

Phytoremediation: *In situ* Alternative for Pollutant Removal from Contaminated Natural Media: A Brief Review

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Abstract: Phytoremediation is an *in situ* application by planting crops in areas of contaminated soil. The contaminated media treated by phytoremediation are soil, sediment, sludge, ground, surface, and wastewater. It is a potential method to prevent toxic contaminants from entering the food chain and conserves biological diversity. This innovative technique uses plant species with good biomass yield to alleviate contaminant toxicity in various polluted media in an ecosystem, and harvestable parts of the plants will turn up into bioenergy. This sustainable and cost-effective technology is a fast emerging alternative as compared to conventional remediation methods. Based on literature obtained from different search engines, this review will be beneficial in gathering and critically analyzing the earlier published data for making a new milestone in the field of phytoremediation.

Keywords: pollutants; heavy metals; phytoremediation; mechanism; environment.

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1. Introduction

Phytoremediation, a green technology, is an alternative practice to regulate and conserve the soil medium from being polluted with heavy metal contents through hyperaccumulator plants species [1]. Phytoremediation uses plants and microorganisms *via* enzymatic reactions to remove pollutants from the soil [2]. Phytoremediation is widely used in landfill, agricultural, and industrialization areas to treat contaminated soils [3]. The main aim of phytoremediation is to stop the migration of pollutants to ecosystems [4]. This cost-effective and environmentally friendly technology performs effectively and has a high tolerance for organic and inorganic pollutants. High biomass species such as herbaceous field crops are used to improve the efficiency of accumulating and removing pollutants from the contaminated soil [5]. The socioeconomic values of phytoremediation through biomass productions as well as generating bioenergy can add socioeconomic values to strengthen the national economy. The high biomass plants are usually used for the production of wood and paper [6]. The anthropogenic and occupational activities such as industrial processes, modern agricultural practices, untreated chemical waste, and municipal waste disposal have made humans' health more vulnerable to toxic metals [7]. Various industrial processes such as

mining, smelting, electroplating, energy and fuel production, agricultural activities, chemical waste discharge, and sewage are responsible for heavy metal contamination in soil [8]. The movement of heavy metals into non-contaminated sites causes adverse effects on the environment. The high amount of heavy metals affects the soil microorganisms and is dangerous for the plants' growth, reducing agriculture productivity, soil fertility, and biomass [9]. The plants producing a high amount of biomass accumulate heavy metals from the soil by phytoextraction [10] and bioaccumulate heavy metals in the food chain [11].

Metals are essential in the life process of living organisms. Metals such as iron, chromium, copper, calcium, magnesium, lead, cobalt, manganese, chlorine, zinc, molybdenum, and sodium serve as micronutrients to speed up plant growth. However, the major component of inorganic contaminants in the geo-environment are mainly heavy metals. Heavy metal in high concentration turns toxic, hazardous, and harmful to the environment and living organisms. Heavy metal pollutants can alter the chemical, biological, and physical or radiological integrity of soil and water by causing adverse effects to the living organisms and interfering with the food chains in an ecosystem [12]. Metals in low concentration are vital for living organisms, providing the essential cofactors for enzymes to perform biological reactions. Metals are toxic at higher concentrations, leading to oxidative stress by generating free radicals. In high concentration, metals can act deleteriously by blocking important functional groups, modifying or replacing important metals in pigments or enzymes of biological organisms, and causing damages to their function [13]. Thus, heavy metals make land unsuitable for plant growth, affect the function of microorganisms in the soil, destroy biodiversity, and reduce soil fertility. Soil medium possessing excessive heavy metals causes low crop yield and acute or chronic diseases to humans through the food chain. Heavy metal accumulates in the organism's tissues or organs through the bioaccumulation process. It is transferred into the food chain from the primary consumer to the tertiary consumer, known as biomagnification [14]. Long exposure to heavy metals can cause cancer, skin irritation, damage to organs, congenital disabilities, mutations, cardiovascular diseases, reduced growth rate, and development, and neurologic diseases [15]. Thus, herein, in this review, various aspects of phytoremediation have been briefly summarized.

2. Heavy Metals in the Environment

The biodegradable process assimilates pollutants and corrects most imbalances. However, heavy metals generated through anthropogenic and industrial pollution need to be eliminated. Lone *et al.* reported that various industrial and natural sources are the main sources of heavy metals [16]. The sources of heavy metals can be categorized into point sources and non-point sources. The point source is referred to as the discharge of heavy metal in a specific location, and the point of discharge is easily identified and regulated. An example of point sources is a discharge of chemical waste or leakage of chemical solutions, municipal waste, untreated sewage, drainage from mine areas, and emissions of poisonous gases into the water, air, and soil [17]. Sewage water contains pathogenic bacteria and viruses, organic matter, and nutrients, along with high levels of heavy metals and dissolved salts [18]. Non-point sources result from runoff or leaching of chemicals and sediments into the environment over a wide area. Non-point resources refer to air, soil, and water being polluted from various diffuse sources [19]. The usage of fertilizers, pesticides, and herbicides in modern agricultural practices contaminate the groundwater and soil structure, whereas heavy metals have been leached out and adversely affect the ecosystem [20]. This is known as non-point source water

pollution, which is very difficult to control and causes severe effects on the human population [21]. The unlimited usage of chemical fertilizers, herbicides, and pesticides in agricultural activities has introduced additional heavy metals in the particular ecosystem and bioaccumulation in crops [22]. Non-point sources like air pollution have caused hazardous effects on air quality from sources such as emissions of poisonous gases from factories and vehicles. The development urge for manufacturing factories as well the high demand for transportation keeps the emissions of poisonous gaseous accumulating in the atmosphere and result in it as a non-point source of pollution.

Cadmium is released into the atmosphere by mining and industrial activities, although countries have strict control in place for such pollution [23]. The largest source of cadmium hazardous exposure in human organs is tobacco smoke, although all forms of tobacco contain a certain amount of cadmium [24]. The inorganic cadmium salts are present in food while as, organic compounds of cadmium are comparatively unstable. In comparison to lead and mercury ions, cadmium ions are readily absorbed and distributed over the plant. Cadmium reaches edible leaves, fruits, and seeds and has been found concentrated in the core of kernels in grains like wheat and rice. Cadmium tends to accumulate in milk and fatty tissues [25]. Therefore, making society exposed to cadmium risk while consuming plants, animals, and seafood [26].

Chromium is used in stainless steel, chrome plating, and ceramics for corrosion resistance. It acts as a catalyst in the dyeing and tanning process of leather. Chromium (IV) oxide (CrO_2) is used to manufacture magnetic tape [27].

Petrochemicals, mining, painting, fertilizer, and fungicidal sprays are the key sources of mercury in the environment. Pesticides and pharmaceuticals products are some sources of mercury also [28].

Industries, leaded fuels, old lead plumbing pipes, and lead arsenate site production are sources that accumulate lead in the upper parts of the soil and have been found highly immobile to initiate long-term pollution [29].

Copper occurs naturally in the environment and is used in industries and agricultural activities. Decaying vegetation, mining, metal production, and phosphate fertilizers are the phenomena by which copper enters the environment. The soluble copper compounds pose a bigger threat to human health [30]. Zinc is disposed into the environment during industrial activities and sewage sludge from industrial areas [31].

