for growth and response to stress. Roots may become deformed, reducing water and nutrient absorption and ultimately affecting overall plant health.	Kahle, 1993
Chlorosis and necrosis	Zn, Cu, Pb, Cd, Fe,Mn	High concentrations of heavy metals interfere with the functioning of the chloroplasts, leading to chlorosis (yellowing) in leaves due to the disruption of chlorophyll synthesis. Necrosis (death of tissues) also occurs as a result of the accumulation of toxic levels of metals in plant tissues.	Anjum et al., 2015

and animal health because they persist in the environment for long periods (Jabeen et al., 2009; Halim et al., 2003). Lead (Pb) can remain in the soil for 150 to 5,000 years, and elevated concentrations have been observed for up to 150 years after sludge application (Jabeen et al., 2009). Heavy metals pose a risk to human health because of their persistence and tendency to accumulate in biological systems. Cadmium (Cd) has a biological half-life of around 18 years. A consistent oral intake of 200 µg of cadmium per day may lead to a higher risk of kidney damage, particularly in individuals aged over 50 years (Forstner, 1995). Heavy metals can affect a variety of human organs, and some are carcinogenic (Table 3). HMs enter the food chain and build up in biological tissues. When the intake of these metals exceeds the body's ability to excrete them, bioaccumulation occurs, which can have serious health consequences (Khan et al., 2015). Lead (Pb) is well-known for harming the brain, causing issues like lower IQ, learning disabilities, and memory problems. It also contributes to high blood pressure, anaemia, kidney damage, and problems with reproduction, especially in children and pregnant women (Matta & Gjyli, 2016; Debnath et al., 2019). Mercury (Hg) is another harmful metal and has no known role in human biochemistry or physiology, making it entirely toxic which affects the nervous system, leading to symptoms like tremors, memory loss, and trouble with motor skills. It also harms the kidneys and can cause developmental issues in fetuses, affecting their brain and motor functions (Clarkson & Magos, 2006; Matta & Gjyli, 2016).

Table 3. Impacts of heavy metals on human health

Heavy metal	Effects on human health	References
Lead (Pb)	Causes neurological impairments (e.g., reduced IQ, learning disabilities), hypertension, anaemia, renal dysfunction, and reproductive toxicity.	Matta & Gjyli, 2016; Debnath et al., 2019
Mercury (Hg)	Neurological disorders (e.g., tremors, memory loss), renal toxicity, and developmental effects, especially in fetuses (e.g., impaired cognitive and motor functions).	Clarkson & Magos, 2006; Matta & Gjyli, 2016
Cadmium (Cd)	Renal dysfunction, nausea, vomiting, bone demineralization (osteomalacia), increased risk of cancer (e.g., lung and prostate), and cardiovascular disease.	Morais et al., 2012
Arsenic (As)	Causes skin lesions, cancers (e.g., skin, bladder, lung), cardiovascular disease, neurotoxicity, and developmental toxicity.	Matta & Gjyli, 2016
Chromium (Cr)	Hexavalent chromium (Cr VI) is carcinogenic, leading to lung cancer, kidney and liver damage, respiratory tract irritation, and skin ulcers.	Shekhawat et al., 2015
Nickel (Ni)	Allergic reactions (e.g., dermatitis), respiratory issues (e.g., asthma, fibrosis), and potential carcinogenic effects on the respiratory system.	Morais et al., 2012; Parmar & Thakur, 2013
Zinc (Zn)	Essential at low doses but toxic in excess; causes gastrointestinal distress, nausea, vomiting, and, in severe cases, disruption of copper and iron metabolism.	Parmar & Thakur, 2013
Copper (Cu)	At high doses, causes gastrointestinal irritation, liver and kidney damage, and neurological effects (e.g., Wilson's disease).	Parmar & Thakur, 2013

