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REVIEW ARTICLE

PHYTOREMEDIATION AND ITS APPLICATION

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ABSTRACT

The accumulation of heavy metals in the environment, exacerbated by industrial, agricultural, military, and research activities, has emerged as a critical concern due to its adverse impacts on human health, ecological integrity, and the sustainability of natural resources. This accumulation, driven by factors such as negligence and the high costs of waste disposal, has resulted in extensive contamination of soil, surface water, and groundwater, creating severe environmental challenges. Among these, soil contamination by heavy metals is a critical issue requiring effective remediation strategies to ensure environmental health and ecological restoration. Phytoremediation, a green technology leveraging the inherent abilities of hyperaccumulator plants, has gained recognition as an effective strategy for addressing heavy metal pollution. It entails deploying plants to remove, degrade, or detoxify contaminants via processes including phytoextraction, phytostabilization, rhizofiltration, phytodegradation, and phytovolatilization. While traditional phytoremediation techniques offer potential, their scalability and efficacy are often limited. Advances in genetic engineering, nanoparticle augmentation, and the integration of plant growth-promoting rhizobacteria, phytohormones, and arbuscular mycorrhizal fungi (AMF) have significantly enhanced the effectiveness of phytoremediation strategies. This review examines the adverse biological impacts of heavy and their remediation through phytoremediation, focusing on both traditional and innovative approaches. Emphasis is placed on the mechanisms, applications, and potential of phytoremediation technologies to transform environmental remediation practices, particularly in developing regions where these techniques remain underutilized. The findings highlight the need for further research and development to transition phytoremediation into a commercially viable solution for global environmental challenges.

KEYWORDS

Green Technology, Heavy metal, Hyper-accumulator species, Phytoremediation , Pollutants , Toxicity

1. INTRODUCTION

Phytoremediation, derived from the Greek word *"phyto"* (plant) and the Latin word *"remedium"* (to clean or restore), is widely acknowledged as a cost-effective method for rehabilitating contaminated soil and water (Macek et al., 2000; Eapen and D'Souza, 2005; Cunningham et al., 1997). It represents a sustainable, efficient, and publicly acceptable remediation strategy that is both environmentally and economically advantageous (Revathi et al., 2011). The term encompasses various plant-based technologies utilizing either naturally occurring or genetically engineered plant species to treat polluted environments (Flathman and Lanza, 1998). Anthropogenic activities over the years—particularly industrial operations like mining, pesticide application, gaseous emissions, and the disposal of municipal waste—have led to the accumulation of pollutants in terrestrial and aquatic ecosystems (Shah and Daverey, 2020). These pollutants can biomagnify through food chains, causing a range of detrimental effects on plants, animals, and humans, such as endocrine disruption, immune system dysfunctions, neurotoxicity, and carcinogenic outcomes (Nedjimi, 2009a).

Chemical remediation methods for heavy metal removal, including excavation, precipitation, thermal treatment, electroremediation, and chemical leaching, remain costly and are influenced by the specific pollutants and soil characteristics (Nedjimi and Daoud 2009). In contrast, phytoremediation represents a sustainable approach that utilizes hyperaccumulator plants and their associated microbial communities to immobilize, translocate, or degrade pollutants in soil, water, and other environmental matrices (Liu et al., 2020). This method is considered efficient, cost-effective, and environmentally adaptable (Ashraf et al., 2010; Nedjimi, 2020).

2. PHYTOREMEDIATION AS A CLEANSING TOOL

Phytoremediation is defined as a cost-effective, non-intrusive technology that utilizes plants' ability to metabolize environmental contaminants (Garbisu, 2002). As describe it as the direct application of plants to degrade or sequester contaminants, including heavy metals (Macek et al., 2004). This process, recognized over 300 years ago, highlights certain plant species' capacity to accumulate heavy metals while thriving (Lasat 1999). Phytoremediation can be up to 20 times less expensive than conventional methods, with ideal species exhibiting rapid growth, large biomass, and extensive root systems (Moffat 1995; Lasat 1999).