3. Social Health Impact

The reduced growth and development, organ and nervous system damage, and cancer are caused by heavy metal exposure. Mercury and lead causes autoimmunity, thus damaging own cells. This also leads to rheumatoid arthritis, and diseases of the kidneys, damaging the fetal brain [32]. Arsenic inhibits the functional groups in enzymes. Arsenic poses a chronic effect leading to weight loss accompanied by gastrointestinal disorders. The long-term exposure to lower levels of arsenic decreases the production of blood cells, along with irregular heart function, damaged blood vessels, liver, kidney, and impaired nerve function [28]. Cadmium affects several organs along with the central nervous system. Cadmium compounds known as human carcinogens are mostly exposed to significantly higher cadmium levels compared to passive smokers. Besides, cadmium also severely affects the reproductive system and develops hepatic, hematological, and immunological disorders [33]. Chromium (III) can

be found naturally in vegetarian and non-vegetarian food. Excessive exposure to chromium (III) can lead to skin rashes.

Chromium causes adverse effects on human health, people particularly people working in steel and textile companies. It also causes allergies as it is used in clothes and leather products; even its inhalation can cause nasal irritation and bleeding [34]. Mercury affects the biochemical processes by changing electron transport phenomenon in organelles such as chloroplasts and mitochondria. Mercury poisoning leads to neurological and renal disorders as it tends to cross the blood-brain barrier and affect the brain [35]. Lead is toxic to flora and fauna, including microorganisms. The pollution due to lead contamination found in the environment due to its insoluble form poses a severe human health risk, like, brain damage and retardation. Copper exposure can irritate the nose, mouth, and eyes and cause stomachache, dizziness, vomiting, and diarrhea. Long-term exposure to copper affects the intelligence of the young population, and copper fumes, dust, or mists may result in changes in nasal mucous membranes. Chronic exposure to copper causes Wilson's disease, brain membrane damages, demyelination, renal disease, and copper deposition in the cornea [36]. Copper in the soil adheres to its organic matter and minerals. Copper by interrupting soil activity can affect the activity of microorganisms [37]. Zinc being a trace element, is vital for human growth. However, its excessive exposure leads to disturbed appetite, sense of taste and smell, slower wound healing, and skin sores. The excessive zinc intake can cause stomach cramps, skin irritations, vomiting, nausea, anemia, and arteriosclerosis [38].

4. Environment Impact

4.1. Soil pollution.

Soil is the fundamental resource for human civilization process, produces food, and has been used in constructions for a safe stay. Soil is comprised of organic matter, minerals, water, gases, and on the land surface, it takes space and is categorized by layers that are different of energy, matter and provide support to the rooted plants. Healthy soils can sustain biological productivity, regulate the nutrient cycles, decomposition of organic manure, protect the water quality and inactivate toxic compounds in the soil. Soil also acts as a buffer for temperature change, the hydrological cycle, and the flow of water between the atmosphere and groundwater [39].

Various anthropogenic activities pollute soil, and the level of pollutants in the soil medium exceeds the threshold limits. Soil is physically polluted by being covered with municipal waste or chemically polluted by chemical waste such as heavy metals and hazardous materials. The soil is also polluted biologically either by toxic materials or poor management, which exhausts its fertility and alters its chemical and biological properties to sustain a balanced ecological cycle. Thus, soil pollution results from the accumulation of persistent toxic compounds, chemical wastes, and radioactive materials in the soil. Intensive human activities have led to deforestation and land degradation resulting in severe environmental consequences with serious soil erosions. The source of soil pollution is directly linked to agricultural pollutants, industrial or urban waste accumulations, acidification by airborne pollutants, and oil spills. Agriculture activities give rise to direct and indirect pollution. Modern agriculture implementation in the huge scales of agriculture productions the usage of chemical fertilizers (nitrogen, phosphate, and potassium) is higher than the usage of organic fertilizers. The farmers prefer to use a high amount of chemical fertilizers to speed up the growth rate of plants and

increase food productions. Farmers use pesticides to avoid their plantations being degraded by insects and pests. Pesticides contain various types of organic compounds like atrazine, isoproturon, and lindane and contain heavy metals. Using chemical fertilizers, including pesticides in agricultural activities, causes tremendous effects on soil's biological, chemical, and physical properties, leading to infertile soil.

4.2. Water pollution.

The natural dissolution process or change in soil pH helps heavy metals to get solubilized in groundwater. The sources of groundwater pollution are similar to soil pollution, including landfills, accidental oil spills, agricultural activities, septic tanks, and atmospheric depositions. The groundwater is polluted by heavy metals from sources like a landfill and sewage, leachate from tailings, disposal of liquid wastes, leaked industrial waste, or industrial spills and leaks [40]. The dissolved pollutants from soil water move to groundwater, while organic pollutants freely reach groundwater [41].

5. Phytoremediation

Phyto means plant, and medium means a process to repair, degrade, stabilize, remove, clean, or regulate the soil medium from adverse pollution effects by heavy metals. Phytoremediation involves green plants for removing contaminants from the soil to reinstate the area for public use [42]. Phytoremediation remediates certain contaminants from polluted soil, sludge, sediment, groundwater, surface, and wastewater partially or substantially involving biological process remediation [43]. It is also considered a clean, cost-effective, simple, and environmentally friendly remediation strategy [44]. Phytoremediation *via* mechanisms like phytoextraction, phytodegradation, phytovolatilization, phytostabilization, photodegradation, hemofiltration and phytodesalination remediate contaminants from different polluted media [45]. Table 1 shows the summaries of the descriptions of the phytoremediation process.

Table 1. The Phytoremediation Mechanisms. Modified Source: Ali *et al.*, 2013, Reprinted with permission from Elsevier License Number: 5091820689303; 18th May 2021).

Mechanism	Description
Phytoextraction	The contaminants are stored in shoot tissue by translocation and the harvestable parts of roots.
Phytodegradation	Organic contaminants are broken by the enzymatic process.
Phytovolatilization	Leave surfaces via stomata gas exchange helps in contaminant remediation.
Phytostabilization	An adsorption process in combination with the accumulation, precipitation phenomenon immobilize contaminants within the root zone.
Rhizodegradation	The degradation of contaminants by soil microbes in plant root zones.
Rhizofiltration	The contaminant storage by plants after root uptake from an aqueous growth medium.
Phytodesalination	The removal of salts by plant species mainly in saline soils.

The different uptake of organic and inorganic contaminants through phytoremediation mechanisms and in a different matrix (soil and aqueous medium) are shown in Figure 1. The organic contaminants can be removed from polluted media by phytodegradation, phytovolatilization, phytostabilization, rhizodegradation, and rhizofiltration. At the same time, inorganic pollutants, such as heavy metals, are removed through phytoextraction, phytostabilization, rhizofiltration and phytovolatilization.

Mahawar *et al.*, reported that *Vigna radiata* L. (Wilczek) accumulated a significant amount of metal in the plant tissues [46].

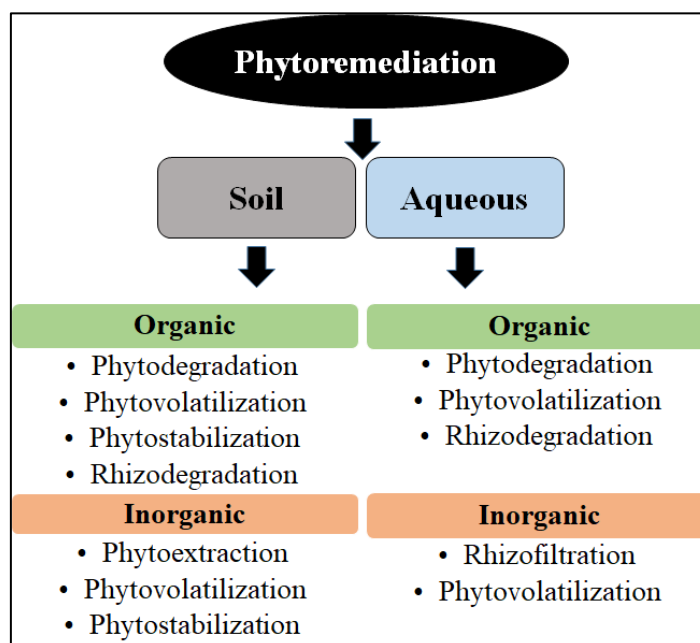


Figure 1. Various mechanisms in phytoremediation as a function of organic and inorganic pollutants in soil and aqueous surface medium.

