REVIEW ARTICLE

Phyto-remediation: An ecologically sound approach to revegetate heavy metal polluted land

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Phytoremediation, that employs hyper-accumulator plant species that are incredibly tolerant to Heavy Metals (HMs) present in the environment or soil, is a feasible and promising method for removing HMs from contaminated environments. This method uses green plants to eliminate, break down, or detoxify dangerous metals. The procedure is simple, efficient, and cost-effective, with widespread implementation on a big scale. Nowadays, phytoremediation is a highly effective approach but its efficacy is largely dependent on the choice of plant species. The purpose of this study is to acquire some information regarding the sources and effects of the heavy metals arsenic, lead, and mercury (As, Pb, and Hg). It also provides a thorough analysis of phytoremediation technology, covering heavy metal uptake mechanisms and a number of related research findings.

Key Words: *Phytoremediation; Heavy metals; Hyper-accumulator; Lead; Mercury*

INTRODUCTION

The build-up of heavy metals in soils and waterways poses a risk to both environmental and human health. These substances accumulate in the body tissues of living organisms through bioaccumulation, and their levels intensify as they progress from lower to higher trophic levels, a phenomenon referred to as bio magnification. The presence of heavy metals in the soil can have toxic effects on soil microbes, ultimately leading to a decrease in their numbers and functional capabilities [1]. The remediation of soil for the preservation of ecosystem processes and functions represents one of the key challenges confronting our society today.

LITERATURE REVIEW

Chemical methods employed for the decontamination of Heavy Metals (HMs), encompassing precipitation, heat treatment, excavation, electro remediation, and chemical leaching, remains an expensive process and are dependent on both soil and pollutant properties [2]. The key drawbacks and constraints of these approaches include the alteration of soil characteristics particularly pH, potential threats of soil fertility decline, challenges in small-scale implementation, and the generation of by-products. Phytoremediation, an environmentally benign method, is a cost-effective strategy for mitigating heavy metal contamination and revegetating contaminated soil. It involves utilizing hyper accumulator plants and their associated rhizospheric microorganisms to stabilize, transfer, or break down pollutants within soil, water, and the surrounding environment [3]. Plants, through their root system, have the potential to engross ionic complexes from the soil even at low concentrations. For the accumulation of heavy metals and regulate their bioavailability, plants spread their root systems into the soil matrix and create rhizosphere ecosystems, which stabilize soil fertility and allow for the reclamation of polluted soil. By considering the soil's conditions, pollutant attributes and the type of plants used. Five phytoremediation techniques have been employed: Phytodegradation, phytofiltration, phytoextraction, phytostabilization, and phytovolatilization (Figure 1). The simplest method for phytoremediation is utilizingheavy metal hyperaccumulators. Plants are classified as tolerant and/or hyper accumulator to Heavy Metals (HMs) when they exhibit accelerated growth, high biomass, and the capability to extract and amass significant quantities of HMs in their shoots, all without demonstrating signs of toxicity when cultivated in contaminated soils with these metals [4]. In light of this, the incorporation of this green technology emerges as a powerful strategy for remediating soils or agro-ecosystems impacted by Heavy Metal (HMs) contamination.

A detailed examination has been undertaken to provide an extensive overview of various dimensions of phytoremediation. The analysis provides a detailed account of the application of various macrophytes for pollutant removal, particularly focusing on heavy metals.

Heavy metals: Source and their consequences

Elements with densities >5 g/cm^3 are described as heavy metals [5,6]. Heavy Metals (HMs) possess a half-life exceeding twenty years, demonstrating their remarkable persistence [7-9]. HMs occur naturally in rocks, but human activities have elevated their presence. The excessive application of sewage sludge, agrochemicals, wastewater, bio solids, and manure serves as a substantial source of HMs in soil [10]. Hazardous heavy metals such as Hg, As, Cd, Pb, Cr, Cu, and others are commonly present in wastewater originating from sources like mines, sewage, dyes, and alloys [11]. Heavy Metals (HMs) are divided into two categories: Essential and non-essential. Elements such as Cobalt (Co), Copper (Cu), Chromium (Cr), Iron (Fe), Nickel (Ni), Manganese (Mn), and Zinc (Zn) fall under the essential HMs, serving as micronutrients but turning toxic with excessive consumption. On the other hand, Cadmium (Cd), Mercury (Hg), and Lead (Pb) are non-essential HMs, posing extreme lethality to living organisms [12]. Anthropogenic activities have a more significant impact on environmental pollution than natural sources [13]. Heavy metal accessibility in the soil solution is influenced by factors such as the metal's nature, soil attributes (like pH, clay content, and organic matter), and exchange reactions, encompassing processes such as precipitation and adsorption-desorption [14,15]. In addition to the above-mentioned sources, heavy metal pollution is exacerbated by the presence of cosmetics and chemical fertilizers [16].

