DOI: https://doi.org/10.59983/s20230102011
AgroEnvironmental Sustainability, 2023, 1(2), 180-191

REVIEW

Recent Advances in Phytoremediation of Hazardous Substances using Plants: A Tool for Soil Reclamation and Sustainability

Meena [1], Sanjay Kumar Tyagi [1,*], Piyush Kumar [1], Nelofar Tanveer [1], Neeraj Pandey [2] and Yatender Rajput [1]

[1] Department of Science, Vivek College of Education, Bijnor 246701, India
[2] Department of Zoology and Environmental Science, Gurukula Kangri (Deemed to be University), Haridwar 249404, India
[*] Author responsible for correspondence; Email: sanjay.tyagiz1969@gmail.com.

ARTICLE HISTORY
Received: 8 July 2023
Revised: 12 August 2023
Accepted: 21 August 2023
Published: 26 September 2023

KEYWORDS
eco-restoration
environmental pollution
plant ecology
waste management

EDITOR
Fidelis O. Ajibade

eISSN 2583-942X

Abstract

Phytoremediation techniques have emerged as a promising approach for soil reclamation and remediation of contaminated sites. This review article provides a comprehensive analysis of the different phytoremediation techniques used for soil reclamation and their effectiveness in removing contaminants from soil. The aim is to evaluate the current state of knowledge and to highlight potential avenues for future research in this field. The review begins with a discussion of the principles underlying phytoremediation, emphasizing the ability of plants to accumulate, tolerate, and detoxify contaminants through various mechanisms such as phytoaccumulation, rhizo-degradation, and rhizo-filtration. Different plant species and their suitability for phytoremediation are reviewed, considering factors such as metal tolerance, biomass production, and pollutant uptake efficiency. In addition, the role of soil amendments and their impact on improving phytoremediation efficiency is critically evaluated. Commonly used amendments, including chelating agents, organic matter, and pH adjusters, are reviewed with emphasis on their ability to increase metal bioavailability and plant uptake. The review also addresses challenges associated with phytoremediation, such as plant growth limitations, long-term sustainability, and potential risks associated with the release of pollutants into the atmosphere during biomass disposal. Strategies to mitigate these challenges, including plant breeding and genetic engineering, are discussed.

Citation: Meena, Tygai, S. K., Kumar, P., Tanveer, N., Pandey, N., & Rajput, Y. (2023). Recent Advances in Phytoremediation of Hazardous Substances using Plants: A Tool for Soil Reclamation and Sustainability. *AgroEnvironmental Sustainability*, 1(2), 180-191. https://doi.org/10.59983/s20230102011

Statement of Sustainability: Phytoremediation techniques can effectively contribute to sustainability thereby helping to advance the field and promote best practices. This review can guide researchers, policymakers, and practitioners toward more sustainable approaches by assessing different techniques, their strengths, limitations, and environmental impacts. It also identifies gaps in current knowledge and highlights areas for further research. Thus, it will help to refine and optimize phytoextraction methods and ultimately contribute to sustainable site and ecosystem management.

1. Introduction

Phytoremediation is a promising technique for removing heavy metals from contaminated soil or water using plants. It is an environmentally friendly and cost-effective method that utilizes the natural ability of certain plant species to accumulate and tolerate heavy metals. Also known as phytoremediation, this approach offers an alternative to traditional remediation methods such as excavation and disposal (McIntyre, 2003). The process of phytoremediation involves the use of hyperaccumulating plants, which are capable of absorbing and concentrating high levels of heavy metals in their tissues (Miransari, 2011). These plants have specialized mechanisms that allow them to take up and store heavy metals without suffering from toxicity. They have developed this unique trait as a defense mechanism against natural predators or in response to specific environmental conditions (Morkunas et al., 2018). Several plant species have been identified as efficient hyperaccumulators of heavy metals. For example, *Alyssum* species are known to accumulate nickel, Thlaspi species can accumulate zinc and cadmium, and *Brassica juncea* (Indian mustard) is effective at accumulating lead, cadmium, and zinc (Baker et al., 2020). These plants are typically fast-growing and have high biomass production, making them ideal candidates for phytoremediation.

To initiate phytoremediation, the contaminated site is prepared by tilling the soil and removing any existing vegetation. Hyperaccumulating plants are then introduced into the contaminated area (Evangelou et al., 2015). The plants are carefully selected based on their ability to thrive in specific soil conditions and target the heavy metals present (Wu et al., 2010). As the hyperaccumulating plants grow, they take up heavy metals from the soil through their roots. The metals are transported through the plant's vascular system and accumulate in their aboveground tissues, such as leaves and stems (Eid and Shaltout, 2016). The concentration of heavy metals in these plant parts can be several orders of magnitude higher than in the surrounding soil (Halim et al., 2015). Once the plants have reached their maximum metal concentration, they are harvested and removed from the site. The harvested biomass, known as "metal-enriched biomass," is then processed to extract the accumulated heavy metals (Yadav et al., 2011). Several techniques can be used for metal recovery, such as incineration, smelting, or leaching. The choice of technique depends on the specific metal and its intended end use or disposal (Cieślik et al., 2015). Phytoremediation offers several advantages over traditional remediation methods. It is a non-invasive approach that does not require extensive excavation or disturbance of the contaminated site (Mani and Kumar, 2014). In addition, it is relatively cost-effective and can be implemented in situ, minimizing transportation and disposal costs. Furthermore, phytoremediation can be combined with other phytoremediation techniques to remediate a wide range of contaminants simultaneously. However, phytoremediation has limitations. The process is often slow, requiring several growing seasons to achieve significant metal removal (Tack and Meers, 2010). It is most effective at sites with moderate levels of contamination rather than heavily contaminated areas. In addition, the availability of hyperaccumulating plant species for certain heavy metals may be limited (Gall et al., 2015).

In summary, phytoremediation is a promising technique for removing pollutants from contaminated environments using specially selected plants. Its environmentally friendly nature, cost-effectiveness, and potential for in situ application make it an attractive option for remediation of contaminated sites. Continued research and development in this area have the potential to improve the efficiency and applicability of phytoremediation in the future. Considering its importance, the current review article aimed to comprehensively analyze different phytoremediation techniques used for soil reclamation and their effectiveness in removing contaminants from soil.

2. Hazardous Substances in Soil Systems and Their Health Implications

2.1. Heavy Metals

Soil systems may contain hazardous elements that pose potential health risks to humans and ecosystems. These elements, often referred to as heavy metals, occur naturally in the Earth's crust, but can also be introduced into the soil through human activities such as industrial processes, mining, and the use of certain agrochemicals (Allouzi et al., 2021). Here are some common hazardous elements found in soil systems and their health effects:

- **Lead (Pb):** Lead is a highly toxic heavy metal that can accumulate in soil from several sources, including lead-based paint, industrial emissions, and leaded gasoline. Ingestion or inhalation of lead-contaminated soil particles can lead to lead poisoning, especially in young children. It can affect neurological development, resulting in learning disabilities, lowered IQ, and behavioral problems. Lead exposure is also associated with an increased risk of cardiovascular disease, kidney damage, and reproductive problems (Zhang et al., 2015).
- **Cadmium (Cd):** Cadmium is primarily released to the environment through industrial processes and the disposal of cadmium-containing batteries. It can contaminate soil and then be taken up by plants and enter the food chain (Kumar and Sharma, 2019). Long-term exposure to cadmium can cause kidney damage, bone disorders, and increase the risk of certain cancers, including lung and prostate cancer (Genchi et al., 2020).
- **Arsenic (Ar):** Arsenic occurs naturally in the earth's crust but can also be released into the environment through mining, smelting, and the use of certain pesticides and wood preservatives. Chronic exposure to arsenic-contaminated soil can lead to several health problems, including skin lesions, cardiovascular disease, respiratory problems, and an increased risk of several types of cancer, including skin, lung, and bladder cancers (Jang et al., 2016).

