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# A Review of Phytoremediation of Heavy Metals Using Macrophytes: Mechanisms, Efficacy, and Future Prospects

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***Abstract: Heavy metal (HM) contamination in aquatic habitats has increased significantly due to the fast pace of industrialization, posing serious risks to environmental stability and public health. Among the available technologies, phytoremediation a plant-based or "green" technology has emerged as a promising approach, especially when utilizing aquatic macrophytes. Certain aquatic macrophyte species can cope with these harsh circumstances, even if there is a high amount of heavy metal contaminants in the water. The potential of this method has been further enhanced by the discovery of hyperaccumulator plants, with the capacity to absorb, move, store, and concentrate significant amounts of contaminants in their harvestable parts. Phytoremediation involves different mechanisms, including phytoextraction, phytovolatilization and rhizofiltration. Numerous aquatic plant species like Eichhornia, Lemna, Potamogeton, Spirodela, Wolffia, Azolla, and Pistia have shown effectiveness in the removal of contaminants like arsenic, cadmium, zinc, copper, lead, chromium, and mercury from polluted water bodies. This review emphasizes on aquatic macrophytes' unique remediation properties and their function as a crucial component of phytotechnologies to reduce aquatic pollution.***
***Keywords: heavy metals, phytoremediation, hyperaccumulator, macrophytes***

## I. INTRODUCTION

Bioremediation is an environmentally sustainable remediation strategy that employs the metabolic capabilities of naturally occurring or engineered microorganisms, fungi, or plants to degrade, transform, or detoxify hazardous contaminants in soil, water, or air into less harmful or non-toxic forms (Dangi et al.,2019; Bala et al.,2022). This method encompasses various processes, including bioaccumulation, biosorption, and phytoremediation, and has proven to be effective in addressing a wide range of pollutants, from heavy metals (HM) to organic compounds (Vijayaraghavan & Balasubramanian, 2015; Hazen et al.,2018). Among these approaches, phytoremediation has gained significant attention due to its green and sustainable nature (Muthusaravanan et al.,2018; Shmaefsky, 2020).

Phytoremediation, specifically, is a sustainable technique that uses plants to remove, stabilize, or reduce heavy metal concentrations in contaminated soils. This technique works by eliminating, accumulating, stabilizing, or transforming the contaminants into less harmful forms (Shen et al., 2022; Yadav et al., 2018). Notably, even in soils with low concentrations of heavy metals, plants can absorb these elements through their root systems, thus playing a key role in soil restoration and revitalization (Pulford & Watson, 2003; Tangahu et al.,2011). Plants used in phytoremediation often possess a high tolerance for toxic elements, making them ideal for restoring polluted sites. This method involves the natural ability of plants to accumulate or break down pollutants through processes such as phytoextraction, phytostabilization, rhizofilteration and phytodegradation, as shown in Fig.1, offering an effective alternative to conventional remediation techniques (Pandey et al.,2021).

The process of phytoremediation is highly dependent on the establishment of intricate rhizosphere ecosystems, which are rich in microbial communities and biological activity. These rhizospheres enhance heavy metal absorption and contribute to the biological breakdown of pollutants (Chen et al., 2018). Additionally, the underground ecosystems foster beneficial microorganisms that promote nutrient cycling, biological metabolism, and soil health rejuvenation (Vijayaraghavan & Balasubramanian, 2015). The overall effectiveness of the phytoremediation process is improved by the presence of these microbes (Wang,2022; Gomathy et al., 2021).

 

Phytoremediation is an attractive substitute to conventional remediation techniques due to its numerous benefits. It is not only sustainable and economical but also has minimal environmental impact. Unlike mechanical or chemical remediation methods, it avoids further disruption to the ecosystem and preserves the natural landscape (Guidi, 2023; Singh & Pant,2023). The aesthetic appeal and potential of phytoremediation for habitat restoration make it particularly valuable for urban and rural settings alike. Moreover, this approach contributes to ecosystem services such as carbon sequestration, erosion control, and the promotion of biodiversity (Zazai et al., 2018; Garbisu et al., 2020).

In essence, phytoremediation utilizes the natural biological, physical, and chemical processes of plants to eliminate, immobilize, and detoxify pollutants from various mediums such as soil, sediments, and water (Arora et al., 2006; Umali et al., 2006). During this process, plants take up pollutants through their roots and transport them to surface of their structures, where they can be stored, degraded, or rendered harmless. This method not only aids in cleaning up contaminated environments but also enhances the health of ecosystems by stabilizing soils and promoting biodiversity (Ashraf et al., 2018; Sharma et al., 2014). Among the plants used in phytoremediation, macrophytes play a crucial role, particularly in aquatic environments, offering an effective solution for the remediation of polluted water bodies. Plants such as *Eichhornia crassipes, Pistia stratiotes, Lemna, Typha, Phragmites* have been used by several researchers to extract heavy metals from aqueous effluents, their effectiveness have been serially investigated (Bokhari et al., 2016; de Souza et al.,2018; de Campos et al.,2019; Martínez et al.,2023).

This review highlights the role of phytoremediation through macrophytes as an essential and powerful tool for environmental restoration, offering insights into its potential to effectively address water contamination challenges. The current review offers broad applicability of this green technology by concentrating on the usage of wild macrophytes for environmentally friendly phytoremediation techniques for water bodies contaminated by heavy metals.

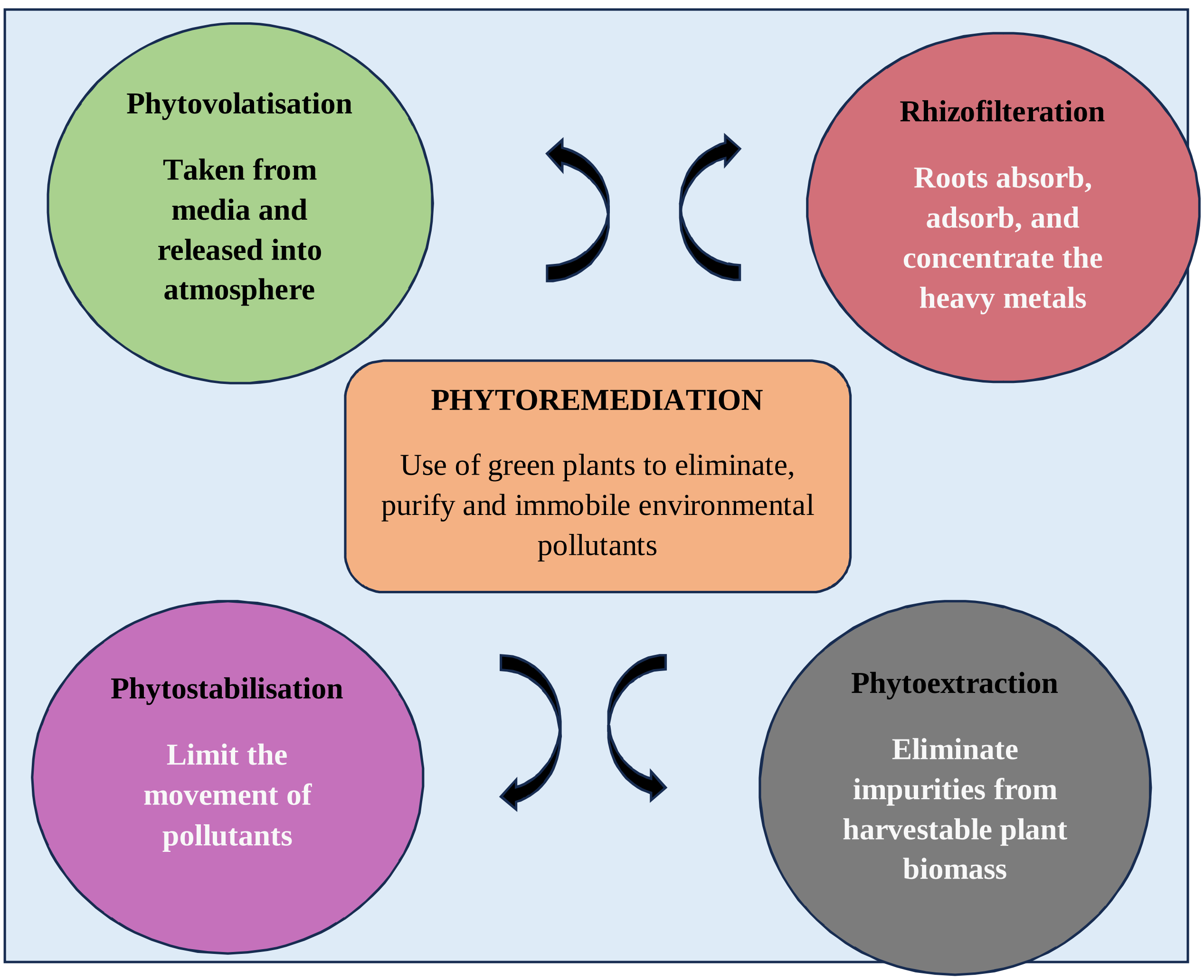


Fig.1 Processes involved in phytoremediation of heavy metal by macrophytes

## II. MACROPHYTES

Macrophytes are large aquatic plants that grow in or near water and are visible to the naked eye (Penning et al.,2008; Rawat & Singh,2023). They are found in both freshwater and marine habitats and play a vital role in aquatic ecosystems. These plants provide habitat, food, and oxygen for aquatic life, stabilize sediments, and contribute to nutrient cycling (Thomaz,2023; Kumar et al., 2023).

### *A. Types of Macrophytes*

Macrophytes are generally classified into four main categories based on their growth and development habits and their relationship with water:

#### *1) Submerged Macrophytes*

These plants have roots anchored in the sediment and grow entirely underwater.

They play a crucial role in oxygenating water and providing habitat for fish and other aquatic organisms. Examples**:** *Zostera, Potamogeton, Hydrilla*

#### *2) Floating-leaved Macrophytes*

These plants are rooted in the sediment but have leaves that float on the water's surface. They provide the water shade, which lowers the temperature and inhibits the formation of algae. Examples: *Nymphaea, Nelumbo*

#### *3) Free-floating Macrophytes*

These plants are not rooted in the sediment and float freely on the water's surface. They are effective at nutrient uptake and can spread quickly, sometimes causing problems by blocking sunlight and oxygen from reaching the water below. Examples**:** *Lemna, Eichhornia*

#### *4) Emergent Ma crophytes*

These plants are rooted in shallow water, with stems and leaves growing above the water surface. They are often found in wetlands and along shorelines, playing a key role in stabilizing sediments and filtering pollutants. Examples: *Typha, Phragmites*

## III. ECOLOGICAL IMPORTANCE OF MACROPHYTES

Macrophytes provide habitat for aquatic organisms, promoting oxygenation, nutrient cycling, water quality improvement, and erosion control. They offer shelter, spawning grounds, and nursery areas, and contribute to water quality by filtering pollutants and sediments (Mandal & Bera,2025; Gopal,2020). Emergent macrophytes anchor soil, stabilizing riverbanks, and shorelines (Gopal, 2016). Aquatic macrophytes also have a physiologically significant role by eliminating mineral nutrients and heavy metal from water bodies (Uka et al., 2021), as well as act as indicators for water quality (Ghavzan et al.,2006; Rameshkumar et al., 2019). According to recent reports, certain aquatic plants have potential to remediate contaminated and polluted waterways. A variety of vegetation types may collect a much larger number of heavy metals in various areas of the body parts without being hazardous (Reeves et al., 2021). Plants such as *Eichhornia crassipes* (Kamel;2013), *Pistia stratiotes* (Veselý et al.;2011), *Azolla pinnata* (Thayaparan et al.; 2013), *Myriophyllum spicatum* (Kamel; 2013), *Lemna minor* (Leblebici and Aksoy; 2011 and Bokhari et al. ;2016), *Salvinia natans* (Dhir; 2009) have been used by several researchers to remove heavy metals from aqueous effluents, their effectiveness have been serially investigated. Their ability to absorb heavy metals, filter sediments, and control nutrients makes macrophytes a valuable tool for improving degraded aquatic ecosystems and mitigating the effects of pollution. This review's objective is to evaluate the present status of phytoremediation as an inventive method and the potential of aquatic macrophytes in the remediation of heavy metal-contaminated water.