Consequences of heavy metal pollution

The accelerated global development and urbanization have amplified the possibility of heavy metal contamination in ecosystems [17]. According to literature, about 10 million people globally have been affected by soil contaminated with heavy metals [18]. The growing prevalence of heavy metals in soils is worrisome, not only for plant growth and productivity but also due to the potential health threats to both humans and animals [19]. Plant growth is adversely affected by heavy metals, leading to a decline in both physiological and morphological responses, disruption of nutrient uptake processes, and ultimately reducing plant yield [20,21]. Heavy metals negatively affect plant growth by decreasing chlorophyll content, inducing chlorosis and necrosis, and resulting in plant death through decreased chlorophyll content and stomatal closure [22,23]. Human health is negatively affected by heavy metals, and consequently, several heavy metals and metalloids can pose dangers even at lower concentrations [24-26]. The presence of heavy

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metals induces oxidative stress by generating free radicals [27]. Furthermore, they have the potential to act as replacements for primary metals in both pigments and enzymes [28]. Among heavy metals, Arsenic (As), Mercury (Hg), Cadmium (Cd), Chromium (Cr), Copper (Cu), Lead (Pb), Tin (Sn), and Zinc (Zn) are identified as the most toxic [29]. Within these heavy metals, Mercury (Hg), Cadmium (Cd), Lead (Pb), and Arsenic (As) are non-essential, while Copper(Cu) and Zinc (Zn) are recognized as trace elements. Depending on the type of toxic heavy metal, its concentration, and oxidation state, a spectrum of health problems can emerge (Table 1).

TABLE 1

Health hazards associated with specific heavy metals

Heavy metal	Related hazardous effects	Reference
As	Interferes with key cellular functions in human body	Tripathi et al., [30]
Cd	Chronic anemia, mutagenic, renal failure and carcinogenic etc.	Degraeve [31], Salem et al., [32]
Cr	Hair loss	Salem et al., [32]
Cu	Brain and kidney injury, liver cirrhosis, stomach and intestinal inflammation have all been linked to elevated levels	Wuana and Okieimen [33]
Hg	Anxiety, autoimmune disorders, depression, trouble with coordination, exhaustion, loss of hair, insomnia, irritability, ulcers, and brain, kidney, and lung damage are just a few of the symptoms	Ainza et al., [34], Verma et al., [35]
Ni	Nickel itch is allergic dermatitis; inhalation can cause lung, nose, and sinus cancers; throat and/or stomach cancers. Causes hair loss by being hematotoxin, neurotoxic, genotoxic, nephrotoxic, and hepatotoxic	Khan et al., [36], Das et al., [37]
Pb	Decreased intelligence, learning difficulties, and balance issues in infants, as well as renal failure, cardiovascular disease	Wuana and Okieimen, [33], Mishra et al., [38]
Zn	Overdosing will result in dizziness and exhaustion	Hess and Schmid [39]

Mechanism of phytoremediation

The term "phytoremediation" combines "phyto" (plant) and and the Latin suffix "remedium" meaning "restore." is an approach that utilizes both natural and transgenic plants to restore ecosystems impacted by pollution [30-40]. In the implementation of phytoremediation for mitigating heavy metal effects, two defense strategies; avoidance and tolerance, can be employed [41]. Through the application of these strategies, plants manage to prevent heavy metal concentrations from reaching lethal thresholds [42]. The mechanism of avoidance involves plants using root cells to limit and regulate the uptake and translocation of heavy metals into their tissues [43]. This process involves a range of defense mechanisms, including root sorption, metal precipitation, and exclusion [43]. Plants, when exposed to Heavy Metals (HMs), undergo the root sorption process, leading to the immobilization of metals. Various root exudates function as ligands for heavy metals, forming complexes within the rhizosphere to limit the bioavailability and lethality of these metals. In a similar fashion, exclusion barriers existing between the root and shoot systems restrict the availability of Heavy Metals (HMs) from the soil to the roots. Moreover, arbuscular mycorrhiza have the potential to function as exclusion barriers in the rhizosphere, through processes such as absorption, adsorption, or chelation of Heavy Metals (HMs). The inclusion of Heavy Metals (HMs) in the plant cell wall serves as an additional mechanism for avoidance. The carboxylic groups, specifically in the pectin groups of the cell wall, function as cation exchangers, restricting the penetration of Heavy Metals (HMs) into the cells [44]. Plants utilize the tolerance strategy when heavy metal ions enter the cytosol to address the challenge of their toxicity. This is achieved through mechanisms such as inactivation, metal chelation, and compartmentalization of heavy metals [43]. The concentration of Heavy Metals (HMs) is reduced in the cytoplasm through the process of chelation, involving various organic and inorganic ligands [45]. After chelation, Heavy Metal (HM) ligand complexes move from the cytosol to inactive compartments like the vacuole, leaves, petioles, leaf sheaths, and trichomes. These compartments function as storage sites without inducing any toxicity [46].