- **Mercury (Hg):** Mercury is released into the environment through industrial processes, coal burning, and small-scale gold mining. It can contaminate soil and water and bioaccumulate fish and seafood. Exposure to high levels of mercury can damage the nervous system, causing tremors, memory loss, and developmental problems in children. It can also affect the cardiovascular and immune systems (Budnik and Casteleyn, 2019).
- **Chromium (Cr):** Chromium occurs in several forms, with trivalent chromium [Cr (III)] being an essential nutrient, while hexavalent chromium [Cr(VI)] is highly toxic. Industrial activities such as chromate production and leather tanning can release hexavalent chromium into the soil. Exposure to high levels of hexavalent chromium can cause respiratory problems, skin irritation, and an increased risk of lung cancer (Kumar and Kumar, 2019a).

These hazardous elements can enter the human body through a variety of routes, including ingestion of contaminated food and water, inhalation of airborne particles, and dermal contact (Table 1). The health effects of exposure to these elements depend on factors such as concentration and duration of exposure, individual susceptibility, and route of exposure (Domenech and Marcos, 2021). To reduce the health risks associated with hazardous elements in soil systems, it is critical to identify and remediate contaminated sites, particularly in areas where human exposure is likely. Remediation techniques such as phytoremediation (the use of plants to remove heavy metals), soil washing, and containment measures can be used to reduce the levels of hazardous elements in the soil. In addition, implementing proper waste management practices, reducing industrial emissions, and monitoring soil quality can help prevent further contamination and protect human health (Xu et al., 2021).

Table 1. Heavy metals sources, health impacts, and complications.

Heavy Metals	Sources	Impacts	Health Complications	Reference
Iron	Building construction sites, industries wastes, ammunition scrapyard, etc.	Clogging of blood and choking of the respiratory system in aquatic animals.	Yield free radicals in liver cells, heart cells, and brain cells which results in increasing in metabolic acidity	Järup (2003); Rehman et al. (2021); Vakili et al. (2020)
Lead	From a polluted water source and use of lead-based repairing or lead piping.	By binding with the sulfhydryl group present on various enzymes and altering the appropriate functioning of enzymes or substituting metals that perform as cofactors in numerous enzymatic reactions	By imitating calcium, it crosses the blood-brain barrier. It affects the neurotransmission and central nervous system, also destroys the myelin sheaths, and decreases neuron numbers to reduce their growth.	Flora et al. (2012); Kumar et al. (2020a); Undaryati et al. (2020)
Cadmium	Sewage sludge, phosphate fertilizers, nickel-cadmium batteries, electroplating	Extremely bio-accumulative and It substitutes zinc's position in metallothionein.	It accumulates Biologically in the - renal tissue which is the cause of toxicity in the nephron.	Genchi et al. (2020); Kumar et al. (2019); Fatima et al. (2019)
Arsenic	Mining sites of arsenic, processing of metals, storage sites of timber, secretion from coke furnaces	Oxidative anxiety in living tissues	It is found to be highly poisonous compared to other arsenic forms. MMA(III) is collected inside the body cells as a transitional product.	Jomova et al. (2011); Recio-Vazquez et al. (2011); Sodhi et al. (2019); Nurchi et al. (2020);
Mercury	Coal-fired power plants, cement, gold production, caustic soda, and volcanoes	In the kidneys, Hg^{2+} bioaccumulates and affects the nervous system of the developing fetus after it passes the placental barrier	Respiratory diseases like bronchitis and asthma may be caused by mercury vapors. Hunter–Russell syndrome can be a result of Severe exposure.	Bernard et al. (2001)

2.2. Pesticides

While pesticides are effective tools for controlling pests and improving crop yields, they can have hazardous effects on soil systems. These effects result from the chemical composition and persistence of pesticides and their interaction with the soil environment. Here are some of the hazardous effects of pesticides in soil systems:

- **Soil contamination:** Pesticides can contaminate soil, resulting in long-term adverse effects. They can persist in soil for long periods, depending on their chemical properties and degradation rates. Over time, repeated applications can lead to the accumulation of pesticides in the soil, resulting in increased levels of contamination (Prashar and Shah, 2016).

- **Loss of biodiversity:** Pesticides can have detrimental effects on soil organisms, including beneficial insects, earthworms, and microorganisms. These organisms play a critical role in maintaining soil fertility, nutrient cycling, and overall ecosystem health. Pesticides can directly harm these organisms, disrupting the delicate balance of the soil ecosystem and reducing biodiversity (Chagnon et al., 2015).
- **Soil degradation:** Pesticides can degrade soil quality by altering soil structure and composition. Some pesticides can bind to soil particles, changing their physical properties and reducing soil porosity. This can reduce water infiltration, increase surface runoff, and contribute to soil erosion. In addition, pesticide residues can inhibit the growth of plant roots, leading to poor nutrient uptake and stunted plant development (Siedt et al., 2021).
- **Water contamination:** Pesticides applied to agricultural fields can be transported off-site through runoff and leaching, contaminating nearby water bodies. Rainfall can wash pesticide residues from the soil into streams, rivers, and groundwater sources. This contamination poses risks to aquatic ecosystems, affecting fish, amphibians, and other aquatic organisms. In addition, pesticide-contaminated water can enter the human food chain, potentially causing health problems (Kumar and Kumar, 2019b).
- **Non-target species and pollinators:** Pesticides can have unintended effects on non-target organisms, including beneficial insects such as pollinators. Bees and other pollinators play an important role in the reproduction of many plants, including crops. Pesticides can be toxic to these beneficial insects, leading to population declines and disruption of ecosystem services such as pollination (Ndakidemi et al., 2016).
- **Development of pesticide resistance:** Frequent and repeated use of pesticides can lead to the development of pesticide resistance in target pests. Some pests can develop genetic mechanisms to survive exposure to pesticides, rendering them ineffective over time. This can lead to a cycle of increased pesticide use, further exacerbating the hazardous effects on soil systems and the environment (Brevik et al., 2018).

To mitigate the hazardous effects of pesticides on soil systems, sustainable agricultural practices are essential. Integrated pest management (IPM) techniques promote the use of a combination of methods, including biological control, crop rotation, and judicious use of pesticides. In addition, organic farming practices, which rely on natural pest control methods and avoid synthetic pesticides, can help minimize the harmful effects of pesticides on soil systems (Enders and Begcy, 2021).

