

Phytoremediation-A Green Technology for Sustainable Management of Heavy Metals

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Abstract

Rapid urbanisation and industrialisation has led to broad dispersal of pollutants especially heavy metals in the environment. Beyond critical limit, heavy metals are hazardous for the growth as they harm metabolic activities of organisms. Natural and anthropogenic inputs add heavy metals in the ecosystem. Heavy metal mobilisation induced by anthropogenic activities like processing for varied applications as well as their extraction from the ores has led to their liberation into the environment. They are non-biodegradable and persist in the soil for longer time, thus contaminate the food chain. Exposure to heavy metals in humans especially children have posed number of behavioural, neurological, carcinogenic and even mutagenic disruptions. Hence, due attention is required for remediation of metal contaminated systems. Conventional treatment processes for removal are costlier, labour intensive, disturb the rhizospheric microflora and certainly not eco-friendly. Phytoremediation is one such green technology and is the active areas of current research. It is a non-conventional technique employed to alleviate the toxic effect of metal contaminants. Number of effective metal hyperaccumulators has been exploited in remediation of contaminated ecosystems. This paper comprehensively focuses on the heavy metal sources, toxicity and strategies involved in their remediation.

Keywords

Contaminants; Heavy metals; Hyperaccumulators; Phytoextraction; Phytoremediation

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Introduction

Heavy metal contamination has become global concern disrupting environment and harming human health (Rai *et al.*, 2019). Industrial activities like mining and smelting releases large amount of heavy metals leading to worldwide contamination (Padma *et al.*, 2024). The continuously increasing population, economic globalisation, faulty agricultural practices have excessively enhanced the heterogeneity of pollutants or contaminants in the environment (Janani *et al.*, 2021). Poor disposal of electronic wastes and batteries also pose a major risk of heavy metal pollution into the biosphere (Chakraborty *et al.*, 2022). Anthropogenic inputs have profoundly altered the biogeochemical cycle of heavy metals. They pile up in living organisms and their content increases as they pass in a food chain. Heavy metals are ubiquitous, non-biodegradable metallic elements with specific density $> 5 \text{ g cm}^{-3}$ than water (Sidhu *et al.*, 2016). Beyond critical limit, heavy metals are hazardous for the growth as they alter normal metabolism of living organisms. Exposure to heavy metals resulted in exposing humans especially children to various diseases such as cancer, behavioural abnormalities, birth defects, neurological and mutagenic disruptions (Wu *et al.*, 2016).

Heavy metals do not undergo degradation either chemical or microbial and have longer shelf life in soil so their removal has become a complicated task. Physiochemical techniques for remediation of heavy metals include incineration, soil leaching, degradation by enzymes, and ion exchange (Muthusarayanan *et al.*, 2018). However, these conventional treatment approaches are costlier, labour intensive, disturb the rhizospheric microflora and certainly not eco-friendly. Thus, a non-conventional, low cost, plant-based green technology called phytoremediation is employed to alleviate the toxic effect of metal contaminants. Plants accumulate heavy metals from the environment thus maintaining physical structure of soil. This paper comprehensively focuses on heavy metal sources, toxicity and methodologies required for removal from contaminated sites.

Sources and environmental impact of heavy metals

Natural sources include volcanic eruptions, forest fire, combustion of fossil fuel, weathering of rocks and soil erosion. The impact of metals obtained from natural sources is less as compared to those from anthropogenic sources such as sewage sludge supplementation, industrial discharge, pesticides, fertilizers, smelters, mines and thermal power plants (Ali *et al.*, 2013). The source and toxicity of some heavy metals on humans and plants is provided in Table 1. Metal toxicity effect plants and human health, hamper the ecological balance and thus it has become crucial to manage this problem through recent research developments.

Table 1 Sources and toxic effects of heavy metals to plants and human health

Heavy Metal	Anthropogenic Source	Toxic Effect	Reference
Arsenic (As)	Combustion of fossil fuels, herbicides, fungicides	Humans: Cancer, Hypertension, atherosclerosis, developmental delays in children	Garkalet <i>al.</i> (2024)
		Plants: Inhibit root extension and proliferation, lower yield.	Finnegan and Chen (2012)
Cadmium (Cd)	Mining, Smelting and synthetic fertilizers	Humans: Renal tubular damage, kidney stones, bone damage	Haideret <i>al.</i> (2021)
		Plants: Chlorosis, stunted growth, necrosis, decreased chlorophyll content	
Chromium (Cr)	Cement and steel industries, electroplating, paints, dyes, metal plating, paper production	Humans: Cancer, pathophysiological defects, damage to male reproductive system	Hossiniet <i>al.</i> (2022)
		Plants: Reduced germination, total biomass, nutrient uptake, chlorophyll content and transpiration	Ali <i>et al.</i> (2023)

