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Heavy Metal Remediation: A much-needed Strategy for Removal of Environmental Contaminants

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Abstract

Arsenic, cadmium, and lead are three non-vital heavy metals that are harmful to the environment, food safety, and the health of both humans and animals whenever present in excessive quantities. Poisonous metals and metalloid soil can be found worldwide. In higher amounts, some may cause neurological and behavioral abnormalities, particularly in children, while others are endocrine disruptors, carcinogens, teratogens, and mutagenic. The prevention, control, and remediation of heavy metal contamination have grown to be a top national priority in light of the real situation with soil pollution in our nation. To eliminate this kind of pollution, a variety of procedures have been used, including chemical, physical, biological, and integrative methods. Using plants and associated soil bacteria, phytoremediation lowers pollutant concentrations or their hazardous effects on the environment. It is a relatively new method that has gained widespread appeal for being an affordable, effective, unique and environment-friendly technique. The distribution of heavy metals in the environment, their sources, and the ecotoxicity they have on the environment are thoroughly explained in this review paper. Some of the procedures for creating heavy metal-free soil by using various soil remediation techniques are also described.

Keywords: Environmental pollution; Bioremediation; Heavy metal; Lead; Hazard; Contamination

Introduction

Due to vast economic development and expeditious growth in many fields such as industry and agriculture, the environment is becoming more polluted (Alengebawy et al., 2021). Heavy metal and metalloid soil contamination is a significant issue that many nations throughout the world are now dealing with (Chiampo et al., 2021). Heavy metals and metalloids are usually mentioned as a group of elements that have densities >5 g cm^{-3} (Arora and Khosla, 2021). Heavy metals such as chromium (Cr), nickel (Ni), arsenic (As), lead (Pb), copper (Cu), mercury (Hg), and cadmium (Cd) are indestructible hazardous substances derived from industrial discharge or natural mineral sources (Sarker et al., 2021). Although heavy metals are present naturally in the soil, anthropogenic and geologic activities mainly increase the concentration of these heavy elements to amounts that are destructive to both animals and plants (Obiora and Chibuike, 2014). Anthropogenic activities like electroplating, mining, and smelting operation are responsible for the contamination of the environment. Natural phenomena including volcanic eruptions and weathering are the origin of toxic metal pollution (Mekuto et al., 2020).

Due to the quick evolution of technology, humans and the ecosystem have been vulnerable to many chemical toxicants including pesticides (fungicides, herbicides, and insecticides). As pesticides are synthesized chemical compounds, used in the agricultural sector to control pests. But uncontrolled use of these chemicals causes bioaccumulation and biomagnification in food chains and reduces crop production (Alengebawy et al., 2021). Due to the rich and diverse binding properties of the associations between heavy metals and soil, the soil matrix is a primary transportation medium for heavy metals. Soils are polluted by metalloids and metals from gasoline, metal wastes, animal manure, sludge, atmospheric deposition, and wastewater irrigation (Rajasekar et al., 2019).

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Various health effects are linked with exposure to metalloids and heavy metals: kidney and bone problems, tumor formation, neuro-behavioural and developmental disorders, and blood pressure problems (Chiampo et al., 2021). Heavy metals' effects rely mainly upon their chemical nature. Inorganic arsenic (As) compounds are easily absorbed and interfere to a larger extent with cellular reactions as compared to the organic forms due to their very poor cellular absorption. Heavy metals attach themselves to the binding sites of proteins and eliminate the original metals, causing toxicity and cellular failure (Kapahi and Sachdeva, 2019). The high concentrations of heavy metals in soils have harmful effects on soil enzymes' biodiversity, especially in soils where organic matter content is low or has declined (Celestino et al., 2016). Hence, it is essential to take remediation steps to inhibit heavy metals from entering atmospheric, terrestrial, and aquatic environments, and relieve the contaminated land (Wang et al., 2020). Remediation is the removal of contaminants or pollution from the environment (e.g., sediment, groundwater, soil, and surface water) to protect human health and revive the environment (Kapahi and Sachdeva, 2019). For the remediation of soil, sediments, and water polluted with heavy metals, a variety of treatment techniques including physical, biological, and chemical were considered. Such methods include adsorption, thermal treatment, chlorination, chemical extraction, ion exchange, electrokinetics, membrane separation, bioleaching, and phytoremediation or Photobiol remediation (Rajasekar et al., 2019).

