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Plants: A promising tool for soil remediation for environmental sustainability

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Abstract

The issue of soil contamination caused by various anthropogenic activities is a global concern. The detrimental effects of these contaminants on the environment cannot be overemphasized in terms of the threat posed to plants and animals. The contaminants affect the soil properties, the crop biomass, and its yield. Moreover, these contaminants contain some toxic heavy metals (HMs) that cannot be decomposed, which accumulate in the ecosystem. Thus, they enter the food chain in the ecosystem. Researchers have widened their research in proffering solutions to the problems posed by soil contamination with possible remediation strategies. Several strategies have been adopted in remediating HMs contaminated soil, but these techniques are very expensive and affect the physio-chemical properties of the soil. In contrast, the use of plants for remediation purposes known as phytoremediation found its application in the removal of contaminants in soil. In this method, the plant absorbs these metals from the soil thereby reducing the concentration of the metals in the contaminated soil. Phytoremediation is classified as a green technology due to its ability to remove contaminants without introducing any secondary pollutants. The concept of phytoremediation in cleaning up contaminated soils is straightforward. Phytoremediation should be embraced as it does not require special skills for environmental sustainability. The review focuses on the strategies for remediation of toxic HMs from contaminated soils for environmental sustainability using the green plant.

Keywords: Anthropogenic activities, HMs, Phytoremediation, Soil contaminants

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Introduction

Soil is the topmost layer of the earth's surface (Kibblewhite et al., 2008). It is the major medium for growing plants that the human population and livestock depend on directly or indirectly. The soil conditions have a great influence on the performance and metabolic processes of the plants grown on it. Industrialization and urban development have led to a continued increase in soil contamination globally through the abundance of various contaminants deposited (Ashraf et al., 2019). Soil is one of the major parts of the ecosystem that is beneficial to living things (Robinson et al., 2012) but when contaminants accumulate in it, it becomes toxic to life. Natural and anthropogenic sources are the major ways through which the contaminants enter the soil. Naturally occurring processes include rock weathering, earthquakes, floods, etc., while anthropogenic sources are human activities such as the use of various chemicals, mining activities, waste disposal, oil spillage, and numerous industrial activities (Sparks, 1995). The list of various human activities that cause soil contamination is highlighted in Table 1.

The problem of soil pollution by contamination with HMs through various agents in the environment has seriously affected the health of plants, animals, humans, and the environment at large. Soil is said to be contaminated if the quantity of the HM(s) is beyond the regulatory threshold level in soil (Lukumon and Gin, 2016). Various health risks emerge because of the contaminants in the soil on humans and the environment. It has become necessary to ensure that HMs in the soil do not go beyond the regulatory threshold level.

To achieve this, several remediation technologies have been put in place with the primary aim of reducing or eliminating these toxic contaminants from the soil. These methods have helped to reclaim polluted sites with HMs. These methods involve physio-chemical or mechanical strategies like excavation and landfill, electric field application, soil washing, solidification, etc. (DalCorso et al., 2019). The challenges of Physico-chemical approaches include high cost, irreversible alteration in the soil properties, poor efficiency when the contaminants in the soil are at low concentration, and the introduction of secondary pollutants into the soil (DalCorso et al., 2019). Developing a cost-effective, proficient, and eco-friendly method(s) in remediating the soils that are contaminated with HMs brings about the green technology called phytoremediation. Phytoremediation is a technology that uses plants to uptake, break down or immobilize contaminants present in the environment (Jankaite and Vasarevičius, 2005).

Phytoremediation is also known as green technology as it removes contaminants in the soil without introducing any secondary pollutants (Raza et al., 2020). According to Arya et al., (2017), phytoremediation is approved by the populace due to the lesser risk of transferring contaminants to other uncontaminated sites, as the soil is not excavated. The cost and energy required using phytoremediation are low compared to some other techniques (Ifon et al., 2019). The contaminant-enriched plant parts should be properly disposed of or used for product recovery. The use of plant species whose parts are edible should be avoided in reclaiming soil that has been heavily polluted with HMs as the HM will enter into the food chain through human and animal consumption. Thus, the use of non-edible plant species as hyper-accumulators is essential for the safety of humans and animals. This review highlights the need to embrace phytoremediation as a means of remediating contaminants in the environment and throws more light on its strategies, challenges, and opportunities.