Copper (Cu)	Sewage sludge, mining, smelting, agrochemicals	Humans: hepatic and neurodegenerative disorder, anaemia, damaged liver and kidney	Kumar <i>et al.</i> (2021)
		Plants: Altered root system designs, nutritional inequities, oxidative stress	
Mercury(Hg)	Small-scale gold mining, cement production, coal burning	Humans: tremors, emotional changes, insomnia, neuromuscular changes, headaches	Shahidet <i>et al.</i> (2020)
		Plants: Inhibition of plant growth, nutrient imbalance, genotoxicity, oxidative stress and lipid peroxidation	
Nickel (Ni)	Alloy production, electroplating, batteries, food industry	Humans: Contact dermatitis, cardiovascular disease, asthma, lung fibrosis, respiratory tract cancer	Genchiet <i>et al.</i> (2020)
		Plants: Reduced seed germination, biomass accumulation, chlorosis and necrosis, oxidative damage	Hassan <i>et al.</i> (2019)
Lead (Pb)	Mining, Pb acid batteries, insecticides, printing	Humans: Impact cognitive performance, post natal growth, delays puberty in infants and children. In adults it causes cardiovascular problem, central nervous system defects	Kumar <i>et al.</i> (2020)
		Plants: reduced seed germination, membrane damage, nutrient uptake, carbon metabolism and yield	Zulfiqaret <i>et al.</i> (2019)

Phytoremediation-a green technology

Phytoremediation involves use of plants for absorption of heavy metals from contaminated soils. It is an *in situ*, cost-effective, novel and green approach for remediation of heavy metals (Ali *et al.*, 2013). Metal accumulation in shoots, leaves and other parts of the plants depends upon different plant species (Rashid *et al.*, 2014). Plants possess various detoxification mechanisms for removal of contaminants. This methodology can be employed for large contaminated sites where other remediation techniques are costly and less effective (Garbisu and Alkorta, 2003). Phytoremediation comprises of different technological subgroups such as phytoextraction, phytofiltration, phytostabilisation and phytovolatilisation (Ali *et al.*, 2013). Among them phytoextraction is most promising technique for remediation of contaminated sites. It is the uptake of toxic elements from soil or water by plants through roots and their translocation and sequestration in the aboveground parts of the plant (Bhargava *et al.*, 2012). To achieve this, plants are grown on metal rich sites and their aboveground parts are extracted resulting in eradication of some toxic metals from soil. The progress of phytoextraction as a possible eco-friendly clean-up mechanism depend on availability of metals, soil type, metal speciation and accumulation potential of plant (Bhargava *et al.*, 2012). Some recent studies focuses on uptake, accumulation and translocation of metal by hyperaccumulators, so that improved variety of plants capable of phytoremediation are developed (Diarra *et al.*, 2021). Many fast-growing plant species are been examined so that they can be used in phytoextraction. Ideally, plant used for phytoextraction should possess the ability to grow in varied climatic and soil conditions, fast growth rate, higher biomass and must accumulate array of heavy metals in aerial parts (Seth, 2012). However, no plant fulfills the above attributes and hence, some non-accumulator plants can be genetically modified for achieving these criteria.

Recently many comparative reports have been documented on physiological, biochemical and molecular data of hyperaccumulator and non-hyperaccumulator plant species (Abbas *et al.*, 2018; Merlot *et al.*, 2018, Hussain *et al.*, 2019). Phytoextraction of heavy metals involve two methods, firstly, hyperaccumulators are employed that accumulate high amount of heavy metals but generate less biomass or above ground portion, secondly, some other plants are used that accumulate very less amount of

heavy metal but produce large biomass (Ali *et al.*, 2013). Like, fast growing *Populus* spp. and *Salix* spp. trees used in forestry systems are employed in phytoextraction studies because of massive root system, higher growth rate and large biomass of these plants (Domínguez *et al.*, 2008; Pajević *et al.*, 2016).

The natural method of phytoextraction has some disadvantages such as less biomass, immobility of metals in soil, slow growth of plants. Therefore, some chemical substances are added to enhance the absorption and metal uptake by plants. This technique is called chelate-assisted phytoextraction that increase or enhance the phytoavailability of metals (Sidhu *et al.*, 2018). Several chemical chelates such as ethylenediaminetetraacetic acid (EDTA), diethylenetriaminepentaacetic acid (DTPA), S,S-ethylenediaminedisuccinic acid (EDDS) are available and several experiments have been conducted to study their role in enhancing metal uptake in various plant species (Ashraf *et al.*, 2010, Sidhu *et al.*, 2017). The soil-metal-chelate-plant interactions determine the success of phytoextraction technique. Many factors such as soil properties, metal species, chelate added, and stage of plant growth affect these interactions. In this regard, more exhaustive research for evaluation of mechanism related to solubilisation of metal by chelate and uptake of metal-chelant complex by plant is needed.

Conclusion and future prospects

The contamination of soil by heavy metal is a major environmental problem, therefore efficient remediation techniques are needed to solve this issue. The conventional methods for clean-up have many limitations. In contrast, phytoremediation is a promising and environmental friendly solution. Many native plants are being screened for evaluating their phytoremediation efficiency. Further, studies are being conducted to modify some plants genetically so as to boost phytoremediation of heavy metals. Advancement in the field of molecular biology also helps in understanding the mechanism adopted by plants for accumulation and detoxification of heavy metals. Thus, phytoremediation is considered as an effective green technology with excellent potential.

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