Sources of heavy metals

There are different ways by which heavy metals can enter the soil. The sources of heavy metal pollution include anthropogenic activities and natural processes (Perusic et al., 2019). Sedimentary rocks, volcanic eruptions, rock weathering, and soil formation are examples of natural sources, while residential effluents, industry, mining, and agriculture are examples of human sources (Alengebawy et al., 2021).

Natural sources

The geological or natural sources of heavy metals in the environment involve volcanic eruptions, forest fires, sea-salt sprays, biogenic sources, rock weathering, and particles of wind-borne soil (Hossain et al., 2020). Fire generates volatile heavy metals like Hg and Se which are part of carbonaceous matter. High concentrations of materials of geologic origin include Mn, Co, Cr, Cu, Sn, Zn, Ni, Cd, Pb, and Hg. Volcanoes along with toxic and harmful gases are high-level emitters of Mn, Zn, Al, Pb, Cu, Ni, and Hg (Srivastava et al., 2017). Natural weathering activity results from the release of metals from their endemic spheres into various environmental sections. Heavy metals can be found as oxides, hydroxides, sulphates, sulphides, silicates, phosphates, and organic molecules (Hossain et al., 2020). The surface properties of the adsorbents, pH, presence of anions, and cations affect the interactions between metals/metalloids and soil components (Chiampo et al., 2021).

Anthropogenic sources

The global trends of urbanization and industrialization on Earth have led to an increase in the anthropogenic share of heavy metals in the environment. Mining, industrial and agricultural activities are major sources of heavy metals (Ali et al., 2019). Increased usage of inorganic fertilizers and agrochemicals in modern agricultural practices, leads to agricultural pollution and degradation of the ecosystem (Srivastava et al., 2017). In different sectors, heavy metals and metalloids are used as a result of increasing world production and market demand. Trace amounts of copper, zinc, selenium, vanadium, iron, and manganese are essential for numerous biological processes, such as in respiration systems, nervous system, biosynthesis of complex compounds, functioning and regulation of enzymes (Chiampo et al., 2021). Irrigation by liquid waste released from fertilizer factories and paper mills is adding various alkalies, cyanides, ammonia, and heavy metals into the water bodies. Natural weathering activity results from the release of metals from their endemic spheres into various environmental sections. Heavy metals can be found as oxides, hydroxides, sulphates, sulphides, silicates, phosphates, and organic molecules (Gautam et al., 2016). Anthropogenic sources of heavy metals involve agricultural sources and pesticides as environmental pollutants (Alengebawy et al., 2021).

Agricultural sources of heavy metals

Agro-ecosystems are generally affected by numerous types of pollutants, including agricultural pollutants, which are known as abiotic and biotic by-products of farming practices (Alengebawy et al., 2021). A major donor of heavy metals in agricultural soil is atmospheric deposition, livestock manure, phosphate-based fertilizers, sewage sludge and irrigation waters (Srivastava et al., 2017; Zhang et al., 2019). Particulate matter (PM) discharged by vehicles and industries ultimately accumulates in soil and the food chain. Coal-fired power plants are one major source of Hg contamination in soil and the long-term consumption of amaranth, lettuce, water spinach, cowpea, and grains grown in Hg-contaminated soils are injurious to human health (Zhang et al., 2019).

Pesticides as sources of heavy metals

The introduction of heavy metals due to the constant input of fertilizer and pesticides for food production is carried to surface water by infiltration. Cd and Zn are most commonly present in phosphate fertilizers and the input of these fertilizers is in direct proportion to the concentration of heavy metals. Other metals found in pesticides are Pb, Hg, and As (Rajasekar et al., 2019).