## IV. OVERVIEW OF HEAVY METAL CONTAMINATION

Global development brings forth new challenges, especially in the realms of environmental protection and conservation (Garg, 2023). The drive for economic, agricultural, and industrial growth often takes precedence over the need for a safe, pure, and sustainable environment. Mining, smelting, refining, and manufacturing are the main industrial processes that expose humans to heavy metals (Nriagu, 1996; Fu & Xi,2020; Adnan et al.,2024). Unsafe or excessive use of fertilizers, fungicides, and pesticides are some of which are prohibited can be another source of contamination (Srivastav,2020; Nath et al., 2023). In coastal regions, industrial operations, including chemical, metal, and other industries, have significantly contributed to the discharge of toxic effluents into coastal water bodies (Satapathy & Panda,2018; Luo et al., 2022).

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These pollutants, when released into the environment, are absorbed by living organisms, entering the food chain, and leading to harmful effects through processes such as bioaccumulation and biomagnification (Dembitsky, 2003; Sood et al. 2019).

Elements having density between 5.308 and 22.00 g/cm2 are termed as heavy metals and these originate both from natural and anthropogenic sources (Aslam et al. 2024). These metals are leading contaminants for environment because of being non-biodegradable and can be transferred through trophic levels and accumulate in the biota insistently (Nancharaiah et al. 2016; Upadhyay,2022). Heavy metals like cadmium, copper, lead, chromium, zinc, and nickel are particularly concerning in areas under high anthropogenic pressure, acting as critical environmental pollutants (United States Environmental Protection Agency, 1997). Due to their diverse chemical characteristics and biological processes, heavy metals form a diverse range of substances, with toxicity varying according to the specific metal and its concentration. Metals such as mercury (Hg), cadmium (Cd), nickel (Ni), lead (Pb), copper (Cu), zinc (Zn), chromium (Cr), and cobalt (Co) are highly toxic, both in their elemental forms and as soluble salts. Even trace amounts of these metals in the atmosphere, soil, or water can pose serious risks to living organisms, impacting ecosystems and human health alike (Mishra et al.,2018; Mitra et al.,2022).

Moreover, India's tanning industry continues to pose environmental and health risks, with tannery runoff contaminating the water supply for an estimated 3.5 million people (ENS, 2006). Mining activities, an integral part of the economies of many developing countries, including Brazil, China, India, and Peru, also present significant environmental challenges (De Sa,2019; Mundaca,2024). Mining for precious metals, coal, and other resources impacts health through water contamination from extraction methods and pollutants released into local water sources. In addition, mining contributes to long-term environmental degradation, such as beach erosion caused by sand mining, biodiversity loss, and declining fish populations (WHO, 2008; Rentier & Cammeraat, 2022; Rangel-Buitrago et al.,2023).

As industrialization expands, the trade-off between economic growth and environmental sustainability becomes more pronounced. This underscores the need for stringent regulations, comprehensive monitoring, and proactive strategies to mitigate heavy metal pollution and safeguard ecosystems for future generations (Khanam,2023; Chen & Ding,2023). The various sources of heavy metals, their health risks, and management strategies are summarised below in Table 1.

Table 1. Sources of heavy metals, their health effects, and management strategies available

| Heavy metal | Source | Health effect | Available control method | References |
|---|---|---|---|---|
| Lead | Paints, pigments, batteries, smelting, ceramics, Ayurvedic herbs, lead-based solder or pipes, and tainted water | Reproductive system dysfunction, high blood pressure, kidney and tumor infections, improper hemoglobin synthesis | Lead pipe removal, activated carbon filtration, phytoremediation, phosphate-based chemical treatments, legal prohibitions | ATSDR (2007) |
| Mercury | Batteries, lightbulbs, switches, dental fillings, and pesticides | Lung damage, tremor, memory issues, neurological and renal disorders, and brain damage | Filtration with activated carbon, polymers based on sulfur, switching to safer substitutes (like LED bulbs), appropriate disposal, and recycling | WHO,2011 EPA |
| Cadmium | Burning fossil fuels, metal smelting, industrial pollutants, and agriculture | Anemia, osteoporosis, lung/prostate cancer, kidney disorders, and testicular atrophy | Electrochemical remediation, soil washing, phytoremediation (e.g. using Brassica species,), and emission control laws | Genchi et al. (2020);Wang et al (2021) |
| Arsenic | Contaminated groundwater, paints, colors, medications, soaps, and fertilizers | Weakness, coloring of the skin, nausea, problems with the neurological system, heart problems, and damage to DNA | Iron oxide filtration, coagulation-filtration, reverse osmosis, and phytoremediation | WHO,2011 EPA |
| Chromium | Paper, colors, cement, rocks, electroplating, magnetic tapes, and rubber | respiratory problems, kidney and liver damage, nose ulcers, and asthma | Ion exchange, chemical precipitation, electrochemical reduction, and activated carbon adsorption | ATSDR,(2000b) |

| | | | | |
|---|---|---|---|---|
| Nickel | Pigments, arc welding, diesel exhaust, cigarette smoke, and electroplating | Lung damage, tremors, neurological conditions, and brain damage | replacement of products containing nickel, industrial wet scrubbers, and personal protective equipment (PPE) | WHO,2011 ATSDR |
| Copper | Algicides, fungicides, mining, plumbing, and industrial waste | Wilson's disease, liver and kidney damage, and digestive distress | Ion exchange, chemical precipitation, membrane filtration, phytoremediation | US EPA |
| Zinc | Batteries, fertilizers, industrial pollutants, and galvanizing steel | Immune system malfunction, nausea, vomiting, and disruption of copper metabolism | Remediation of soil, filtration of water (such as reverse osmosis), and industrial substitution | WHO,2011 EPA |
| Iron | Steel manufacturing, water pipes, natural sources, and supplements | Diabetes, liver and heart disease, and hemochromatosis | Chelation treatment, extraction from water through filtration and oxidation | CDC, WHO,2011 |
| Cobalt | Mining, welding, metal alloys, batteries, and colors | Lung illness, cardiomyopathy, skin irritation, and thyroid problems | Substitution in products, air filtration, PPE, regulated disposal | ATSDR,2004; WHO,2011 |
| Thallium | Glass production, electronics, and pesticides | Hair loss, peripheral neuropathy, coma, and stomach trouble | Reverse osmosis, activated alumina, ion exchange, and stringent regulatory oversight | WHO,2011, EPA |
| Silver | Jewelry, electronics, photography, and antimicrobials | Skin darkening (argyria), liver and re spiratory damage | Reverse osmosis, recycling, substit ution, and filtering | ATSDR; WHO,2011 |
| Gold | Jewellery, dentistry, and electr onics | Rare rashes, allergic responses, and n o significant harmful effects in eleme ntal form | Electronic waste recovery and safe handling procedures | WHO,2011 |
| Platinum | Jewelry, chemical, and autom otive catalyst industries | Asthma, mucosal irritation, and allerg ic responses | Emission control systems | WHO,2011, OSHA |
| Uranium | Nuclear power, mining, and p hosphate fertilizers | Bone problems, radioactive cancer, a nd kidney damage | Reverse osmosis, soil cleansing, ra diation shielding, and ion exchange | IAEA NFCIS,2004 |

## V. MECHANISMS OF PHYTOREMEDIATION

Phytoremediation is a eco-friendly and cost-effective method for environmental remediation that utilizes the innate abilities of plants to extract, transform, or stabilize contaminants in soil, water, or air (Jeevanantham et al.,2019; Sharma et al.,2023). This green technology offers an eco-friendly alternative to conventional cleanup methods by harnessing biological processes to restore contaminated environments (Park & Oh,2023; Lavanya et al.,2024). Based on the mode of work, phytoremediation can be categorized into various subtypes like phytoaccumulation, phytomining, phytovolatisation and phytodegradation.

Aquatic macrophytes including aquatic plants and micro/macroalgae are especially effective in treating heavy metal polluted water. These contaminants may originate from both natural sources and human activities such as mining, industrial discharge, and agricultural runoff (Mukherjee et al., 2018; Bhat et al., 2022). Aquatic macrophytes contribute to remediation through several mechanisms, including, phytotransformation, rhizofiltration, phytostabilization, and phytovolatilization (Akhtar et al.,2017; Bora & Sarma,2019; Kristanti & Hadibarata,2023).

The efficiency of these mechanisms is influenced by various factors, including the species of plant used, environmental conditions, contaminant concentration, and treatment duration (Ansari et al,2020; Xiao et al.,2021). To prevent recontamination, it is essential to manage and dispose of the harvested biomass properly. Ongoing monitoring and evaluation of phytoremediation systems are crucial to ensure their long-term effectiveness and ecological safety (Evangelou et al.,2015).

Floating aquatic plants possess extensive root systems that hang freely in the water, enabling them to absorb contaminants efficiently from their surrounding environment. Since they may store large amounts of contaminants, including heavy metals, many of these are categorized as hyperaccumulators. Two noteworthy examples are duckweed (*Lemna spp.*) and water hyacinth (*Eichhornia crassipes*).