Cadmium (Cd) exposure can cause kidney damage and bone loss, and increase the risk of cancer, particularly lung, kidney and prostate cancer. It also leads to heart disease (Morais et al., 2012). Arsenic (As) is known for causing skin problems and various cancers, including skin, bladder, and lung cancers. It can also damage the heart and nerves and cause developmental issues, especially in children (Matta & Gjyli, 2016). Chromium (Cr VI), a toxic form of chromium, is linked to lung cancer, damage to the kidneys and liver, and problems with the skin and breathing (Shekhawat et al., 2015). Nickel (Ni) can cause skin allergies like rashes and can affect the lungs, causing asthma and other breathing problems. Long-term exposure can also make the lungs more vulnerable to cancer cancer (Morais et al., 2012; Parmar & Thakur, 2013). Zinc (Zn) is important in small amounts but can be harmful in excess. Too much zinc can cause stomach problems like nausea and vomiting, and it can interfere with the body's use of other essential metals like copper and iron. Copper (Cu) can also be dangerous at high levels, causing stomach issues, liver and kidney damage, and even neurological problems, as seen in Wilson's disease, where copper builds up in the body (Parmar & Thakur, 2013).

4. Phytoremediation: A natural solution for heavy metal contamination

Phytoremediation utilizes plants' remarkable ability to absorb and concentrate elements and compounds from their surroundings, and has enormous potential for pollutant removal. Plant roots, which are typically found in soil, play an important role in metal removal via processes such as filtration, adsorption, cation exchange, and inducing chemical changes in the rhizosphere. Metal absorption, accumulation, and movement are influenced by plant species, growth stage, and elemental characteristics (Rascio & Izzo, 2011). Plants also use physiological adaptations to limit toxic metal accumulation, sequestering metals in their roots (Nouri et al., 2009). Thus, carefully selecting the appropriate plant species can significantly improve metal removal efficiency. Trees primarily remove air pollutants through their leaf stomata for gases and by adsorbing particulate matter on their leaf surfaces with their dense leaves, branches, and twigs, providing a large surface area for particulate removal via wet and dry deposition processes which makes them suitable for long term monitoring (Yang et al., 2005; Nowak et al., 2006). Phytoremediation is the use of plants to remove or neutralize environmental contaminants (Cunningham et al., 1995).

Heavy metals (HMs) are extremely harmful to plants because they disrupt the balance of oxidants and antioxidants, resulting in oxidative stress and physiological damage. Plants typically maintain low levels of free radicals to avoid such damage. This balance is achieved by toxic metals being taken up, moved, and stored in the roots or transported to the shoots via xylem vessels, where they are sequestered in vacuoles and detoxify the metals. Because of their low metabolic activity, vacuoles are ideal sites for metal storage (Marques et al., 2009; Wu et al., 2010; Ali et al., 2013). Various metal-binding proteins, such as Cu chaperone ATX1-like proteins, glutathione (GSH), metallothioneins (MTs), and phytochelatins (PCs), chelating agents such as NTA (nitrilotriacetic acid), citrate, oxalate, malate, succinate, tartrate, phthalate, salicylate as well as organic ligands, play critical roles in the binding, storage, and detoxification of these harmful metals, particularly in plant parts such as the cuticle, epidermis, and trichomes, which are less likely to suffer cellular damage and are the ideal site for metal detoxification (Marques et al., 2009; Chandra et al., 2015; Saxena et al., 2019).

4.1 Techniques of phytoremediation

Phytoremediation of heavy metals is typically classified into four types: phytoextraction, in which metal-accumulating plants are grown on contaminated soil and harvested to remove metals; rhizofiltration, in which plant roots absorb metals from polluted water or effluents and are then harvested to reduce metal concentrations; phytoestabilization, in which metals are immobilized in the substrate; and phytovolatilization, in which plants are used to volatilize pollutants (Salt et al., 1995).

4.1.1 Phytoextraction

Among the various phytoremediation methods, phytoextraction is an important process for removing heavy metals from contaminated sites. It involves using plants to absorb metal pollutants through their roots and concentrate them in aboveground parts, which can then be harvested. This process is known as phytoextraction (Ali et al., 2013; Saxena et al., 2019). Phytoextraction can be economically advantageous if the metals extracted from plants are used as bio-ore to extract valuable and functional metals, a process known as phytomining (Chandra et al., 2015). Plants with high biomass, rapid growth rates, and a high tolerance for metal accumulation are best suited for phytoextraction (Lee, 2013). Natural phytoextraction occurs when plants naturally accumulate metals, whereas induced phytoextraction occurs when substances such as chelators or soil amendments are added to the soil to enhance metal uptake by the plants (Sarwar et al., 2017; Saxena et al., 2019).