Dai *et al.* stated that plant *Bidens pilosa* L. remediated cadmium even from clean soil and hypothesized that ecotypes of hyperaccumulator in different climate zone may exhibit a varying degree of phytoremediation potential [47]. Nawrot *et al.*, compared the bioconcentration factor (BF) and translocation factor (TF) along with plant morphology in Suncont and found that Suncont seedlings presented better properties and adaptability for phytoremediation purposes[48]. Rathika *et al.*, 2021 revealed that *Brassica juncea* could be used to remediate lead-contaminated soil [49]. Kumar *et al.* reported the elimination of copper from the soil by the roots of *Odontarrhena obovata* (*Alyssum obovatum*), and it was suggested that in the combination of plant growth-promoting (PGP) microorganisms, the copper uptake could occur effectively [50]. Vetiver grass (*Chrysopogon zizanioides*) was used by Chintani *et al.* to remediate Cr and Ni from the soil by using different metal concentrations. This grass exhibited higher remediation towards Cr as compared to Ni [51]. They established that *C. zizanioides* could be used for less polluted sites. Cruzado-Tafur *et al.* used various plant family species to study their potential to be used for phytoremediation purposes [52]. With the help of statistical analysis and other component analysis, Lisiak-Zielińska *et al.* revealed by their correlation study among different heavy metals in a plant (*Taraxacum officinale*) [53]. They found that different metals were translocated to different parts with varying degrees of concentration. *Mangifera persiciforma*, *Bischofia javanica*, *Neolamarckia cadamba*, three other plants *Dianella ensifolia*, *Syngonium podophyllum*, and *Schefflera odorata* were used for heavy metal remediation by Wu *et al.* [54]. They used these planting landscape tree and ground cover plants for the phytoremediation of heavy metals. Therefore, the plants used to phytoremediate the contaminants can generate the solid biomass, which either can be utilized for extraction for metals for other beneficial commercial purposes.

5.1. Mechanisms of phytoremediation.

There are seven main mechanisms (phytoextraction, phytodegradation, phytovolatilization, phytostabilization, rhizodegradation, rhizofiltration, phytodesalination)

which describes the activity or processes carried out by the plants to remove the contaminants (Figure 2) [55,56].

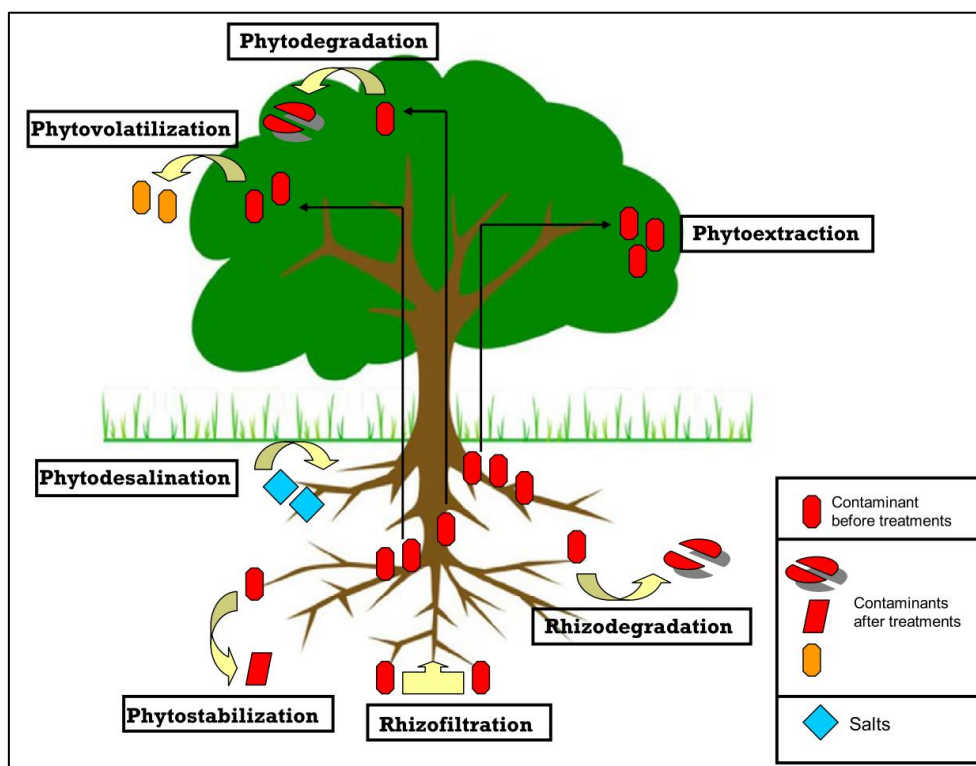


Figure 2. A detailed mechanism of phytoremediation of contaminated soil [56]. Reprinted with permission from Elsevier.

5.1.1. Phytoextraction.

Phytoextraction or phytoaccumulation or phytosequestration and phytoabsorption are mechanisms by which plants translocate contaminants, absorb and store in shoots tissue and the parts of roots [57,58]. The plants eliminate or accumulate heavy metals from solid or liquid media by taking metals essential for plant growth, e.g., Fe, Mn, Zn, Cu, Mg, Mo, and Ni. The metals (Cd, Cr, Pb, Co, Ag, Se, and Hg) with unknown biological functions have been also reported [59]. In phytoextraction, phytomining, or biomining, plants are used to get an economic return by extracting from metals by a plant from polluted containing a high concentration of metals. The process can be applied in mining to produce and accumulate metals by cropping [60]. Phytoextraction is an effective approach to remove the contamination without disturbing the soil structure and fertility [61]. This process can be used to remediate pollutants from diffusely polluted areas, an area where they occur in low concentrations. The effectiveness of the phytoextraction mechanism depends upon selecting appropriate plant species that remediate heavy metals and generate large biomass employing known crop production and management practices [62].

5.1.2. Phytodegradation.

By phytodegradation (phytotransformation), organic contaminants in plants are degraded by enzymes like oxygenase and dehalogenase, particularly to degrade chlorinated solvents and pesticides nitroreductases which are involved in the degradation of nitroaromatic compounds [63]. The phytodegradation process takes place within plant tissue, and it breaks down the contaminants by metabolic processes. The plants can accumulate organic

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contaminants and decompose them by metabolic reactions. The herbicides, insecticides, and chlorinated solvents are broken down into simpler molecules and absorbed by the plant's roots to speed up their growth. Phytodegradation or phytotransformation and is simply a contaminant destruction process.

5.1.3. Phytovolatilization.

The uptaken pollutants by plants are released to the environment *via* transpiration or volatilization. In this mechanism, organic pollutants and heavy metals such as selenium (Se), mercury (Hg), and arsenic (As) are transformed enzymatically into volatile forms [64]. Phytovolatilization occurs in growing plants and trees, which uptakes nutrients, water, and the organic contaminants present in the soil structures. The contaminants pass through the plant's roots and reach the leaves' surface, where they will be volatilized and evaporate from the stomata into the atmosphere.

5.1.4. Phytostabilization.

Phytostabilization is the technique used by selected plant species for the stabilization of organic or inorganic contaminants. This technique reduces the bioavailability of contaminants and checks the track of migration towards the groundwater and food chain. This mechanism is used to restore a plantation cover at sites where the native vegetation is lacking due to the high metal concentrations in the soil structure. The phytostabilization shrinks the accumulation of heavy metals and limits their leaching into water resources [65].