Effects of heavy metals

35 metals are harmful to us because of occupational or residential exposure, out of which 23 are heavy metals: arsenic, antimony, bismuth, cerium, cadmium, chromium, cobalt, copper, gallium, gold, iron, lead, mercury, nickel, tellurium, platinum, silver, thallium, tin, uranium, zinc, and vanadium (Jaishankar et al., 2014). Different body organs are affected by several chronic and acute toxic effects of heavy metals. Kidney and gastrointestinal dysfunction, nervous system disorders, vascular damage, skin lesions, birth defects, immune system dysfunction, and cancer are some examples of the complexity of heavy metals' toxic effects (Naseri et al., 2021). As an important element, manganese is included in many physiological functions of the body. By reducing apoptotic cellular death, it exerts potential neuroprotective action with its little exposure (Mitra et al., 2022). These metals accumulate in living organisms and are shifted from one trophic level to another in the food chains. Methylated forms of heavy metals like Hg are accumulated in biota to a higher extent and are then therefore biomagnified in food chains due to their affinity for lipids (Ali et al., 2019). Some metals are specifically toxic to the sensitive, quickly developing systems of fetuses, infants and young children. Hg and Pb in particular can readily cross the placenta and may damage the fetal brain (Hejna et al., 2018).

Table 1. Sources and effects of various heavy metals

Serial no.	Heavy metals	Types	Sources	Effects	References
1.	Zinc (Zn)	Essential (Harmless)	Industrial and mining operations, sewer sludge, and high fertilizer usage	Gastrointestinal disorders, kidney, and liver abnormalities	Hussain et al., 2017
2.	Copper (Cu)	Essential (Harmless)	Copper polishing, Plating, Printing	Increased frequency of infections and cardiovascular risk	Araya et al., 2007
3.	Iron (Fe)	Essential (Harmless)	High intake of iron supplements & oral consumption	may lead to tissue damage	Hurrell et al., 2014
4.	Cobalt (Co)	Essential (Harmless)	Used in the production of metal alloys such as superalloys, high strength steels, hard metals, and magnetic alloys; manufacture of paint, and making of jewelry	Inflammations in the higher respiratory tract, such as bronchitis and rhinitis, pneumoconiosis, lung cancer, and congestive heart failure	Vihlborg et al., 2020
5.	Chromium (Cr)	Non-Essential (Toxic)	Prosthodontic devices, restorative devices, orthodontic appliances and in alloys and coatings of standard tools used by dentists	May cause lung, nasal, and sinus cancer; ulceration of mucous nasal membranes, chronic rhinitis, chronic irritation; kidney, and reproduction disorders	Budiawan et al., 2017

6.	Lead (Pb)	Non-Essential (Toxic)	Smoking-related activities, painting, leaded petrol, contaminated food, drinking water, smelting	Disturbances of body functions related to reproductive, neurological, and cardiovascular systems	Debnath et al., 2019
7.	Arsenic (As)	Non-Essential (Toxic)	Certain kinds of food, atmospheric air, insecticides and herbicides; electronic equipments	Different types of cancers, skin lesions, and problems with the respiratory and nervous systems	Chung et al., 2014
8.	Mercury (Hg)	Non-Essential (Toxic)	Industrial thermometers, barometers, batteries, pesticides and traditional gold mining	Hg salts have immunomodulatory and allergen properties, and may cause permanent damage to the brain, liver, and kidneys at long-term exposures	Pratama et al., 2020
9.	Cadmium (Cd)	Non-Essential (Toxic)	Industrial applications like the production of alloy, batteries, and burning of fossil fuels	Severe pulmonary and gastrointestinal irritants, acute ingestion, vomiting, and abdominal pain	Sutton et al., 2012