When there is a notable accumulation of Heavy Metals (HMs), the described strategies might fall short in remediating contaminated sites. This is due to the potential of HMs to induce the production of Reactive Oxygen Species (ROS) in the cytoplasm, leading to oxidative stress [47]. In the face of such a scenario, plant cells adopt the use of antioxidant enzymes, including Superoxide Dismutase (SOD), Catalase (CAT), Peroxidase (POD), and Glutathione Peroxidase (GR). Moreover, non-enzymatic antioxidant compounds like glutathione, flavonoids, carotenoids, ascorbate, and tocopherols are brought into action. These elements are employed to trigger the scavenging of Reactive Oxygen Species (ROS) [47,48] Therefore, the antioxidant defense mechanism is highly crucial and imperative in dealing with the stress induced by Heavy Metals (HMs).

Phytoremediation practices

Phytoremediation techniques consist of phytoextraction, phytovolatilization, phytostabilization, phytofiltration, phytodegradation and rhizodegradation (Figure 1).

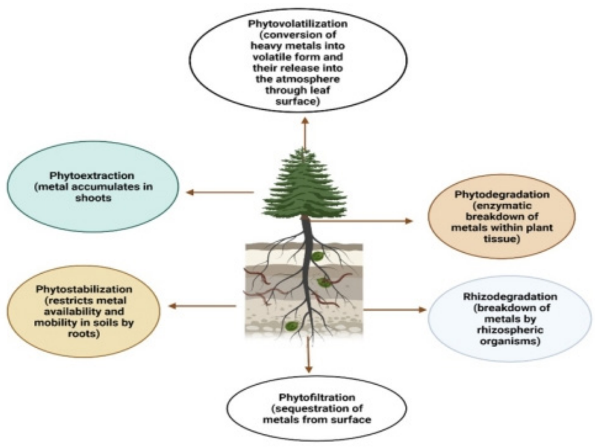

Figure 1) *Phytoremediation techniques for heavy metals uptake*

Phytoextraction: Phytoextraction, also referred to as phytoaccumulation, phytoabsorption, or phytosequestration, involves the absorption of contaminants from soil or water by plant roots. These contaminants are subsequently transported to and stored in the above ground biomass, particularly in the shoots [49-51]. One long-term approach for the Heavy Metals (HMs) detoxification is the harvesting of biomass. Phyto extraction, utilizing plant species such as Invasive Plant Species (IPS), which grow quickly and have deep roots. It serves as an efficient method to eradicate different harmful heavy metals from the environment. Phyto extraction comprises two main concepts, with the first being continuous phytoextraction. This natural phenomenon is inherent in specific plant species known as hyper accumulators, allowing them to store higher concentration of Heavy Metals (HMs) without facing negative consequences. Induced phytoextraction involves the incorporation of additional components to the plant to control the effects of Heavy Metals (HMs) through the formation of complex with phytochelatin. This complex is then translocated to different parts of the plant, including the vacuole, cell membrane, and other metabolically inactive areas [52,53]. As per the studies of Begonia et al., [54], plants exhibiting rapid proliferation and a resilient root system, such as Coffee weed (Sesbania exaltata), are successful in the phytoextraction process for eliminating Pb from polluted soil. Yang et al., [55] examined the field performance of three Napier grass (Pennisetum purpureum) cultivars in absorbing Cd and Zn. The research demonstrated that P. purpureum cv. Guiminyin exhibited the highest shoot accumulation of Cd and Zn. P. stratiotes commonly referred to as water lettuce, has gained broad usage, notably due to its capability for hyper accumulating Heavy Metals (HMs) [56].

Phytofiltration: Phytofiltration is a technique where plant roots, shoots, and seedlings are employed to cleanse pollutants from a waste area or contaminated water [57]. In the practice of phytofiltration, plant roots, shoots, and seedlings are employed to extract pollutants from either a waste area or contaminated water. This method can be executed *in situ*, with plants grown directly within the polluted water body, resulting in cost savings. According to da Conceiçao Gomes et al., [58] three categories of phytofiltration are detailed as rhizofiltration (involving roots), caulofiltration (involving shoots), and blastofiltration (involving seedlings). Rhizofiltration involved the use of plant roots to draw in pollutants from polluted soils and water, cleansing the environment through processes such as accumulation, adsorption, absorption, and precipitation into plant biomass [59]. Terrestrial and rapidly proliferating aquatic plants are both applicable in rhizofiltration for the extraction of cadmium, chromium, copper, nickel, lead and zinc [60]. For the phytoremediation of pesticide-contaminated agro-industrial wastewater, water hyacinth is a viable, affordable, and ecologically friendly solution.