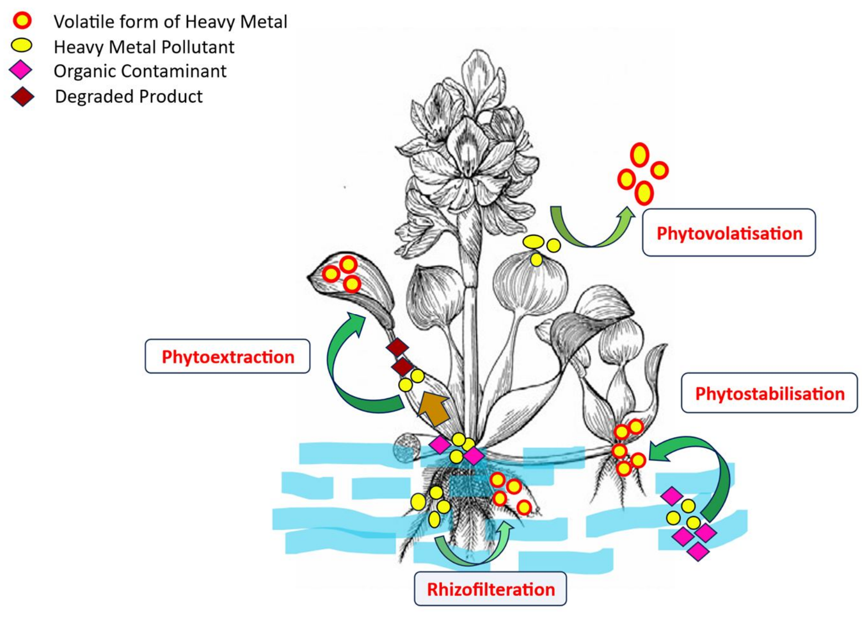


Fig.2 Mechanism of Phytoremediation in water ecosystem

On the other hand, submerged aquatic plants remain completely underwater and absorb contaminants through their entire bodies—including roots, stems, and leaves. These plants contribute significantly to nutrient cycling and heavy metal regulation in aquatic ecosystems. Commonly used submerged species for phytoremediation include waterweed (*Elodea spp.)* and pondweed (*Potamogeton spp.)*.

Together, both floating and submerged aquatic plants play essential roles in maintaining water quality by removing pollutants and enhancing aquatic ecosystem health. Their ability to improve water conditions makes them an effective and long-term solution for restoring polluted aquatic environments (Ali et al.,2020; Chawla et al.,2024).

By optimizing key factors involved in uptake, such as plant species, environmental parameters, and contaminant bioavailability, the efficiency of phytoremediation can be significantly improved. Plants may act as excluders or accumulators, depending on how they absorb substances as shown in Fig.2. Accumulators can move pollutants to aerial tissues, where they may degrade or undergo biotransformation into less harmful forms (Sinha et al.,2007; Kvesitadze et al.,2015; Zhang et al.,2021).

However, certain limitations exist in the interaction between ionic contaminants and plant uptake processes. Plants may reach a physiological threshold beyond which they cannot accumulate additional contaminants (Tangahu et al., 2011; Li et al.,2023). Hyperaccumulators, in contrast, can thrive in contaminated conditions with minimal maintenance and often produce more biomass than non-accumulator species (Nedjimi ,2021; Memon,2022). These specialized plants can concentrate heavy metals like cadmium (Cd), zinc (Zn), lead (Pb), manganese (Mn), nickel (Ni), and cobalt (Co) at levels 100 to 1000 times higher than those found in non-accumulator species (Obinna & Ebere, 2019).

Additionally, microorganisms including bacteria and fungi in the rhizosphere (the root-soil interface) play a critical role in enhancing metal mobilization and breaking down organic pollutants, thereby increasing the bioavailability of metal ions for plant uptake (Erdei et al., 2005; Manoj et al.,2020; Gavrilescu,2022).

Aquatic macrophytes also influence the physicochemical properties of water bodies. During periods of high photosynthetic activity, these plants and other photosynthetic autotrophs can lower dissolved $CO_2$ levels, leading to increased dissolved oxygen and higher pH in the water. This altered environment further supports contaminant removal as aquatic macrophytes absorb and store pollutants within their biomass (Obinna & Ebere, 2019).

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## VI. MECHANISM OF METAL ABSORPTION AND TRANSLOCATION IN PLANTS

Plants can extract and accumulating metal ions directly from the soil solution. A metal must first pass through the root surface to enter the plant system (Banuelos & Ajwa,1999; Thakur et al.,2016). This uptake can occur either passively where metal ions diffuse through the porous cell walls of root tissues or actively, wherein metal ions are transported symplastically through living root cells. In active uptake, the ions must cross the plasmalemma, a selectively permeable membrane that regulates entry into the symplast (Pilon-Smits, 2005; Tangahu et al.,2011).

Plants possess a range of membrane-bound metal transport proteins that identify and bind specific metal ions based on their chemical structure (De Caroli et al.,2020; Jogawat et al.,2021). These transporter proteins facilitate the uptake and mobilization of essential micronutrients and, sometimes inadvertently, non-essential or toxic metals due to chemical mimicry (Mitra,2017; Vatansever et al.,2017). For example, phosphate transporters can absorb arsenate ($As^{5+}$), which is chemically like phosphate ($PO_4^{3-}$) (Abedin et al., 2002).

The model plant *Arabidopsis thaliana* has been found to contain over 150 cation transporters, and often several transporters exist for the same metal ion (Axelsen & Palmgren, 2001; Hawkesford, 2003). Competitive interactions among metals for the same transport systems have been observed—for example, copper (Cu) and zinc (Zn), as well as nickel (Ni) and cadmium (Cd), compete for identical carrier proteins (Clarkson & Luttge, 1989).

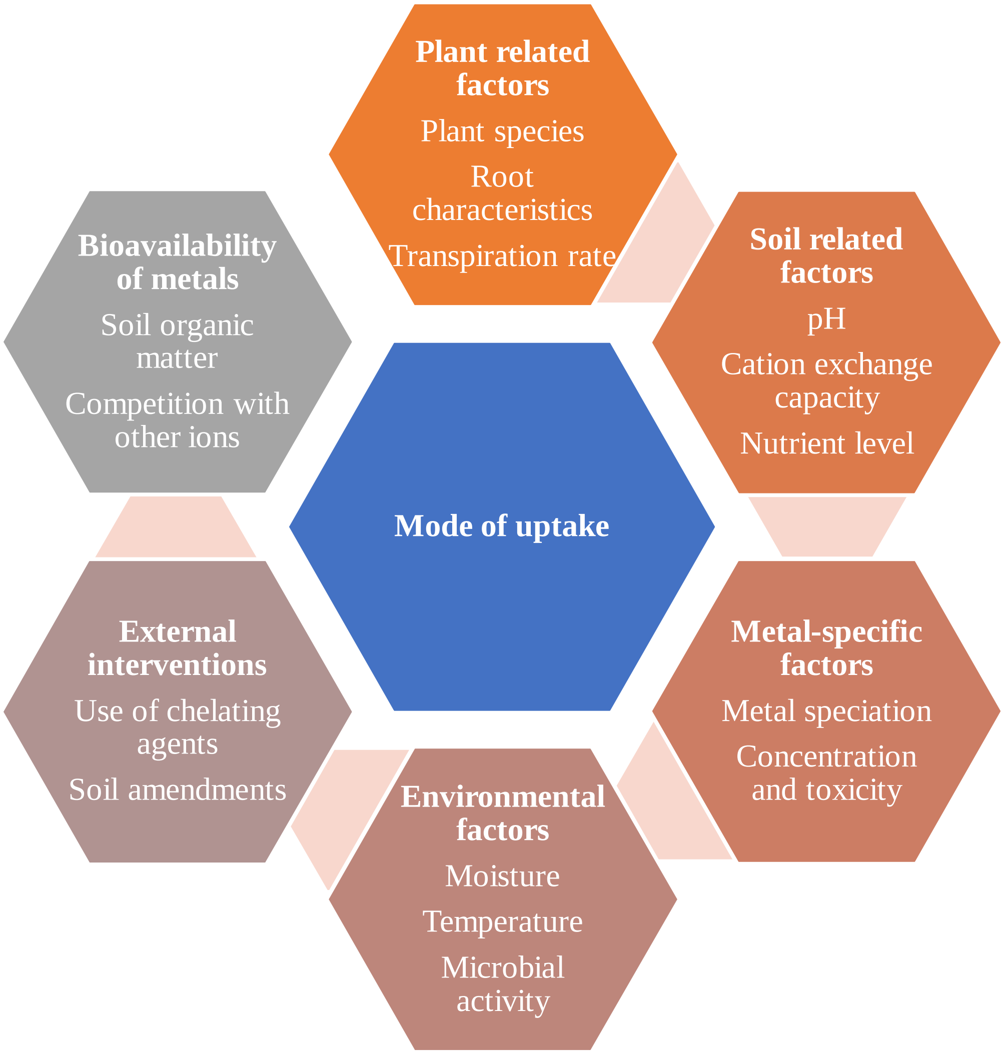


Fig.3 Methods of uptake of Heavy Metal

Once metals are absorbed by the roots, they are translocated through the xylem vascular system to the aerial parts of the plant, such as leaves and stems. This internal transport is often mediated by metal-chelator complexes, which prevent the metals from binding to the negatively charged surfaces of xylem vessels.

Organic ligands such as citrate, malate, histidine, and nicotianamine play a significant role in this process by forming stable, mobile complexes with metal cations (Stephen et al., 1996; von Wirén et al., 1999; Clemens,2019). The various methods of uptake of heavy metal are illustrated in Fig.3.

Following translocation, metals accumulate in the shoot biomass, which can then be harvested (Evangelou et al.,2013). Depending on the contaminant and context, the biomass may be incinerated, disposed of as hazardous waste, or subjected to metal recovery techniques, such as phytomining, for valuable elements like gold or nickel (Karaca et al.,2018; Ghosh & Maiti,2021).

## VII. TYPES OF PHYTOREMEDIATION

When heavy metals are accumulated in plants then phytoextraction, phytovolatisation, phytostabilisation and rhizofilteration occur (Chandra et al.,2015; Sarwar et al., 2017; Awa and Hadibarata,2020).

A basic description of the several steps of phytoremediation is given here.

### *A. Phytoextraction*

Phytoextraction is a specific kind of phytoremediation that occurs when heavy metals or other pollutants are taken up by plant roots from the soil or water and then moved to the aboveground sections of the plant, like the stems and leaves (Ghori et al., 2016; Asgari et al.,2019). These plants are later harvested and removed, thereby extracting the contaminants from the site (Robinson et al.,2015). This technique has been acknowledged as a low-impact, economical, and ecologically friendly repair strategy. Phytoextraction can cost over ten times less per hectare compared to traditional soil remediation technique (Salt et al., 1995a; Robinson et al.,2003).

Apart from its financial benefits, phytoextraction also has environmental advantages (Corzo et al.,2020). The plant cover reduces soil erosion and minimizes leaching during the remediation process. Repeated cycles of planting and harvesting can significantly decrease contaminant concentrations in the soil over time (Vandenhove et al., 2001).