2.3. Persistent Organic Compounds (POPs)

Persistent organic compounds (POCs) are a group of toxic chemicals composed of multiple fused aromatic rings that are persistent in the environment, meaning they can remain in soil systems for long periods. These contaminants can have significant health impacts on both humans and ecosystems (Schweitzer and Noblet, 2018). When POCs are present in soil systems, they can enter the human body through a variety of pathways. A common route of exposure is the consumption of contaminated food and water. POPs can accumulate in plants grown in contaminated soil, and when these plants are consumed by humans, the contaminants can enter the body. In addition, POCs can leach into groundwater and contaminate drinking water sources, resulting in direct exposure (Lebelo et al., 2021). The health effects of POCs vary depending on the specific chemical, the level of exposure, and the duration of exposure. Some POCs, such as polychlorinated biphenyls (PCBs) and dioxins, are known to be highly toxic and can have adverse effects on human health. They have been linked to a wide range of health problems, including reproductive and developmental disorders, hormonal imbalances, suppression of the immune system, and an increased risk of certain types of cancer (Borgå et al., 2022). Children are particularly vulnerable to the health effects of POCs. Exposure to these pollutants during critical developmental periods can disrupt normal growth and developmental processes, leading to long-term health consequences. Prenatal exposure to POCs has been associated with reduced birth weight, impaired cognitive development, and increased risk of neurodevelopmental disorders (Davidsen et al., 2021).

In addition to direct human health effects, POCs can also have adverse effects on ecosystems. These contaminants can bioaccumulate in the food chain, becoming more concentrated as they move up the food web. Predatory animals, such as birds and mammals, are particularly vulnerable to the effects of POCs because they accumulate higher levels of these chemicals through their diets. This bioaccumulation can lead to reproductive failure, impaired immune function, and population declines in affected species (Ross and Birnbaum, 2003). To mitigate the health effects of POPs in soil systems, it is critical to implement effective pollution control measures. These include proper waste management practices, regulations governing the use and disposal of hazardous chemicals, and remediation of contaminated sites.

In addition, monitoring and testing programs can help identify areas with high levels of POC contamination and inform remediation efforts (Rajmohan et al., 2019). In general, the presence of polycyclic organic contaminants in soil systems poses significant health risks to both humans and ecosystems. Efforts should be made to minimize the release and exposure of these toxic chemicals to protect human health and the environment (Chang et al., 2022).

2.4. Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are a group of organic compounds composed of fused aromatic rings. They are formed by the incomplete combustion of organic materials such as fossil fuels, wood, and other organic substances. PAHs are ubiquitous pollutants found in various environmental matrices, including soil systems, due to their wide range of sources and resistance to degradation (Kim et al., 2013). When PAHs contaminates soils, they can have significant health impacts on both humans and ecosystems. Here are some of the health concerns associated with PAHs in soil systems:

- **Human exposure:** PAHs can enter the human body through several routes, including ingestion, inhalation, and dermal contact. Humans can be exposed to PAHs by consuming food grown on contaminated soil, inhaling contaminated dust particles, or by direct contact with contaminated soil. Occupational exposure can also occur for people who work in industries such as coal tar processing, asphalt production, or waste incineration (Qu et al., 2015).
- **Carcinogenicity:** Several PAHs have been classified as carcinogens by international agencies, including the International Agency for Research on Cancer (IARC). Long-term exposure to high levels of PAHs has been associated with an increased risk of developing several types of cancer, including lung, skin, bladder, and gastrointestinal cancers. Some PAHs can bind to DNA, causing mutations and potentially leading to the development of cancerous cells (Domingo and Nadal, 2017).
- **Respiratory effects:** Inhalation of airborne PAHs from contaminated soil can cause adverse respiratory effects. PAHs can irritate the respiratory system, causing symptoms such as coughing, wheezing, and shortness of breath. Prolonged exposure to high levels of PAHs may contribute to the development or aggravation of respiratory diseases such as asthma or chronic obstructive pulmonary disease (COPD) (Jiang et al., 2016).
- **Developmental and reproductive effects:** PAHs can cross the placental barrier and be transferred from a pregnant woman to a developing fetus. Exposure to high levels of PAHs during pregnancy has been associated with adverse birth outcomes, including low birth weight, preterm birth, and developmental abnormalities. Some studies also suggest a potential link between PAH exposure and reduced fertility in both men and women (Drwal et al., 2019).
- **Disruption of soil ecosystems:** PAH contamination in soil can have adverse effects on soil microbial communities and other soil-dwelling organisms. These compounds can inhibit the growth and activity of beneficial soil microorganisms, disrupt nutrient cycling processes, and alter the ecological balance of soil ecosystems. Such disruptions can negatively impact soil fertility, plant growth, and overall ecosystem health (Meynet et al., 2012).

To mitigate the health effects of PAHs in soil systems, it is critical to implement effective pollution prevention measures, remediation strategies, and monitoring programs. Proper management of contaminated sites, safe disposal of hazardous wastes, and adoption of cleaner technologies can help reduce the release of PAHs into the environment. In addition, promoting awareness, implementing regulations, and conducting research on the health effects of PAHs are essential to protect human health and the integrity of soil ecosystems (Alegbeleye et al., 2017).

3. Phytoremediation Technique for Soil Reclamation

Phytoremediation is a technique used in soil reclamation and environmental remediation. It involves the use of plants to extract, immobilize, or degrade contaminants in the soil, thereby improving soil quality and reducing pollution levels. Figure 1 depicts different mechanisms and processes used by plants in contaminated removal from soils. This approach utilizes the natural ability of certain plants, known as hyperaccumulators, to absorb and accumulate high concentrations of metals and other contaminants from the soil into their tissues (Xiang et al., 2022). The process of phytoremediation typically involves several steps: The first step is to identify and select suitable hyperaccumulator plant species capable of efficiently accumulating the target pollutants. These plants have specific mechanisms that allow them to tolerate and absorb high concentrations of contaminants (Seth, 2012). Before planting the hyperaccumulator species, the contaminated site must be prepared. This may involve removing the top layer of soil or incorporating soil amendments to improve fertility and overall conditions for plant growth (Kidd et al., 2015). The hyperaccumulator plants are then sown or transplanted into the contaminated soil. Adequate care and maintenance, such as watering, fertilization, and weed control, are provided to ensure optimal plant growth and development (Kidd et al., 2015). As hyperaccumulator plants grow, they take up contaminants from the soil through their root systems. These contaminants can include heavy metals such as cadmium, lead, zinc, nickel, and arsenic, as well as organic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and pesticides (Meena et al., 2021). Once hyperaccumulator plants have reached maturity and accumulated a significant amount of contaminants, they are harvested. The above-ground biomass, including leaves, stems, and flowers, is typically collected (Saleem et al., 2020). The harvested plant biomass is then processed to extract the accumulated contaminants. Various methods such as incineration, chemical leaching, or solvent extraction may be used, depending on the nature of the contaminants and the intended subsequent use or disposal (Dastyar et al., 2019). The extracted contaminants are safely disposed of in accordance with environmental regulations or, if feasible, recycled for other uses. The remaining plant residues, if uncontaminated, can be composted or used for energy production (Brunner and Rechberger, 2015). Table 2 depicts some plants used for phytoextraction of heavy metals contaminants from soil in previous studies.