Phytostabilization: Phytostabilization entails multiple mechanisms like precipitation, sorption, complexation, and the reduction of metal valence in the root zone of plant roots. Its aims include averting erosion, leaching, or run-off and transforming heavy metals [61]. A prime example of heavy metal conversion is seen in the reduction of Cr+6, a more toxic metal form, to Cr+3, a less toxic and more mobile species [62]. Typically, this method is utilized to mitigate the detrimental impacts of heavy metals in contaminated soil, water, sludge, or sediment by impeding their entry into groundwater and the food chain [63]. Phytostabilization, which is also known as phytoimmobilization, encompasses the amalgamation of toxic heavy metals with plant root exudates to transform them into a non-toxic state within ecosystems [64]. Heavy Metals (HMs) interacting with derivatives of amino acids, proteins, and sugars in the rhizosphere give rise to complexes that help to immobilize the toxicity of these hazardous metals. For instance, the toxic form of arsenic transforms into a non-toxic state (As-tris-thiolate) after forming a complex with ferric sulfate in the rhizosphere, particularly within the vacuoles.

Phytovolatilization: Phytovolatilization encompasses plants absorbing pollutants from the soil, converting them into a volatile form, and subsequently releasing them into the atmosphere [65]. Commonly chosen plants for phytovolatilization include Nicotiana tabacum, Crinum americanum, Triticum aestivum, Arabidopsis thaliana, Bacopa monnieri, and Trifolium repens [66]. According to Herath and Vithanage [66], phytovolatilization aids in breaking down organic pollutants like phenol, acetone, and chlorinated benzene (BTEX). One important advantage of phytovolatilization is that, once the plantation is fully established, it requires very little more management. It also disturbs the soil the least and preserves the texture of the soil [67-68]. However, the application of this method is limited as it doesn't eliminate the pollutant entirely; rather, it is transferred from one area (soil) to another (atmosphere), where it could be redeposited [69].

Phytodegradation: During phytodegradation, organic pollutants are either broken down by the enzymes involved in the metabolism of the plant, or they are broken down after being sequestered by the plant through a variety of metabolic processes [70]. Dehalogenase, peroxidase, nitrilase, nitroreductase and phosphatase are among the enzymes that break down contaminants [71]. In this method, pollutants are directly absorbed into the plant tissue through the root system. The effectiveness of this process depends on the root's efficiency of uptake, rate of transpiration, and other relevant chemical and physical characteristics. The process of phytodegradation can be used to decontaminate areas impacted by organic pollutants, such as herbicides and chlorinated solvents [72]. It can be applied to groundwater and surface water restoration [68]. Several plants can be employed in this approach; sunflower (Helianthus annus) is a popular option for methyl benzotriazole [73]. Ethylene dibromide can be effectively treated with Leucocephala [74]. This approach has some limitations, including the requirement that the groundwater be within ten feet of the surface and the soil be three feet deep. Chelating chemicals, which bind soil particles with pollutants, are an essential part of increasing plant absorption [75].

Rhizodegradation: The microbial decomposition of organic contaminants in the soil within the rhizosphere is known as rhizodegradation [76]. The plant has an impact on the rhizosphere within a radius of roughly 1 mm surrounding the root [77]. The principal reason for the enhanced breakdown of pollutants in the rhizosphere is probably due to the rise in both the numbers and metabolic activities of microbes. Plants have the potential to boost the activity of microorganisms in the rhizosphere by 10-100 times by the secretion of exudates that are abundant in carbohydrates, amino acids, and flavonoids. The exudates released by plant roots, enriched with nutrients provide carbon and nitrogen sources to soil microbes, fostering a nutrient-rich environment that enhances microbial activity. Plants not only secrete organic substrates to support the growth and activities of rhizospheric microorganisms but also release specific enzymes with the ability to degrade organic contaminants in soils [78,79].

Phytodesalination

Phytodesalination, a recently developed and emerging technique that utilizes halophytic plants to to address saline soils and stands as the most often employed biological technique for this kind of decontamination [80-83]. Plant species, as well as soil characteristics including salinity, sodicity, and porosity, as well as other climatic elements especially rainfall, all have an impact on the efficacy of phytodesalination [81]. Two halophytic plants, Sesavium partulacastrum and Suaeda maritime, were discovered to be able to extract roughly 504 kg and 474 kg of NaCl, respectively, from one hectare of saline soil in a period of four months [82]. Research on the ability of halophytic plants to desalinate salt has shown encouraging outcomes for the recovery of soil impacted by sodium (Na+) and chloride (Cl^{-}) ions. Although this bioremediation technique is not effective for decontaminating heavy metal and Polycyclic Aromatic Hydrocarbon (PAH)-polluted soils, it holds potential for addressing salt-affected soils [84-86].