Effects of heavy metals on plants

Both essential and non-essential heavy metals usually produce common toxic effects on the plants, such as accumulation of low biomass, chlorosis, inhibition of photosynthesis and growth, nutrient assimilation, and altered water balance and senescence, which ultimately leads to plant death (Parihar et al., 2016). Accumulation of metals in plants is significantly affected by a large number of factors such as plant life cycle, plant structure, plant vigor, root system depth, soil pH, temperature, partial oxygen pressure, nutrient interface, carbohydrate level, respiration rate and microbial presence (Kumar et al., 2019). Like every living organism, plants are also sensitive both to the excess availability and deficiency of some ions of heavy metals as essential micronutrients, while the same at much higher concentrations and even more ions such as Cd, and Hg are strongly poisonous to all the metabolic activities (Pichhode and Nikhil, 2016). Effects of heavy metals on seeds exhibit various abnormalities. Germination gets decreased, reduced elongation of root and shoot, alteration of membranes, decreased total soluble protein level, oxidative damage, altered protein metabolisms, altered sugar and loss of nutrients are some of the effects (Sethy and Ghosh, 2013).

Effects on aquatic life

Many environmental factors influence the growth of aquatic animals including temperature and accessible presence of toxicants. In water polluted with toxicants, e.g., heavy metals, fish growth may be inhibited. Growth inhibition is one of the most definite symptoms of the toxic action of metals on larvae of fish. Therefore, fish body mass and length are the best indicators of environmental conditions (Khayatzadeh and Abbasi, 2010). Heavy metals may negatively impact a variety of metabolic functions in growing fish, especially in embryos, which might slow down development and cause morphological and functional abnormalities (Kentouri et al., 2015). Whereas biomagnification is the outcome of dietary intake, bioconcentration is the direct uptake of a material by a live creature from the medium through the gills, skin, or lungs. Fish that actively filter many large amounts of water through their gills are exposed to a much higher bioconcentration. Additionally, biomagnification takes place in predatory organisms (Joseph et al., 2011).

Remediation methods

To clean up heavy metal-contaminated areas, in-situ and ex-situ remediation methods such as phytoremediation, vitrification, bioremediation, and electrokinetic extraction have been developed (Song et al., 2018). Here, in this paper we are discussing these four major remediation methods.

Phytoremediation

Several phytoremediation strategies apply to the remediation of heavy metal-contaminated soils, including a) *Phytostabilization* - using plants to reduce heavy metal bioavailability in soil, b) *Phytoextraction* - using plants to extract and remove heavy metals from the soil, c) *Phytovolatilization* - using plants to absorb heavy metal from the soil and release into the atmosphere as volatile compounds, and d) *Phytofiltration* - using hydroponically cultured plants to absorb or adsorb heavy metal ions from groundwater and aqueous waste (Wang et al., 2020). Toxic metal pollution poses a severe threat to the ecosystem, and phytostabilization of heavy metals using green plants is currently gaining greater attention as it provides a practical, environmentally acceptable method. The primary mechanism underlying phytostabilization is the complexation of metal ions with the root mucilage/exudates or with the cell walls and also attached with metal-binding molecules like metallothioneins and phytochelatins; finally sequestering them to the root vacuole (Shackira et al., 2019).

Using plant-hyperaccumulators to absorb contaminants (mainly heavy metals) from the environment, transport them, and concentrate them in the biomass of harvestable organs is known as phytoextraction (Pajević et al., 2016). To be suitable for phytoextraction purposes, plant species should meet the following criteria: a) metal tolerance toward elements present in toxic levels, b) high biomass production, and c) effective accumulation of heavy metals in easy-to-harvest parts (Suman et al., 2018). Plants can be linked with a variety of organic compounds and by that means affect the fate and transport of many environmental contaminants. Volatile organic compounds may be volatilized from leaves and stems (direct phytovolatilization) or the soil due to plant root actions (indirect phytovolatilization) (Limmer et al., 2016).

Vitrification

One of the most effective methods for treating polluted soil and solid industrial waste is vitrification. The method relies on heating contaminated soil to temperatures between 1400-2000°C, and frequently much higher, where the soil melts and a stable glass-ceramic substance (vitreous material) is created. This process greatly lowers the organic compounds' solubility and obliterates them (Trifunović, 2021). The vitrification process was highly effective in the remediation of tons of heavy metal-rich materials and can be exploited further for the remediation of large amounts of soils and asbestos-based materials (Dellisanti et al., 2009).