Plants species and HMs contaminated soil

In using plants to remediate contaminated soils, plants are categorized into excluders, accumulators, and indicators (Baker and Whiting, 2012). The plant species that check the contaminants from entering into the roots of the plant are called excluders. Excluders are used for the stabilization of contaminants in the soil to prevent the leaching of the contaminants (de Vos et al., 1991). The accumulators are plant species that allow the contaminants in the soil to enter the cells of the roots and accumulate the contaminants into their biomass. Indicators are the plant species that easily show the symptoms of contaminants toxicity in the soil (Mc Grath et al., 2022). The accumulators are the categories of plant species that are commonly used for phytoremediation purposes. They can accumulate contaminants in their roots and shoots without showing any severe toxic symptoms. There are several methods of determining the efficiency of plant species' contaminants accumulation in its shoots and roots viz bio-concentration factor (BCF), bio-accumulation factor (BAF), and translocation factor (TF). When the values for these phytoremediation indices are greater than 1, the plant is regarded as a good phytoremediator or hyper-accumulator but if it is less than 1 it shows that the plant is a good phytostabilizer (Rascio and NavarieIzzo, 2011). Table 2 present some hyper-accumulator plants species. Hype-accumulators can accumulate metals in their tissues 100 times more than non-hyper-accumulating species under the same conditions (Rascio and NavarieIzzo, 2011).

Phytoremediation strategies

The strategies that the plant used to phyto-remediate soils varied from one plant species to another. Phytoextraction, Phyto stabilization, phytovolatilization, phytodegradation, and Phyto filtration are popular phytoremediation strategies in HMs polluted soil.

Phytoextraction

The use of plants to take up the contaminants deposited in the soil or water bodies, translocate, and accumulate the contaminants in its part is called (Jacobs et al., 2017). The processes of HMs extraction during phytoextraction involves the mobilization of HMs in rhizosphere and uptake them by the roots, translocating the available HM ions from the plant roots to the aboveground plant parts and finally the HM ions sequestration and compartmentation into the different plant tissues phytoextraction (Ali, 2013). Several factors such as the type of plant species selected, the bioavailability of the HM present in the soil, soil type and conditions, and rhizosphere properties will determine the efficiency of phytoextraction (Mahjoub, 2014). The plant root's depth also determines the success of phytoextraction. Thus, this strategy is limited to the zone influenced by the plant roots. Identification of an effective hyperaccumulator is a prerequisite for the successful phytoremediation of HMs. Phytoextraction approaches can be induced by the application of chelators to the soil (Yan et al., 2010). Phytoextraction is the best phytoremediation strategy to adopt when there is a plan to recover the economic number of metals from the plants, which is referred to as phytomining.

Phytostabilization

This is the use of plant species that are metal-tolerant to immobilize HMs in the soil and reduce their bioavailability. This prevents the HMs from entering the ecosystem (Marques et al., 2009). Phytostabilization is majorly used for HMs-contaminated soils at highly polluted or waste sites. This method helps to hold HMs to prevent bioavailability during removal and to minimize their migration into the ecosystem. The immobilization of the HMs and the movement through the soil is a result of their absorption and binding to the plant. The plant not only stabilizes the HMs in the soil but also prevents HMs from leaching. The disposal of hazardous plant parts is not required in phytostabilization, it is not expensive to practice and not disruptive like some soil remediation techniques. Plant species selection is highly essential for effective phytostabilization. The use of organic or inorganic materials to amend the contaminated soil enhances phytostabilization efficiency. These amendments can reduce the solubility and bioavailability of the HMs or change the metal speciation. These amendments also improve the soil properties, thereby becoming more beneficial to the plant.

Phytovolatilization

This is the use of plant species to take up toxic elements from the soil and convert them into a less toxic form which is eventually released into the environment through transpiration is called phytovolatilization. This method helps to detoxify some organic contaminants and HMs from the soil (Mahar et al., 2016). This method is suitable for the remediation of soils that are contaminated by organic compounds although it can still be used to remediate HMs in the soil. The major advantage of this phytoremediation strategy is that the contaminants in the soil are removed from the soil and released directly to the environment in gaseous form. Thus, the process of harvesting and disposal is eliminated. Although the method does not remove the HMs from the soil completely. Conducting an environmental risk assessment is important before adopting this strategy.