5.1.5. Rhizodegradation.

Rhizodegradation is an enzymatic degradation of pollutants in soil media microorganisms [66]. The microorganisms such as worms, algae, fungi, and bacteria consumed and decomposed organic substances for nutrition, continuous energy flow, and nutrient cycles.

5.1.6. Rhizofiltration.

The process is quite similar to the phytoextraction mechanism where hyperaccumulator plants accumulate the heavy metals from the soil, whereas hemofiltration is performed *via* the accumulation of heavy metals by plants roots in the aqueous medium. The plants have been planted at the contaminated river site nearby landfill areas or industrial waste dumping area to perform their function by removing the heavy metals present in groundwater. Saturated roots with heavy metals after harvesting should be disposed of safely. The plants with higher root biomass and high accumulating capacity of heavy metal and tolerance to contaminants possess high efficiency of contaminant removal from the soil [67].

5.1.7. Phytodesalination.

Phytodesalination utilizes halophytic plants salts from salt-affected soils [45]. Halophytic plants are considered well adapted to tolerate heavy metals compared to glycophytic plants [68]. For example, the potential of *Suaeda maritima* and *Sesuvium portulacastrum* in accumulation and absorption of Sodium Chloride (NaCl) from highly saline soil medium has been studied [69]. Shelef *et al.*, 2012, 2011, 2010 proved that halophyte plants

could reduce the salinity of wastewater, *Bassia indica* is an annual halophyte with unique adaptations for salt tolerance [70–72].

5.2. Growth strategies of plants in contaminated soils.

Plants can be grouped into excluders, indicators, and hyperaccumulators [73]. Metal excluders plant species prevent metals translocation or accumulation to the aerial parts although retain high amounts of metals in root tissues [74]. Metal indicators retain metals in the tissues above the ground levels similar to those surrounding soil with linear relations concerning concentration. Metal hyperaccumulator plant species translocate actively concentrated metals in the shoots at levels higher than in soil. Jaffre *et al.* were the first researchers who introduced the term hyperaccumulation to describe plant species *Sebertia accuminata* that accumulates higher concentrations [75]. The plants accumulate heavy metals from the soil, categorized as micronutrients, and play an essential role in speeding up and ensuring healthy plant growth [76]. Several plant species can grow in soil with high concentrations of certain elements that are toxic to other sensitive plants. The metal hyperaccumulating plant species accumulate, translocate, and tolerate the larger amount of heavy metals during their entire growth cycle, attributed to their fast-growing characteristics along with a high rate of biomass production [77].

The hyperaccumulator plant species accumulate the heavy metals 50 to 100 times higher and remove metals efficiently compared to other non-accumulator plants species [78,79]. Many plant species have been identified which are effective for phytoremediation. The fast-growing plant species producing high biomass accumulates an adequate amount of metals in shoots and are being exploited for phytoextraction of heavy metals from contaminated soil media.

6. Phytomining

Phytomining is also known as phytoextraction using hyperaccumulator plant species with good biomass yield to eliminate heavy metals from the soil. The capability of hyperaccumulator plants to extract metals from soils that can be exploited to recover metals ore deposits. This technology, through cropping, can recover metals from mining industries, and extra profit can be generated. The countries enriched with metals such as gold, silver, iron, copper can potentially phytomining these metals. The phytoextraction represents a sustainable reprocessing process by which a higher value product can be obtained. The mining industries, e.g., gold, iron, tin, manganese, silver, platinum, copper, zinc, lead, chromium, nickel, titanium, bauxite, and pyrite, can be benefited by phytomining.

7. Advantages and Limitations of Phytoremediation

7.1. Advantages of phytoremediation.

The techniques of phytoremediation to control the contamination of heavy metal pollution have advantages and disadvantages, which requires critical research on plants and soil conditions to improve and understand the mechanism accurately [65]. Phytoremediation practices can be considered eco-friendly compared to the physical and chemical processes, which poses a greater threat to the ecosystem. The advantages primarily include effectiveness in contaminant accumulation and removal, low cost, applicability for different contaminants,

and environmentally friendly mechanism [80]. Another benefit of green plants' heavy metal remediation technology is the reducing capability of heavy metal ions to minimal levels. Phytoremediation is used in the remediation of selected hazardous and toxic sites. It evades the excavation process and transport of polluted substances and lowers the risk of contamination and spreading. A phytoremediation is a low-cost approach for removing contaminants from environmental media. It is more appropriate for large sites with moderate contamination levels, and at the same time, specific disposal sites are not needed [81]. Phytoremediation is an economical treatment for waste sites containing hazardous contaminants, particularly in industrialization areas, to shrink the mobility of heavy metals via groundwaters. It can be applied to various toxic metals and can cover a broad range of environmental contaminants [82].

Phytoremediation can replace conventional techniques and save biological components of the soil from obliteration. Phytoremediation helps the soil by improving the soil ecosystem and reducing the cost multifold times compared to the cost that occurs for currently adopted technologies. Besides, it can generate a recyclable metal-rich plant residue.

Phytoremediation along with removing pollutants can produce biomass which can be changed in the form of bioenergy resources. The hyperaccumulating plants can be an alternative bioenergy crop [83].

7.2. Limitations of phytoremediation.

The effectiveness of phytoremediation technologies to accumulate and regulate the contaminated soil is restricted to hyperaccumulator plants. Phytoremediation remediates pollutants adhered to the soil surface, mostly non-leachable. The removal of contaminants requires their contact with the roots of plants. This can be achieved by standard agricultural practices or irrigating plants with contaminated water, but such activities can generate contaminants with a potential threat. The lengthy and time-consuming remediation by plants is a lengthy process. It has been reported that it takes several years or longer to remediate the waste site. The consumption of contaminated plants by wildlife will lead to bioaccumulation in the food chain. The generated biomass after phytoextraction can be considered hazardous waste.

Furthermore, preserving the vegetation in extensively contaminated areas is challenging and will pose a greater risk to human health as pollutants can enter the food chain [84]. Phytoremediation efficiency of plants is restricted by their slow growth rate and generation of lower biomass of certain plant species, particularly hyperaccumulator plants. Phytoremediation needs clean-up time as compared to conventional physical or chemical techniques. The contaminated soils are also poor in macronutrients, which limit plant growth, thus slowing the remediation process. In addition, the microbial populations in the contaminated soils are repeatedly reduced in both diversity as well as abundance. The contaminated soils do not contain the appropriate microorganisms for the effective degradation of the contaminants, thus limiting the phytoremediation technology's effectiveness.

8. Prospects in Using Selected Crops for Phytoremediation

Phytoremediation is an emerging environmentally friendly technology using hyperaccumulator plant species. The hyperaccumulator plant species with high biomass has the potential to accumulate hazardous heavy metals discharged into the environment by natural