3. HEAVY METALS (HMS)

Arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), nickel (Ni), chromium (Cr), and aluminum (Al) are among the primary heavy metals (HMs) responsible for toxicity in soil ecosystems, affecting both plant and animal life. These metals can bioaccumulate in plants, subsequently entering the food chain and posing significant health risks to humans (Nedjimi, 2009; Awa and Hadibarata, 2020). While some heavy metals such as iron (Fe), copper (Cu), selenium (Se), and zinc (Zn) are essential micronutrients in trace amounts, their excessive concentrations can result in environmental toxicity (Masson et al., 2010; Ashraf et al., 2019). The availability of HMs in soil solutions is influenced by factors including the

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metal species, soil characteristics—such as pH, clay content, and organic matter—and dynamic exchange processes like precipitation and adsorption–desorption (Naidu et al., 2003; Shah and Daverey, 2020). The main symptoms of HM toxicity in plants include reduced growth and a decline in photosynthetic activity (Sharma et al. 2020).

4. Heavy Metal Toxicity

Humans and ecosystems are vulnerable to chemical hazards from heavy metals through direct ingestion of contaminated soils, consumption of crops and vegetables cultivated on polluted lands, or drinking water filtered through such soils (McLaughlin et al., 2000). As reported that subsistence farmers who consume rice grown on contaminated soils face chronic dietary exposure to cadmium (Chaney et al., 2005). Reported that cadmium is not essential for plant metabolic processes and is highly phytotoxic, potentially causing rapid plant mortality (Kuzovkina et al., 2004).

A report by a U.S. environmental advocacy organization highlighted that the most polluted areas globally pose a health risk to over 10 million people in various countries (Jadia and Fulekar, 2009). Heavy metals in living systems are categorized as essential or non-essential: essential metals, including manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), and zinc (Zn), are vital for growth, development, and physiological functions (Gohre and Paszkowski, 2006), whereas non-essential metals like cadmium (Cd), lead (Pb), mercury (Hg), and arsenic (As) have no known biological role (Bidar et al., 2006; Peng et al., 2009). Elevated heavy metal concentrations in soil can increase crop uptake and negatively impact plant growth (Schmidt, 2003). In high concentrations, these metals disrupt metabolic activities, inhibit growth, and may result in plant death (Schaller and Diez, 1991).

5. Hyper-Accumulator Species

Some plant species possess the natural ability to accumulate toxic heavy metals (HMs) in quantities surpassing the levels found in the soil (Memon et al. 2001). Plants growing in contaminated soils employ strategies to mitigate HM toxicity, such as preventing accumulation, detoxification, or excretion of metals from their tissues (Kadukova and Kavuličova 2010). Hyperaccumulator plants thrive in soils with high HM concentrations due to their biochemical pathways, which maintain lower metal levels in the cytoplasm than in the surrounding soil through vacuolar compartmentalization, thereby protecting cellular organelles from toxicity (Nedjimi 2009).

Plants employ two main strategies to guard against toxic HMs: restricting metal uptake and accumulating metals while utilizing tolerance mechanisms. The former limits absorption by precipitating metals, while the latter involves sequestering or compartmentalizing toxic metals within the vacuoles of plant cells (Clemens 2006). Microorganisms, such as arbuscular mycorrhizal fungi (AMF) and various bacteria, also contribute to this process by releasing chelating agents, including citric acid, oxalic acid, and phenolic substances, which reduce HM uptake by plant cells (Gómez-Garrido et al. 2018). Many plants form complexes with phytochelatins (PCs), which are transported into vacuoles as metal-peptide complexes to manage HM toxicity (Yang et al. 2005). Based on metal concentrations in their tissues, plants are categorized into three groups: HM accumulator, HM indicator , and HM excluder (Baker and Brooks 1989). Accumulator species absorb HMs into their shoots or roots at levels higher than the surrounding soil, indicator species accumulate HMs proportionally to soil concentrations, and excluder species restrict HM entry into roots or prevent their translocation to shoots (Kadukova and Kavuličova 2011). Hyperaccumulators, which incorporate elevated HM concentrations in their above-ground tissues during normal growth and reproduction, which makes them valuable for phytoremediation efforts (Nedjimi and Daoud 2009).

6. Uptake, Translocation And Detoxification Of HMs

The accumulation of heavy metals (HMs) in plants depends on factors like the type of metal, its solubility, how it's transported, and the plant species or variety involved (Lasat, 2002). Metals can accumulate in different plant organs, be transformed, or even released into the atmosphere through the leaves' stomata (Kanwar et al., 2020). Plants absorb HMs from the soil through two main pathways: the symplastic pathway, where metals pass through the plasma membrane via specific ion channels, or the apoplastic pathway, which moves metals through spaces between cell walls (Hall, 2002; Shah and Daverey, 2020). Metal availability is greater in acidic soils (low pH) due to the secretion of root exudates, while basic soils (high pH) reduce metal mobility because they bind to soil particles (Clemens, 2006; Antoniadis et al., 2017).