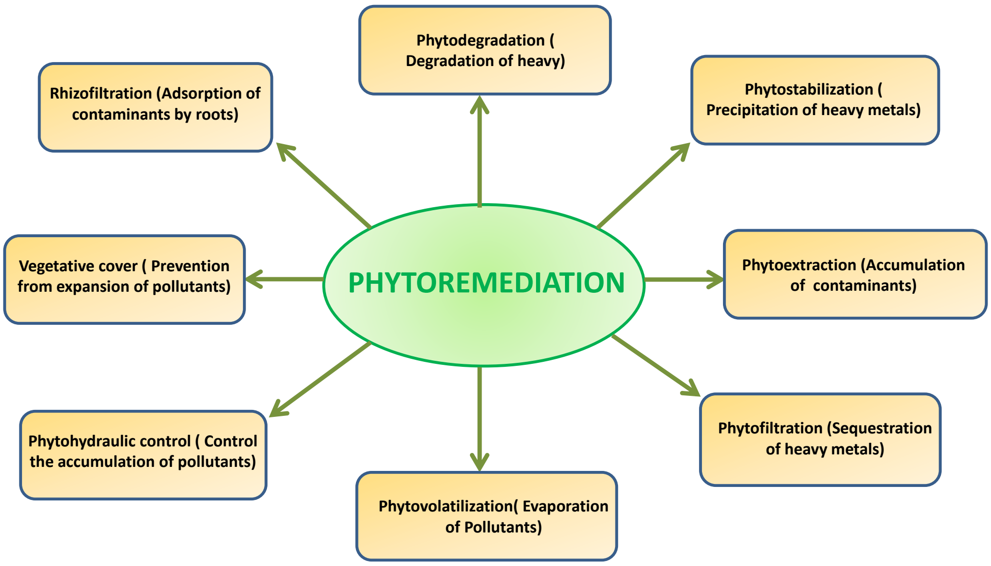

Figure 1. Different mechanisms and processes used by plants in contaminated removal from soils.

Table 2. Various plants used for phytoextraction of heavy metals contaminants from soil.

Contaminants	**Plants**	**References**
Cd	Castor (*Ricinus communis*)	Huang et al. (2011)
Cd, Pb, Zn	Corn (*Zea mays*)	Meers et al. (2010)
Se	*Brassica juncea* and *Astragalus bisulcatus*	Dixit et al. (2015)
Cr	*Spartina argentinensis*	Nalla et al. (2012)
Cd, Cu, Ni, Pb	Jatropha (*Jatropha curcas* L.)	Abhilash et al. (2009)
As	*Pteris vittata*	Datta et al. (2017)
Cd, Cu, Pb, Zn	*Populus* spp. (*P. deltoides*, *P. nigra*, *P. trichocarpa*)	Ruttens et al. (2011)
Ni	*Alyssum bertolonii* and *A. murale*	Mengoni et al. (2012)
Cd, Cu, Fe, Cr, Pb, Zn	Water fern (*Azolla pinnata*)	Kumar et al. (2020b)
Cd, Cu, Fe, Cr, Mn, Zn	Water hyacinth (*Eichhornia crassipes*)	Kumar et al. (2021)

Phytoremediation offers several advantages as a soil remediation technique. Phytoremediation is a sustainable and environmentally friendly approach that avoids the use of harsh chemicals or mechanical soil excavation methods (Oladoye et al., 2022). Compared to traditional remediation methods such as soil excavation and off-site disposal, phytoremediation can be more cost-effective, especially for large-scale remediation projects (Liu et al., 2018). By keeping contaminated soil in place and improving its quality, phytoremediation minimizes the risk of soil erosion and associated environmental impacts (Le Guern et al., 2018). In addition to removing contaminants, hyperaccumulator plants can help improve soil structure, fertility, and nutrient content, promoting long-term soil restoration (Burges et al., 2018). Phytoremediation projects can often gain support and acceptance from local communities due to their non-invasive nature and potential aesthetic benefits (Kennen and Kirkwood, 2015).

Despite its benefits, phytoremediation also has some limitations and considerations. Phytoremediation is a relatively slow process, requiring several years for the hyperaccumulator plants to accumulate significant amounts of contaminants (Raskin et al., 1997). Figure 2 shows some hyperaccumulator plant species for decontamination of soil and water bodies. The success of phytoremediation depends on the suitability of the hyperaccumulator plants for the specific soil conditions and contaminants present. Factors such as pH, nutrient availability, and moisture can affect plant growth and metal uptake (Robinson et al., 2006). The number of known hyperaccumulator plant species is relatively small, and their adaptation to different environmental conditions may be limited (Meharg, 2003).

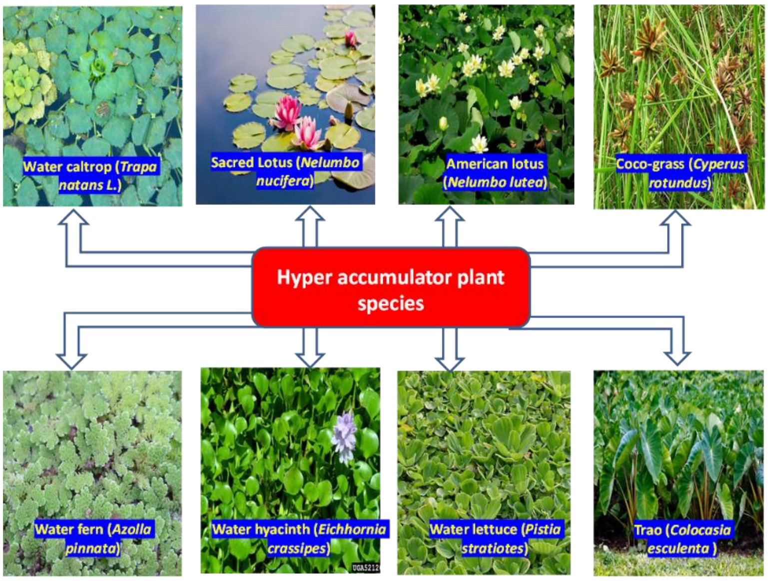

Figure 2. Some hyperaccumulator plant species for decontamination of soil and water bodies.

4. Limitations and Future Directions

Phytoremediation is considered a sustainable and cost-effective method for environmental cleanup compared to traditional remediation techniques (Mir et al, 2017). However, like any other technology, phytoremediation has its limitations. Not all plant species have the ability to effectively extract or tolerate high levels of contaminants. Finding suitable plant species with high accumulation capacities for specific pollutants can be challenging (Bhargava et al, 2012). Phytoremediation is a time-consuming process as plants need sufficient time to accumulate contaminants from the soil. It may take several years to achieve significant remediation results, which might not be suitable for urgent or time-sensitive cleanup projects (Jeevanantham et al, 2019). Phytoremediation is primarily effective for contaminants in the root zone of plants. Contaminants that are present at greater depths or in inaccessible areas may not be easily remediated using this technique (Saleh et al, 2004). The success of phytoremediation depends on the physicochemical properties of the soil, such as pH, organic matter content, and nutrient availability. Unsuitable soil conditions can hinder plant growth and, consequently, the effectiveness of phytoremediation (Robinson et al, 2006). The efficiency of phytoremediation can be influenced by environmental factors such as temperature, rainfall, and sunlight. Extreme conditions or seasonal variations can affect plant growth and, subsequently, the remediation process (Muerdter et al., 2018).

