A REVIEW ON PHYTOREMEDIATION TECHNIQUES AND ITS BY-PRODUCTS

Ashwini Anil Farkade[1], Dr. Kiran B. Sangve[2]

Assistant Professor, Department of Zoology, M.B. Patel College of Arts, Commerce and Science, Deori, Maharashtra, India
Professor& Head, Department of Zoology, Brijlal Biyani Science College, Amravati, Maharashtra, India

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Abstract - *Phytoremediation is a developing clean up technology that employs plants to break down, remove, stabilize, or isolate pollutants in contaminated soil and water. It has gained attention as an innovative and cost-effective alternative to conventional hazardous waste treatment methods. Phytoremediation uses plants to clean contaminated soil and water and is being promoted by the EPA as a cost-effective, innovative approach to hazardous waste site remediation. It has recently gained recognition as an innovative and economical alternative to traditional cleanup techniques used at hazardous waste sites. The U.S. Environmental Protection Agency (EPA) aims to safeguard human health and the environment while supporting the development and use of innovative technologies like phytoremediation to improve site cleanup efforts. Plants possess natural characteristics that make them well suited for cleaning contaminated soils. Their root systems provide a large surface area that allows efficient absorption and accumulation of water and nutrients needed for growth. Plants also have advanced metabolic and uptake mechanisms, along with transport systems capable of selectively absorbing various ions from the soil.*

Key words – Soil contamination, heavy metals, trace elements, phytoextraction, hyperaccumulator, toxicity, lead, cadmium, mercury, biomass, etc

INTRODUCTION

Soil contamination is a major environmental issue resulting from the spread of industrial and urban wastes produced by anthropogenic activities. Both regulated and unregulated waste disposal, accidental spills, industrial processes, mining and smelting of metal ores, and the application of sewage sludge to farmland allow contaminants to spread to previously clean areas through dust or leaching, thereby polluting the ecosystem. Soil pollution is caused by a wide variety of inorganic and organic substances, including heavy metals, flammable and decomposable materials, hazardous wastes, explosives, and petroleum products. Among inorganic pollutants, heavy metals are the most significant contributors. Soil microorganisms are capable of breaking down organic pollutants, whereas metals must be immobilized or physically removed from the soil. (Adriano D. C., 1986) Although many metals are necessary for biological functions, they become toxic at elevated concentrations by inducing oxidative stress through the formation of free radicals. Metals can also exert toxicity by displacing essential elements in pigments or enzymes, thereby interfering with their normal function. As a result, metal contamination makes land unsuitable for plant growth and leads to a loss of biodiversity. (Alloway, B. J.,1990). The use of phytoremediation is key to achieving sustainable development. Plant based methods provide a low-cost method of land remediation and are the best strategy for future use (Misra et., al. 2019).

Over time, plants have developed diverse genetic adaptations that enable them to tolerate potentially toxic concentrations of metals and other pollutants. While most metal-tolerant plants limit the uptake of harmful metals, certain species known as hyperaccumulators can absorb and withstand high levels of toxic metals and other ions, sometimes reaching several percent of their dry weight. In addition, plant roots release various substances that modify the soil environment by supplying nutrients and energy to microorganisms or by forming stable metal complexes. The root zone supports increased microbial activity, which can further aid in the breakdown of contaminants in soil. (Henry J. R.,2000)

Table 1. Nature of metal toxicity

Sr.No.	Metal	Sources	Symptoms
1	Mercury	Industrial discharge vapour	CNS and PNS disorders, renal failure, blurred vision, numbness of limbs, lips, muscles, etc

2	Lead	Industrial waste, dust, polluted food, paint	Nervous disorders, renal failure, blood poisoning and anaemia, encephalopathy
3	Cadmium	Industrial discharge, dust, fumes, polluted water	Renal, pulmonary and skeletal diseases, proteinuria, glucosuria
4	Arsenic	Industrial waste, polluted water, medicinal use	Respiratory and skin cancer, nervous disorder
5	Nickel	Aerosols, industrial dust	Pulmonary disorders, dermatitis, etc
6	Chromium	Industrial waste, fumes	Respiratory disorders including cancer
7	Tin	Industrial dust, medicinal use	CNS disorders, vision and pneumonoconiosis

Methods of phytoremediation processes

The term *phytoremediation* encompasses a range of plant-based technologies that utilize higher plants to remediate contaminated ecosystems, including rhizofiltration, phyto extraction, phyto volatilization, phytodegradation and phytostabilization.

