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A Comprehensive Review Of Phytoremediation Strategies For Heavy Metal Detoxification From Water

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***Abstract*:** Due to the rapid development of urbanization and industrialization, heavy metal contamination has emerged as a significant environmental issue. Drinking water, contaminated with heavy metals such as Cd, Cr, Pb, Zn, Hg, poses a major health concern for human beings. Heavy metal-induced toxicity involves processes such as ROS generation, weakening of antioxidant defenses, enzyme inactivation, and oxidative stress. Additionally, some metals bind to specific macromolecules. Conventional methods for treating heavy metal contamination are not always effective in completely removing water contaminants. Phytoremediation, a relatively new technology, is widely acknowledged as an economical, efficient, and environmentally friendly approach for removing heavy metals from polluted water. Aquatic plants play a crucial role in phytoremediation by absorbing pollutants through their roots and, in some cases, through their leaves. Common examples of these plants include water hyacinth, duckweed, and various submerged species like water milfoil and waterweed. These plants uptake pollutants such as heavy metals, nutrients, and organic compounds, contributing to the improvement of water quality.
Key words: *Heavy metals, Toxicity, Phytoremediation.*

Introduction

Water, a vital resource for all living organisms. Its unique properties make it an unparalleled solvent, essential for chemical reactions and the transportation of nutrients but its quality is increasingly under threat due to human activities. Pollution from industrial discharges, agricultural discharge, and improper waste disposal has compromised the pristine state of many water bodies. Contaminants including heavy metals, pesticides, and nutrients, are altering the composition and characteristics of water, raising concern about its safety for both the environment and human consumption. Heavy metals are naturally occurring elements, but human activities, particularly industrial processes, have significantly increased their presence in the water bodies. Metals like lead (Pb), mercury (Hg), cadmium (Cd), Chromium (Cr) and others pose serious threats to both aquatic ecosystems and human health.[1]Reduction of the HM content of water is difficult therefore, only oxidation state transformation is applicable resulting in significant disruptions in aquatic life metabolism as well as ecological instability.[2]Heavy metals are characterized by their higher atomic weight or higher density and the term 'heavy metal' is used to describe metalloids or metallic elements which have toxic effects on humans and other living organisms [3]. HMs are apportioned into two categories viz. essential and in-essential. Metals (Co, Cu, Cr, Fe, Mg, Mn, Mo, Ni, Se, and Zn) have been recognized as essential elements for various physiological and biochemical activities. Other metals (Al, Sb, Ba, Cd, Au, In, Pb, Hg, Pt, Ag, Sr, Sn, Ti, V, and U) are non-essential since they have no known biological roles and are extremely lethal to living organisms [4,5].

Source of some heavy metals and its toxic forms in aquatic environment.

In freshwater ecosystem, numerous natural and anthropogenic sources contribute to the heavy metal pollution, such as direct atmospheric precipitation, geological process, and discharge of abundant human activities.Despite allowed guidelines and updated legislation, metal ions are commonly emitted as dangerous contaminants in aqueous effluents from sectors.[6,7]

Arsenic

As toxicity depends on its speciation, and generally inorganic arsenic species are more toxic than those of organic species[8]. As (III) is more toxic than As(V), and dimethylarsinic acid (DMAA) and monomethylarsonic acid (MMAA) are more toxic than their parent compounds'.Pesticides, fungicides, sedimentary rocks, geothermal water and weathered volcanic rocks, human activities such as mining, manufacturing, gold treatment and wood preservation are considered as a main sources of As contamination[9,10, 11].

Lead (Pb)

Lead is toxic to aquatic life, and its effects can range from sublethal to lethal, depending on the concentration and duration of exposure. Lead toxicity can disrupt various physiological processes in aquatic organisms[12].In aquatic environments, lead can exist in different forms, including dissolved lead ions (Pb^{2+}) and particulate lead. Dissolved lead is more readily taken up by aquatic organisms and is generally considered the more bioavailable and toxic form. The common sources of Pb contamination are Batteries and electrical, pigments and paints, alloys and solders; pesticides; glass; fertilizer; refiners; fuel; smoking, automobile exhaust, coal combustion, etc. [13,14,15].

Chromium (Cr)

Chromium can exist in several oxidation states, with hexavalent chromium (Cr(VI)) being more toxic than trivalent chromium (Cr(III)). Cr(VI) is considered highly toxic to aquatic life and humans. Cr(VI) is the more toxic form in aquatic environments. It can exist as chromate (CrO_4^{2-}) or dichromate ($Cr_2O_7^{2-}$) ions. Cr(III) is less soluble and generally less toxic but can still have adverse effects at high concentrations. Pigments, fertilizers, textile, cooling tower blowdown, electroplating and metal electroplating and coating operations are the common pollution sources of Cr contamination[16,17,18].