4.1.2 Rhizofiltration

Rhizofiltration is a phytoremediation technique that uses the roots of certain plants to clean up contaminated water and soil. The roots absorb, concentrate, and precipitate pollutants like heavy metals and radioactive elements from low-concentration sources such as wastewater for immediate remediation. This method can be applied directly in natural water bodies (in situ) or in controlled tank systems (ex-situ). However, ideal plants for rhizofiltration should have large, fibrous root systems, high tolerance and accumulation capacity for metals, be easy to manage, cost-effective, and generate minimal waste (Pandey et al., 2021). Terrestrial plants are also suitable for rhizofiltration because of their well-developed, fibrous root systems that offer a large surface area for contaminant uptake. While pollutants may not be entirely removed from the soil, they are often transformed into less toxic forms and effectively immobilized within the root zone, minimizing their mobility (Salt et al., 1995).

4.1.3 Phytostabilization

Phytostabilization, also called place-inactivation, is a technique that uses certain plants to stabilize and immobilize contaminants in soil and groundwater. Through root absorption, accumulation, and chemical changes in the root zone (rhizosphere), plants help reduce the movement and bioavailability of pollutants, preventing them from entering groundwater or the food chain. This method also helps control soil erosion, limits the spread of toxic metals, and allows vegetation to grow in heavily polluted areas. By using plants that can thrive in contaminated soils, phytostabilization changes the soil conditions to convert harmful metals into less toxic, more stable forms, often with the help of soil amendments (Wuana & Okeiemen, 2011; Pandey et al., 2021).

4.1.4 Phytovolatilization

Phytovolatilization is a process where plants absorb contaminants like heavy metals (e.g., As, Hg, Se) from the soil, convert them into less toxic, volatile forms, and release them into the atmosphere through transpiration, mainly via their leaves (Doty et al., 2007). This method helps detoxify pollutants, though the released vapors can eventually re-enter the environment (Feng et al., 2017). Fast-growing trees are especially effective in this technique due to their rapid uptake and transpiration rates (Jabeen et al., 2009).

However, plants have developed three basic strategies for growing on contaminated and metalliferous soils (Baker & Walker, 1990). **Metal excluders-** are plants that prevent metals from entering their above-ground parts, even when metal concentrations in the soil are high. However, they still accumulate a significant amount of metals in their roots; **Metal indicators-** are plants that gather metals in their aerial parts, and the amount of metal in these plants reflects the metal levels in the soil; **Accumulators**, or hyperaccumulators- are plant species that can concentrate metals in their above-ground tissues to levels much higher than what's found in the soil or nearby plants. A plant is considered a hyperaccumulator if its leaves contain more than 0.1% of metals like nickel, cobalt, copper, chromium, or lead, or 1% of zinc, based on dry weight, regardless of the metal concentration in the soil (Baker & Walker, 1990).

5. Plants used in Phytoremediation

The ideal plants for phytoremediation should have several key characteristics. They must be able to hyperaccumulate heavy metals (HMs), preferably in their aboveground components, making it easier to harvest and manage the accumulated toxins. These plants should also be able to tolerate extreme conditions such as high pH, salinity, and toxic metal concentrations. Rapid growth and the ability to produce large amounts of biomass are critical characteristics for ensuring effective remediation over short periods. The plants with extensive, highly branched root systems maximize contaminant uptake from the soil. Finally, resistance to diseases and pests is essential for maintaining their health and efficiency during the remediation process (Baker et al., 2020; Mahar et al., 2016).