Phyto extraction, also known as phyto accumulation, involves the uptake of contaminants from soil or water and their subsequent translocation to the aerial parts of plants, including shoots, stems, and leaves (Ghori et al., 2016; Iqbal et al., 2015). This technique relies on the efficient absorption of contaminants by plant roots and their accumulation in harvestable aboveground tissues (Brennan & Shelley, 1999). Effective translocation requires specific conditions, such as the presence of contaminants—particularly metals—in soluble forms that facilitate uptake. Once absorbed, these metals are chelated within the plant and transported to aerial tissues for accumulation (Gupta et al., 2016).

Phyto stabilization involves the immobilization of heavy metals in soil and water through their adsorption and accumulation within the plant rhizosphere or root zone (Pinto et al., 2015). This technique reduces the bioavailability of contaminants by promoting their precipitation and stabilization using various organic and inorganic amendments, such as biosolids, composted manure, fly ash, NPK fertilizers, limestone, dolomite, and red mud (Radziemska et al., 2017). Unlike phyto extraction, phyto stabilization limits contaminant mobility, thereby preventing their accumulation in plant tissues and reducing leaching into deeper soil layers or groundwater. However, this approach primarily isolates contaminants within the soil–root interface and does not provide a permanent solution for the complete removal of pollutants from contaminated environments (Vangronsveld et al., 2009).

Rhizo filtration is defined as the use of terrestrial or aquatic plants to absorb, concentrate, and precipitate contaminants from polluted aqueous environments, particularly those with low contaminant concentrations, within their root systems. This technique is effective for the partial treatment of industrial effluents, agricultural runoff, and acid mine drainage, and is commonly applied for the removal of metals such as lead, cadmium, copper, nickel, zinc, and chromium, which are predominantly retained in plant roots. (Chaudhary et.al., 1998) Rhizofiltration is conceptually similar to phyto extraction; however, it employs plants grown in constructed wetlands or hydroponic systems for contaminant remediation (Horne, 2000). In such systems, artificial growth media, such as vermiculite–sand mixtures, are used to support plant development. The plants function as hydraulic barriers, facilitating the removal of contaminants from groundwater and surface water by promoting upward water flow, during which pollutants are absorbed into root tissues and subsequently concentrated and precipitated (Roy et al., 2015). Plant species with extensive fibrous root systems and abundant root hairs, providing a high surface area, are particularly effective for rhizo filtration (Tomé et al., 2008). This technique is widely applied for the treatment of groundwater and wastewater contaminated with heavy metals and radionuclides, including radium (Ra), uranium (U), and cesium (Cs) (Tomé et al., 2008; Mikheev et al., 2017; Yang et al., 2015)

Table 2. Phytoremediation includes the following processes and mechanisms of contaminant removal

Sr no	Process	Mechanism	Contaminant
1	Rhizofiltration	Rhizosphere accumulation	Organics/Inorganics
2	Phytostabilisation	Complexation	Inorganics
3	Phytoextraction	Hyper-accumulation	Inorganics
4	Phytovolatilization	Volatilisation by leaves	Organics/Inorganics
5	Phytotransformation	Degradation in plant	Organics

Phytovolatilization, also referred to as an evapotranspiration-based mechanism, is primarily utilized for the remediation of contaminants such as mercury (Hg), selenium (Se), and certain organic solvents (Karami & Sumsuddin, 2010). In this process, contaminants are taken up from the soil and subsequently volatilized either directly from aerial plant parts, such as stems and leaves, or indirectly from the root zone. Within the plant, these contaminants are transformed into less toxic volatile forms and are then released into the atmosphere through stomatal transpiration, thereby reducing their overall toxicity and environmental impact (Limmer & Burken, 2016; Rascio & Navari-Izzo, 2011).

Phytodegradation, also known as phytotransformation, refers to the breakdown of pollutants through metabolic processes mediated by plants. In this process, contaminants are absorbed by specific plant species and subsequently degraded by enzymes such as dehydrogenases, oxygenises, and reductases, along with the involvement of inorganic nutrients (Vishnoi & Srivastava, 2008; Zayed & Terry, 2003). Phyto degradation occurs within plant root and shoots cells via enzymatic metabolic pathways that enhance degradation rates, resulting in the transformation of contaminants into smaller, less toxic compounds. Consequently, this mechanism reduces pollutant toxicity and supports plant growth in contaminated environments (Rao et al., 2014).

Phytoremediation includes several distinct mechanisms, which are outlined below. Defining these mechanisms is essential for understanding the range of processes mediated by vegetation, the fate and transport of contaminants, the location at which remediation occurs, and the management strategies required to achieve effective remediation outcomes. Different phytoremediation processes may be applicable to specific types of contaminants or contaminated media and often require the selection of appropriate plant species suited to the particular remediation objective.