Advances in genetic engineering provide opportunities to increase the accumulation capacity of plants for specific contaminants. Scientists can modify plant genes to increase tolerance, uptake, and translocation of contaminants, potentially improving the efficiency and effectiveness of phytoremediation (Ibañez et al., 2016). Studying interactions between plants and beneficial microorganisms can improve phytoremediation. Certain microbes can help mobilize and detoxify contaminants, improving plant uptake and overall remediation efficiency (Mishra et al., 2017). Nanoparticles can be used to improve the efficiency of phytoremediation. They can be engineered to bind with contaminants, increasing their availability for plant uptake and accelerating the remediation process (Ramezani et al., 2021). Integrating phytoremediation with other remediation techniques, such as chemical extraction or thermal treatment, can provide a comprehensive and synergistic approach to environmental remediation. This combined approach can potentially overcome the limitations of phytoremediation and achieve faster and more efficient remediation outcomes (Kuppusamy et al., 2017). While phytoremediation has been extensively studied in the laboratory, its large-scale implementation and practical application at real contaminated sites are still limited. Future research should focus on field-scale trials and monitoring to assess the efficacy, economic viability, and long-term sustainability of phytoremediation (Gong et al., 2018).

5. Conclusion

In conclusion, while phytoremediation has shown promise as an environmentally friendly and cost-effective technique for environmental remediation, it has certain limitations that need to be addressed. Through ongoing research and development, including genetic engineering, plant-microbe interactions, nanotechnology, and combined remediation approaches, the future of phytoremediation looks promising. These advances can potentially overcome existing limitations and make phytoremediation a more efficient and widely used method for environmental remediation.

Author Contributions: Conceptualization, Meena, Piyush Kumar; Data curation, Sanjya Kumar Tyagi; Funding acquisition, Piyush Kumar; Investigation, Nelofar Tanveer; Methodology, Sanjya Kumar Tyagi, Piyush Kumar; Resources: Meena; Software, Neeraj Pandey; Supervision, Meena Piyush Kumar; Validation, Yatender Rajput; Visualization, Piyush Kumar, Neeraj Pandey; Writing – original draft, Meena, Piyush Kumar; Writing – review & editing, Nelofar Tanveer, Neeraj Pandey, Yatender Rajput. All authors have read and agreed to the published version of the manuscript.

Funding: Not applicable.

Acknowledgment: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not applicable.

Data/Supplementary Information Availability: Not applicable.

References

Abhilash, P. C., Jamil, S., & Singh, N. (2009). Transgenic plants for enhanced biodegradation and phytoremediation of organic xenobiotics. *Biotechnology Advances*, 27(4), 474-488.

Alegbeleye, O. O., Opeolu, B. O., & Jackson, V. A. (2017). Polycyclic aromatic hydrocarbons: a critical review of environmental occurrence and bioremediation. *Environmental Management*, 60, 758-783. https://doi.org/10.1007/s00267-017-0896-2

Allouzi, M. M. A., Tang, D. Y. Y., Chew, K. W., Rinklebe, J., Bolan, N., Allouzi, S. M. A., & Show, P. L. (2021). Micro (nano) plastic pollution: The ecological influence on soil-plant system and human health. *Science of the Total Environment*, 788, 147815. https://doi.org/10.1016/j.scitotenv.2021.147815

Baker, A. J., McGrath, S. P., Reeves, R. D., & Smith, J. A. C. (2020). Metal hyperaccumulator plants: a review of the ecology and physiology of a biological resource for phytoremediation of metal-polluted soils. In Phytoremediation of Contaminated Soil and Water, CRC Press, London, UK, pp. 85-107.

Bernard S, Enayati A, Redwood L., (2001). Autism: a novel form of mercury poisoning. Review. *Medical Hypotheses*, 56, 462–471 https://doi.org/10.1054/mehy.2000.1281

Bhargava, A., Carmona, F. F., Bhargava, M., & Srivastava, S. (2012). Approaches for enhanced phytoextraction of heavy metals. *Journal of Environmental Management*, 105, 103-120. https://doi.org/10.1016/j.jenvman.2012.04.002

Borgå, K., McKinney, M. A., Routti, H., Fernie, K. J., Giebichenstein, J., Hallanger, I., & Muir, D. C. (2022). The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. *Environmental Science: Processes & Impacts,* 24(10), 1544-1576. 10.1039/d1em00469g 10.1039/D1EM00469G

Brevik, K., Lindström, L., McKay, S. D., & Chen, Y. H. (2018). Transgenerational effects of insecticides—implications for rapid pest evolution in agroecosystems. *Current Opinion in Insect Science*, 26, 34-40. https://doi.org/10.1016/j.cois.2017.12.007

Brunner, P. H., & Rechberger, H. (2015). Waste to energy–key element for sustainable waste management. *Waste Management*, 37, 3-12. https://doi.org/10.1016/j.wasman.2014.02.003

Budnik, L. T., & Casteleyn, L. (2019). Mercury pollution in modern times and its socio-medical consequences. *Science of the Total Environment*, 654, 720-734. https://doi.org/10.1016/j.scitotenv.2018.10.408

Burges, A., Alkorta, I., Epelde, L., & Garbisu, C. (2018). From phytoremediation of soil contaminants to phytomanagement of ecosystem services in metal contaminated sites. *International Journal of Phytoremediation*, 20(4), 384-397. https://doi.org/10.1080/15226514.2017.1365340

Chagnon, M., Kreutzweiser, D., Mitchell, E. A., Morrissey, C. A., Noome, D. A., & Van der Sluijs, J. P. (2015). Risks of large-scale use of systemic insecticides to ecosystem functioning and services. *Environmental Science and Pollution Research*, 22, 119-134. https://doi.org/10.1007/s11356-014-3277-x

Chang, J., Fang, W., Liang, J., Zhang, P., Zhang, G., Zhang, H., & Wang, Q. (2022). A critical review on interaction of microplastics with organic contaminants in soil and their ecological risks on soil organisms. *Chemosphere*, 306, 135573. https://doi.org/10.1016/j.chemosphere.2022.135573

Cieślik, B. M., Namieśnik, J., & Konieczka, P. (2015). Review of sewage sludge management: standards, regulations and analytical methods. *Journal of Cleaner Production*, 90, 1-15. https://doi.org/10.1016/j.jclepro.2014.11.031

Dastyar, W., Raheem, A., He, J., & Zhao, M. (2019). Biofuel production using thermochemical conversion of heavy metal-contaminated biomass (HMCB) harvested from phytoextraction process. *Chemical Engineering Journal*, 358, 759-785. https://doi.org/10.1016/j.cej.2018.08.111

Datta, R., Das, P., Tappero, R., Punamiya, P., Elzinga, E., Sahi, S., & Sarkar, D. (2017). Evidence for exocellular arsenic in fronds of *Pteris vittata*. *Scientific Reports*, 7(1), 2839.

