Phytoremediation: A Promising and Sustainable Approach to Eradicate Heavy Metals from Heavy Metals-Polluted Soils and Revegetating them

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ABSTRACT
Rapid industrialization, increased waste production and surge in agricultural activities, mining, contaminated irrigation water and industrial effluents contribute to the contamination of water resources due to heavy metal accumulation. Phytoremediation is a realistic and promising strategy for heavy metal removal from polluted areas, based on the employment of hyper-accumulator plant species that are extremely tolerant to heavy metals present in the environment/soil. Green plants are used to remove, decompose, or detoxify hazardous metals in this technique. Five types of phytoremediation methods viz. Phytostabilization, rhizofiltration, phytoextraction and phytovolatilization are used for decontamination of the soil. Traditional phytoremediation methods have significant limits in terms of large-scale application, thus biotechnological efforts to modify plants for heavy metal phytoremediation ways are being explored to improve the efficacy of plants as heavy metal decontamination candidates. It is relatively economic, efficient and environment friendly. New metal hyperaccumulators with high efficiency are being explored and employed for their use in phytoremediation and Phyto mining. This review comprehensively discusses different strategies and biotechnological approaches for the removal of various heavy metal containments from the environment, with emphasis on the advancements and implications of phytoremediation, along with their applications in cleaning up various toxic pollutants.

KEYWORDSSustainability, Waste management, Heavy metals, Phytoremediation, Phytoextraction

INTRODUCTION

Environmental pollution has emerged as a significant public health issue due to its role as a primary contributor to health hazards and the onset of several severe diseases worldwide. Heavy metals are a significant form of environmental pollution. Despite the long-standing awareness of the health consequences associated with heavy metals, exposure to these substances persists and is, in fact, escalating in certain regions. Heavy metals can have fatal consequences on human health (Jarup, 2003). Heavy metals are of more significance than other forms of environmental pollution due to their resistance to degradation. The remediation procedure for contaminated soils, groundwater, and surface water contaminated with heavy metals requires the implementation of measures to eliminate the metals from the affected areas (Cunningham et al, 1995). Contaminated soils containing heavy metals can undergo several treatment methods such as acid leaching, soil washing, physical or mechanical separation of the contaminant, electro-chemical treatment, electrokinetic, chemical treatment, thermal or pyrometallurgical separation, and biochemical processes (Padmavathiamma et al, 2007; Raskin et al, 1997; Sumiahadi and Acar, 2018; Susarla et al, 2002). The remediation procedures employed for the removal of heavy metals from contaminated groundwater include extraction, treatment by activated carbon adsorption, utilisation of microorganisms, and air stripping (Xiaomei et al, 2005). Phytoremediation, a technique within the field of bioremediation, offers an alternate approach for the cleanup of heavy metals. Phytoremediation is a sustainable and efficient method that uses plants with the ability to accumulate metals to remove harmful substances such as radionuclides and organic contaminants from polluted soils and water. This approach is both cost-effective and environmentally benign (Lindqvist et al, 1991; Gisbert et al, 20003).

Table No. 1: Sources of Heavy Metals

Sr No.	Heavy metal	Sources	Reference
01	Copper	Heavy metals from electroplating industry, mining smelting and refining process.	Seaward and Richardson, 1989

02	Mercury	Metal released due to volcanic eruption, forest fire, burning of wood, emissions from the industries releasing caustic soda, coal and peat.	Knox et al, 1999
03	Zinc	Releases from the electroplating industries, smelting, mining and refining procedure	Seaward and Richardson, 1989
04	Lead	Lead releases from mining and smelting of metallic ores, municipal and industrial sewage waste containing Lead (Pb), burning of Gasoline enriched in lead.	Lone et al, 2008; Amjad et al, 2023
05	Nickel	Nickel releases from the Gaseous exchange occurring in the ocean, weathering of geological matter and soil and forest fires.	Bartucca et al, 2023
06	Selenium	Combustion of fossil fuels. Selenium release from glass industry, refining of oil, synthesis of varnish and pigments.	Khan et al, 2023
07	Chromium	Solid waste release from tanneries, sludge waste and electroplating industry.	Bartucca et al, 2023
08	Cadmium	Sewage sludge, burning of fossil fuels, fertilizers, refining and smelting of metals. Anthropogenic activities and geogenic sources.	Alloway, 2013; Kabata-Pendias, 2000; Nriaguand Pacyna, 1988
09	Arsenic	The sources of arsenic include semiconductors, volcanoes, coal power, and plant preservatives.	Nriagu, 1994; Walsh et al, 1979