Table 4. Examples of hyperaccumulators and recommended phytoremediation methods

Sr. No.	Plant species	Toxic elements	Method	Reference
1	*Alyssum murale, Thalaspi spp., Berkheya codil*	Ni	Phytoextraction	Bani et., al, Skuza et., al (2010,2018,2022)
2	*Brassica oleracea*	Tl	Phytoextraction	Al-Najar et., al, 2005, Kidd et., al,2009
3	*Arabidopsis halleri*	Cd, Zn, Ni	Phytoextraction	Skuza et., al 2022, Corso et., al 2021, Huang et., al 2011
4	*Azollapinnata, Thalaspi caerulescenace*	Cd, Zn, Ni Cu	Phytoextraction Rhizofiltration	Rai et., al 2008, Talebi et., al, 2009, Kumar et., al,2020, Padmavathiamma et., al,2007
5	*Brassica juncea,*	Pb,Cd,Cu,	Rhizofiltration	Skuza et., al 2022 Yadav et., al

	Minuartia verna	Ni,Zn,Cr		2022
6	*Betula occidentalis, Agrostis tenuis*	Pb	Rhizofiltration	Koptsik et., al 2014
7	*Eleocharis acicularis, Pteris rittate*	Cu,Cd,Zn, As,Pb	Phytoextraction	Ernst, W.H.O. 2005, Nurfitri 2017
8	*Euphorbia sp., Ipomea alpine*	Cu,As,Cd, Pb,Zn	Phytostabilization	Skuza et., al 2022, Conesa et., al 2006, Silva Gonzaga et., al 2006
9	*Thlaspica erulescens*	Cd	Phytoextraction	Skuza et., al 2022 Yadav et., al 2022
		Zn	Rhizofiltration	
10	*Tagetes minuta*	As,Pb	Phytoextraction	Miranda Pazcel et.,al, 2018, Salazar et.,al 2014

Phytoremediation derives from the Greek term *phyton* (plant) and the Latin verb *remediare* (Raskin et., el 1994). This approach relies on the ability of certain plant species to establish and survive in contaminated environments, where they interact with biological, chemical, and physical processes to facilitate the removal or stabilization of xenobiotic compounds within the ecosystem. (Meagher, Susarla et., al 2005,2002) To date, approximately 400 ecotypes of metal-accumulating plants have been identified and are collectively referred to as hyperaccumulators. These plants possess the unique capacity to concentrate specific metals in their tissues at levels far exceeding those found in most plant species, often by several orders of magnitude. A plant is classified as a hyperaccumulator when, under natural growing conditions, the metal concentration in the above-ground tissues (expressed on a dry weight basis) exceeds established threshold values: greater than 100 μg g^{-1} for cadmium (Cd), thallium (Tl), and selenium (Se); more than 300 μg g^{-1} for cobalt (Co), copper (Cu), and chromium (Cr); over 1000 μg g^{-1} for nickel (Ni), arsenic (As), lead (Pb), or rare earth elements (REEs); above 3000 μg g^{-1} for zinc (Zn); and exceeding 10,000 μg g^{-1} for manganese (Mn). (Babau, Reeves, et., al. 2027,2020).

Table. 3 Threshold concentrations for classification of metal hyperaccumulator plants

Sr. No.	**Metal/Element Group**	**Threshold concentration in shoot tissue (μg g^{-1} dry weight)**
1	Cadmium (Cd)	>100
2	Thallium (Tl)	>100
3	Selenium (Se)	>100
5	Cobalt (Co)	>300
6	Copper (Cu)	>300
7	Chromium (Cr)	>300
8	Nickel (Ni)	>1000
9	Arsenic (As)	>1000
10	Lead (Pb)	>1000
11	Zinc (Zn)	>3000
12	Manganese (Mn)	>10,000
13	Rare Earth Elements (REEs)	>1000

The use of biofuel crops in phytoremediation has been reported by Amin et al. (2022). Among the plant species evaluated—*Abelmoschus esculentus*, *Avena sativa*, *Guizotia abyssinica*, and *Glycine max*—*A. sativa* exhibited the highest zinc uptake, tolerance, and biomass production, indicating its suitability for combined phytoremediation and biofuel applications. The conversion of phytoremediation-derived plant biomass into renewable energy presents a significant global opportunity, particularly given that bioenergy currently contributes approximately 14% of global energy demand. Energy crops selected for phytoremediation should be fast-growing, produce high biomass, possess deep root systems, and yield economically valuable products. (Kumar Yadav et.,al 2018). Table 5 summarizes energy crops used in phytoremediation for biofuel production.