or anthropogenic activities. Meers *et al.* have studied the potential of crop *Zea mays* for the phytoremediation of heavy metals on contaminated soils [85]. *Zea mays* tend to accumulate heavy metals from the contaminated medium to the harvestable area. The heavy metals near the roots play an essential part by stabilizing the active heavy metal and reducing the heavy metal leaching into the groundwater and dispersion into the vast area. Indian mustard (*Brassica juncea*) and Amaranth (*Amaranthus paniculatus*) have hyperaccumulation traits where they can accumulate a high concentration of lead and copper [86]. *Brassica juncea* has been consumed by people in their daily diet. The hyperaccumulator short rotation plants can be planted on a huge scale to remediate the soil and meet people's needs. *Bassia indica* has also been used for salt phytoremediation in constructed wetlands. *Bassia indica* is an annual halophyte with exclusive adaptations for salt tolerance [68]. Kumar *et al.* revealed that *Spinacia oleracea* has the hyperaccumulating characteristic of accumulating more heavy metals to reduce pollution [50]. *Sorghum* species have been used to remediate heavy metals cadmium and zinc contaminated soil. The heavy metals were accumulated primarily in the roots of sorghum plants. The metals applied at lower concentrations were less toxic in the shoots compared to their effect in roots. It is safe to be consumed by people as well as wild animals. *Sorghum bicolor* has also been used commercially in ethanol productions [87]. Transgenic plants can phytoremediate toxic metals from contaminated soil [88,89]. Reed beds plant can accumulate Zinc and Chromium and perform the phytoremediation mechanisms [90]. *Jatropha curcas*, locally known as "Pokok Jarak" has been planted commercially to generate biodiesel which is cost-effective, bio-degradable, renewable energy, eco-friendly products, and non-toxic compared to petrol-diesel. *Jatropha curcas* is a potential biofuel plant for sustainable environmental development [91]. The plant species has been encouraged for extensive plantations in the polluted area across the world. Mangrove plant species *Sonneratiac aseolaris* accumulate heavy metals and serve essential functions in the estuarine ecosystem and serve as a habitat for various species such as mammals, reptiles, birds, crabs, and insects [92]. The crops like rapeseed, maize, wheat, and short rotation coppice, grew on contaminated soil and can be used for metal recovery and biogas production. The production of bioenergy from such plants can be determined by their phytoextraction potential, the destiny of heavy metals contaminants in the plants, and lastly, the potential use of such crops for the sustainable management of polluted soils [93].

9. Conclusions

Phytoremediation of pollutants is a fast-growing technology. This cost-effective technology is an alternative to the conventional remediation process of contaminants removal from soil. The fast-growing plants with high biomass and good metal uptake ability are used for phytoremediation. The bioaccumulation of contaminants in the food chain can be avoided by using non-edible plant species. Besides, plants with high biomass have been used to formulate biodiesel, which can substitute fuel energy for petrol-diesel. Thus, it can be stated that phytoremediation has tremendous potential for removing contaminants like heavy metals and hence can be used for the protection of the environment and alleviating risk to human health.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Saxena, G.; Purchase, D.; Mulla, S.I.; Saratale, G.D.; Bharagava, R.N. Phytoremediation of heavy metal-contaminated sites: Eco-environmental concerns, field studies, sustainability issues, and future prospects. In *Reviews of Environmental Contamination and Toxicology* **2020**, *249*, 71–131.
2. Greipsson, S. Phytoremediation. *Nature Education Knowledge* **3** (10): 7 <http://www.nature.com/scitable/knowledge/library/phytoremediation-...> 1 of 5 1/1/2015 11: 41 PM. *Figure* **2011**, *2*, 2.
3. Urionabarrenetxea, E.; Garcia-Velasco, N.; Anza, M.; Artetxe, U.; Lacalle, R.; Garbisu, C.; Becerril, T.; Soto, M. Application of *in situ* bioremediation strategies in soils amended with sewage sludges. *Sci. Total Environ.* **2021**, *766*, 144099, <https://doi.org/10.1016/j.scitotenv.2020.144099>.
4. Wang, L.; Hou, D.; Shen, Z.; Zhu, J.; Jia, X.; Ok, Y.S.; Tack, F.M.G.; Rinklebe, J. Field trials of phytomining and phytoremediation: A critical review of influencing factors and effects of additives. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 2724–2774, <https://doi.org/10.1080/10643389.2019.1705724>.
5. Poonam; Bhardwaj, R.; Sharma, R.; Handa, N.; Kaur, H.; Kaur, R.; Sirhindi, G.; Thukral, A.K. Prospects of Field Crops for Phytoremediation of Contaminants. In *Emerging Technologies and Management of Crop Stress Tolerance*; Elsevier **2014**, *2*, 449–470 ISBN 9780128010877.
6. Licht, L.A.; Isebrands, J.G. Linking phytoremediated pollutant removal to biomass economic opportunities. *Biomass and Bioenergy* **2005**, *28*, 203–218, <https://doi.org/10.1016/j.biombioe.2004.08.015>.
7. Rai, P.K.; Lee, S.S.; Zhang, M.; Tsang, Y.F.; Kim, K.H. Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environ. Int.* **2019**, *125*, 365–385, <https://doi.org/10.1016/j.envint.2019.01.067>.
8. Samarghandi, M.R.; Nouri, J.; Mesdaghinia, A.R.; Mahvi, A.H.; Nasser, S.; Vaezi, F. Efficiency removal of phenol, lead and cadmium by means of UV/TiO₂/H₂O₂ processes. *Int. J. Environ. Sci. Technol.* **2007**, *4*, 19–25, <https://doi.org/10.1007/BF03325957>.
9. Yu, H.; Zheng, X.; Weng, W.; Yan, X.; Chen, P.; Liu, X.; Peng, T.; Zhong, Q.; Xu, K.; Wang, C.; *et al.* Synergistic effects of antimony and arsenic contaminations on bacterial, archaeal and fungal communities in the rhizosphere of *Miscanthus sinensis*: Insights for nitrification and carbon mineralization. *J. Hazard. Mater.* **2021**, *411*, 125094, <https://doi.org/10.1016/j.jhazmat.2021.125094>.
10. Oh, K.; Li, T.; Cheng, H.; Hu, X.; He, C.; Yan, L.; Shinichi, Y. Development of Profitable Phytoremediation of Contaminated Soils with Biofuel Crops. *J. Environ. Prot. (Irvine, Calif.)* **2013**, *04*, 58–64, <https://doi.org/10.4236/jep.2013.44a008>.
11. Purakayastha, T.J.; Chhonkar, P.K. Phytoremediation of Heavy Metal Contaminated Soils. In **2010**, 389–429.
12. Marmiroli, N.; Maestri, E. Trace elements contamination and availability: human health implications of food chain and biofortification. *Trace Elem. as Contam. Nutr. Consequences Ecosyst. Hum. Heal. John Wiley & Sons Inc.*, New York **2008**, 23–53.
13. Malayeri, B.E.; Chehregani, A.; Yousefi, N.; Lorestani, B. Identification of the hyper accumulator plants in copper and iron mine in Iran. *Pakistan J. Biol. Sci.* **2008**, *11*, 490–492, <https://doi.org/10.3923/pjbs.2008.490.492>.
14. Yousafzai, A.M.; Ullah, F.; Bari, F.; Raziq, S.; Riaz, M.; Khan, K.; Nishan, U.; Sthanadar, I.A.; Shaheen, B.; Shaheen, M.; *et al.* Bioaccumulation of Some Heavy Metals: Analysis and Comparison of *Cyprinus carpio* and *Labeo rohita* from Sardaryab, Khyber Pakhtunkhwa. *Biomed Res. Int.* **2017**, *2017*, 1–5, <https://doi.org/10.1155/2017/5801432>.
15. Gisbert, C.; Ros, R.; De Haro, A.; Walker, D.J.; Bernal, M.P.; Serrano, R.; Navarro-Aviñó, J. A plant genetically modified that accumulates Pb is especially promising for phytoremediation. *Biochem. Biophys. Res. Commun.* **2003**, *303*, 440–445, [https://doi.org/10.1016/S0006-291X\(03\)00349-8](https://doi.org/10.1016/S0006-291X(03)00349-8).
16. Lone, M.I.; He, Z.L.; Stoffella, P.J.; Yang, X.E. Phytoremediation of heavy metal polluted soils and water: Progresses and perspectives. *J. Zhejiang Univ. Sci. B* **2008**, *9*, 210–220, <https://doi.org/10.1631/jzus.B0710633>.
17. Khatri, N.; Tyagi, S. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Front. Life Sci.* **2015**, *8*, 23–39, <https://doi.org/10.1080/21553769.2014.933716>.
18. Sharma, S.; Bhattacharya, A. Drinking water contamination and treatment techniques. *Appl. Water Sci.* **2017**, *7*, 1043–1067, <https://doi.org/10.1007/s13201-016-0455-7>.
19. Jain, C.K.; Singh, S. Best management practices for agricultural non-point source pollution: Policy