Table No. 2: Different phytoremediation processes for HM uptake (Lone et al, 2008)

Types of phytoremediation	Scope of application	Mechanism	Contaminant
Phytovolatilization	Volatile contaminants	Volatilization by leaves	Organics/Inorganics
Phyto stabilization	Mining contamination	Complexation	Inorganics
Phytoextraction	Low-to-medium contaminated sites	Hyperaccumulation	Inorganics
Rhizofiltration	Wastewater	Rhizosphere accumulation	Organics/Inorganics

MECHANISMS OF HEAVY METAL UPTAKE BY PLANT

Various scholars have been investigating the absorption of contaminants by plants and the underlying mechanisms. It can be utilised to optimise the variables in order to enhance the efficiency of plant absorption. Plants function as both "accumulators" and "excluders". Accumulators persist despite the fact that they gather pollutants in their above-ground tissues. They undergo biodegradation or biotransformation, converting the pollutants into inert substances within their tissues. The excluders limit the absorption of contaminants into their biomass. Plants have developed precise and effective ways to acquire necessary micronutrients from the environment, even when they are found in low parts per million (ppm) concentrations. Through the use of chelating compounds produced by plants, as well as changes in pH and redox processes induced by plants, plant roots are capable of solubilizing and absorbing micronutrients from extremely low concentrations in the soil, including some that are almost insoluble (Sinha et al, 2007). Plants have developed precise systems to transport and store micronutrients. The same pathways are also implicated in the absorption, transportation, and accumulation of harmful substances, which possess chemical characteristics that resemble those of vital elements. Therefore, the methods by which plants absorb micronutrients are highly important in the field of phytoremediation. The plant cell plasma membrane utilises various transport mechanisms and specialised proteins for ion uptake and translocation. These include proton pumps, which are ATPases that consume energy and generate electrochemical gradients. Additionally, co- and anti-transporters are involved, which are proteins that utilise the electrochemical gradients generated by ATPases to actively uptake ions. Lastly, channels are present, which are proteins that facilitate the transport of ions into the cell. Each mode of transportation is prone to absorbing a variety of ions. An elemental issue arises from the interaction between ionic species during the absorption of different heavy metal pollutants. Translocation into shoots is necessary after roots absorption, as harvesting root biomass is typically impractical. There is limited knowledge about the several ways in which metal ions are transferred from the roots to the shoots (Ashraf et al, 2015).

The methods by which plants absorb and transport substances are expected to be tightly regulated. Plants typically do not gather trace elements in excess of their immediate metabolic requirements. These requirements are rather low, often ranging from 10 to 15 ppm for most trace elements, which is sufficient for most demands. Exceptional cases exist in the form of "hyperaccumulator" plants, which have the ability to absorb poisonous metal ions at concentrations reaching thousands of parts per million (ppm). Another concern pertains to the manner in which dangerous metal ions are retained within plants, namely in hyperaccumulating plants, and the mechanisms by which these plants prevent metal toxicity. Various mechanisms are implicated. The vacuole is a significant site for storage (Ashraf et al, 2015).

The process of transpiration, when water evaporates from the leaves of plants, acts as a mechanism to facilitate the absorption of nutrients and other elements from the soil into the roots of plants. This mechanism, known as evapotranspiration, is also responsible for transferring contaminants into the plant shoots. Contamination is transferred from the roots to the shoots, which are then collected. This process allows for the removal of contamination while keeping the original soil untouched. Plants utilised in phytoextraction techniques are referred to as "hyperaccumulators." These plants have a shoot-to-root metal concentration ratio that exceeds one. Plants that do not accumulate often have a shoot-to-root ratio well below one. Hyperaccumulators ideally flourish in hazardous settings, necessitate minimal upkeep, and yield substantial biomass. However, only a limited number of plants fully meet these criteria (Salido et al, 2003).

Plant species with the ability to accumulate metals can increase the concentration of heavy metals such as Cd, Zn, Co, Mn, Ni, and Pb up to 100 or 1000 times more than non-accumulator (excluder) plants. Typically, microorganisms such as bacteria and fungi that reside in the rhizosphere, the area around plant roots, often play a role in releasing metal ions, hence enhancing their availability for biological processes. Their contribution to the removal of organic pollutants is considerably more substantial compared to their impact on inorganic chemicals (Erdei, 2005).