Biotechnological processes

Genetic engineering techniques have been used in recent decades to boost the potential of plants for Heavy Metal (HMs) decontamination. Plants have been genetically altered by genetic engineering through the incorporation of genes from bacteria and plants known as hyper accumulators, which are distinguished by their exceptional transformation, degradation, or accumulation capabilities [84]. Numerous studies have highlighted the use of transgenic methods to bolster phytoremediation. This strategy involves introducing genes to plants exhibiting rapid growth rate to improve tolerance and hyper accumulation of hazardous heavy metals [85]. Choose plant species that are well-adapted to the local climate. This approach can be applied to amplify biomass, augment metal storage capacity, and foster the hyper accumulation of various heavy metals [86]. For the successful implementation of a phytoextraction strategy, plants should produce a large volume of green foliage and are easily harvestable, preferably multiple times throughout the year [87]. Despite this, in the wild, most native species identified as hyper-accumulators tend to be herb or shrub plants with limited green biomass. Researchers are actively working on creating transgenic varieties characterized by higher biomass [88]. Essential traits for plants that are good candidates for phytoremediation encompass substantial root volume, significant foliage biomass, a notable transpiration rate facilitating efficient metal assimilation, and the production of ample exudates. The rapid growth rate and/or substantial biomass aid in reducing the time frame needed for soil remediation. The understanding of the eco-physiology of metal hyper-accumulation in plants has advanced in the last few years due to the evolution of molecular tools, including the identification of heavy metal transporters, the production of enzymes, and the development of metal-detoxifying chelators.

Despite the notable potential of genetic engineering in phytoremediation, there are still hurdles to overcome. The intricacies associated with decontamination of Heavy Metal (HM) accumulation means that genetic manipulation of several genes to improve the desired features can be a laborious and less effective approach. In certain parts of the world, it is challenging to obtain license and approval for genetically modified plants due to worries about their use, which could endanger the safety of both food and ecosystems. Other approaches are required to improve and boost the productivity of plant species used in phytoremediation because of the complexity of genetic engineering.

CONCLUSION

The pollution caused by heavy metals poses a serious threat to human health on a global scale. Phytoremediation is a more economical, socially acceptable, and environmentally benign technology as compared to other chemical approaches for decontamination of heavy metals. To improve the phytoremediation potential of plants, a variety of bioremediation techniques have been widely used. These approaches encompass genetic engineering, transgenic transformation, the utilization of phytoremediation assisted by phytohormones, microbial applications, AMF inoculation, and the introduction of Nanoparticles (NPs). Phytoremediation is a technology that is still in its early stages and primarily in the research phase. Research in this area is highly interdisciplinary, mandating a well-rounded understanding of soil chemistry, plant biology, ecology, soil microbiology, and environmental engineering. Fortunately, open-minded scientific communities worldwide recognize and highly promote multidisciplinary studies and research. Research is currently being done to evaluate native plants' capacity for phytoremediation of particular heavy metals. Assessing the impact of various parameters on phytoremediation's efficiency is another aspect of the study. Additionally, efforts are being made to genetically alter specific plants in an effort to increase the effectiveness of their phytoremediation of heavy metals and other xenobiotics. The development and successes of these kinds of molecular investigations will be essential to comprehending the understanding and enhancing the efficacy of phytoremediation.