Davidsen, N., Lauvås, A. J., Myhre, O., Ropstad, E., Carpi, D., Mendoza-de Gyves, E., & Pistollato, F. (2021). Exposure to human relevant mixtures of halogenated persistent organic pollutants (POPs) alters neurodevelopmental processes in human neural stem cells undergoing differentiation. *Reproductive Toxicology*, 100, 17-34. https://doi.org/10.1016/j.reprotox.2020.12.013

Dixit, R., Malaviya, D., Pandiyan, K., Singh, U., Sahu, A., Shukla, R., Singh, B., Rai, J., Sharma, P., Lade, H. (2015) Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. *Sustainability* 7(2), 2189–2212.

Domenech, J., & Marcos, R. (2021). Pathways of human exposure to microplastics, and estimation of the total burden. *Current Opinion in Food Science*, 39, 144-151. https://doi.org/10.1016/j.cofs.2021.01.004

Domingo, J. L., & Nadal, M. (2017). Carcinogenicity of consumption of red meat and processed meat: A review of scientific news since the IARC decision. *Food and Chemical Toxicology,* 105, 256-261. https://doi.org/10.1016/j.fct.2017.04.028

Drwal, E., Rak, A., & Gregoraszczuk, E. L. (2019). Polycyclic aromatic hydrocarbons (PAHs)—Action on placental function and health risks in future life of newborns. *Toxicology*, 411, 133-142. https://doi.org/10.1016/j.tox.2018.10.003

Eid, E. M., & Shaltout, K. H. (2016). Bioaccumulation and translocation of heavy metals by nine native plant species grown at a sewage sludge dump site. *International Journal of Phytoremediation*, 18(11), 1075-1085. https://doi.org/10.1080/15226514.2016.1183578

Enders, L., & Begcy, K. (2021). Unconventional routes to developing insect-resistant crops. *Molecular Plant*, 14(9), 1439-1453. https://doi.org/10.1016/j.molp.2021.06.029

Evangelou, M. W., Papazoglou, E. G., Robinson, B. H., & Schulin, R. (2015). Phytomanagement: phytoremediation and the production of biomass for economic revenue on contaminated land. In Phytoremediation: Management of Environmental Contaminants, Volume 1, Springer, pp. 115-132. https://doi.org/10.1007/978-3-319-10395-2_9

Fatima, G., Raza, A. M., Hadi, N., Nigam, N., & Mahdi, A. A. (2019). Cadmium in human diseases: It's more than just a mere metal. *Indian Journal of Clinical Biochemistry*, 34, 371-378. https://doi.org/10.1007/s12291-019-00839-8

Flora G, Gupta D, and Tiwari A. (2012) Toxicity of lead: a review with recent updates. *Interdisciplinary Toxicology*. 5(2), 47–58. https://doi.org/10.2478/v10102-012-0009-2

Gall, J. E., Boyd, R. S., & Rajakaruna, N. (2015). Transfer of heavy metals through terrestrial food webs: a review. *Environmental Monitoring and Assessment*, 187, 1-21. https://doi.org/10.1007/s10661-015-4436-3

Genchi, G., Sinicropi, M. S., Lauria, G., Carocci, A., & Catalano, A. (2020). The effects of cadmium toxicity. *International Journal of Environmental Research and Public Health*, 17(11), 3782. https://doi.org/10.3390/ijerph17113782

Gong, Y., Zhao, D., & Wang, Q. (2018). An overview of field-scale studies on remediation of soil contaminated with heavy metals and metalloids: Technical progress over the last decade. *Water Research*, 147, 440-460. https://doi.org/10.1016/j.watres.2018.10.024

Halim, M. A., Majumder, R. K., & Zaman, M. N. (2015). Paddy soil heavy metal contamination and uptake in rice plants from the adjacent area of Barapukuria coal mine, northwest Bangladesh. *Arabian Journal of Geosciences*, 8, 3391-3401. https://doi.org/10.1007/s12517-014-1480-1

Huang, H., Yu, N., Wang, L., Gupta, D., He, Z., Wang, K., Zhu, Z., Yan, X., Li, T., & Yang, X. (2011) The phytoremediation potential of bioenergy crop *Ricinus communis* for DDTs and cadmium cocontaminated soil. *Bioresoure Technology* 102(23), 11034–11038.

Ibañez, S., Talano, M., Ontañon, O., Suman, J., Medina, M. I., Macek, T., & Agostini, E. (2016). Transgenic plants and hairy roots: exploiting the potential of plant species to remediate contaminants. *New biotechnology*, 33(5), 625-635. https://doi.org/10.1016/j.nbt.2015.11.008

Jang, Y. C., Somanna, Y., & Kim, H. J. I. J. (2016). Source, distribution, toxicity and remediation of arsenic in the environment–a review. *International Journal of Applied Environmental Sciences*, 11(2), 559-581.

Järup, L. (2003). Hazards of heavy metal contamination. *British Medical Bulletin*. 68, 167–182.

Jeevanantham, S., Saravanan, A., Hemavathy, R. V., Kumar, P. S., Yaashikaa, P. R., & Yuvaraj, D. (2019). Removal of toxic pollutants from water environment by phytoremediation: a survey on application and future prospects. *Environmental Technology & Innovation*, 13, 264-276. https://doi.org/10.1016/j.eti.2018.12.007

Jiang, X. Q., Mei, X. D., & Feng, D. (2016). Air pollution and chronic airway diseases: what should people know and do?. *Journal of Thoracic Disease*, 8(1), E31. https://doi.org/10.3978/j.issn.2072-1439.2015.11.50

Jomova, K., Jenisova, Z., Feszterova, M., Baros, S., Liska, J., Hudecova, D., Rhodes, C.J., & Valkoc, M. (2011). Arsenic: toxicity, oxidative stress and human disease. *Journal of Applied Toxicology*. 31:95–107 https://doi.org/10.1002/jat.1649

Kennen, K., & Kirkwood, N. (2015). Phyto: principles and resources for site remediation and landscape design. Routledge, England, UK, pp. 378.