Table 1 List of list various human activities that cause soil contamination

HMs	Source	Harmful effects on humans	Harmful effects on plants	References
Lead (Pb)	-Batteries -Burning of leaded petrol -Metal products, -Paints, -Smelting operations, -Coal-based thermal power plants, -Insecticides, herbicides etc	-Short term memory loss/ Damage to fetal brain, -Kidney Problem, -Nervous system disruption -Renal failure	-Germination of seeds, elongation of roots and seedling development is inhibited, -ATP production is inhibited -Lipid peroxidation	(Patra et al., 2020; Chandra et al., 2018b; Gupta and Kumar, 2017)
Cadmium (Cd)	-Electroplating -Batteries - Dyes -Fertilizers containing $Po4^{3-}$ -Zinc smelting -Waste batteries -Paint sludge, -Fuel combustion Combustion	-Kidney damage, -Weak and brittle bones -Spinal and leg pain -Renal, pulmonary, Reproductive effects	-Chlorosis and rolling of leaves -Induction of lipid peroxidation -Alter the uptake the minerals	(Patra et al., 2020; Chandra et al., 2018b; Gupta and Kumar, 2017)
Chromium (Cr)	-Timber treatment -leather tanning -pesticides -dyes -Mining, -Industrial coolants - Chromite mine	-DNA mutation -Carcinogens, - Skin damage, -Gastrointestinal hemorrhage -Perforations in the nasal septum	-Reduction of plant biomass -Affect germination process -Reduction in oil content of lemongrass	(Patra et al., 2020; Chandra et al., 2018b)
Mercury (Hg)	-Fumigants, -Thermal power plants -Fluorescent Lamps -Spoiled thermometers	-Blindness -Deafness -Brain damage, -Digestive problems -Kidney damage.	-Reduction in number of leaf, -Leaf chlorosis -Reduced biomass and yield -Reduced stomata conductance.	(Rodrigues et al., 2012)
Arsenic (As)	-Timber treatment -Paints -Pesticides -Geothermal -Natural processes	-Cancers -Vascular disease -Dermal disease -Respiratory damage.	-Stunted growth	(Gupta and Kumar, 2017)
Zinc (Zn)	-Dyes -Paints -Timber treatment -Fertilizers -Electroplating	-Depression -Increased thirst	- Chlorosis on the leaf	(Gupta and Kumar, 2017)
Manganese (Mn)	-Fertilizer -Industrial wastewater discharges -Steel production	-Cardiovascular problem -Central nervous problem -Respiratory problem	-Chlorosis on the leaf -Stunted growth	(Seth, 2012)

Table 2 Some plants tested for HMs accumulation

HMs	Plant species	References
Lead (Pb)	*Medicago sativa*	(Koptsik, 2014)
	Helianthus annuus	(Koptsik, 2014)
	Euphorbia cheiradenia	(Chehregani and Malayeri, 2007)
	Hydrilla Verticillata	(Reeves, 2022)
	Bacopa monnieri	Chehregani and Malayeri, 2007)
	Brassica juncea	(Reeves, 2022)
	Azolla filiculoides	(Chehregani and Malayeri, 2007)
Cadmium (Cd)	*Phytolacca Americana*	(Peng et al., 2008)
	Sedum alfredii	(Xiong et al., 2004)
	Arabis gemmifera	(Kubota and Takenaka, 2003)
	Turnip landraces	(Li et al., 2016)
Chromium (Cr)	*Pteris vittata*	(Kalve et al., 2011)
	Brassica juncea	(Kalve et al., 2011)
Nikel (Ni)	*Alyssum murale*	(Bani et al., 2010)
	Psychotria douarrei	(Cunningham and Ow, 1996)
Mercury (Hg)	*Achillea millefolium*	(Wang et al., 2012)
	Silene vulgaris	(Pérez-Sanz et al., 2012)
	Marrubium vulgare	(Rodriguez et al., 2003)
Arsenic (As)	*Pteris vittata*	(Kalve et al., 2011)
	Corrigiola telephiifolia	(García-Salgado et al., 2012)
	Eleocharis acicularis	(Sakakibara et al., 2011)
Copper (Cu)	*Eleocharis acicularis*	(Chaney et al., 2012)
	Aeolanthus biformifolius	(Chaney et al., 2012
Zinc (Zn)	*Thlaspi caerulescens*	(Wang et al., 2012)
	Eleocharis acicularis	(Sakakibara et al., 2011)
Uranium (U)	*Brassica juncea*	(Sakakibara et al., 2011)

Phytofiltration

Phytofiltration is the use of plants' parts such as roots (rhizofiltration), shoots "stems and leaves" (caulofiltration), or seedlings (blastofiltration) to remove pollutants from waters bodies that have been contaminated (Mesjasz-Przybyłowicz et al., 2004). HMs in the contaminated media are either adsorbed onto the plant root surface or absorbed by the roots. When the plant roots get saturated, it will be uprooted and properly disposed or the HM extract from the plants' parts is reused as an economic resource. Plant species with a huge root, high biomass, and tolerant to HMs should be used for Phytofiltration (Yan et al., 2020).