Cadmium (Cd)

Cadmium is highly toxic to aquatic organisms, even at low concentrations. It can accumulate in the tissues of aquatic organisms, leading to biomagnification in the food chain[19].Cadmium typically exists as dissolved cadmium ions (Cd^{2+}) in aquatic environments. Cd^{2+} is the most bioavailable form and is readily taken up by aquatic organisms. Some common Cd pollution sources are pigments and paints; fuel, Steel and plastics industry, cooling tower, metal electroplating and coating operation, nickel cadmium battery, cadmium film, solar cell, galvanized pipe, welding, fertilizer and nuclear emission device[20,21,22].

Copper (Cu)

Copper is an essential element but can be toxic to aquatic organisms at elevated concentrations. Cu toxicity is more common in freshwater environments than in marine waters.Copper in aquatic environments exists as Cu^{2+} ions, which are highly toxic to many aquatic species. Complexation with organic matter can reduce copper toxicity. Batteries and electrical; pigments and paints; alloys and solid; fuel; catalysts; fertilizers; pesticides are common factors that increases the copper level in environment[23,24].

Zinc (Zn)

Zinc is an essential micronutrient for aquatic life, but excessive levels can be toxic. Toxicity depends on the specific form of zinc, with ionic zinc (Zn^{2+}) being the most bioavailable and potentially toxic form[25,26]. In aquatic environments, zinc primarily exists as dissolved Zn^{2+} ions, which can be absorbed by aquatic organisms. Brass mapping, wood pulp production, grinding and newsprint production, iron and steel plants with zinc lines, zinc and brass metal products, refineries and pipelines are the common factors of Zn contamination[27,28].

Heavy metals toxicity on human beings

Heavy metals have harmful effects on human health. The human body is generally exposed to heavy metal ions in one of four ways that are, the ingestion of metal-contaminated food, drinking contaminated water, skin contact, and inhalation in metal-contaminated air [29]. Heavy metals may react with biological systems by losing one or more electrons and forming metal cations which have affinity to the nucleophilic sites of vital macromolecules[30.The general mechanism involved in heavy metal-induced toxicity is recognized to be the production of reactive oxygen species resulting oxidative damage and health related adverse effects on human body and resulting the health issues may include cardiovascular disorders, neuronal damage, renal injuries and risk of cancer and diabetics[31]. Heavy metals are not easily eliminated after entering the human body and tend to continuously accumulate over time. Also, once they exceed the physiological load of the human body, they will cause physiological structural changes .these changes will then lead to acute, chronic, or long-term hazardous effects[32].

Waste water treatment technologies

Currently, remediation technologies based on physical, chemical and biological approaches are widely used to remove heavy metals from contaminated water[33]. Conventional treatment methods are not always effective towards complete removal of water contaminants. Bioremediation with engineered microorganisms, electrocoagulation, chemical precipitation, chelation, membrane separation, ion-exchange resins, adsorption, coagulation, reduction, reverse osmosis, evaporation, solvent extraction, sorption by nano materials and flocculation are some methods for removing heavy metals from aqueous solutions. Each of these methods has advantages and disadvantages; however, most of them are expensive, ineffective when it comes to reducing HMs from large volumes of water, and have advantages such as non-selectivity, high energy consumption, and the use of chemical products, all of these factors need careful disposal of the harmful waste produced[35,36,37,38,39]. Therefore, the research is oriented towards low cost and eco-friendly technology to assess the long-term impact of urban pollution on environment quality which named as phytoremediation.

Phytoremediation technique is a branch of bioremediation technique that employs the application of plants for the remediation of wastewater. Aquatic plant species have the capacity to absorb excess contaminants such as organic and inorganic, heavy metals, and pharmaceutical pollutants present in agricultural, domestic and industrial wastewater[34].

Phytoremediation: A plant based eco-friendly technology

Phytoremediation techniques used in different media have been extensively discussed by several workers worldwide. Phytoremediation is a realistic and promising strategy for heavy metal removal from polluted areas (water and soil), based on the employment of hyper-accumulator plant species that are extremely tolerant to HMs present in the environment. Green plants (aquatic and terrestrial) are used to remove, decompose, or detoxify hazardous metals in this technique[40,41].

Plants used its natural properties to remediate hazardous wastes through physical, chemical, and biological processes from wastewater and sewage [42]. New metal hyperaccumulators with high efficiency are being explored and employed for their use in phytoremediation. The plants require some heavy metals in a certain limit for their growth and development but above that limit these metals becomes toxic to the plants and influence the metabolic functions. Toxicity of heavy metals causes ROS production, affecting physiological processes such as photosynthesis, respiration and cell disintegration and even death of the plants[43,44].Some plants have tolerant capacity toward heavy metals due to presence of anthocyanins, thiols and antioxidants are called hyperaccumulator. These aquatic plants can tolerate, uptake, and translocate high levels of certain heavy metals that would be toxic to most organisms. A large number of aquatic macrophytes (emerging, submerged and free floating) have been utilized widely in hydroponics or in field experiment such as constructed wetlands [45,46].The primary role of plants in phytoremediation is to supply the oxygen required by heterotrophic microorganisms in the root zone, absorb nutrients, increase, and stabilize the hydraulic conductivity of the substrate[47].Several aquatic plant species belongs to the several families Ranunculaceae, Lemnaceae, Cyperaceae, Haloragaceae, Hydrocharitaceae, Potamogetonaceae, Typhaceae, Najadaceae, Pontederiaceae, Juncaceae and Zosterophyllaceae are the main representatives for the phytoremediation of aquatic environment [48].