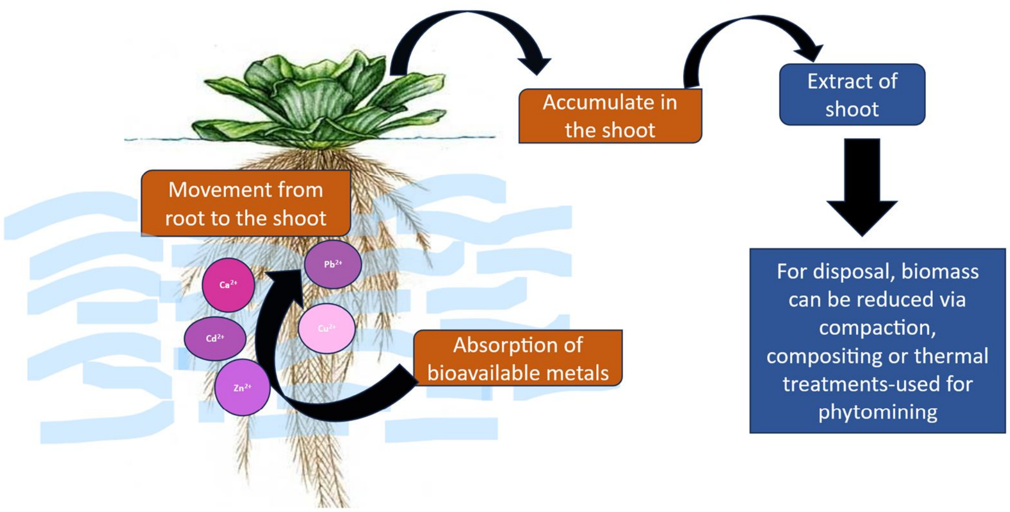


Fig.4 Mechanism of Phytoextraction

The technique has gained considerable global attention over the past two decades. Also referred to as phytoaccumulation, phytoabsorption, or phytosequestration, phytoextraction depends on plants' capacity to take up pollutants via their roots and either retain them within the root structures or transport them to aerial parts. *Brassica juncea* and *Thlaspi caerulescens* are among the most used species for phytoextraction due to their high metal uptake capabilities (Ali et al.,2017; Su et al.,2018).

The procedure of remediation keeps going till the plants are harvested. However, since trace amounts of contaminants often remain in the soil after each cycle, multiple rounds of cultivation and harvesting are typically required to achieve substantial cleanup.

Once decontaminated, the soil can support healthy plant growth again. The duration needed to complete this process depends on several factors, including the type and concentration of contaminants, the plant's growth cycle, and the plant species' efficiency in metal uptake and accumulation.

In some cases, harvested plant biomass can be incinerated to generate energy. Additionally, metals present in the plant ash can be recovered and recycled (Erakhrumen, 2007; Chandra et al., 2018). Although phytoextraction is often mistakenly used interchangeably with phytoremediation, it is important to note that phytoextraction is a specific method within the broader concept of phytoremediation (Prasad et al., 2005).

As shown in Fig.4, contaminants are either retained in the root system or transported to the upper plant parts. This process is repeated over successive crops until a significant level of decontamination is reached. The effectiveness of this technique is influenced by the plant's ability to accumulate and exclude metals, the extent of contamination, and the duration of the growing season (Blaylock and Huang, 2000; Keller et al.,2003).

### *B. Phytostabilization*

Phytostabilization, often referred to as *in-situ inactivation*, is mainly applied for the remediation of contaminated soil, sediment, and sludge (United States Environmental Protection Agency, 2000). This technique involves the use of plant roots to reduce the mobility as well as bioavailability of contaminants within the soil matrix. One key advantage of phytostabilization is that it does not require the disposal of hazardous biomass or waste material (Radziemska et al.,2017; Bernal et al.,2019). Furthermore, it is particularly effective when quick immobilization is required to safegaurd both groundwater and surface water resources.

Certain plant species are used in this process to immobilize contaminants at polluted sites through several mechanisms, including accumulation by root hairs, adsorption onto the root surface, and precipitation within the rhizosphere (Berti and Cunningham, 2000; Munshower et al., 2003; Mendez and Maier, 2008) (Fig.5). These mechanisms help limit contaminant mobility, prevent their entry into the food chain, and ultimately reduce their bioavailability (Shackira & Puthur,2019). Since phytostabilization retains contaminants within the root zone, it prevents their translocation into the aerial parts of the plant (Berti and Cunningham, 2000).

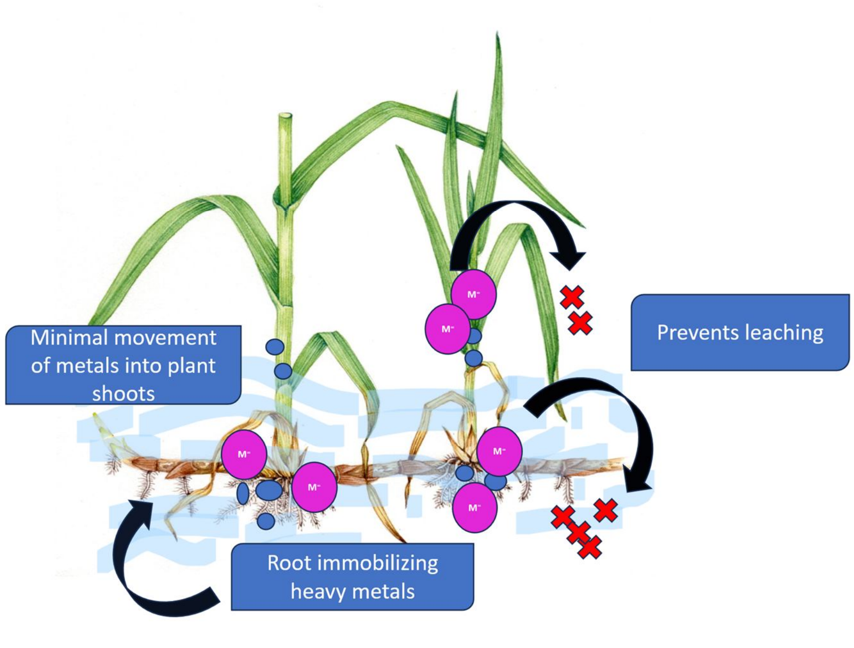


Fig.5 Mechanism of Phytostabilisation

Phytostabilization also facilitates the reestablishment of vegetation in metal-contaminated areas where natural plant growth is otherwise inhibited (Regvar et al., 2006; Shackira & Puthur,2019). Metal-tolerant plant species can be effectively used to stabilize contaminated sites by reducing the movement of pollutants via wind, water, or leaching into groundwater. Moreover, plant-associated microbiota plays an important role in enhancing plant growth and metal tolerance, while simultaneously minimizing metal uptake into aboveground plant tissues by reducing metal bioavailability in the rhizosphere.

These associated microorganisms employ various mechanisms to immobilize or inactivate heavy metals in the root zone. The microbial strategies for metal resistance include:
(1) restricting metal uptake by forming a permeability barrier or actively expelling metals from the cell;
(2) attaching metals to extracellular polymers; and
(3) transforming metals into less toxic forms through chemical detoxification (Koźmińska et al., 2018).

### *C. Rhizofiltration*

Rhizofiltration is a phytoremediation technique specifically designed to treat contaminated surface water, groundwater, and wastewater containing low concentrations of pollutants (Ensley, 2000; Biswal,2025). This method utilizes both terrestrial and aquatic plants to absorb, adsorb, and precipitate contaminants from aqueous environments directly onto or within their root systems (Tiwari et al.,2019; Khan et al.,2023). Commonly targeted pollutants include heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), nickel (Ni), zinc (Zn), and chromium (Cr), which predominantly accumulate in the plant roots (United States Environmental Protection Agency, 2000).

The roots play a central role in rhizofiltration. They act as natural filters, removing toxic substances through physical adsorption and biochemical interactions within the rhizosphere the region of soil and water influenced by root activity (D. Schrey et al.,2014) as shown in Fig.6. Fluctuations in pH and the release of root exudates in this zone contribute significantly to the immobilization of pollutants, enhancing their retention on root surfaces (Wu et al., 2024).

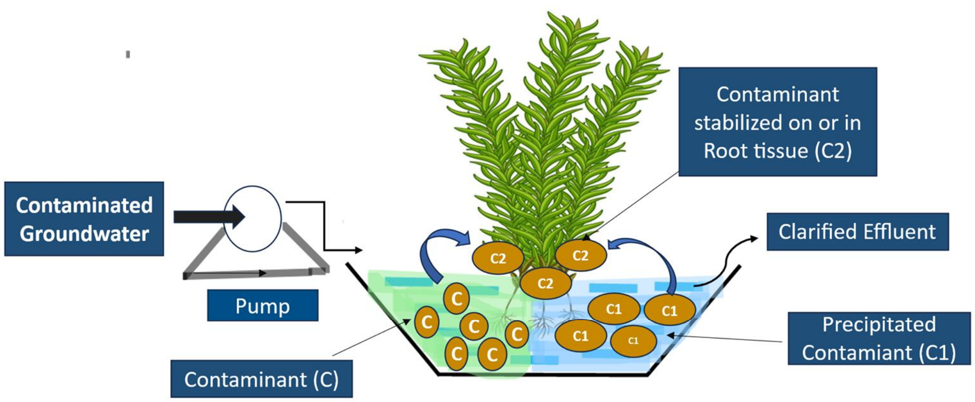


Fig.6 Mechanism of Rhizofilteration

Once the roots have absorbed or adsorbed enough contaminants, the plants can be harvested and safely disposed of, thus effectively removing the pollutants from the environment (Dushenkov et al.,1995; Rawat et al., 2012a). Plants used for rhizofiltration must possess specific characteristics: they should have extensive root systems, high tolerance to heavy metals, the ability to accumulate large amounts of contaminants, and low maintenance requirements (Verma et al.,2006).

Various plant species, including fibrous-rooted terrestrial plants and aquatic macrophytes, are suitable for rhizofiltration applications. These species can be effectively used to treat wastewater, industrial effluents, nuclear waste, and other contaminated water sources (Galal et al., 2018). Heavy metal ions such as Cd, Pb, Cr, Ni, Zn, and Cu often found in soil and water due to anthropogenic activities can be efficiently removed through this method (Sreelal & Jayanthi, 2017).

Moreover, the rhizosphere hosts complex biochemical reactions facilitated by the plant roots, which promote the binding and stabilization of contaminants. Once the roots reach their maximum absorption capacity, the contaminated root biomass or the entire plant can be harvested for disposal or further processing (Abhilash et al., 2009; Benavides et al., 2019).

*D. Phytovolatilization*

Phytovolatilization is a remediation process in which plants absorb contaminants from the soil or water, transform them into volatile forms, and release them into the atmosphere (Moreno et al.,2004; Arya et al.,2017) (Fig.7). This technique has been explored for elements like selenium, arsenic, and mercury, which can be converted into volatile compounds such as dimethyl selenide and elemental mercury (Vithanage et al.,1012; Zayed et al.,2020; Sharma et al.,2024). While these transformed compounds are often less toxic than their original forms, they may still pose environmental and health risks, making the process somewhat controversial (Sakakibara et al., 2010).

Most plants can volatilize dimethyl selenide; however, this ability might be inhibited by co-contaminants like boron and sulfate. High salinity and boron levels can be detrimental to plant survival. Despite these limitations, certain plant species can be integrated into regular crop rotations, allowing selenium contaminated soils to be phytovolatilized while also producing biomass that may be used as livestock feed a potential alternative for treating selenium loaded irrigation drainage water (Dhillon & Bañuelos.,2017; Zayed et al.,2020).