REFERENCES

1. Khan S, El-Latif Hesham A, Qiao M, et al. Effects of Cd and Pb on soil microbial community structure and activities. Environ Sci Pollut Res. 2010; 17:288-296.
2. Nedjimi B, Daoud Y. Ameliorative effect of CaCl2 on growth, membrane permeability and nutrient uptake in Atriplex halimus subsp. schweinfurthii grown at high (NaCl) salinity. Desalination. 2009;249(1):163-166.
3. Liu S, Yang B, Liang Y, et al. Prospect of phytoremediation combined with other approaches for remediation of heavy metal-polluted soils. Environ Sci Pollut Res. 2020; 27:16069-16085.
4. Kramer U. Metal hyper accumulation in plants. Annu Rev Plant Biol. 2010; 61:517-534.
5. Saif S, Khan MS. Assessment of heavy metals toxicity on plant growth promoting rhizobacteria and seedling characteristics of Pseudomonas putida SFB3 inoculated greengram. Acta Sci Agric. 2017; 1:47-56.
6. Prieto MJ, Acevedo SO, Prieto GF, et al. Phytoremediation of soils contaminated with heavy metals. Biodivers Int J. 2018;2(4):362-376.
7. Asati A, Pichhode M, Nikhil K. Effect of heavy metals on plants: an overview. Int J Appl Innov Eng Manag. 2016;5(3):56-66.
8. Hadia-e-Fatima AA. Heavy metal pollution-A mini review. J Bacteriol Mycol Open Access. 2018;6(3):179-181.
9. Kapoor D, Singh MP. Heavy metal contamination in water and its possible sources. In Heavy metals in the environment. 2021;179-189. Elsevier.
10. de Figueiredo CC, Chagas JK, da Silva J, et al. Short-term effects of a sewage sludge biochar amendment on total and available heavy metal content of a tropical soil. Geoderma. 2019; 344:31-39.
11. Ene A, Bosneaga A, Georgescu L. Determination of heavy metals in soils using XRF technique. Rom Journ Phys. 2010;55(7-8):815-820.
12. Sandeep G, Vijayalatha KR, Anitha T. Heavy metals and its impact in vegetable crops. Int J Chem Stud. 2019;7(1):1612-1621.
13. Duruibe, Ogwuegbu, Egwurugwu. Heavy metal pollution and human biotoxic effects. Int J Phys Sci. 2007;2(5):112-118.
14. Naidu R, Oliver D, McConnell S. Heavy metal phytotoxicity in soils. In Proceedings of the Fifth National Workshop on the Assessment of Site Contamination, National Environment Protection Council Service Corporation 2003;235-241.
15. Shah V, Daverey A. Phytoremediation: A multidisciplinary approach to clean up heavy metal contaminated soil. Environ Technol Innov. 2020; 18:100774.
16. Callender E. Heavy metals in the environment-historical trends. Environ Geochem. 2005; 9:67.
17. Khan IU, Rono JK, Liu XS, et al. Functional characterization of a new metallochaperone for reducing cadmium concentration in rice crop. J Clean Prod. 2020; 272:123152.
18. Ashraf S, Ali Q, Zahir ZA, et al. Phytoremediation: Environmentally sustainable way for reclamation of heavy metal polluted soils. Ecotoxicol Environ Saf. 2019; 174:714-727.
19. Feng D, Guo D, Zhang Y, et al. Functionalized construction of biochar with hierarchical pore structures and surface O-/N-containing groups for phenol adsorption. Chem Eng J. 2021; 410:127707.
20. Rizwan M, Ali S, Rizvi H, et al. Phytomanagement of heavy metals in contaminated soils using sunflower: a review. Crit Rev Environ Sci Technol. 2016;46(18):1498-1528.
21. Sabreena, Hassan S, Bhat SA, et al. Phytoremediation of heavy metals: An indispensable contrivance in green remediation technology. Plants. 2022;11(9):1255.
22. □o□nowski AC, Wyszkowski M, Rolka E, et al. Mineral materials as a neutralizing agent used on soil contaminated with copper. Materials. 2021;14(22):6830.
23. Singh J, Lee BK. Influence of nano-TiO2 particles on the bioaccumulation of Cd in soybean plants (Glycine max): A possible mechanism for the removal of Cd from the contaminated soil. J Environ Manage. 2016; 170:88-96.
24. Kara Y. Bioaccumulation of Cu, Zn and Ni from the wastewater by treated Nasturtium officinale. Int J Environ Sci Technol. 2005; 2:63-67.
25. Haferburg G, Kothe E. Microbes and metals: interactions in the environment. J Basic Microbiol. 2007;47(6):453-467.
26. Arora M, Kiran B, Rani S, et al. Heavy metal accumulation in vegetables irrigated with water from different sources. Food Chem. 2008;111(4):811-815.
27. Mudipalli A. Metals (micro nutrients or toxicants) & Global Health. Indian J Med Res. 2008;128(4):331-334.
28. Malayeri BE, Chehregani A, Yousefi N, et al. Identification of the hyper accumulator plants in copper and iron mine in Iran. Pak J Biol Sci. 2008;11(3):490-492.
29. Ghosh S. Wetland macrophytes as toxic metal accumulators. Int J Environ Sci. 2010;1(4):523-528.
30. Tripathi RD, Srivastava S, Mishra S, et al. Arsenic hazards: strategies for tolerance and remediation by plants. Trends Biotechnol. 2007;25(4):158-165.
31. Degraeve N. Carcinogenic, teratogenic and mutagenic effects of cadmium. Mutat Res Rev Genet Toxicol. 1981;86(1):115-135.
32. Salem HM, Eweida EA, Farag A. Heavy metals in drinking water and their environmental impact on human health. In Int Conference on the Environ Hazards Mitigation, Cairo Univ Egypt 2000; 542-556.
33. Wuana RA, Okieimen FE. Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. Int Sch Res Notices. 2011.
34. Ainza C, Trevors J, Saier M. Environmental mercury rising. Water Air Soil Pollut. 2010; 205:47-48.
35. Verma A, Roy A, Bharadvaja N. Remediation of heavy metals using nano phytoremediation. In Advanced oxidation processes for effluent treatment plants. 2021; 273-296. Elsevier.
36. Khan MA, Ahmad I, Rahman IU. Effect of environmental pollution on heavy metals content of Withania somnifera. J Chin Chem Soc. 2007;54(2):339-343.
37. Das KK, Das SN, Dhundasi SA. Nickel, its adverse health effects & oxidative stress. Indian J Med Res. 2008;128(4):412-425.
38. Mishra S, Dwivedi SP, Singh RB. A review on epigenetic effect of heavy metal carcinogens on human health. Open Nutraceuticals J. 2010;3(1).
39. Hess R, Schmid B. Zinc supplement overdose can have toxic effects. J Paediatr Haematol/Oncol. 2002; 24:582-584.
40. Beharti A. Phytoremediation: As a degradation of heavy metals. Int J Eng Technol Res. 2014; 2:137-139.
41. Thakur S, Singh L, Wahid ZA, et al. Plant-driven removal of heavy metals from soil: uptake, translocation, tolerance mechanism, challenges, and future perspectives. Environ Monit Assess. 2016; 188:1-1.
42. Hall JÁ. Cellular mechanisms for heavy metal detoxification and tolerance. J Exp Bot. 2002;53(366):1-1.
43. Dalvi AA, Bhalerao SA. Response of plants towards heavy metal toxicity: an overview of avoidance, tolerance and uptake mechanism. Ann Plant Sci. 2013;2(9):362-368.