Phytodegradation

The use of plant species to degrade and completely mineralize contaminants in the soil or water bodies is called phyto-degradation or phytotransformation (Yan et al., 2020). During phyto-degradation, the plant takes up the contaminants and breaks them down through various metabolic processes within the plant system. The contaminants outside the plant system can also be broken down by the effects of the enzymes released by the plants (Kenneth et al., 2017). Phytodegradation is a contaminant destruction process, and the main mechanism is that the plant will uptake the pollutant and metabolism (Yan et al., 2020). For plants to be able to degrade contaminants in the soil, they must be able to take up the compound. The compound uptake depends on hydrophobicity, solubility, and polarity. Moreover, plant uptake of the organic compound also relies on the plant species, the age of the pollutant, and the soil properties. The overview of some phytoremediation strategies is shown in Table 3.

Advantages and setback of phytoremediation

Phytoremediation technology has numerous advantages and setbacks that should be considered when adopting such a process. The advantages of phytoremediation include but are not limited to the following: the cost of remediating contaminated medium using plants is lesser compared to other techniques, the process is easy to control (Shah & Daverey, 2020) and the techniques can is be carried out in both in situ and ex-situ, the uptake of the compound by the plants' part can be recovered by phytomining companies and reused, it is eco-friendly, sunray is the energy required for the phytoremediation process, easier to use on a large scale and also highly acceptable by the public. However, the technology has some limitations which are not limited to the following, the time required to clean up the contaminated soil can be long, sites, where the pollutants are more than 5 m in depth, are not suited for the phytoremediation (Abdel-Shafy and Mansour, 2018).

The degree of contaminant solubility in the soil determines the efficiency of phytoextraction; for metals, only free metal ions, soluble metal complexes, or those that can be adsorbed to organic soil constituents are readily available for plants uptake. Moreover, metals that are bound to soil organic matter, precipitated or embedded in the structure of silicate minerals are not available for plants uptake. Thus, phytoremediation is not suitable in this condition if not aided. High concentrations of the contaminants are hazardous and toxic to most plant species; phytoremediation is restricted to the area where the levels of pollutants concentration are not toxic or beyond the threshold level of the proposed plant(s) to be used for remediation. In some cases, phytoremediation transfers contaminants from the soil to the atmosphere, the technology is not efficient in removing strong sorbet, and the level of the bioavailability and toxicity of the contaminant of biodegradation cannot be easily predicted. Bioaccumulation of the contaminants in the system of humans or livestock that consume the plant that takes up the contaminant is possible through biomagnification (Rehman et al., 2017), thus the contaminant will enter the food chain. The efficiency of phytoremediation is dependent on the soil properties, season variation, the plant root length, pest and disease stress, etc. A sustainable method of disposing of the plants used for phytoremediation remains a major concern in the phytoremediation process.

Table 3 Overview of some phytoremediation strategies

Mechanism	Contaminants
Phytoextraction	Metals (Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Se, Zn), metalloids, radionuclides, perchlorate, BTEX, PCP, short-chained aliphatic and other organic compounds not tightly bound to soils
Phytostabilisation	Metals (As, Cd, Cr, Cu, Hg, Pb, Zn), phenols, tetrachloromethane, trichloromethane and other chlorinated solvents
Rhizodegradation	BTEX, other petroleum hydrocarbons, PAHs, PCP, chlorinated solvents, pesticides, PCBs, and other organic compounds
Phytodegradation	Chlorinated solvents, herbicides, methyl bromide, tetrabromoethane, tetrachloroethane, dichloroethane, atrazine, organochlorine insecticide P based pesticides, PCBs, phenols, anilines, nitriles, nitrobenzene, picric acid, the nitro based explosives, nitromethane, nitroethane and nutrients, and other organic Compounds
Phytovolatilisation	Chlorinated solvents, some inorganics (Se, Hg, As) tritium, m-xylene

BTEX = (benzene, toluene, ethylbenzene, and xylenes); PAHs = (polycyclic aromatic hydrocarbons); PCBs = (polychlorinated biphenyls); PCP = (pentachlorophenol). Source: (Mahjoub, 2014)

Conclusion

The soil is an important part of the ecosystem and is now facing threats due to the release of contaminants majorly from anthropogenic activities that bring the need for remediation. Humans and livestock depend on soil for survival directly or indirectly for food. Thus, the prevention of HMs from the food chain and the web is highly important. However, remediating these HMs in contaminated soil is not negotiable. Among all the remediation technologies developed in recent times, the use of plants in remediating contaminated soils stands out, it is a green technology and cost-effective. Awareness of the use of plants for remediation of HMs soil should be publicized since is an eco-friendly approach and poses no threat to the soil microflora or change the soil properties. Phytoremediation could be assisted using chelators such as ethylenediaminetetraacetic (EDTA), microbial, or organic substances such as humic acid to decontaminate HMs that are not readily available for plant uptake. More studies should be carried out on phytoremediation concerning the factors that influence the uptake of the contaminants by plants, the strategy to make the HMs readily available, and how genetic engineering can boost the phytoremediation potential of selected plant species.

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