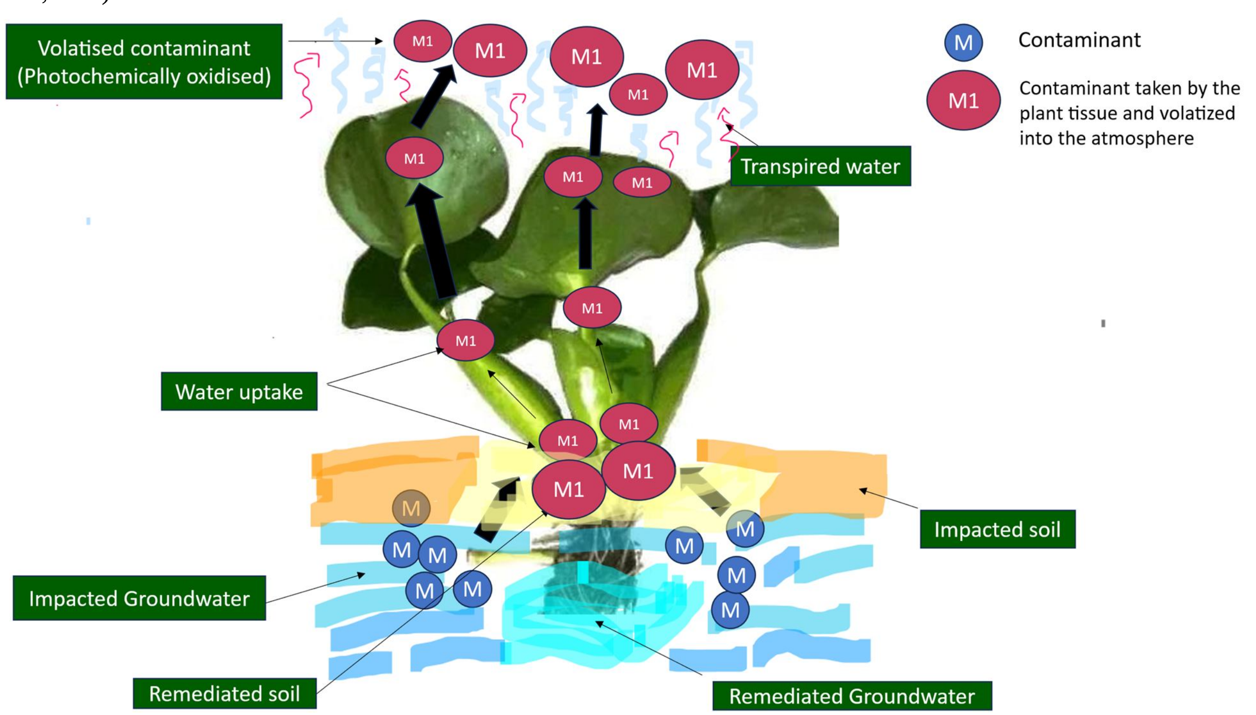


Fig.7 Mechanism of Phytovolatisation

Phytovolatilization is sometimes considered a permanent remediation strategy, as the volatilized compounds are unlikely to redeposit near the original site. Although the microbial role in selenium volatilization was long known, the ability of plants to perform this function was only confirmed later (Raskin et al., 1997). Unlike other phytoremediation techniques that generate reusable byproducts, phytovolatilization does not leave behind materials that can easily trace or track contaminant migration (Jabeen et al., 2009). The United States Environmental Protection Agency (2000) notes that mercuric mercury ($Hg^{2+}$) is one of the primary metal contaminants targeted by phytovolatilization. A key benefit of this method is the conversion of toxic mercuric ions into elemental mercury ($Hg^0$), a less toxic form (Singh & Prasad,2015). However, this volatilized mercury may be recycled through atmospheric deposition, eventually accumulating in aquatic ecosystems and undergoing microbial conversion into highly toxic methylmercury a significant environmental concern.

## VIII. BIOACCUMULATION EFFICIENCY IN PHYTOREMEDIATION

The efficiency of macrophytes in heavy metal phytoremediation largely depends on their ability to absorb, translocate, and store metals without exhibiting phytotoxic effects (Suresh and Ravishankar 2004; Pilon-Smits 2005; Anjum et al. 2014; Mahmood et al. 2015; Manorama et al.,2020). This efficiency varies across plant species and is influenced by factors such as metal type and concentration, duration of exposure, and environmental conditions including pH, temperature, and nutrient availability (Magdziak et al.,2014).

Aquatic macrophytes like *Hydrilla verticillata* and *Azolla* spp. have demonstrated strong accumulation capacities for metals such as zinc (Zn), cadmium (Cd), and chromium (Cr), making them promising candidates for large-scale phytoremediation initiatives (He et al., 2016a; Shafi et al., 2015). Some species exhibit high bioaccumulation rates for specific heavy metals but are less effective for others. For example, *Salvinia minima* is particularly efficient at accumulating Cd (II) and PB (II), but shows relatively lower uptake for Cr (VI) due to its the anionic nature of this ion and its low capacity to be adsorbed by the negatively charged functional groups of the root's surface (OLGUÍN et al., 2002). Similarly, *Eichhornia crassipes* has demonstrated high accumulation potential for lead (Pb) and copper (Cu), yet its efficiency for mercury (Hg) remains limited (Singh et al., 2022). Conversely, species such as *Typha natans* and *Phragmites australis* can absorb a broad spectrum of heavy metals—including Pb, Cd, and nickel (Ni)—though typically at moderate accumulation rates. In a comparative study on the accumulation of Cd, Pb, and Ni in several macrophytes, Eid et al. (2019) reported that *P. australis* accumulated the highest concentrations of Cd and Ni, while *E. crassipes* accumulated the highest concentration of Pb. *Ludwigia stolonifera* and *Echinochloa stagnina* were able to accumulate all three metals, but with comparatively lower efficiency. In comparative study by Ahmad et al., 2016a in between C. demersum and P. natans reveal that C. demersum serves as a good accumulator of Co, Mn, and Cd metals while P. natans serves as a good accumulator of Cd. These findings underscore the importance of selecting suitable plant species based on the specific contaminant profile of a polluted site to enhance phytoremediation performance. Table 2 provides a list of numerous macrophytes along with their efficacy in accumulating heavy metals.

Table 2. List of Macrophytes with their efficiency in accumulating heavy metals in water