Rhizospheric microorganisms and mycorrhizae that associate with plant roots can also enhance metal uptake (Lasat, 2002). The movement of HMs from roots to shoots is driven by root hydraulic activity and leaf transpiration, processes that are key for phytoremediation efforts (Kadukova and Kavuličova, 2010).

7. Application Of Plants For Phytoremediation

Plants function as natural solar-powered pumps and filters, absorbing water-soluble contaminants via their roots and translocating them throughout their tissues, where these substances may be metabolized, sequestered, or volatilized (Cunningham et al., 1997; Doty et al., 2007). To date, around 400 plant species from over 45 families have been identified as metal hyperaccumulators, including families such as Brassicaceae, Fabaceae, Euphorbiaceae, Asteraceae, Lamiaceae, and Scrophulariaceae (Salt et al., 1998; Dushekov, 2003; Ghosh and Singh, 2005).

Certain crops, like alpine pennycress (*Thlaspi caerulescens*), I*pomea alpine, Haumaniastrum robertii, Astragalus racemosus,* and *Sebertia acuminate* exhibit exceptional capabilities to bioaccumulate heavy metals including cadmium (Cd), zinc (Zn), copper (Cu), cobalt (Co), selenium (Se), and nickel (Ni), respectively (Lasat, 2000). Furthermore, species like willow (*Salix viminalis* L.), maize (*Zea mays* L.), Indian mustard (*Brassica juncea* L.), and sunflower (*Helianthus annuus* L.) have shown considerable heavy metal uptake and tolerance, making them suitable for phytoremediation efforts (Schmidt, 2003).

8. Grasses As Potential Phytoremediators

Grasses are preferred for phytoaccumulation due to their rapid growth rates, tolerance to stressful environments, and ability to produce high biomass (Malik et al., 2010). Certain plant and wild species, known as accumulators, are particularly effective at accumulating toxic heavy metals (Ghosh and Singh, 2005; Brunet et al., 2008).

- **Vetiver grass (*Vetiveria zizanioides L.*)**

Vetiver's extensive root system makes it highly efficient for phytoremediation, outperforming other plants in absorbing heavy metals and chemicals (Truong and Baker, 1996).

- **Cogon Grass (*Imperata cylindrica L.*)**

Cogon grass typically thrives on light-textured acidic soils with a clay subsoil and and can thrive across a broad pH range, from highly acidic to slightly alkaline conditions (Kirchner, 2002). It is commonly found in various ecosystems, particularly in areas that have undergone disturbances (Mekonnen, 2000).

- **Carabao Grass (*Paspalum conjugatum L.*)**

Carabao grass is a vigorous, creeping perennial species characterized by long stolons that root at the nodes, enhancing its ability to cover and stabilize contaminated sites.

9. Phytoremediation Of Water Pollutants

Cortez (2005) studied potential phytoremediator plants in Nueva Ecija, Philippines, finding that morning glory *(Ipomea violacea L.*) and hydracharitaceae (*Ottelia alismoides L.*) had lead (Pb) concentrations about 210% higher than in the water. As investigated the ability of water hyacinth (*Eichhornia crassipes*) to remove the phosphorus pesticide ethion (Xia and Ma, 2006). As examined the heavy metal accumulation in different organs of *Typha latifolia L* (Letachowicz et al., 2006).

10. Phytoremediation Of Soil Pollutants

As identified maize as an ideal phytoremediator due to its rapid growth and high biomass yield (Huang and Cunningham, 1996). The introduction of hyperaccumulating genes could enhance the plant's ability to adapt to various climates (Clemens et al., 2002). The solubility of Pb2+ in soil significantly affects its uptake by plants , while soil pH plays a crucial role in metal availability (Huang et al., 1997). As reported that soils with pH below 5.6 had higher amounts of exchangeable metals compared to those above 5.6 (Cholpecka et al., 1996) . Additionally, chelates like EDTA are used to enhance metal solubility and translocation to shoots (Bizily et al., 1999).

11. Phytoremediation Techniques

Phytoremediation encompasses various methods, including rhizofiltration, phytostabilization, phytovolatilization, phytodegradation, and phytoextraction (Jadia and Fulekar, 2009; Long et al., 2002).

The success and mechanisms of phytoremediation are influenced by factors such as the type of pollutant, its availability to plants, and the characteristics of the soil (Cunningham and Ow, 1996).