Table 5. List of energy crops used in phytoremediation with consideration of bioenergy

Sr.No.	Bioenergy Crop	Soil Pollutants	Sustainable Bioenergy Production
1	Jatropha curcas	Heavy metals	Biodiesel (seed oil)
2	Populus spp.	Organics, heavy metals	Bioethanol (biomass)
3	Salix spp.	Organics, heavy metals	Bioethanol (biomass)
4	Arundo donax	Organics, heavy metals	Bioenergy, bioethanol (biomass)
5	Miscanhtus	Organics, heavy metals	Bioethanol (biomass)
6	Ricinus communis	Organics, heavy metals	Biodiesel (biomass and seed oil)
7	Zea mays	Heavy metals	Bioenergy (biomass)
8	Halianthus annuus	Heavy metals	Bioenergy, bioethanol (biomass and seed oil)
9	Brassica spp.	Heavy metals	Biofuel, biodiesel (seed oil)
10	Canabis sativa	Heavy metals	Bioenergy (biomass)

Benefits and Limitations of Phytoremediation

As with any remediation strategy, phytoremediation offers numerous advantages but also presents several inherent limitations. The principal benefits of phytoremediation include a significant reduction in both organic and inorganic contaminants, as well as a decrease in the volume of waste requiring landfill disposal. The presence of vegetation contributes to the preservation and, in many cases, enhancement of soil structure and quality, as root exudates stimulate microbial communities in the rhizosphere, increase humic substance content, and improve overall soil fertility. Additionally, vegetative cover helps mitigate wind erosion, while the technique eliminates the need for costly specialized equipment or highly trained personnel. Phytoremediation can be implemented *in situ*, thereby minimizing soil disturbance and reducing the risk of contaminant dispersion. Compared with conventional remediation technologies, it is generally more cost-effective and easier to implement and maintain, given that plants are inexpensive, readily available, and renewable. Furthermore, phytoremediation is environmentally sustainable, socially acceptable, and typically associated with lower noise emissions, as vegetation—particularly trees—can act as a natural barrier to industrial noise.

Despite these advantages, the application of phytoremediation is constrained by several factors. Its effectiveness is limited by root depth, as well as by the solubility and bioavailability of contaminants. The remediation process is often prolonged, potentially requiring several years to decades to achieve desired outcomes. Consequently, phytoremediation is primarily suitable for sites with low to moderate levels of contamination. In cases involving phytoextraction, the harvested plant biomass must be managed as hazardous waste, necessitating appropriate treatment or disposal. The success of phytoremediation is also influenced by climatic conditions and seasonal variability, as plant damage caused by pests, diseases, or extreme weather events can reduce remediation efficiency. Careful selection of plant species is essential to prevent the introduction of invasive or ecologically unsuitable species that could disrupt local biodiversity. Additional concerns include the potential mobilization of metals into other environmental compartments, such as water or air, and their subsequent entry into the food chain. Finally, agricultural and cultivation practices introduced during phytoremediation may alter the mobility and distribution of trace elements within the soil.

Utilization of Phytoremediation by-product

Phyto extraction is a plant-based remediation approach that relies on the repeated cultivation and harvesting of vegetation on metal-contaminated soils to progressively reduce contaminant concentrations to levels that comply with regulatory standards. The regulatory acceptance and practical feasibility of this technique largely depend on the ability to establish a reliable mass balance between the observed decrease in soil metal concentrations and the amount of metal removed through plant uptake and biomass production. Conceptually, metal removal can be quantified by measuring metal concentrations in harvested plant tissues and multiplying these values by the corresponding biomass yield, followed by comparison with the reduction in soil metal inventories. However, despite its apparent simplicity, accurately closing this mass balance under field conditions remains challenging due to spatial heterogeneity of soil contamination, variability in plant growth, metal bioavailability, and losses associated with leaching or erosion. A significant limitation to the large-scale implementation of phyto extraction is the management and disposal of metal-contaminated biomass generated after each harvesting cycle. Continuous cropping and removal of plants result in the accumulation of substantial quantities of hazardous biomass, which, if improperly managed, may pose secondary environmental and health risks. Consequently, the safe handling, treatment, and disposal of this biomass represent critical logistical and economic constraints for the commercial viability of phyto extraction technologies. Plant biomass constitutes stored solar energy in the form of organic matter and is commonly classified as a combustible renewable resource. Chemically, biomass is composed predominantly of carbon, hydrogen, and oxygen and is therefore characterized as an oxygenated hydrocarbon. On an empirical basis, woody biomass can be approximated by the chemical formula $CH_{1.44}O_{0.66}$, which is frequently used in thermochemical and energy-related assessments. This intrinsic energy content of biomass presents opportunities for coupling phyto extraction with biomass valorization strategies, provided that appropriate measures are implemented to manage the associated metal contaminants.