| S.No. | Macrophyte | Part of the plant | Heavy metal | Accumulation | Efficiency | References |
|---|---|---|---|---|---|---|
| 1. | *Hydrilla verticillata* (Water thyme) | Stem (shoot), leaves, cell wall | As | (8546 ug) | 72% | Srivastava et al., 2011 |
| | | Leaves,root | Cr | 15mg/l | | Phukan et al., 2015 |
| | | Root,Shoot | Cd | 3mg/l | | |
| | | Roots, Submerged leaves | Cd | 145 mg g−1 in 1 mg L−1 Cd solution | 14% | He et al., 2016b |
| 2. | *Lemna gibba* (Common duckweed) | Fronds | As | 0.54 to 110.8 mg kg 1 (fresh weight), 61.7 to 1966.48 mg kg 1 (dry weight) | 40.3% | Mkandawire & Dudel, 2005 |
| | | | | 631.31 (BCF) | 91.0–96.4% | Abdallah, 2012 |
| | | | Pb | 297.1 (BCF) | 86.2–94.8% | |
| | | | Cr | | | |
| 3. | *Vallisneria spiralis* (Eel grass) | Root | Hg | 158 mg kg−1 | 70–84% | Rai & Tripathi, 2009 |
| 4. | *Spirodela polyrrhiza* (Greater duckweed) | Fibrous roots, broad leaves | Fe | 18.996 mg $g^{-1}$ | 77.5% | Mishra & Tripathi, 2008 |
| | | | Zn | 1.5 mg $g^{-1}$ | 82 | |
| | | | Cu | 0.145 mg $g^{-1}$ | 76 | |
| | | | Cd | 0.14 mg $g^{-1}$ | 65 | |
| | | | Cr | 0.065 mg $g^{-1}$ | 62 | |
| | | Root | | | | |
| | | | Cr, Pb, Zn | 0.353±0.003 µmol g-1 Dry weight | | Bala & Thukral, 2011 |
| 5. | *Eichhornia Crassipes* (Water hyacinth) | Fibrous roots, broad leaves | Fe | 25.5 mg $g^{-1}$ | 78.6% | Mishra & Tripathi, 2008 |
| | | | Zn | 5.52 mg $g^{-1}$ | 85 | |
| | | | Cu | 2.76 mg $g^{-1}$ | 86 | |
| | | | Cd | 0.27 mg $g^{-1}$ | 77 | |
| | | | Cr | 0.276 mg $g^{-1}$ | 81 | |
| | | | Cd | | 91.30% | Singh et al., 2022 |
| | | | Cu | | 93.55% | |
| | | | Fe | | 92.81% | |
| | | | Mn | | 93.45% | |
| | | | Pb | | 89.66% | |
| | | | Zn | | 94.44% | |
| 6. | *Pistia stratiotes* (Water lettuce) | Fibrous roots, broad leaves | Fe | 15.334 mg $g^{-1}$ | 90% | Mishra & Tripathi, 2008 |
| | | | Zn | 0.98 mg $g^{-1}$ | 82 | |
| | | | Cu | 0.875 mg $g^{-1}$ | 88 | |
| | | | Cd | 0.321 mg $g^{-1}$ | 70 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Cr | 0.075 mg $g^{-1}$ | 70 | |
| | | | Ag | 1161.53 ± 0.31e (BCF) | | Odjegba & Fasidi, 2004 |
| | | | Cd | 2026.67 ± 1.00b (BCF) | | |
| | | | Cr | 1607.57 ± 0.42c (BCF) | | |
| | | | Cu | 2454.10 ± 0.24a (BCF) | | |
| | | | Hg | 1015.23 ± 0.24f (BCF) | | |
| | | | Ni | 675.80 ± 0.24g (BCF) | | |
| | | | Pb | 1515.87 ± 0.18d (BCF) | | |
| | | | Zn | 2452.67 ± 0.21a(BCF) | | |
| | | | | 66% in 24 hours | | |
| | | Root | | | | |
| | | | Cr | | 58–80% | Maine et al., 2004 |
| 7. | *Typha natans* (Floating cattail) | | Cd | 0.67–3.65 mg/L | | Kumar & Chopra., 2016 |
| | | | Cu | 1.52–6.45 mg/L | | |
| | | | Fe | 1.88–8.75 mg/L | | |
| | | | Ni | 0.47–2.64 mg/L | | |
| | | | Pb | 0.54–3.66 mg/L | | |
| | | | Zn | 1.84–7.62 mg/L | | |
| 8. | *Ceratophyllum demersum* (Hornwort) | | Pb | 1284.35 (BCF) | 92.0–95.0% 13.0–84.3% | Abdallah., 2012 |
| | | | Cr | 1039.67(BCF) | | |
| 9. | *Azolla pinnata* (Mosquito fern) | Root, stem, leaves | Cu | 45 (BCF) | | Shafi et al.,2015 |
| | | | Pb | 4.94 (BCF) | | |
| | | | Cr | 3.857 (BCF) | | |
| | | | Cd | 7 (BCF) | | |
| | | | Zn | 35 (BCF) | | |
| 10. | *Azolla caroliniana* (Eastern mosquito fern) | Roots, Fronds | Zn | 2732.08(BCF) | 4% | Deval et al., 2012 |
| 11. | *Spirodela intermedia* (Intermediate duckweed) | Root | As | 900 lg g-1 – DW | | da-Silva et al., 2017 |
| | | | | | | Miretzky et al., 2004 |
| 12. | *Lemna minor* (Lesser duckweed) | Root | Cd | | | Balen et al., 2011 |
| | | | Zn | | | |
| | | | Cu | 558 BCF | 92.2% | Bokhari et al., 2016 |
| | | | Cd | 455.5 BCF | 94.3% | |
| | | | Pb | 523.1 BCF | 89% | |
| | | | Ni | 336 BCF | 84% .2% | |
| 13. | *Salvinia minima* (Water spangles) | Root | Cr | $BCF_{0.300mg\ L\ Cd}$ = 2,676 | | Iha & Bianchini., 2015 |
| | | | Cd | $BCF_{0.400mg\ L\ Ni}$ = 900 | | |
| | | | Ni | $BCF_{1.00mg\ L\ Pd}$ =1786 | | |
| | | | Pb | $BCF_{10.00mg\ L\ Zn}$ =1046 | | |
| | | | Zn | | | |
| | | | | 2,718 BCF | | |
| | | | | 784 BCF | | |
| | | | | 3,304 BCF | | |
| | | Root | Cd | | | Olguín et al., 2002 |
| | | | Cr | | | |
| | | | Pb | | | |
| 14. | *Salvinia herzogii* (Giant salvinia) | Root | Cr | 75% in 24 hours | 70–83% | Maine et al., 2004 |
| 15. | *Myriophyllum aquaticum* (Parrot's feather) | Leaves | Ni | 10 mg L-$^{1}$ | | Harguinteguy et al., 2015 |
| | | | Pb | 3798.9± 1032.5 mg kg-$^{1}$ | | |
| | | | Zn | 2348.4±713.2 mg $kg^{-1}$ | | |
| 16. | *Egeria densa* (Dense waterweed) | Leaves | Ni | 10 mg $L^{-1}$ | | Harguinteguy et al., 2015 |
| | | | Pb | 2302.5± 882.1 mg $kg^{-1}$ | | |
| | | | Zn | 1083.6± 568.1 mg $kg^{-1}$ | | |
| 17. | *Vallisneria natans* (Asian tapegrass) | Leaves, Root | As (III) | 3.45–6.96 mg kg–1 | 62.86–75.97%(root) | Li et al., 2018 |
| | | | AsB | 0.52–1.87 mg kg–1 | 75.75–107.08%(leaves) | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | As (V) | Main | | |
| 18. | *Typha latifolia* (Broadleaf cattail) | Root, Shoot | Cd | 279 mg/kg (root)<br>131 mg/kg(shoot) | 1.87% (30 mg/kg of Cd) | Yang & Shen., 2020 |
| 19. | *Ludwigia stolonifera* (Creeping ludwigia) | Root, leaves | Al<br>Cu<br>Fe<br>Mn<br>Ni<br>Cd<br>Zn<br>Cr<br>Pb | 955.27 mg $kg^{-1}$<br>886.17 mg $kg^{-1}$<br>3461.50 mg $kg^{-1}$<br>178.37 mg $kg^{-1}$<br>1286.17 mg $kg^{-1}$<br>4.63 mg $kg^{-1}$<br>505.33 mg $kg^{-1}$<br>13.97 mg $kg^{-1}$<br>49.77 mg $kg^{-1}$ | | Galal et al., 2019 |
| | | | Pb | 689.51 BCF | 90.08% | Aboelkassem et al., 2022 |
| 20. | *Typha domingensis* (Southern cattail) | Root | Zn<br>Pb<br>Ni<br>Cr<br>Cd | 21.83 mg $L^{-1}$<br>20.33 mg $L^{-1}$<br>18.77 mg $L^{-1}$<br>15.18 mg $L^{-1}$<br>13.42 mg $L^{-1}$ | 49.4%<br>38.7%<br>35.6%<br>30.4%<br>28.3% | Soudani et al., 2022 |
| 21. | *Scirpus grossus* (Greater clubrush) | Shoot, Leaves,Root | Pb | 400 mg/L | | Tangahu et al., 2013 |
| 22. | *Rotala rotundifolia* (Roundleaf toothcup) | Stem<br>Leaves | Pb | 289,668 BCF<br>137,310BCF | | Lase et al., 2024 |
| 23. | *Hygrophila polysperma* (Indian swampweed) | Stem<br>Leaves | Pb | 50,694 ± 0,741 b mg/kg<br>112,070 ± 115,155 ab mg/kg | | Lase et al., 2024 |
| 24. | *Alisma plantago-aquatica* (European Water-plantain) | Leaves<br>Root | Cu<br>Pb | 72,64 mg/kg<br>44,9 mg/kg | | Rumyantseva et al., 2021 |
| 25. | *Sagittaria montevidensis* (Giant arrohead) | Root, Shoot | Mn<br>Al<br>Vn<br>As<br>Cu<br>Pb<br>Cd | 3,530.4 BCF<br>672.6 BCF<br>623.4 BCF<br>347.1 BCF<br>303.4 BCF<br>55.1 BCF<br>17.8 BCF | | Demarco et al., 2019 |
| 26. | *Elodea canadensis* (Canadian waterweed) | Root | Cr | 3.89 BAF | 65% | Sankaranarayanan et al., 2023 |
| 27. | *Limnobium laevigatum* (Amazon frogbit) | Leaves | Pb<br>Zn | 903<br>4673 | | Fernández San Juan et al., 2018 |
| | | Root | Pb<br>Zn | 4670<br>677 | | |
| 28. | *Ludwigia peploides* (Creeping water primrose) | Leaves | Pb<br>Zn | 203<br>739 | | Fernández San Juan et al., 2018 |
| | | Root | Pb<br>Zn | 425<br>940 | | |
| 29. | *Veronica anagallis-aquatica* (Water speedwell) | Root | Cd | 8.79 BCF | | Ahmad et al., 2016b |
| 30. | *Ipomeo aquatica (Water spinach)* | Root | Zn<br>Cu<br>Pb | 618.61 L/Kg<br>55.33 L/Kg<br>458.72 L/Kg | | Nur et al., 2022 |
| | | Root<br>Leaf<br>Stem | Pb | 0.63 mg L1<br>0.63 mg L1<br>20 mg L1 | | Chanu & Gupta., 2016 |
| 31. | *Salvinia molesta (Giant salvinia)* | Leaves | As | 103 lg g-1 DW | | da Silva et al., 2018 |
| 32. | *Potamogeton perfoliatus* (Perfoliate pondweed) | | Cd<br>Cu<br>Pb<br>Zn | 1.88 µg/g<br>13.14 µg/g<br>13.32 µg/g<br>57.96 µg/g | | Matache et al., 2013 |
| 33. | *Mentha aquatica* (Water mint) | Root | Cd | 130.40 mg/kg | | Hasanpour et al., 2019 |
| 34. | *Mentha longifolia* (Horsemint) | Root, Shoot | Cd<br>Cr<br>Cu<br>Fe | 7.4 mg $kg^{-1}$<br>16.0 mg $kg^{-1}$<br>681.2 mg $kg^{-1}$<br>2054.3 mg $kg^{-1}$ | | Gharib et al., 2021 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Zn | 668.2 mg kg$^{-1}$ | | |
| | | | Pb | 9.3 mg kg$^{-1}$ | | |
| 35. | *Nasturtium officinale* | | Cd | 73 BCF | | Duman et al., 2009 |
| | (Watercress) | | Co | 420 BCF | | |
| | | | Cr | 10.3 BCF | | |
| 36. | *Azolla filiculoides* | | Ni | | 76.82% | Naghipour et al., 2018 |
| | (Water fern) | | Cd | | 92.84% | |
| | | | Pb | | 97.12% | |
| 37. | *Potamogeton crispus* | Root | Cd | 755 lg g$^{-1}$ | | Sivaci et al., 2008 |
| | (Curly pondweed) | | | | | |
| | | Root | Pb | 6648.12 g g−1 | | Upadhyay et al., 2014 |
| | | | Cr | 6206.84 g g−1 | | |
| 38. | *Myriophyllum heterophyllum* | Root | Cd | 132 lg g$^{-1}$ | | Sivaci et al., 2008 |
| | (Twoleaf watermilfoil) | | | | | |
| 39. | *Potamogeton pectinatus* | Root | Pb | 3708.33 g g−1 | | Upadhyay et al., 2014 |
| | (Fennel pondweed) | | | | | |
| 40. | *Scirpus grossus* | Root, Shoot | Pb | 3236 mg/kg | | Tangahu et al., 2013 |
| | (Greater club rush) | | | 485,261BCF | | |
| 41. | *Phalaris arundinacea* | Root | Zn | 1.31 ± 1.06 | | Polechońska & Klink., 2014 |
| | (Reed canary grass) | | Mn | 1.07 ± 1.01 | | |
| | | | Fe | 0.26 ± 0.26 | | |
| | | | Cu | 0.83 ± 0.71 | | |
| | | | Co | 1.37 ± 1.61 | | |
| | | | Pb | 0.22 ± 0.21 | | |
| | | | Ni | 0.71 ± 0.60 | | |
| | | | Cd | 4.43 ± 5.07 | | |
| | | | Cr | 0.63 ± 0.60 | | |
| 42. | *Wolffia globosa* | Fronds | Cd | 143.12 mgkg−1 FW | 99% | Xie et al., 2013 |
| | (Asian watermeal) | | | 255 BCF | | |
| | | | | 80.65 mg/kg | | |
| | | | Cd | 73.53 mg/kg | | Upatham et al., 2002 |
| | | | Cr | | | |
| 43. | *Hydrocotyle ranocloides* | Root, Shoot | Mn | 5056 BCF | | Demarco et al., 2018 |
| | (Floating pennywort) | | Cu | 667 BCF | | |
| | | | Pb | 126 BCF | | |
| | | | Fe | 1015 BCF | | |
| | | | Cd | 27 BCF | | |
| 44. | *Arundo donax* | Root, Shoot | As | 600 g L$^{-1}$(BCF) | | Srivastava et al., 2011 |
| | (Giant cane) | | | | | |
| 45. | *Salvinia natans* | Root | Hg | 275–780 BCF | 60-96% | Sitarska et al., 2023 |
| | (Floating watermoss) | | | 350.84 mg/g DM | | |
| 46. | *Cabomba piauhyensis* | Root | As | 66.86 mg kg−1 dw | 55.8% | Abu Baker et al., 2013 |
| | (Red cabomba) | | Al | 856.82 mg kg−1 dw | 83.8% | |
| | | | Zn | 280.82 mg kg−1 dw | 93.7% | |
| 47. | *Myriophyllum spicatum* | Root, Shoot | Fe | 8.5±3.2 | | Galal & Shehata., 2014 |
| | (Eurasian watermilfoil) | | Mn | 105.9±57.6 | | |
| | | | Zn | 8.3±3.6 | | |
| | | | Cu | 2.6±1.9 | | |
| | | | Cd | 20.2±20.9 | | |
| | | | Pb | 0.9±0.7 | | |
| | | | Ni | 139.7±136.9 | | |
| 48. | *Vossia cuspidate* | Root, Shoot | Mn | 240.9 BF | | Farahat et al., 2021 |
| | (Hippo grass) | | Fe | 236.4 BF | | |
| | | | Pb | 41.1 BF | | |
| | | | Zn | 52.0 BF | | |
| | | | Cu | 131.6 BF | | |
| | | | Ni | 50.6 BF | | |
| | | Root, Shoot | Cr | 5.1 mg kg$^{-1}$ | | Tarek et al., 2017 |
| | | | Cu | 2185.8 mg kg$^{-1}$ | | |
| | | | Pb | 308.0 mg kg$^{-1}$ | | |
| | | | Fe | 3386.4 mg kg$^{-1}$ | | |
| | | | Ni | 1467.4 mg kg$^{-1}$ | | |
| | | | Co | 49.0 mg kg$^{-1}$ | | |
| 49. | *Echinochloa stagnina* | Root, Shoots | Fe | 2.43 BF | | Abdelaal et al., 2021 |
| | (Burgu millet) | | Cu | 0.27 BF | | |
| | | | Zn | 0.74 BF | | |
| | | | Mn | 2.29 BF | | |