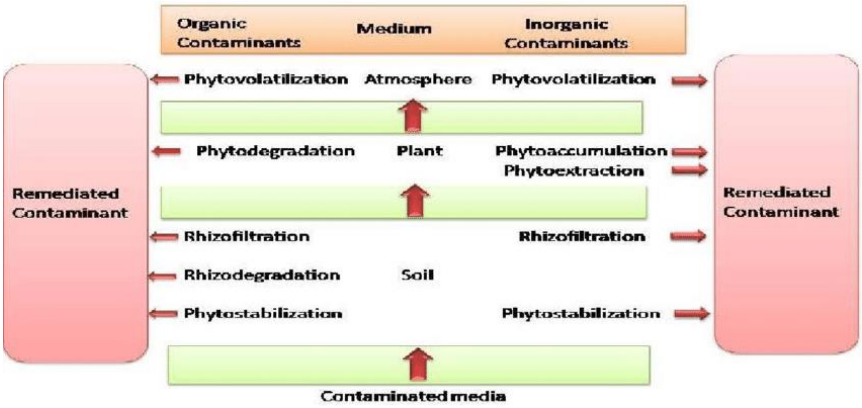

Figure 1: Phytoremediation Technology (ITRC, 2009).

11.1 Degradation

11.1.1 Phytodegradation

Phytodegradation, also called phytotransformation, is a process by which plants break down organic pollutants through internal and external metabolic mechanisms (Prasad and Freitas, 2003). This process involves converting complex organic compounds into simpler molecules or integrating them into the plant's tissues (Trap et al., 2001). The technique has proven effective in the remediation of a wide range of organic contaminants, including herbicides, munitions, and chlorinated solvents, and is applicable to pollutants found in soil, sediment, and groundwater (EPA, 2000). Typically, phytodegradation includes the uptake of pollutants followed by enzymatic breakdown within the plant system (Wenzel, 2009).

11.1.2 Rhizodegradation

Rhizodegradation is a process in which plant roots enhance both the number and diversity of microbial activity in the rhizosphere, leading to improved degradation of contaminants (Rani and Juwarkar, 2012). This method is primarily effective in addressing soil contamination and has shown success in the treatment of various organic pollutants, including petroleum hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), chlorinated solvents, pesticides, polychlorinated biphenyls (PCBs), and compounds like benzene, toluene, ethylbenzene, and xylenes (EPA, 2000).

11.2 Accumulation

11.2.1 Phytoextraction

Phytoextraction, also known as phytoaccumulation, is a highly effective method for remediating contaminated soils through the uptake of pollutants by plant roots, leading to the accumulation of these contaminants in the plant's aboveground tissues, followed by harvesting and disposal of the biomass (Wenzel, 2009). This process is mainly applicable to a range of contaminants, including metals (such as Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, and Zn), metalloids (like As and Se), radionuclides (such as 90Sr, 137Cs, 234U, and 238U), and nonmetals, which generally do not undergo further degradation within the plant (Salt et al., 1995; Pivetz, 2001). Factors such as growth rate, disease resistance, and element selectivity are crucial for the efficacy of phytoextraction (Ghosh and Singh, 2005).

As assessed the growth performance and copper extraction capabilities of *Elsholtzia splendens* for copper phytoextraction (Jiang et al., 2004). As indicated that the use of maize for cadmium phytoextraction resulted in a reduction in the percentage of exchangeable cadmium in the soil where it was planted (Zhang et al., 2009).

11.2.2 Rhizofiltration

Rhizofiltration is a technique that involves the elimination of contaminants from water through plant roots, which act by absorbing, concentrating, and precipitating the pollutants (Juwarkar et al., 2010). This method is effective for removing heavy metals such as Pb, Cd, Cu, Ni, Zn, and Cr, which mainly accumulate in the root zone. Various plants, including sunflower, Indian mustard, tobacco, rye, spinach, and corn, have been evaluated for their lead removal potential, with sunflower demonstrating the highest efficiency (Jadia and Fulekar, 2009).

11.3 Dissipation

11.3.1 Phytovolatilization

Phytovolatilization is a process where plants transform contaminants into volatile forms, removing them from soil or water (Terry et al., 1995). This mechanism may also involve the diffusion of contaminants through plant stems before reaching the leaves, where they are released into the atmosphere (Raskin and Ensley, 2000). This technique is primarily used for volatile contaminants like mercury and selenium, with some plants converting selenium into volatile forms such as dimethylselenide (Banuelos, 2000). The transformation of mercury involves converting the toxic mercuric ion into less harmful elemental mercury (Henry, 2000).