- interventions and way forward. *World Water Policy* **2019**, *5*, 207–228, <https://doi.org/10.1002/wwp2.12015>.
20. Zhang, L.; Yan, C.; Guo, Q.; Zhang, J.; Ruiz-Menjivar, J. The impact of agricultural chemical inputs on environment: Global evidence from informetrics analysis and visualization. *Int. J. Low-Carbon Technol.* **2018**, *13*, 338–352, <https://doi.org/10.1093/ijlct/cty039>.
 21. Liu, Y.; Li, H.; Cui, G.; Cao, Y. Water quality attribution and simulation of non-point source pollution load flux in the Hulan River basin. *Sci. Rep.* **2020**, *10*, 3012, <https://doi.org/10.1038/s41598-020-59980-7>.
 22. He, H.; Shi, L.; Yang, G.; You, M.; Vasseur, L. Ecological risk assessment of soil heavy metals and pesticide residues in tea plantations. *Agric.* **2020**, *10*, 47, <https://doi.org/10.3390/agriculture10020047>.
 23. Tchounwou, P.B.; Yedjou, C.G.; Patlolla, A.K.; Sutton, D.J. Heavy metal toxicity and the environment. In *Exs* **2012**, *101*, 133–164.
 24. Ganguly, K.; Levänen, B.; Palmberg, L.; Åkesson, A.; Lindén, A. Cadmium in tobacco smokers: A neglected link to lung disease? *Eur. Respir. Rev.* **2018**, *27*, 170122, <https://doi.org/10.1183/16000617.0122-2017>.
 25. Figueroa B., E. Are more restrictive food cadmium standards justifiable health safety measures or opportunistic barriers to trade? An answer from economics and public health. *Sci. Total Environ.* **2008**, *389*, 1–9, <https://doi.org/10.1016/j.scitotenv.2007.08.015>.
 26. Castro-González, M.I.; Méndez-Armenta, M. Heavy metals: Implications associated to fish consumption. *Environ. Toxicol. Pharmacol.* **2008**, *26*, 263–271, <https://doi.org/10.1016/j.etap.2008.06.001>.
 27. Valix, M.; Cheung, W.H.; Zhang, K. Role of heteroatoms in activated carbon for removal of hexavalent chromium from wastewaters. *J. Hazard. Mater.* **2006**, *135*, 395–405, <https://doi.org/10.1016/j.jhazmat.2005.11.077>.
 28. Mudgal, V.; Madaan, N.; Mudgal, A.; Singh, R.B.; Mishra, S. Effect of Toxic Metals on Human Health. *Open Nutraceuticals J.* **2014**, *3*, 94–99, <https://doi.org/10.2174/18763960010030100094>.
 29. Tangahu, B.V.; Sheikh Abdullah, S.R.; Basri, H.; Idris, M.; Anuar, N.; Mukhlisin, M. A review on heavy metals (As, Pb, and Hg) uptake by plants through phytoremediation. *Int. J. Chem. Eng.* **2011**, *2011*, 1–31, <https://doi.org/10.1155/2011/939161>.
 30. Lamichhane, J.R.; Osdaghi, E.; Behlau, F.; Köhl, J.; Jones, J.B.; Aubertot, J.N. Thirteen decades of antimicrobial copper compounds applied in agriculture. A review. *Agron. Sustain. Dev.* **2018**, *38*, 28, <https://doi.org/10.1007/s13593-018-0503-9>.
 31. Mertens, J.; Smolders, E. Zinc. In **2013**, 465–493.
 32. Guerra, F.; Trevizam, A.R.; Muraoka, T.; Marcante, N.C.; Canniatti-Brazaca, S.G. Heavy metals in vegetables and potential risk for human health. *Sci. Agric.* **2012**, *69*, 54–60, <https://doi.org/10.1590/S0103-90162012000100008>.
 33. Apostoli, P.; Catalani, S. Metal ions affecting reproduction and development. In *Metal ions in life sciences*; De Gruyter **2011**, *8*, 263–303.
 34. Bregnbak, D.; Johansen, J.D.; Jellesen, M.S.; Zachariae, C.; Menné, T.; Thyssen, J.P. Chromium allergy and dermatitis: Prevalence and main findings. *Contact Dermatitis* **2015**, *73*, 261–280, <https://doi.org/10.1111/cod.12436>.
 35. Rice, K.M.; Walker, E.M.; Wu, M.; Gillette, C.; Blough, E.R. Environmental mercury and its toxic effects. *J. Prev. Med. Public Heal.* **2014**, *47*, 74–83, <https://doi.org/10.3961/jpmph.2014.47.2.74>.
 36. Członkowska, A.; Litwin, T.; Dusek, P.; Ferenci, P.; Lutsenko, S.; Medici, V.; Rybakowski, J.K.; Weiss, K.H.; Schilsky, M.L. Wilson disease. *Nat. Rev. Dis. Prim.* **2018**, *4*, 21, <https://doi.org/10.1038/s41572-018-0018-3>.
 37. Keiblinger, K.M.; Schneider, M.; Gorfer, M.; Paumann, M.; Deltedesco, E.; Berger, H.; Jöchlinger, L.; Mentler, A.; Zechmeister-Boltenstern, S.; Soja, G.; *et al.* Assessment of Cu applications in two contrasting soils—effects on soil microbial activity and the fungal community structure. *Ecotoxicology* **2018**, *27*, 217–233, <https://doi.org/10.1007/s10646-017-1888-y>.
 38. De Paula, R.C.S.; Aneni, E.C.; Costa, A.P.R.; Figueiredo, V.N.; Moura, F.A.; Freitas, W.M.; Quaglia, L.A.; Santos, S.N.; Soares, A.A.; Nadruz, W.; *et al.* Low zinc levels is associated with increased inflammatory activity but not with atherosclerosis, arteriosclerosis or endothelial dysfunction among the very elderly. *BBA Clin.* **2014**, *2*, 1–6, <https://doi.org/10.1016/j.bbacli.2014.07.002>.
 39. Zeiss, M.R. Soil health: Managing the biotic component of soil quality - Introduction. *Appl. Soil Ecol.* **2000**, *15*, 1–2, [https://doi.org/10.1016/S0929-1393\(00\)00066-4](https://doi.org/10.1016/S0929-1393(00)00066-4).
 40. Barakat, M.A. New trends in removing heavy metals from industrial wastewater. *Arab. J. Chem.* **2011**, *4*, 361–377, <https://doi.org/10.1016/j.arabjc.2010.07.019>.
 41. Hashim, M.A.; Mukhopadhyay, S.; Sahu, J.N.; Sengupta, B. Remediation technologies for heavy metal contaminated groundwater. *J. Environ. Manage.* **2011**, *92*, 2355–2388, <https://doi.org/10.1016/j.jenvman.2011.06.009>.
 42. Pilon-Smits, E. Phytoremediation. *Annu. Rev. Plant Biol.* **2005**, *56*, 15–39, <https://doi.org/10.1146/annurev.arplant.56.032604.144214>.
 43. Vishnoi, S.R., Srivastava, P.N. Phytoremediation—green for environmental clean. In Proceedings of the Proceedings of Taa I2007: the 12th World lake conference **2007**, *1016*, 1021.
 44. Gaur, N.; Flora, G.; Yadav, M.; Tiwari, A. A review with recent advancements on bioremediation-based abolition of heavy metals. *Environ. Sci. Process. Impacts* **2014**, *16*, 180–193,