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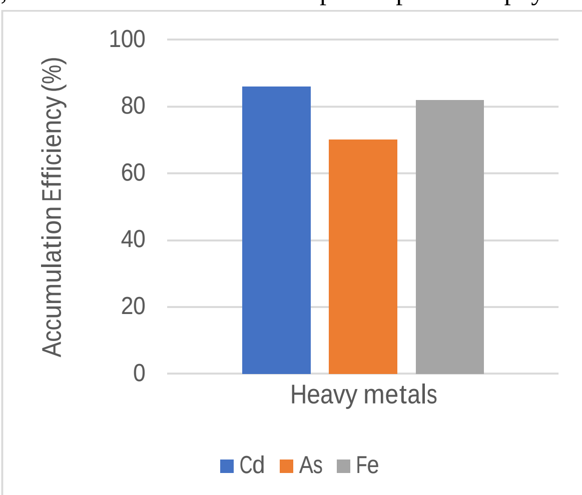
| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Co | 0.98 BF | | |
| | | | Cd | 1.05 BF | | |
| | | | Ni | 3.18 BF | | |
| | | | Pb | 2.59 BF | | |
| 50. | *Phragmites australis* (Common reed) | Root, stem, leaf | Cd | 1.14 BCF | 93% | Bello et al., 2018 |
| | | | Pb | 0.86 BCF | 95% | |
| | | | Ni | 1.6 BCF | 84% | |

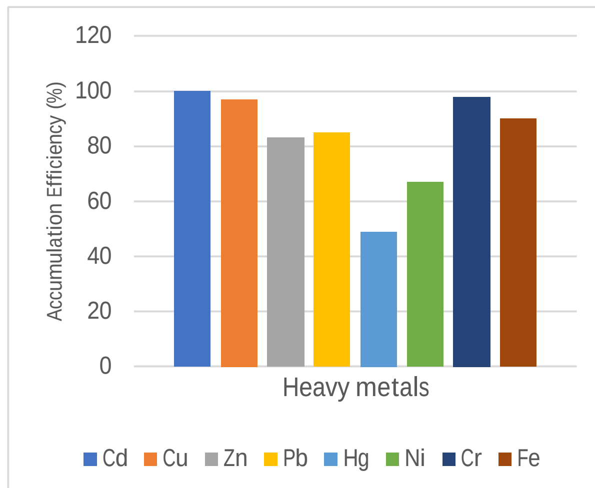
## IX. EVALUATING MACROPHYTE-MEDIATED HEAVY METAL REMOVAL

The comparative accumulation efficiency of different aquatic macrophyte species in removing heavy metals (Cu, Cd, Pb, Cr, As, Fe, Zn etc.) from contaminated water is shown in the graph (Fig.8) representing the concentration of a particular metal absorbed by the plant's root or shoot tissue; notably, species like *Eichhornia crassipes*, *Azolla pinnata* and *Salvinia minima* exhibit significantly higher uptake rates, especially for Cd, Cu, Pb and Cr. For instance, *E. crassipes* can absorb up to ~99% of Cd and Cr from solution, while *A. pinnata* demonstrates robust phytoextraction across a range of metals including Cr.

In contrast, species such as *Typha natans* and *Pistia stratiotes* accumulate more Cu, Pb, Cr and Fe in roots than in shoots, indicating a phytostabilization role while *Hydrilla verticillate* show notable efficiency to control Cd and Fe from polluted water. Differences in translocation factors (shoot/root ratios) are evident: floating macrophytes often show high root accumulation but limited transfer to shoots ($TF < 1$), whereas some hyperaccumulators achieve $TF > 1$ and thus contribute effectively to phytoextraction (Baruah et al.,2021). The stark contrast in graph underscores how biomass, root morphology, and metal tolerance drive species-specific efficiency, which informs selection of optimal plants for phytoremediation strategies.




a.

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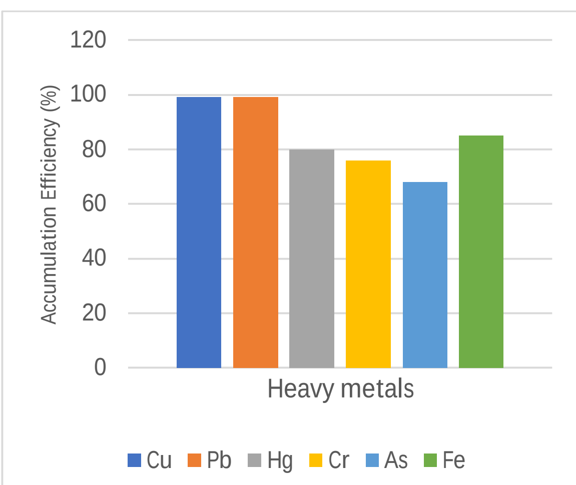


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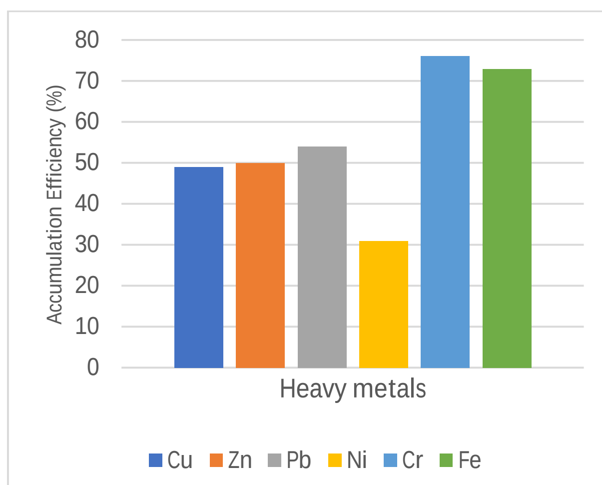
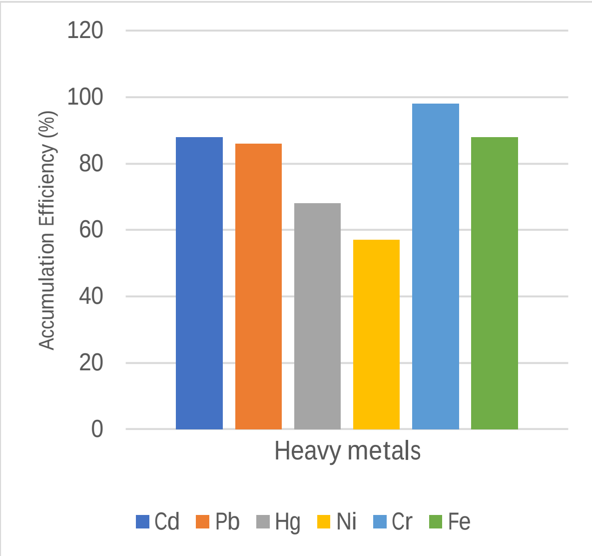



d.

e. 

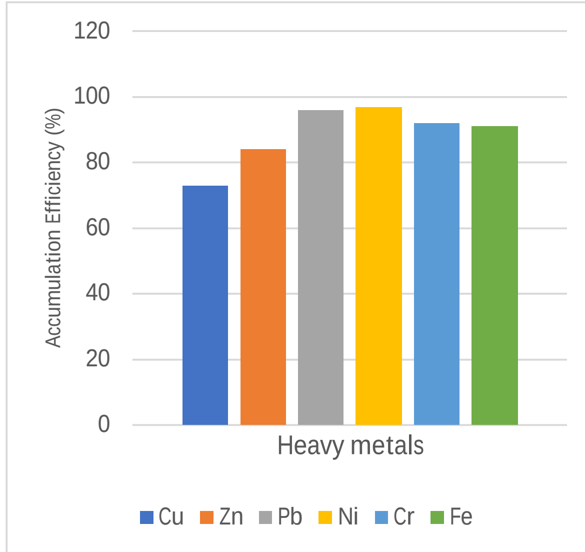

f. 


Fig.8 (a) Efficiency (%) of *Hydrilla verticilata* for Heavy metal accumulation (b) Efficiency (%) of *Eicchornia crassipes* for Heavy metal accumulation (c) Efficiency (%) of *Pistia stratiotes* for Heavy metal accumulation (d) Efficiency (%) of *Typha natans* for Heavy metal accumulation (e) Efficiency (%) of *Azolla pinnata* for Heavy metal accumulation (f) Efficiency (%) of *Salvinia minima* for Heavy metal accumulation

## X. ADVANTAGES OF PHYTOREMEDIATION

Phytoremediation, as a sustainable biological approach to environmental cleanup, offers multiple notable advantages:

1) This technique is environmentally friendly, as it minimally disturbs the surrounding ecology and helps maintain the natural landscape (Pilon-Smits, 2005; Bhat et al.,2019;).
2) Phytoremediation is particularly effective for treating deep-seated and low-level contaminated zones, where traditional physical or chemical methods might struggle (Diarra et al.,2022; Wuana & Okieimen,2011).
3) It is versatile, capable of addressing a wide range of environmental pollutants, including heavy metals, radionuclides, pesticides, and hydrocarbons (Ali et al., 2013).
4) Due to its visually appealing nature, phytoremediation is well-received by the public, especially in urban or residential areas. It is often favored when other technologies are impractical or less effective, offering a low-cost alternative (Ghosh and Singh, 2005).
5) Compared to many conventional remediation methods, phytoremediation incurs lower operational, maintenance, and implementation costs (Salt et al., 1995).
6) Growing plants on contaminated soils can stabilize metals, reducing the risk of leaching and runoff into groundwater or surrounding ecosystems (Raskin and Ensley, 2000). Moreover, fast-growing, high-biomass plants can be harvested and utilized for bioenergy production (Chaney et al., 2010).
7) Phytoremediation also enables the recycling and recovery of valuable metals through techniques like phytomining, adding an economic incentive to the process (Anderson et al., 1999; Zulkernain et al.,2023).
8) Importantly, this method is considered the least harmful to both the environment and human health, offering a "green" solution compared to more invasive technologies (McCutcheon and Schnoor, 2004).