44. Ernst WH, Verkleij JA, Schat H. Metal tolerance in plants. Acta Bot Neerl. 1992;41(3):229-248.

45. Gupta DK, Vandenhove H, Inouhe M. Role of phytochelatins in heavy metal stress and detoxification mechanisms in plants. Springer Berlin Heidelberg; 2013.

46. Eapen S, D'souza SF. Prospects of genetic engineering of plants for phytoremediation of toxic metals. Biotechnol Adv. 2005;23(2):97-114.

47. Dal Corso G, Fasani E, Manara A, et al. Heavy metal pollutions: state of the art and innovation in phytoremediation. Int J Mol Sci. 2019;20(14):3412.

48. Jozefczak M, Remans T, Vangronsveld J, et al. Glutathione is a key player in metal-induced oxidative stress defenses. Int J Mol Sci. 2012;13(3):3145-3175.

49. Sekara A, Poniedzialeek M, Ciura J, et al. Cadmium and lead accumulation and distribution in the organs of nine crops: implications for phytoremediation. Pol J Environ Stud. 2005;14(4):509-516.

50. Yoon J, Cao X, Zhou Q, et al. Accumulation of Pb, Cu, and Zn in native plants growing on a contaminated Florida site. Sci Total Environ. 2006;368(2-3):456-464.

51. Rafati M, Khorasani N, Moattar F, et al. Phytoremediation potential of Populus alba and Morus alba for cadmium, chromuim and nickel absorption from polluted soil. Int J Environ Res. 2011;5(4):961-970.

52. Raza A, Habib M, Kakavand SN, et al. Phytoremediation of cadmium: physiological, biochemical, and molecular mechanisms. Biology. 2020;9(7):177.

53. Tak HI, Ahmad F, Babalola OO. Advances in the application of plant growth-promoting rhizobacteria in phytoremediation of heavy metals. Rev Environ Contam Toxicol. 2012:33-52.

54. Begonia GB, Miller GS, Begonia MF, et al. Chelate-enhanced phytoextraction of lead-contaminated soils using coffeeweed (Sesbania exaltata Raf.). Bull Environ Contam Toxicol. 2002; 69:624-631.

55. Yang WJ, Gu JF, Zhou H, et al. Effect of three Napier grass varieties on phytoextraction of Cd-and Zn-contaminated cultivated soil under mowing and their safe utilization. Environ Sci Pollut Res. 2020; 27:16134-16144.

56. Hanks NA, Caruso JA, Zhang P. Assessing Pistia stratiotes for phytoremediation of silver nanoparticles and Ag (I) contaminated waters. J Environ Manage. 2015; 164:41-45.

57. Javed MT, Tanwir K, Akram MS, et al. Phytoremediation of cadmium-polluted water/sediment by aquatic macrophytes: role of plant-induced pH changes. In Cadmium toxicity and tolerance in plants. 2019; 495-529.

58. da Conceiçao Gomes MA, Hauser-Davis RA, de Souza AN, et al. Metal phytoremediation: General strategies, genetically modified plants and applications in metal nanoparticle contamination. Ecotoxicol Environ Saf. 2016; 134:133-147.

59. Mahajan P, Kaushal J. Role of phytoremediation in reducing cadmium toxicity in soil and water. J Toxicol. 2018.

60. Olguin EJ, Garcia-Lopez DA, Gonzalez-Portela RE, et al. Year-round phytofiltration lagoon assessment using Pistia stratiotes within a pilot-plant scale biorefinery. Sci Total Environ. 2017; 592:326-333.

61. Nwoko CO. Trends in phytoremediation of toxic elemental and organic pollutants. Afr J Biotechnol. 2010;9(37):6010-6016.