- <https://doi.org/10.1039/c3em00491k>.
45. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of heavy metals-Concepts and applications. *Chemosphere* **2013**, *91*, 869–881, <https://doi.org/10.1016/j.chemosphere.2013.01.075>.
 46. Mahawar, L.; Popek, R.; Shekhawat, G.S.; Alyemeni, M.N.; Ahmad, P. Exogenous hemin improves Cd²⁺ tolerance and remediation potential in *Vigna radiata* by intensifying the HO-1 mediated antioxidant defence system. *Sci. Rep.* **2021**, *11*, 2811, <https://doi.org/10.1038/s41598-021-82391-1>.
 47. Dai, H.; Wei, S.; Skuza, L.; Zhang, Q. Phytoremediation of two ecotypes cadmium hyperaccumulator *Bidens pilosa* L. sourced from clean soils. *Chemosphere* **2021**, *273*, 129652, <https://doi.org/10.1016/j.chemosphere.2021.129652>.
 48. Nawrot, N.; Wojciechowska, E.; Pazdro, K.; Szmagliński, J.; Pempkowiak, J. Uptake, accumulation, and translocation of Zn, Cu, Pb, Cd, Ni, and Cr by *P. australis* seedlings in an urban dredged sediment mesocosm: Impact of seedling origin and initial trace metal content. *Sci. Total Environ.* **2021**, *768*, 144983, <https://doi.org/10.1016/j.scitotenv.2021.144983>.
 49. Rathika, R.; Srinivasan, P.; Alkahtani, J.; Al-Humaid, L.A.; Alwahibi, M.S.; Mythili, R.; Selvankumar, T. Influence of biochar and EDTA on enhanced phytoremediation of lead contaminated soil by *Brassica juncea*. *Chemosphere* **2021**, *271*, 129513, <https://doi.org/10.1016/j.chemosphere.2020.129513>.
 50. Kumar, A.; Tripti; Voropaeva, O.; Maleva, M.; Panikovskaya, K.; Borisova, G.; Rajkumar, M.; Bruno, L.B. Bioaugmentation with copper tolerant endophyte *Pseudomonas lurida* strain EOO26 for improved plant growth and copper phytoremediation by *Helianthus annuus*. *Chemosphere* **2021**, *266*, 128983, <https://doi.org/10.1016/j.chemosphere.2020.128983>.
 51. Chintani, Y.S.; Butarbutar, E.S.; Nugroho, A.P.; Sembiring, T. Uptake and release of chromium and nickel by Vetiver grass (*Chrysopogon zizanioides* (L.) Roberty). *SN Appl. Sci.* **2021**, *3*, 285, <https://doi.org/10.1007/s42452-021-04298-w>.
 52. Cruzado-Tafur, E.; Torró, L.; Bierla, K.; Szpunar, J.; Tauler, E. Heavy metal contents in soils and native flora inventory at mining environmental liabilities in the Peruvian Andes. *J. South Am. Earth Sci.* **2021**, *106*, 103107, <https://doi.org/10.1016/j.jsames.2020.103107>.
 53. Lisiak-Zielińska, M.; Borowiak, K.; Budka, A.; Kanclerz, J.; Janicka, E.; Kaczor, A.; Żyromski, A.; Biniak-Pieróg, M.; Podawca, K.; Mleczek, M.; *et al.* How polluted are cities in central Europe? - Heavy metal contamination in *Taraxacum officinale* and soils collected from different land use areas of three representative cities. *Chemosphere* **2021**, *266*, 129113, <https://doi.org/10.1016/j.chemosphere.2020.129113>.
 54. Wu, D.; Yu, X.; Lai, M.; Feng, J.; Dong, X.; Peng, W.; Su, S.; Zhang, X.; Wan, L.; Jacobs, D.F.; *et al.* Diversified effects of co-planting landscape plants on heavy metals pollution remediation in urban soil amended with sewage sludge. *J. Hazard. Mater.* **2021**, *403*, 123855, <https://doi.org/10.1016/j.jhazmat.2020.123855>.
 55. Peer, W.A.; Baxter, I.R.; Richards, E.L.; Freeman, J.L.; Murphy, A.S. Phytoremediation and hyperaccumulator plants. In *Topics in Current Genetics* **2006**, *14*, 299–340 ISBN 3540221751.
 56. Cristaldi, A.; Conti, G.O.; Jho, E.H.; Zuccarello, P.; Grasso, A.; Copat, C.; Ferrante, M. Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. *Environ. Technol. Innov.* **2017**, *8*, 309–326, <https://doi.org/10.1016/j.eti.2017.08.002>.
 57. Hunt, A.J.; Anderson, C.W.N.; Bruce, N.; García, A.M.; Graedel, T.E.; Hodson, M.; Meech, J.A.; Nassar, N.T.; Parker, H.L.; Rylott, E.L.; *et al.* Phytoextraction as a tool for green chemistry. *Green Process. Synth.* **2014**, *3*, <https://doi.org/10.1515/gps-2013-0103>.
 58. Erdei, L.; Mezosi, G.; Mécs, I.; Vass, I.; Foglein, F.; Bulik, L. Phytoremediation as a program for decontamination of heavy-metal polluted environment. *Acta Biol. Szeged.* **2005**, *49*, 75–76.
 59. Cho-Ruk, K.; Kurukote, J.; Supprung, P.; Vetayasuporn, S. Perennial plants in the phytoremediation of lead-contaminated soils. *Biotechnology* **2006**, *5*, 1–4, <https://doi.org/10.3923/biotech.2006.1.4>.
 60. Wilson-Corral, V.; Anderson, C.W.N.; Rodriguez-Lopez, M. Gold phytomining. A review of the relevance of this technology to mineral extraction in the 21st century. *J. Environ. Manage.* **2012**, *111*, 249–257, <https://doi.org/10.1016/j.jenvman.2012.07.037>.
 61. Asgari Lajayer, B.; Khadem Moghadam, N.; Maghsoodi, M.R.; Ghorbanpour, M.; Kariman, K. Phytoextraction of heavy metals from contaminated soil, water and atmosphere using ornamental plants: mechanisms and efficiency improvement strategies. *Environ. Sci. Pollut. Res.* **2019**, *26*, 8468–8484, <https://doi.org/10.1007/s11356-019-04241-y>.
 62. Rodriguez, L.; Lopez-Bellido, F.J.; Carnicer, A.; Recreo, F.; Tallos, A.; Monteagudo, J.M. Mercury recovery from soils by phytoremediation. In *Environmental Chemistry: Green Chemistry and Pollutants in Ecosystems*, Springer **2005**, 197–204 ISBN 3540228608.
 63. Dhir, B. Introduction. In *Phytoremediation: Role of Aquatic Plants in Environmental Clean-Up*; Springer India: India **2013**, 1–20.
 64. Neumann, P.M.; De Souza, M.P.; Pickering, I.J.; Terry, N. Rapid microalgal metabolism of selenate to volatile dimethylselenide. *Plant, Cell Environ.* **2003**, *26*, 897–905, <https://doi.org/10.1046/j.1365-3040.2003.01022.x>.
 65. Singh, S. Phytoremediation : A Sustainable Alternative for Environmental Challenges. *Int. J. Green Herb. Chem.* **2012**, *1*, 133–139.