Hyperaccumulators are primarily used for biological monitoring. Plant samples are more commonly used to estimate ecosystem quality because they are sensitive to chemical changes in environmental composition and accumulate pollutants. Plants as bioindicators have numerous advantages, including low costs, the ability to sample over time, visible indicators of contamination and high availability (Ugulu et al., 2012). An ideal hyperaccumulator plant should accumulate at least 100 mg kg-1 (0.01% dry weight) of As and Cd, 1,000 mg kg-1 (0.1% dry weight) of Co, Cu, Cr, Ni, Se, and Pb, and 10,000 mg kg-1 (1% dry weight) of Zn and Mn (Reeves & Baker, 2000). Plants that accumulate metals are primarily chosen for phytoremediation. There are currently over 500 plant species known to be hyperaccumulators of one or more metals (Van Der Ent et al., 2013). Notable representatives include members of the Brassicaceae, Asteraceae, Caryophyllaceae, Lamiaceae, Euphorbiaceae, Poaceae, Rubiaceae and others (Ali et al., 2013; Chandra et al., 2015).

Plants have shown remarkable ability to accumulate heavy metals in their tissues, making them valuable tools for environmental monitoring and remediation. *Robinia pseudoacacia* is a bioaccumulator of lead (Pb), zinc (Zn), and cadmium (Cd), making it a reliable indicator of metal pollution (Filipović-Trajković, 2012). Similarly, *Eucalyptus cladocalyx* and *Cupressus sempervirens* var. *fastigiata* are good bioindicators of air metallic pollution. In these species, cadmium (Cd) and zinc (Zn) are predominantly detected in leaves, while copper (Cu) and lead (Pb) are more concentrated in the bark (Alatou and Sahli, 2019). *Mangifera indica* (5.35) and *Polyalthia longifolia* (4.30) have high metal accumulation index (MAI) values, demonstrating their ability to thrive and accumulate heavy metals in polluted environments (Uka et al., 2020). Furthermore, *Aesculus hippocastanum* (horse chestnut) leaves in Belgrade Park were found to contain extremely high concentrations of Cu (110.2 mg/g dry weight), Pb (20.3 mg/g), and Cd (5.9 mg/g), which exceed toxic levels for plants (Unterbrunner et al., 2007).

Thlaspi caerulescens, a well-known zinc, cadmium, lead and nickel hyperaccumulator, has been widely researched for its ability to absorb and accumulate heavy metals. According to studies, this species can accumulate up to 1000 mg/kg of cadmium in its tissues without showing any symptoms of toxicity (Brown et al., 1995; Gerard et al., 2000) . Some populations of *Thlaspi caerulescens* from southern France have been found to accumulate cadmium in their aerial parts at concentrations up to 3000 mg/kg (Gerard et al., 2000). In certain populations of *T. caerulescens*, cadmium uptake is influenced by the presence of zinc in the soil. In the 3160 μM Zn treatment, the concentration of cadmium in the shoot tissue of *T. caerulescens* reached 1290 mg/kg without showing any visible signs of cadmium or zinc toxicity (Brown et al., 1995). Another example is *Alyssum murale*, a nickel hyperaccumulator capable of bioaccumulating more than 1% of its dry weight (Baker & Brooks, 1989). Hyperaccumulator plants like *Alyssum murale* and *Alyssum corsicum* are capable of accumulating up to 400 kg of nickel per hectare (Ali et al., 2013). *Nerium indicum* and *Platanus acerifolia* were effective in sequestering copper (Cu) pollution, *Pittosporum tobira* was effective in decreasing zinc (Zn) and cadmium (Cd) pollution, and *Cedrus deodara* was effective in reducing lead (Pb) and cadmium (Cd) pollution (Liang et al., 2017). Several plant species, including *Crotalaria micans*, *Leucaena leucocephala*, *Bidens pilosa*, *Pueraria lobata*, and *Conyza canadensis*, have been shown to effectively remove Ni from a serpentine site in Taiwan (Ho et al., 2013). *Berkheya coddii* exhibits a high tolerance to nickel (Ni) in its environment and within its tissues, efficiently absorbing and transporting Ni from the roots to the shoots (Van Der Ent et al., 2015). An experiment conducted in New Zealand found that it takes two years for *B. coddii* to remediate moderately Ni-contaminated soils (100 mg Ni/kg) to meet the European Union's standard of 75 mg Ni/kg. However, for heavily polluted soils (2000–10,000 mg Ni/kg), with a biomass production of 22 t/ha, the cleanup process takes approximately 34 to 138 years (Koptsik, 2014). Salix species, such as *Salix alba* and *S. viminalis*, are effective accumulators of heavy metals like zinc (Zn), nickel (Ni), and cadmium (Cd), and their rapid growth and substantial biomass production make them suitable for phytoremediation of contaminated soils (Mleczek et al., 2010; Kovačević et al., 2025). *Pteris vittata* has been recognized for its ability to efficiently absorb, transport, and store arsenate (AsV) and arsenite (AsIII) in its tissues (Gonzaga et al., 2006).