11.4 Immobilization

11.4.1 Phytostabilization

Phytostabilization, also known as phytoimmobilization, is mainly applied to remediate contaminated soil, sediment, and sludge (Wenzel, 2009). In this method, plants help reduce water infiltration through the soil, thereby limiting leachate production, restricting direct exposure to contaminated substrates, and reducing soil erosion that could spread toxic metals to surrounding environments (Raskin and Ensley, 2000). The stabilization process involves mechanisms such as adsorption, precipitation, complex formation, and reduction in metal valence states (Ghosh and Singh, 2005). Advantages of phytostabilization is the elimination of the need for hazardous material or biomass disposal, making it particularly effective when rapid immobilization is necessary to protect ground and surface waters (Zhang et al., 2009).

11.4.2 Hydraulic Control

Hydraulic control is a remediation technique that can regulate and potentially stop the migration of groundwater contaminant plumes, limit infiltration and leaching processes, and facilitate upward movement of water from the water table (Pivetz, 2001). This approach is applicable for treating a wide range of pollutants in soil, sediment, or groundwater and is particularly effective in controlling groundwater contamination, as the specific characteristics of the contaminants are less critical to its success (EPA, 2000).

12. Emerging Trends And Advanced Technologies In Enhancing Phytoremediation

12.1 Microbial-Assisted Phytoremediation

Several plants rely on associations with rhizospheric microbes to adapt and thrive in environments that are toxic and limited in nutrients (Weyens et al. 2009; Abhilash et al. 2012). Plants release a variety of chemicals via their root exudates, including organic acids, phenolic compounds, and amino acids, which are crucial for facilitating these interactions (Tanimoto 2005).

For instance, *Arthrobacter* inoculation in *Ocimum gratissimum* has been shown to induce phytoextraction of cadmium (Cd) through root uptake (Prapagdee and Khonsue, 2015).

12.2 AMF inoculation-assisted phytoremediation

Arbuscular mycorrhizal fungi (AMF) establish mutualistic relationships with plant roots, playing a significant role in enhancing phosphorus availability to plants (Zhang et al., 2015). AMF contribute to heavy metal (HM) remediation through two main mechanisms: (a) by stabilizing HMs via the release of chelating compounds and binding them to their cell walls, and (b) by facilitating phytoextraction through improved plant growth, altered root exudation, and lowered soil pH in the rhizosphere (Cabral et al., 2015). For example, AMF inoculation in *Cassia italica* was shown to markedly enhance cadmium (Cd) tolerance by restricting its movement to the aboveground tissues (Hashem et al., 2016).

12.3 Earthworm-assisted phytoremediation

Earthworms significantly contribute to the decomposition of organic matter, nutrient cycling, and overall soil health improvement (Sharma et al., 2020). Through the activity of their gut microbiota, they release organic acids like humic and fulvic acids, which help to reduce soil pH and consequently increase the bioavailability of nutrients and heavy metals (HMs) in the rhizosphere (Lemtiri et al., 2016; Wang et al., 2020). For example, found that the presence of earthworms in the growth substrate enhanced the cadmium (Cd) phytoremediation efficiency of *Solanum nigrum* (Wang et al., 2020).

12.4 Nanoparticles-assisted phytoremediation

The addition of nanoparticles (NPs) is an innovative approach to enhancing the removal efficiency of heavy metals (HMs) (Zhu et al., 2019). These particles improve phytoremediation capacity through various mechanisms, including (a) interacting with HMs via adsorption or redox reactions, (b) promoting plant growth, and (c) facilitating HM phytoremediation (Song et al., 2019). The supplementation of Cd-contaminated soil with nano-TiO_2 was shown to boost Cd removal in soybean (*Glycine max*) plants (Singh and Lee, 2016).

13. Conclusion

Phytoremediation is an emerging and promising green technology offering cost-effective and environmentally friendly solutions for the remediation of contaminated soils, sediments, and waters. It harnesses the natural abilities of plants to degrade organic pollutants and accumulate heavy metals, making it a viable alternative to traditional remediation methods.

However, despite its potential, several challenges remain, particularly in enhancing its efficiency and adapting it to site-specific conditions. Advancements in genetic engineering, nanotechnology, and plant-microbe interactions present new opportunities for improving phytoremediation processes.

Future research should focus on understanding the underlying biochemical mechanisms, optimizing plant traits for hyperaccumulation, and integrating innovative technologies to further enhance remediation outcomes. Collaboration among researchers, policymakers, and local communities will be essential for the successful and sustainable application of phytoremediation on a larger scale.

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