1. Phytoextraction

Phytoextraction refers to the process by which plant roots absorb and transport pollutants to the above-ground parts of the plant, specifically the shoots. These shoots can then be collected and burned to generate energy, while also recycling the metal from the resulting ash (Erakhrumen and Agbontalor, 2007; Erdei, 2005; Size and Cost, 2005; Ibeanusi et al, 2004; Sas-Nowosielska et al, 2008).

2. Phytostabilization

Phytostabilization refers to the utilisation of specific plant species to immobilise contaminants in the soil and groundwater. This is achieved through the absorption and accumulation of contaminants in plant tissues, the adsorption onto roots, or the precipitation within the root zone. These processes effectively prevent the migration of contaminants in the soil, as well as their movement through erosion and deflation (Erakhrumen and Agbontalor, 2007; Erdei, 2005; Size and Cost, 2005; Ibeanusi et al, 2004).

3. Rhizofiltration

Rhizofiltration is a process that involves the use of plant roots to remove contaminants from water or soil.

Rhizofiltration refers to the process of pollutants being adsorbed or precipitated onto plant roots, or absorbed and sequestered within the roots, in the presence of a solution containing contaminants. This process is commonly used in engineered wetlands to treat municipal wastewater (Erakhrumen and Agbontalor, 2007; Erdei, 2005; Size and Cost, 2005; Ibeanusi et al, 2004).

4. Phytovolatilization

Phytovolatilization refers to the process by which plants release volatile compounds into the atmosphere.Phytovolatilization refers to the process in which a plant absorbs a contaminant and then releases it, or a modified version of it, into the atmosphere by transpiration. Phytovolatilization is the process by which trees and other plants absorb water containing pollutants. Certain pollutants have the ability to move from the plants to the leaves and then evaporate into the environment, even at relatively low quantitiesErakhrumen and Agbontalor, 2007; Erdei, 2005; Size and Cost, 2005; Ibeanusi et al, 2004).

Plants also play a crucial secondary role in physically stabilising the soil through their root system, which helps prevent erosion, protects the soil surface, and minimises the impact of rain. Simultaneously, plant roots exude nutrients that support a diverse microbial life in the rhizosphere. The makeup of bacterial communities in the rhizosphere is influenced by intricate interactions among soil type, plant species, and root zone location. The rhizosphere often exhibits larger microbial populations compared to soil without roots. This is due to a symbiotic relationship between soil microorganisms and plants. This mutually beneficial connection has the potential to optimise some bioremediation procedures. Plant roots can serve as sites for the adsorption or deposition of metal pollutants (Sas-Nowosielska et al, 2008). The root zone holds particular significance in the field of phytoremediation. The root has the ability to absorb the pollutants, which can then be stored or metabolised by the plant. Another process of phytoremediation is the degradation of pollutants in the soil by the action of plant enzymes that are released from the roots (Merkl et al, 2005).

DISCUSSION

Over the past 10–20 years, plant scientists have gained a comprehensive understanding of how plants respond to stress produced by exposure to contaminants and how this affects their gene expression. Nevertheless, plants alone may not consistently possess the ability to adequately address significant environmental pollution. The effectiveness of phytoremediation, which is primarily evaluated in enclosed and controlled conditions and focused on a single pollutant, is often dependent on the specific species of plants involved. There is still a significant amount of work that needs to be done before phytoremediation can be widely used in agriculture and forestry to eliminate pollutants. In order to enhance the ability of plants to survive and improve their effectiveness in remediation, we can utilise microbial-assisted phytoremediation, biostimulants, or genetic engineering techniques. A recently published operative handbook details the eco-compatible remediation of degraded soils. The handbook documents the five-year experience of the Ecoremed project, which was funded by the European Union. It also offers practical recommendations, including the implementation of a more comprehensive phytostabilization approach. Collectively, the various methodologies can be employed effectively to facilitate the growth of plants in contaminated areas and enhance their ability to efficiently restore the ecosystems through phytoremediation (Bartucca et al, 2023).

CONCLUSIONS

Phytoremediation is an environmental remediation technique that utilises green plants to remove toxins from the environment. Phytoremediation offers a viable green technology option for addressing areas contaminated with heavy metals. Prior research indicates that numerous plants possess a significant capacity to accumulate heavy metals and can be effectively utilised in the phytoremediation of such metals. This eco-friendly technology can be utilised to restore contaminated soils without causing any detrimental impact on soil structure. Certain plant species, such as herbs and woody plants, have demonstrated significant capacity to absorb harmful metals.

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