Kidd, P., Mench, M., Álvarez-López, V., Bert, V., Dimitriou, I., Friesl-Hanl, W., & Puschenreiter, M. (2015). Agronomic practices for improving gentle remediation of trace element-contaminated soils. *International Journal of Phytoremediation*, 17(11), 1005-1037. https://doi.org/10.1080/15226514.2014.1003788

Kim, K. H., Jahan, S. A., Kabir, E., & Brown, R. J. (2013). A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. *Environment International*, 60, 71-80. https://doi.org/10.1016/j.envint.2013.07.019

Kumar, A., Kumar, A., MMS, C. P., Chaturvedi, A. K., Shabnam, A. A., Subrahmanyam, G., & Yadav, K. K. (2020a). Lead toxicity: health hazards, influence on food chain, and sustainable remediation approaches. *International Journal of Environmental Research and Public Health*, 17(7), 2179. https://doi.org/10.3390/ijerph17072179

Kumar, S., & Sharma, A. (2019). Cadmium toxicity: effects on human reproduction and fertility. *Reviews on Environmental Health*, 34(4), 327-338. https://doi.org/10.1515/reveh-2019-0016

Kumar, V., & Kumar, P. (2019b). A review on feasibility of phytoremediation technology for heavy metals removal. *Archives of Agriculture and Environmental Science*, 4(3), 326-341. https://doi.org/10.26832/24566632.2019.0403011

Kumar, V., & Kumar, P. (2019c). Pesticides in agriculture and environment: Impacts on human health. (Kumar, V., Kumar, R., Singh, J. and Kumar, P. (eds) In Contaminants in Agriculture and Environment: Health Risks and Remediation, Volume 1, Agro Environ Media, Haridwar, India, pp. 76-95. https://doi.org/10.26832/AESA-2019-CAE-0160-07

Kumar, V., Kumar, P., Eid, E. M., Singh, J., Adelodun, B., Kumar, P., & Choi, K. S. (2021). Modeling of water hyacinth growth and its role in heavy metals accumulation from unoperated old Ganga canal at Haridwar, India. *Rendiconti Lincei. Scienze Fisiche e Naturali*, 32, 805-816. https://doi.org/10.1007/s12210-021-01024-x

Kumar, V., Kumar, P., Singh, J., & Kumar, P. (2020b). Potential of water fern (*Azolla pinnata* R. Br.) in phytoremediation of integrated industrial effluent of SIIDCUL, Haridwar, India: removal of physicochemical and heavy metal pollutants. *International journal of phytoremediation*, 22(4), 392-403. https://doi.org/10.1080/15226514.2019.1667950

Kuppusamy, S., Thavamani, P., Venkateswarlu, K., Lee, Y. B., Naidu, R., & Megharaj, M. (2017). Remediation approaches for polycyclic aromatic hydrocarbons (PAHs) contaminated soils: Technological constraints, emerging trends and future directions. *Chemosphere*, 168, 944-968. https://doi.org/10.1016/j.chemosphere.2016.10.115

Le Guern, C., Jean-Soro, L., Béchet, B., Lebeau, T., & Bouquet, D. (2018). Management initiatives in support of the soil quality of urban allotment gardens: E xamples from N antes (F rance). *Land Degradation & Development*, 29(10), 3681-3692. https://doi.org/10.1002/ldr.3123

Lebelo, K., Malebo, N., Mochane, M. J., & Masinde, M. (2021). Chemical contamination pathways and the food safety implications along the various stages of food production: a review. *International Journal of Environmental Research and Public Health*, 18(11), 5795. https://doi.org/10.3390/ijerph18115795POPs

Liu, L., Li, W., Song, W., & Guo, M. (2018). Remediation techniques for heavy metal-contaminated soils: Principles and applicability. *Science of the Total Environment*, 633, 206-219. https://doi.org/10.1016/j.scitotenv.2018.03.161

Mani, D., & Kumar, C. (2014). Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: an overview with special reference to phytoremediation. *International Journal of Environmental Science and Technology*, 11, 843-872. https://doi.org/10.1007/s13762-013-0299-8

McIntyre, T. (2003). Phytoremediation of Heavy Metals from Soils. In: Tsao, D.T. (eds) Phytoremediation. Advances in Biochemical Engineering/Biotechnology, Volume 78, pp. 98-119. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-45991-X_4

Meena, M., Sonigra, P., & Yadav, G. (2021). Biological-based methods for the removal of volatile organic compounds (VOCs) and heavy metals. *Environmental Science and Pollution Research*, 28, 2485-2508. https://doi.org/10.1007/s11356-020-11112-4

Meers, E., Van Slycken, S., Adriaensen, K., Ruttens, A., Vangronsveld, J., Du Laing, G., Witters, N., Thewys, T., Tack, F. (2010) The use of bio-energy crops (*Zea mays*) for 'phytoattenuation' of heavy metals on moderately contaminated soils: a field experiment. *Chemosphere* 78(1), 35–41.

Meharg, A. A. (2003). Variation in arsenic accumulation–hyperaccumulation in ferns and their allies: rapid report. *New Phytologist*, 157(1), 25-31. https://doi.org/10.1046/j.1469-8137.2003.00541.x

Mengoni, A., Cecchi, L., & Gonnelli, C. (2011). Nickel hyperaccumulating plants and Alyssum bertolonii: model systems for studying biogeochemical interactions in serpentine soils. In Bio-Geo Interactions in Metal-Contaminated Soils, pp. 279-296. Berlin, Heidelberg: Springer Berlin Heidelberg.

Meynet, P., Hale, S. E., Davenport, R. J., Cornelissen, G., Breedveld, G. D., & Werner, D. (2012). Effect of activated carbon amendment on bacterial community structure and functions in a PAH impacted urban soil. *Environmental Science & Technology*, 46(9), 5057-5066. https://doi.org/10.1021/es2043905

Mir, Z. A., Bharose, R., Lone, A. H., & Malik, Z. A. (2017). Review on phytoremediation: An ecofriendly and green technology for removal of heavy metals. *Crop Research*, 52 (1-3), 74-82.

Miransari, M. (2011). Hyperaccumulators, arbuscular mycorrhizal fungi and stress of heavy metals. *Biotechnology Advances*, 29(6), 645-653. https://doi.org/10.1016/j.biotechadv.2011.04.006

Mishra, J., Singh, R., & Arora, N. K. (2017). Alleviation of heavy metal stress in plants and remediation of soil by rhizosphere microorganisms. *Frontiers in Microbiology*, 8, 1706. https://doi.org/10.3389/fmicb.2017.01706

Morkunas, I., Woźniak, A., Mai, V. C., Rucińska-Sobkowiak, R., & Jeandet, P. (2018). The role of heavy metals in plant response to biotic stress. *Molecules*, 23(9), 2320. https://doi.org/10.3390/molecules23092320

Muerdter, C. P., Wong, C. K., & LeFevre, G. H. (2018). Emerging investigator series: the role of vegetation in bioretention for stormwater treatment in the built environment: pollutant removal, hydrologic function, and ancillary benefits. *Environmental Science: Water Research & Technology*, 4(5), 592-612. https://doi.org/10.1039/C7EW00511C

Nalla, S., Hardaway, C. J., & Sneddon, J. (2012) Phytoextraction of selected metals by the first and second growth seasons of *Spartina alterniflora*. *Instrumentation Science & Technology*, 40(1), 17–28.