Biomass is primarily composed of lignin, hemicellulose, cellulose, mineral matter, and ash, with high moisture and volatile matter content, low bulk density, and variable calorific value depending on species. In phyto extraction, *Brassica juncea* can produce approximately 6 tonnes/ha of dry biomass, accumulating 10,000–15,000 mg/kg of lead.

Post-harvest management of metal-contaminated biomass remains a critical challenge for large-scale phyto extraction. Composting and compaction have been proposed as potential treatment methods. While composting can reduce the overall volume of harvested biomass, leaching tests have demonstrated that soluble organic compounds formed during the composting process may enhance the solubility and mobility of metals such as lead. Consequently, metal-contaminated compost still requires appropriate handling and disposal prior to release into the environment. Similarly, compaction of harvested biomass reduces its bulk, thereby lowering transportation costs to hazardous waste disposal facilities, but also necessitates careful collection and treatment of leachate to prevent environmental contamination. Although compaction shares several advantages with composting, there remains limited research on its efficacy for metal-rich biomass residues.

Thermochemical conversion processes, including combustion, gasification, and pyrolysis, represent promising strategies for the integrated utilization of phyto extraction biomass. Combining phyto extraction with energy recovery could enhance the economic viability of remediation operations. Combustion of contaminated biomass under controlled conditions reduces its volume to 2–5% of the original mass, while the resulting ash may serve as a potential source of metal recovery, aligning with the principles of phytomining. Gasification further transforms biomass into a combustible producer gas through a series of complex reactions involving drying, pyrolysis, gasification, and partial oxidation. This process allows for the recovery of thermal and electrical energy while retaining metals in the residual ash, which can be collected and potentially recycled. Co-firing of metal-laden plant biomass with coal has been reported to reduce mass by over 90% and partition lead into the ash, suggesting opportunities for metal recovery, though cost and feasibility assessments remain limited.

Pyrolysis, conducted under anaerobic conditions, decomposes biomass into pyrolytic oil and char, while retaining heavy metals within the solid residue. Studies on synthetic hyper accumulator biomass indicate that metals can be concentrated by 3–6 times in the char relative to the feedstock, highlighting its potential for subsequent metal recovery in smelting operations. Low-temperature pyrolysis experiments with wood treated with chromium, copper, and arsenate have demonstrated that metals predominantly remain in the residue, minimizing emissions. The influence of metal ions on pyrolysis kinetics and product distribution has been extensively studied, though data specific to phyto extraction biomass remain limited.

Overall, thermochemical treatment of contaminated plant biomass offers an environmentally sound alternative to open burning or uncontrolled disposal, enabling volume reduction, energy recovery, and potential metal reclamation. Future research should focus on the optimization of combustion, gasification, and pyrolysis systems specifically for phyto extraction residues, as well as the development of efficient methods for metal recovery from residual ash or char.

CONCLUSION

Phytoremediation has become a rapidly expanding field of environmental research, with a notable increase in field-scale applications worldwide over the past decade. This approach has been successfully applied to the remediation of sites contaminated with organic pollutants, inorganic compounds, and radionuclides. Owing to its sustainability and cost-effectiveness, phytoremediation is increasingly regarded as a viable alternative to conventional remediation technologies, particularly in developing countries such as India, where low-cost and environmentally compatible solutions are urgently needed. Despite this growing global interest, most phytoremediation studies and practical implementations have been conducted in developed countries. Consequently, there remains a limited understanding of plant species suitable for local climatic and soil conditions in India. At present, the commercial application of phytoremediation for soils contaminated with heavy metals or organic compounds in India is still at an early stage of development. Addressing this knowledge gap is essential for the broader adoption of phytoremediation in the region. In addition to plant selection, the management and disposal of contaminated biomass represent critical challenges for the large-scale implementation of phytoremediation. Although several biomass treatment and disposal methods have been proposed, comprehensive data assessing their effectiveness and environmental safety remain limited. Techniques such as composting and compaction may be employed as preliminary steps to reduce biomass volume; however, leachate generated during compaction must be carefully collected and treated to prevent secondary contamination. Among currently available options, incineration appears to be a more time-efficient and environmentally sound approach compared with direct burning or ashing, making it a preferred method for the final treatment of contaminated plant material.

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