Table 4. List of some plants having metal accumulation potential

Metal	Plants Used	References
Ni	*Alyssum murale* *Alyssum corsicum* *Berkheya coddii*	Baker & Brooks, 1989; Van Der Ent et al., 2015
Cd, Cu, Hg, Ni, Zn	*Salix* sp.	Mleczek et al., 2010; Kovačević et al., 2025
Pb, Cd	*Cedrus deodara*	Liang et al., 2017
Zn, Cd, Ni, Pb	*Thlaspi caerulescens*	Baker & Brooks, 1989
As	*Pteris vittata*	Gonzaga et al., 2006
Pb, Zn	*Nerium oleander*	Doganlar et al., 2012
Pb, Cd, Cu, Zn	*Eucalyptus cladocalyx*	Alatou & Sahli, 2019
Pb	*Ficus religiosa*	Agrahari et al., 2018
Cd	*Solanum nigrum*	Sun et al., 2006
Zn	*Arabidopsis halleri*	Baker & Brooks, 1989
Cd	*Azolla pinnata*	Rai, 2008
Cd, Pb	*Delonix regia*	Ismail et al., 2013

6. Challenges

Phytoremediation has emerged as a sustainable and cost-effective strategy for mitigating heavy metal contamination in soil, water, and air. However, several challenges limit its large-scale application and effectiveness (Salt et al., 1995; Reeves & Baker, 2000; Ghosh & Singh, 2005; Mahar et al., 2016). The use of phytoremediation is limited to shallow soils, streams, and groundwater with lower contaminant concentrations.

- Limited to topsoil remediation as most plant roots cannot reach deep contamination layers.
- A slow process requiring multiple growing seasons for significant results.
- Depends on suitable plant species that tolerate heavy metals, grow quickly, and accumulate contaminants.
- High metal concentrations can be toxic to plants, reducing growth and effectiveness.
- Metals bound to soil components may not be bioavailable for plant uptake.
- Accumulated metals in plants can pose risks if they enter the food chain.
- Harvested biomass with metals requires safe disposal or treatment to prevent recontamination.
- Not effective in sites with mixed contaminants, extreme toxicity, or poor environmental conditions.

7. Conclusion and future prospectives

Heavy metal pollution has emerged as a significant environmental concern due to its persistent and non-biodegradable nature, posing severe threats to soil health, plant growth, and human well-being. Traditional remediation techniques, though effective in certain contexts, are often costly, energy-intensive, and environmentally disruptive. Phytoremediation offers a sustainable, eco-friendly, and cost-effective alternative by utilizing plants' natural ability to absorb, accumulate, and detoxify heavy metals from contaminated environments. Various plant species, including hyperaccumulators and bioindicators, have shown potential in mitigating heavy metal pollution through mechanisms like phytoextraction, rhizofiltration, and phytostabilization. Species such as *Thlaspi caerulescens* (for Cd, Zn, Ni), *Pteris vittata* (for As), *Alyssum murale* (for Ni), and *Salix* sp. (for Zn, Cd, Ni) are highly effective due to their high accumulation capacity, rapid growth, and tolerance to harsh conditions. The selection of suitable plants with traits like high biomass, fast growth, tolerance to harsh conditions, and resistance to pests is crucial for successful phytoremediation.

The future of phytoremediation lies in genetic engineering and biotechnology which hold great potential in enhancing the metal tolerance and accumulation capacity of plants, creating genetically modified hyperaccumulators tailored for specific contaminants. Advances in soil amendments and chelator application can further optimize metal uptake by plants. Furthermore, integrating phytoremediation with other remediation techniques, such as microbial-assisted remediation, could enhance its efficiency and widen its applicability. Extensive research is required to identify and study native plant species with phytoremediation potential, especially in polluted regions.

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