## XI. DRAWBACKS AND CHALLENGES OF PHYTOREMEDIATION

### *A. Limited Contaminant Specificity*

While macrophytes can uptake a wide range of contaminants, their efficiency is often selective and varies depending on the type of pollutant. Some plants may be effective for certain heavy metals like cadmium (Cd) or lead (Pb), but less efficient for others (e.g., arsenic or mercury) (Ali et al., 2013).

### *B. Metal Uptake Inconsistencies*

The uptake of Cd by *Lemna minor* was reduced by Zn (Balen et al. 2011), whereas that of *L. gibba* was reduced by Ni (Demim et al. 2013). The removal rates of heavy metals were higher when *Phragmites australis* and *Typha latifolia* were planted together than when they were cultivated separately (Kumari and Tripathi 2015). In study of Merve et al., 2015 it was found that *Lemna gibba L.* accumulated more Cu, Pb, Zn and As than Lemna minor L. but it showed less accumulation performance than *Lemna minor L.* in compared with the control group samples (LG-0 and LM-0) of *Lemna gibba L.* and *Lemna minor L.*, except for As.

### *C. Slow Remediation Process*

Phytoremediation is inherently time-consuming, especially when compared to physicochemical methods (Wuana & Okieimen,2011). It may require multiple cropping cycles to significantly reduce contamination levels, particularly for highly polluted environments (Tangahu et al., 2011).

### *D. Biomass Disposal Issues*

The harvested biomass itself transforms into hazardous waste after pollutant uptake. To avoid recontamination, which can be logistically and financially difficult, safe disposal or post-processing (such as incineration or metal recovery) is crucial (Rawat et al., 2012; Chandra et al., 2018).

### *E. Environmental Dependence*

The efficiency of macrophyte-based phytoremediation is highly affected by environmental variables, like water pH, temperature, light availability, and contaminant concentration. Suboptimal conditions can drastically reduce uptake efficiency (Galal et al., 2018).

### *F. Risk of Invasive Species*

Many aquatic macrophytes used in phytoremediation, such as *Eichhornia crassipes* (water hyacinth), are highly invasive and can disrupt native ecosystems if not properly managed (Newete & Byrne,2016; Ekperusi et al., 2019). Controlling their spread is crucial during and after phytoremediation activities.

### *G. Limited Root Penetration in Submerged Sediments*

Some aquatic macrophytes may have restricted root systems that do not extend deep into sediments, limiting their ability to remediate contaminants that have settled at the bottom layers of water bodies (Sreelal & Jayanthi, 2017).

### *H. Lack of Standardized Protocols*

Phytoremediation practices vary widely, and there is a lack of universally accepted protocols or operational standards for large-scale implementation (Phang et al.,2024). This can lead to inconsistent results across different sites and conditions (Prasad et al., 2011).

### *I. Limited Genetic Improvement in Aquatic Plants*

While genetic modification has enhanced the phytoremediation potential of terrestrial plants, similar developments in aquatic macrophytes are still in early stages (Sharma et al.,2015). This limits the ability to optimize macrophytes for specific contaminants (Obinna & Ebere, 2019a).

### *J. Seasonal Growth Variability*

The growth and metal uptake capacity of macrophytes may vary seasonally. In temperate climates, their growth may slow down or cease entirely in winter, reducing year-round remediation efficiency (Abhilash et al., 2009).

### *K. Potential for Secondary Pollution*

If plants undergo senescence or are not properly harvested, contaminants may re-enter the water body through decaying biomass, undermining remediation efforts (Erdei et al., 2005).

## XII. CONCLUSION AND FUTURE PROSPECTS

Phytoremediation offers an eco-friendly approach to eliminating persistent contaminants from natural ecosystems, aiming for complete environmental restoration. Among its various strategies, selecting the suitable plant species is essential to its success for successful remediation. Aquatic macrophytes especially those classified as hyperaccumulators play a crucial role in the uptake and stabilization of heavy metals from polluted sites (Ali et al,2020; Pang et al.,2023). These aquatic plants efficiently remove heavy metals through different mechanisms like bioaccumulation and biosorption, driven by complex interactions involving metal transport, chelating agents, and cellular-level responses.

Recent advances in genetic modification have enhanced the capability of plants to absorb and tolerate higher levels of contaminants (Eapen & D'souza,2005; Seth,2012; Fasani et al.,2018). While genetic engineering has been extensively applied to terrestrial plants, its application in aquatic species remains relatively underexplored. Nonetheless, genetically modified plants show promising potential for boosting phytoremediation efficiency through improved metal uptake and stress resistance (Yadav et al.,2010).

Beyond their role in remediation, harvested plant biomass can be repurposed for example, to generate methane or serve as livestock feed making phytoremediation not only effective but also resource-efficient. Unlike traditional physicochemical treatments, aquatic phytoremediation generally requires no post-filtration and can treat large volumes of contaminated water and sediment (Ali et al.,2020).

Given water's vital role in sustaining life, increasing pollution levels mostly due to anthropogenic activities pose a direct threat to ecosystems. Therefore, the implementation of cost-effective, plant-based bioremediation technologies is imperative. Among these, the use of aquatic macrophytes stands out due to their rapid growth, high biomass yield, and natural resilience. Wild aquatic weeds have demonstrated a high tolerance to pollutants, acting as effective buffers that limit contaminant entry into different trophic level of the food chain.

This review emphasizes on the versatile applications of aquatic macrophytes in remediating a large range of inorganic and organic pollutants in aquatic ecosystem. Free-floating species like *Pistia stratiotes* (water lettuce) and *Eichhornia crassipes* (water hyacinth), are particularly valuable because of their exceptional abilities to cumulate heavy metals and reduce water quality parameters like Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD).

The scientific community and various government-ponsored projects have acknowledged the significance of aquatic macrophytes in managing water pollution (Morse et al.,2007). These plants are widely used in constructed wetlands and hydroponic systems for field-scale remediation. Their widespread distribution, high bioaccumulation capacity, reproductive versatility, and invasive nature make them both effective and challenging to manage (Hofstra et al.,2020).

However, several limitations remain. The physicochemical characteristics of the polluted medium, the kind and concentration of pollutants, the choice of plant species, and the surrounding environment are some of the variables that affect the rate at which phytoremediation works (Magdziak et al.,2014; Teiri et al.,2022). Furthermore, the invasive nature of some aquatic macrophytes poses a serious threat to local biodiversity and aquatic ecosystems. Therefore, integrated management strategies including mechanical, physical, biological, and chemical controls are necessary to regulate their spread during phytoremediation processes (Wenzel, 2009; Knight et al.,2014).

Ongoing research is focused on identifying and isolating genes responsible for hyperaccumulation of specific heavy metals. By combining multiple desirable traits into single plant species, scientists hope to develop more efficient phytoremediators. In parallel, proteomic studies are helping to uncover the proteins used in transport of pollutant and their vacuolar sequestration, deepening our understanding of phytoremediation mechanisms at the molecular level.

Despite existing challenges, phytoremediation holds significant promise as a green, low-cost, and non-destructive alternative to traditional method of remediation. It preserves native microbial communities and soil fauna while addressing environmental contamination. As research progresses, particularly in phytoextraction and phytomining, phytoremediation is expected to evolve into a commercially feasible approach for the sustainable management of heavy metal pollution.

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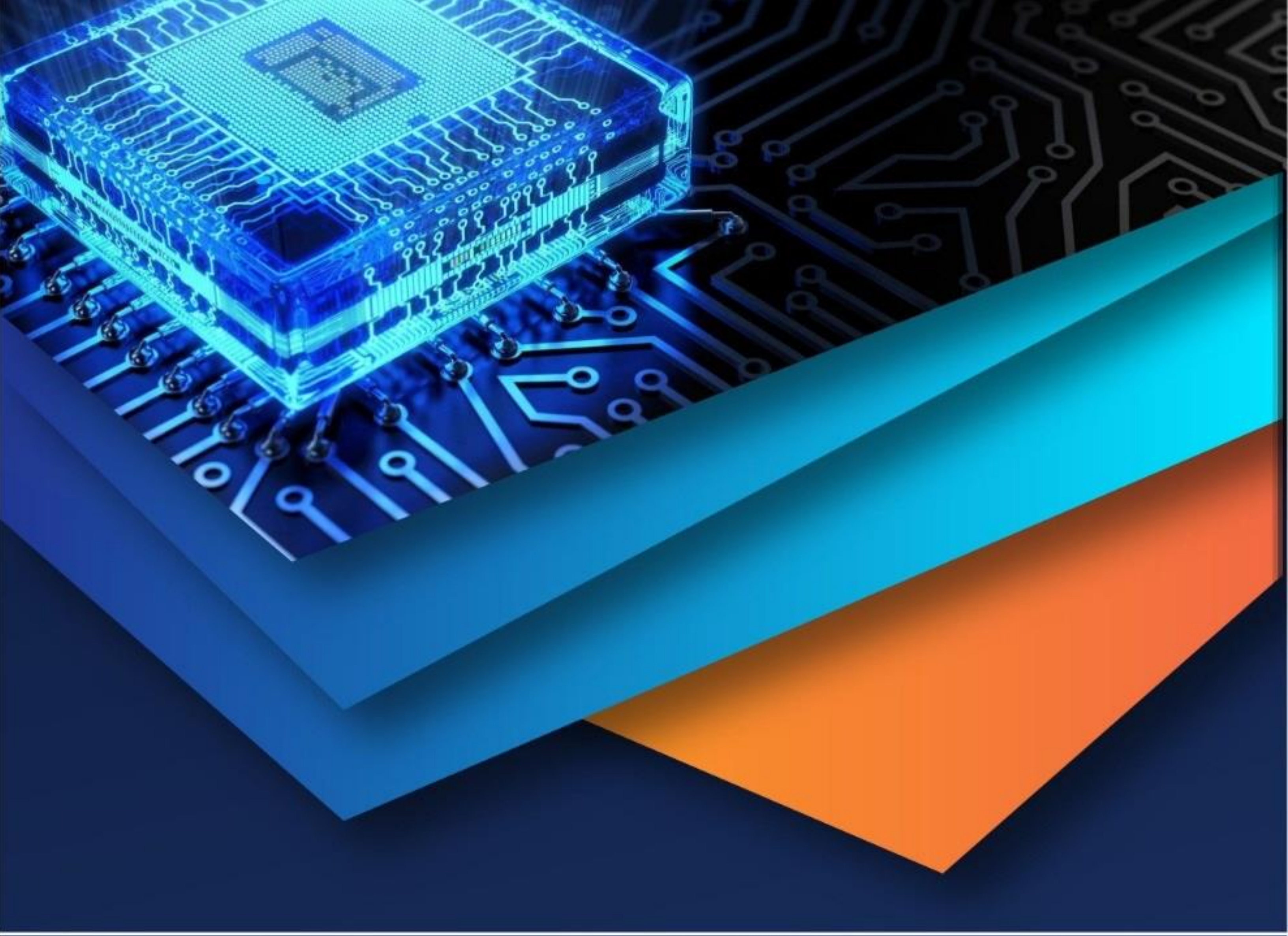


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