62. Wu G, Kang H, Zhang X, et al. A critical review on the bio-removal of hazardous heavy metals from contaminated soils: issues, progress, eco-environmental concerns and opportunities. J Hazard Mater. 2010;174(1-3):1-8.

63. Yan A, Wang Y, Tan SN, et al. Phytoremediation: a promising approach for revegetation of heavy metal-polluted land. Front Plant Sci. 2020; 11:359.

64. Leguizamo MA, Gomez WD, Sarmiento MC. Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands—a review. Chemosphere. 2017; 168:1230-1247.

65. Singh R, Ahirwar NK, Tiwari J, et al. Review on sources and effect of heavy metal in soil: Its bioremediation. Int J Res Appl Nat Soc Sci. 2018:1-22.

66. Herath I, Vithanage M. Phytoremediation in constructed wetlands. Phytoremediation: Management of Environmental Contaminants. 2015:243-263.

67. Cristaldi A, Conti GO, Jho EH, et al. Phytoremediation of contaminated soils by heavy metals and PAHs. A brief review. Environ Technol Innov. 2017; 8:309-326.

68. Vangronsveld J, Herzig R, Weyens N, et al. Phytoremediation of contaminated soils and groundwater: lessons from the field. Environ Sci Pollut Res. 2009; 16:765-794.

69. Sharma P, Pandey S. Status of phytoremediation in world scenario. Int J Environ Bioremediat Biodegrad. 2014;2(4):178-191.

70. Deng Z, Cao L. Fungal endophytes and their interactions with plants in phytoremediation: a review. Chemosphere. 2017; 168:1100-1106.

71. Wang L, Ji B, Hu Y, et al. A review on *in situ* phytoremediation of mine tailings. Chemosphere. 2017; 184:594-600.

72. Castro S, Davis LC, Erickson LE. Phytotransformation of benzotriazoles. Int J Phytoremediation. 2003;5(3):245-265.

73. Doty SL, Shang TQ, Wilson AM, et al. Metabolism of the soil and groundwater contaminants, ethylene dibromide and trichloroethylene, by the tropical leguminous tree, Leuceana leucocephala. Water Res. 2003;37(2):441-449.

74. Mukhopadhyay S, Maiti SK. Phytoremediation of metal enriched mine waste: a review. Global J Environ Res. 2010;4(3):135-150.

75. Pilon-Smits E. Phytoremediation. Annu Rev Plant Biol. 2005; 56:15-39.

76. Kuiper I, Lagendijk EL, Bloemberg GV, et al. Rhizoremediation: a beneficial plant-microbe interaction. Mol Plant Microbe Interact. 2004;17(1):6-15.

77. Yadav R, Arora P, Kumar S, et al. Perspectives for genetic engineering of poplars for enhanced phytoremediation abilities. Ecotoxicol. 2010; 19:1574-1588.

78. Ali H, Khan E, Sajad MA. Phytoremediation of heavy metals—concepts and applications. Chemosphere. 2013;91(7):869-881.

79. Hussain I, Puschenreiter M, Gerhard S, et al. Rhizoremediation of petroleum hydrocarbon-contaminated soils: Improvement opportunities and field applications. Environ Exp Bot. 2018; 147:202-219.

80. Ravindran KC, Venkatesan K, Balakrishnan V, et al. Restoration of saline land by halophytes for Indian soils. Soil Biol Biochem. 2007;39(10):2661-2664.

81. Zorrig W, Rabhi M, Ferchichi S, et al. Phytodesalination: a solution for salt-affected soils in arid and semi-arid regions. J Arid Land Stud. 2012;22(1):299-302.

82. Pivetz BE. Phytoremediation of contaminated soil and ground water at hazardous waste sites. US Environmental Protection Agency, Office of Research and Development, Office of Solid Waste and Emergency Response; 2001.

83. Kotrba P, Najmanova J, Macek T, et al. Genetically modified plants in phytoremediation of heavy metal and metalloid soil and sediment pollution. Biotechnol Adv. 2009;27(6):799-810.

84. Peer WA, Baxter IR, Richards EL, et al. Phytoremediation and hyperaccumulator plants. Molecular biology of metal homeostasis and detoxification: from microbes to man. 2006:299-340.

85. Yang X, Feng Y, He Z, et al. Molecular mechanisms of heavy metal hyperaccumulation and phytoremediation. J Trace Elem Med Biol. 2005;18(4):339-353.

86. Sarma H. Metal hyperaccumulation in plants: a review focusing on phytoremediation technology. J Environ Sci Technol. 2011;4(2):118-138.

87. Salt DE, Blaylock M, Kumar NP, et al. Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. Biotech. 1995;13(5):468-474.

88. Verbruggen N, Hermans C, Schat H. Molecular mechanisms of metal hyperaccumulation in plants. New Phytol. 2009;181(4):759-776.