Ndakidemi, B., Mtei, K., & Ndakidemi, P. A. (2016). Impacts of synthetic and botanical pesticides on beneficial insects. *Agricultural Sciences*, 7(06), 364. https://doi.org/10.4236/as.2016.76038

Nurchi, V. M., Buha Djordjevic, A., Crisponi, G., Alexander, J., Bjørklund, G., & Aaseth, J. (2020). Arsenic toxicity: molecular targets and therapeutic agents. *Biomolecules*, 10(2), 235. https://doi.org/10.3390/biom10020235

Oladoye, P. O., Olowe, O. M., & Asemoloye, M. D. (2022). Phytoremediation technology and food security impacts of heavy metal contaminated soils: A review of literature. *Chemosphere*, 288, 132555. https://doi.org/10.1016/j.chemosphere.2021.132555

Prashar, P., & Shah, S. (2016). Impact of fertilizers and pesticides on soil microflora in agriculture. In Sustainable Agriculture Reviews: Volume 19, pp. 331-361. Springer, Cham. https://doi.org/10.1007/978-3-319-26777-7_8

Qu, C., Li, B., Wu, H., Wang, S., & Giesy, J. P. (2015). Multi-pathway assessment of human health risk posed by polycyclic aromatic hydrocarbons. *Environmental Geochemistry and Health*, 37, 587-601. https://doi.org/10.1007/s10653-014-9675-7

Rajmohan, K. V. S., Ramya, C., Viswanathan, M. R., & Varjani, S. (2019). Plastic pollutants: effective waste management for pollution control and abatement. *Current Opinion in Environmental Science & Health*, 12, 72-84. https://doi.org/10.1016/j.coesh.2019.08.006

Ramezani, M., Enayati, M., Ramezani, M., & Ghorbani, A. (2021). A study of different strategical views into heavy metal (oid) removal in the environment. *Arabian Journal of Geosciences*, 14, 1-16. https://doi.org/10.1007/s12517-021-08572-4

Raskin, I., Smith, R. D., & Salt, D. E. (1997). Phytoremediation of metals: using plants to remove pollutants from the environment. *Current Opinion in Biotechnology*, 8(2), 221-226. https://doi.org/10.1016/S0958-1669(97)80106-1

Recio-Vazquez L, Garcia-Guinea J, Carral P., (2011). Arsenic mining waste in the catchment area of the Madrid detrital aquifer (Spain). *Water, Air, & Soil Pollution*, 214, 307–320. https://doi. org/10.1007/s11270-010-0425-x

Rehman, A. U., Nazir, S., Irshad, R., Tahir, K., ur Rehman, K., Islam, R. U., & Wahab, Z. (2021). Toxicity of heavy metals in plants and animals and their uptake by magnetic iron oxide nanoparticles. *Journal of Molecular Liquids*, 321, 114455. https://doi.org/10.1016/j.molliq.2020.114455

Robinson, B., Schulin, R., Nowack, B., Roulier, S., Menon, M., Clothier, B. & Mills, T. (2006). Phytoremediation for the management of metal flux in contaminated sites. *Forest Snow and Landscape Research*, 80(2), 221-224.

Ross, P. S., & Birnbaum, L. S. (2003). Integrated human and ecological risk assessment: a case study of persistent organic pollutants (POPs) in humans and wildlife. *Human and Ecological Risk Assessment*, 9(1), 303-324. https://doi.org/10.1080/727073292

Ruttens, A., Boulet, J., Weyens, N., Smeets, K., Adriaensen, K., Meers, E., & Vangronsveld, J. (2011). Short rotation coppice culture of willows and poplars as energy crops on metal contaminated agricultural soils. *International Journal of Phytoremediation*, 13(1), 194-207.

Saleem, M. H., Ali, S., Hussain, S., Kamran, M., Chattha, M. S., Ahmad, S., & Abdel-Daim, M. M. (2020). Flax (Linum usitatissimum L.): A potential candidate for phytoremediation? Biological and economical points of view. *Plants*, 9(4), 496. https://doi.org/10.3390/plants9040496

Saleh, S., Huang, X. D., Greenberg, B. M., & Glick, B. R. (2004). Phytoremediation of Persistent Organic Contaminants in the Environment. In: Singh, A., Ward, O.P. (eds) Applied Bioremediation and Phytoremediation. Soil Biology, Volume 1, pp. 116-120. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-05794-0_6

Schweitzer, L., & Noblet, J. (2018). Water contamination and pollution. In Green Chemistry, pp. 261-290. Elsevier. https://doi.org/10.1016/B978-0-12-809270-5.00011-X

Seth, C. S. (2012). A review on mechanisms of plant tolerance and role of transgenic plants in environmental clean-up. *The Botanical Review*, 78(1), 32-62. https://doi.org/10.1007/s12229-011-9092-x

Siedt, M., Schäffer, A., Smith, K. E., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, 751, 141607. https://doi.org/10.1016/j.scitotenv.2020.141607

Sodhi, K. K., Kumar, M., Agrawal, P. K., & Singh, D. K. (2019). Perspectives on arsenic toxicity, carcinogenicity and its systemic remediation strategies. *Environmental Technology & Innovation*, 16, 100462. https://doi.org/10.1016/j.eti.2019.100462

Tack, F. M., & Meers, E. (2010). Assisted phytoextraction: helping plants to help us. *Elements*, 6(6), 383-388. https://doi.org/10.2113/gselements.6.6.383

Undaryati, Y. M., Sudjarwo, S. A., & I'thisom, R. (2020). Literature Review: Effect Of Lead Toxicity On Reproductive System. *Journal of Global Research in Public Health*, 5(1), 1-8. https://doi.org/10.30994/jgrph.v5i1.202

Vakili-G, R., Momtazi-B, A. A., Vakili-G, Z., Aiyelabegan, H. T., Jaafari, M. R., Rezayat, S. M., & Arbabi Bidgoli, S. (2020). Toxicity assessment of superparamagnetic iron oxide nanoparticles in different tissues. *Artificial Cells, Nanomedicine, and Biotechnology*, 48(1), 443-451. https://doi.org/10.1080/21691401.2019.1709855

Wu, G., Kang, H., Zhang, X., Shao, H., Chu, L., & Ruan, C. (2010). A critical review on the bio-removal of hazardous heavy metals from contaminated soils: issues, progress, eco-environmental concerns and opportunities. *Journal of Hazardous Materials*, 174(1-3), 1-8. https://doi.org/10.1016/j.jhazmat.2009.09.113

Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., & Xing, B. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environmental Science & Technology*, 56(23), 16546-16566. https://doi.org/10.1021/acs.est.2c02976

Xu, D. M., Fu, R. B., Liu, H. Q., & Guo, X. P. (2021). Current knowledge from heavy metal pollution in Chinese smelter contaminated soils, health risk implications and associated remediation progress in recent decades: A critical review. *Journal of Cleaner Production*, 286, 124989. https://doi.org/10.1016/j.jclepro.2020.124989

Yadav, B. K., Siebel, M. A., & van Bruggen, J. J. (2011). Rhizofiltration of a heavy metal (lead) containing wastewater using the wetland plant Carex pendula. *Clean–Soil, Air, Water*, 39(5), 467-474. https://doi.org/10.1002/clen.201000385

Yang, L., Yuanyuan, Z., Feifei, W., Zidie, L., Shaojuan, G., and Uwe, S. (2020). "Toxicity of mercury: Molecular evidence." *Chemosphere* 245: 125586. https://doi.org/10.1016/j.chemosphere.2019.125586

Zhang, R., Wilson, V. L., Hou, A., & Meng, G. (2015). Source of lead pollution, its influence on public health and the countermeasures. *International Journal of Health, Animal Science and Food Safety*, 2(1), 18-31. https://doi.org/10.13130/2283-3927/4785