Utilization of aquatic macrophytes in the management of aquatic environment contamination

Aquatic macrophytes play main roles in aquatic ecosystems, including providing food for herbivores, oxygen production, and nutrient element cycling in the water[49]. Many species of aquatic plants have been verified and recognized for their efficiency to accumulate inorganic and organic contaminants from waters through hydroponic or field applications[50]. They are absorb mineral salts and chemicals either from the sediments via the root system, from the aquatic medium through their wide leaf surfaces, or from both sources[51]. Studies have shown that aquatic macrophytes can accumulate large amounts of nitrogen, phosphorus, and metals in their tissues and are potentially useful in the remediation of contaminated aquatic ecosystemsystems[52,53]. In this regard, various aquatic plant species such as Lemna, Wolfia, Azolla, Spirodela, Wolfialla, Hydrilla, Eichhornia, Typha, Pistia, Crinum, Alternanthera, Phragmites and Crysopogon have been tested to phytoremediate and hyperaccumulate metals, metalloids and other contaminants[54,55].

Aquatic plants have developed various mechanisms to absorb contaminants and heavy metals from wastewater, contributing to the process of phytoremediation. The primary pathways through which these plants uptake pollutants include:

1. **Root Uptake:**

Ion Exchange: Aquatic plants can absorb ions from the surrounding water through ion exchange processes occurring at the root surface. This is particularly relevant for heavy metals like copper, zinc, and cadmium[5,9].

Active Transport: Plants can actively transport certain ions across their root membranes using specialized transport proteins. This process allows the uptake of nutrients as well as some heavy metals[57]

2. **Filtration and Adsorption:**

Rhizofiltration: Aquatic plants, especially those with dense root systems, act as natural filters. The roots physically trap particulate matter and adsorb dissolved contaminants onto their surfaces. This is particularly effective for suspended solids and some heavy metals[58].

3. **Bioaccumulation:**

Accumulation in Tissues: Once absorbed by the roots, contaminants can be translocated within the plant to various tissues. In some cases, aquatic plants have the ability to accumulate high concentrations of certain metals in their shoots or leaves[56].

Sequestration: Some plants have the ability to sequester heavy metals in specific cellular compartments, preventing their movement to sensitive parts of the plant[26,43].

4. **Microbial Interactions:**

Rhizosphere Microorganisms: The rhizosphere, the soil or substrate directly influenced by the plant roots, harbors a diverse microbial community. Some of these microorganisms contribute to the immobilization or transformation of contaminants, aiding in their removal from the water[12,31].

5. **Chelation:**

Release of Chelating Compounds: Some aquatic plants release organic compounds called chelators or exudates into the surrounding water. These compounds can form complexes with heavy metals, increasing their solubility and facilitating their uptake by plant roots [59,4].

6. **Metabolism and Transformation:**

Phytoextraction: Certain plants can metabolize and accumulate contaminants in their tissues. This process, known as phytoextraction, involves the uptake and concentration of pollutants in the above-ground biomass, which can then be harvested for removal [3,8,10].

7. **Phytotransformation:** Some plants have the ability to transform or detoxify pollutants through metabolic processes. This may involve the conversion of toxic substances into less harmful forms[60].

It's important to note that the effectiveness of these mechanisms can vary depending on the type of contaminant, the specific plant species, and environmental conditions. Additionally, the success of phytoremediation often requires careful consideration of factors such as water chemistry, nutrient levels, and the overall health of the plant.

Advantages of phytoremediation in aquatic environments[33,34,40]:

1. **Environmental Sustainability:** Phytoremediation is an eco-friendly and sustainable method that harnesses natural plant processes to clean water.
2. **Cost-Effectiveness:** Compared to traditional remediation methods, phytoremediation is often more cost-effective.
3. **Aesthetic Improvement:** Aquatic plants enhance the visual appeal of water bodies, contributing to ecosystem aesthetics.
4. **Biodiversity Support:** Phytoremediation can create or restore habitats for aquatic organisms, fostering biodiversity.
5. **Versatility:** Different plants can be used to target specific contaminants, providing a versatile approach to water remediation.

Conclusion

Phytoremediation is a process that uses plants to remove, detoxify, or stabilize pollutants from the environment, such as soil, water, or air. This environmentally friendly approach relies on the natural ability of certain plants to absorb, accumulate, or transform contaminants, thereby reducing the concentration of pollutants in the water. Aquatic phytoremediation specifically focuses on the use of plants to remediate pollutants in water bodies.AIn summary, aquatic phytoremediation is a promising approach to address water pollution, offering both environmental and economic benefits. However, its success depends on careful consideration of plant selection, site conditions, and potential challenges associated with the specific contaminants being targeted.

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