66. Mukhopadhyay, S.; Maiti, S.K. Phytoremediation of metal mine waste. *Appl. Ecol. Environ. Res.* **2010**, *8*, 207–222.
67. Thakur, S.; Singh, L.; Wahid, Z.A.; Siddiqui, M.F.; Atnaw, S.M.; Din, M.F.M. Plant-driven removal of heavy metals from soil: uptake, translocation, tolerance mechanism, challenges, and future perspectives. *Environ. Monit. Assess.* **2016**, *188*, 206, <https://doi.org/10.1007/s10661-016-5211-9>.
68. Manousaki, E.; Kalogerakis, N. Halophytes present new opportunities in phytoremediation of heavy metals and saline soils. *Ind. Eng. Chem. Res.* **2011**, *50*, 656–660, <https://doi.org/10.1021/ie100270x>.
69. Ravindran, K.C.; Venkatesan, K.; Balakrishnan, V.; Chellappan, K.P.; Balasubramanian, T. Restoration of saline land by halophytes for Indian soils. *Soil Biol. Biochem.* **2007**, *39*, 2661–2664, <https://doi.org/10.1016/j.soilbio.2007.02.005>.
70. Shelef, O.; Gross, A.; Rachmilevitch, S. The use of *Bassia indica* for salt phytoremediation in constructed wetlands. *Water Res.* **2012**, *46*, 3967–3976, <https://doi.org/10.1016/j.watres.2012.05.020>.
71. Shelef, O.; Golan-Goldhirsh, A.; Gendler, T.; Rachmilevitch, S. Physiological parameters of plants as indicators of water quality in a constructed wetland. *Environ. Sci. Pollut. Res.* **2011**, *18*, 1234–1242, <https://doi.org/10.1007/s11356-011-0473-9>.
72. Shelef, O.; Lazarovitch, N.; Rewald, B.; Golan-Goldhirsh, A.; Rachmilevitch, S. Root halotropism: Salinity effects on *Bassia indica* root. *Plant Biosyst.* **2010**, *144*, 471–478, <https://doi.org/10.1080/11263501003732001>.
73. van der Ent, A.; Baker, A.J.M.; Reeves, R.D.; Pollard, A.J.; Schat, H. Hyperaccumulators of metal and metalloid trace elements: Facts and fiction. *Plant Soil* **2013**, *362*, 319–334, <https://doi.org/10.1007/s11104-012-1287-3>.
74. Ghosh, M.; Singh, S.P. A review on phytoremediation of heavy metals and utilization of its byproducts. *Appl. Ecol. Environ. Res.* **2005**, *3*, 1–18, https://doi.org/10.15666/aeer/0301_001018.
75. Jaffré, T.; Brooks, R.R.; Lee, J.; Reeves, R.D. *Sebertia acuminata*: A hyperaccumulator of nickel from New Caledonia. *Science* **1976**, *193*, 579–580, <https://doi.org/10.1126/science.193.4253.579>.
76. Visoottiviseth, P.; Francesconi, K.; Sridokchan, W. The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environ. Pollut.* **2002**, *118*, 453–461, [https://doi.org/10.1016/S0269-7491\(01\)00293-7](https://doi.org/10.1016/S0269-7491(01)00293-7).
77. Sarma, H. Metal hyperaccumulation in plants: A review focusing on phytoremediation technology. *J. Environ. Sci. Technol.* **2011**, *4*, 118–138, <https://doi.org/10.3923/jest.2011.118.138>.
78. Anderson, C.W.N.; Stewart, R.B.; Moreno, F.N.; Gardea-torresdey, J.L.; Robinson, B.H.; Meech, J. a Gold phytomining. Novel Developments in a Plant-based Mining System. In Proceedings of the In Proceedings of the Gold 2003 Conference: New Industrial Applications of Gold **2003**, 35–45.
79. Maestri, E.; Marmiroli, M.; Visioli, G.; Marmiroli, N. Metal tolerance and hyperaccumulation: Costs and trade-offs between traits and environment. *Environ. Exp. Bot.* **2010**, *68*, 1–13, <https://doi.org/10.1016/j.envexpbot.2009.10.011>.
80. Stanley Rungwa; Arpa, G.; Sakulas, H.; Harakuwe, A.; Timi, D. Phytoremediation – An Eco-friendly and Sustainable Method of Heavy Metal Removal from Closed Mine Environments in Papua New Guinea. *Procedia Earth Planet. Sci.* **2013**, *6*, 269–277, <https://doi.org/10.1016/j.proeps.2013.01.036>.
81. Van Ginneken, L.; Meers, E.; Guisson, R.; Ruttens, A.; Elst, K.; Tack, F.M.G.; Vangronsveld, J.; Diels, L.; Dejonghe, W. Phytoremediation for heavy metal-contaminated soils combined with bioenergy production. *J. Environ. Eng. Landsc. Manag.* **2007**, *15*, 227–236, <https://doi.org/10.1080/16486897.2007.9636935>.
82. Jaishankar, M.; Tseten, T.; Anbalagan, N.; Mathew, B.B.; Beeregowda, K.N. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip. Toxicol.* **2014**, *7*, 60–72, <https://doi.org/10.2478/intox-2014-0009>.
83. Jiang, Y.; Lei, M.; Duan, L.; Longhurst, P. Integrating phytoremediation with biomass valorisation and critical element recovery: A UK contaminated land perspective. *Biomass and Bioenergy* **2015**, *83*, 328–339, <https://doi.org/10.1016/j.biombioe.2015.10.013>.
84. Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E. Environmental and Health Impacts of Air Pollution: A Review. *Front. Public Heal.* **2020**, *8*, <https://doi.org/10.3389/fpubh.2020.00014>.
85. Meers, E.; Van Slycken, S.; Adriaensen, K.; Ruttens, A.; Vangronsveld, J.; Du Laing, G.; Witters, N.; Thewys, T.; Tack, F.M.G. The use of bio-energy crops (*Zea mays*) for "phytoattenuation" of heavy metals on moderately contaminated soils: A field experiment. *Chemosphere* **2010**, *78*, 35–41, <https://doi.org/10.1016/j.chemosphere.2009.08.015>.
86. Rahman, M.M.; Tan, P.J.; Faruq, G.; Sofian, A.M.; Rosli, H.; Boyce, A.N. Use of *Amaranthus paniculatus* and Indian Mustard (*Brassica juncea*) for Phytoextraction of Lead and Copper from Contaminated Soil. *Int. J. Agric. Biol.* **2013**, *15*, 903–908.
87. Soudek, P.; Petrová, Š.; Vaňková, R.; Song, J.; Vaněk, T. Accumulation of heavy metals using *Sorghum* sp. *Chemosphere* **2014**, *104*, 15–24, <https://doi.org/10.1016/j.chemosphere.2013.09.079>.
88. Eapen, S.; D'Souza, S.F. Prospects of genetic engineering of plants for phytoremediation of toxic metals. *Biotechnol. Adv.* **2005**, *23*, 97–114, <https://doi.org/10.1016/j.biotechadv.2004.10.001>.
89. Abhilash, P.C.; Jamil, S.; Singh, N. Transgenic plants for enhanced biodegradation and phytoremediation of organic xenobiotics. *Biotechnol. Adv.* **2009**, *27*, 474–488, <https://doi.org/10.1016/j.biotechadv.2009.04.002>.
90. Roslaili, A.A.; Asmalini, K.N.; Nazry, S.M. Study on Phytoremediation Performance and Heavy Metals

- Uptake in Leachate by Reed Beds Plant. In Proceedings of the 2011 International Conference on Environmental, Biomedical and Biotechnology; 2011; Vol. 16, pp. 47–51.
91. Koh, M.Y.; Tinia, T.I. A review of biodiesel production from *Jatropha curcas* L. oil. *Renew. Sustain. Energy Rev.* **2011**, *15*, 2240–2251, <https://doi.org/10.1016/j.rser.2011.02.013>.
 92. Nazli, M.F.; Hashim, N.R. Heavy metal concentrations in an important mangrove species, *Sonneratia Caseolaris*, in Peninsular Malaysia. *EnvironmentAsia* **2010**, *3*, 50–55.
 93. Nedjimi, B. Phytoremediation: a sustainable environmental technology for heavy metals decontamination. *SN Appl. Sci.* **2021**, *3*, 286, <https://doi.org/10.1007/s42452-021-04301-4>.