Bioremediation using microorganisms

Lead (Pb), Zinc (Zn), Cadmium (Cd), copper (Cu), and selenite exposure are among the key heavy metals that are deemed to be harmful to human health. By consuming polluted groundwater, directly ingesting members of the food chain, and lowering the quality of food, heavy metal poisoning of soil poses threats to both humans and the ecosystem. Microorganisms take up heavy metals through the active process of bioaccumulation. Several microorganisms, including bacteria, algae, and fungus, have been employed to clean up habitats that have been polluted with heavy metals (Akabuogu et al., 2018). Microbial life has conquered extremely hostile environments. Metals play a role in all aspects of microbial growth, metabolism, and differentiation. Despite the threat that rising pollution poses to microorganisms' increased toxicity, these organisms have developed a number of methods to adapt to the presence of harmful heavy metals (Jobby and Desai, 2017). Several bacterial species like *Flavobacterium*, *Pseudomonas*, *Enterobacter*, *Bacillus* and *Micrococcus* sp. have been known to consume heavy metals. Due to their large surface-to-volume ratios and possible active chemisorption sites (teichoic acid) on the cell wall, they have a considerable capacity for biosorption (Tarekegn et al., 2020). Microorganisms can also be used to break down toxic chemicals such as pesticides besides hydrocarbon materials. Many bacteria employ the contaminant as a metabolic source. Anaerobic bacteria have also been used for the bioremediation purpose (Ahmed and Sayqal, 2021).

Electrokinetic extraction

Removal of heavy metals from soils by employing an applied electrical DC field is termed "electrokinetic remediation". When the electric potential is applied to dampish soil, the electric current is carried by ions in the pore solution (electromigration) (Ottosen, 2014). Electrokinetic remediation of soils offers many benefits over the other remediation methods that are in widespread use today. These include a) It is an in-situ process that is 50-90% more cost-effective than the presently available metals remediation technologies, such as soil washing and excavation, which are ex-situ methods; b) It is extremely effective in fine-grained low permeability soils where alternative techniques, such as pump and treat, are not feasible (Puvvadi et al., 2015).

Challenges associated with remediation technologies

The aforementioned remediation technologies are costly, labor-intensive, and time-consuming. So, efforts are being made to increase the solubility of these metals in the soil so that they can be freely available for removal. Due to their very stable nature, the use of chelating agents and surfactants in remediation methods to accelerate the removal of pollutants from the soil creates major issues with contaminants leaking into groundwater and the remobilization of metals in the soils (Sidhu, 2016).

Conclusion

Heavy metal pollution is a very important issue for the agriculture sector and food safety because of its deleterious effects and speedy accumulation in the environment. Bioremediation has emerged as a promising technology for the removal of heavy metals from contaminated environments. This method involves the use of micro-organisms or their metabolic products to degrade or detoxify toxic compounds in soil, water, or air. Bioremediation has several advantages over traditional physical and chemical methods. It is a relatively low-cost, eco-friendly, and sustainable approach that does not generate secondary pollutants. Furthermore, bioremediation processes can be tailored to specific contaminants, sites, and conditions, making them highly effective in removing heavy metals such as lead, cadmium, and mercury. Studies have shown that bioremediation methods can effectively reduce heavy metal concentrations in contaminated sites, both in situ and ex situ. Phytoremediation uses plants to absorb heavy metals from the soil. Some heavy metals, such as mercury and lead, are highly persistent and recalcitrant, making their removal a slow and challenging process. Moreover, bioremediation is often dependent on environmental factors such as pH, temperature, and availability of nutrients, which can affect its effectiveness. In conclusion, bioremediation methods hold great potential for the removal of heavy metals from contaminated environments. While more research is needed to optimize these processes, bioremediation has already proven to be a viable and sustainable alternative to traditional remediation methods.

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SK, HG and ZS conceived the concept, wrote and approved the manuscript.

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Ethics approval

Not applicable.

Citation: Kaur S, Gupta H and Singh Z (2023) Heavy Metal Remediation: A much-needed Strategy for Removal of Environmental Contaminants. Environ Sci Arch 2(STI-2):45-53.