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Phytoremediation Approaches for the Detoxification of Heavy Metals in Water

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Abstract: The swift advancement of urbanization and industrialization has led to heavy metal pollution emerging as a significant environmental concern. Drinking water contaminated with heavy metals such as Cd, Cr, Pb, Zn, and Hg presents a serious health threat to humans. Heavy metals are non-biodegradable, remaining in the environment, entering the food chain through crops, and accumulating in the human body via biomagnification. The toxicity caused by heavy metals involves mechanisms like the production of reactive oxygen species (ROS), disruption of antioxidant defenses, enzyme inactivation, and oxidative stress. Additionally, certain metals have the ability to bind with specific macromolecules. Traditional methods for addressing heavy metal pollution are not always fully effective in removing water contaminants. Phytoremediation, a relatively new technology, is increasingly acknowledged as a cost-effective, efficient, and environmentally sustainable method for extracting heavy metals from contaminated water. Aquatic plants play a crucial role in phytoremediation as they take up pollutants through their roots and, in some cases, through their leaves. Notable examples of these plants include water hyacinth, duckweed, and various submerged species such as milkweed and waterwort. These plants absorb pollutants including heavy metals, nutrients, and organic compounds, thus improving water quality. This review explores the processes through which plants absorb, transport, and detoxify heavy metals. Aquatic phytoremediation focuses on employing plants to purify pollutants in water bodies, with strategies designed to enhance plant stabilization and removal.

Keywords: heavy metals, contaminants, pollutants, phytoremediation

I. INTRODUCTION

Water is an essential natural resource for all forms of life. Its unique characteristics render it an excellent solvent, crucial for chemical reactions and the transport of nutrients; however, its quality is threatened by human activities. The growth of industries and urbanization in numerous regions worldwide has resulted in heightened contamination of surface waters, groundwater, and soil by heavy metals. The distribution of metals in the environment is influenced by various environmental factors and the inherent properties of the metals themselves [1]. Heavy metals are present in the environment and their levels are continually rising due to various human activities, including mining, effluent discharge, and agricultural practices. The increased use of synthetic pesticides can contribute to water pollution and pose risks to non-target organisms, thus impacting the environment [2]. Heavy metals constitute a category of hazardous environmental pollutants that raise significant concerns due to their toxic effects on human health when present in concentrations exceeding permissible limits [3]. Pollution stemming from industrial and agricultural runoff, along with inadequate waste management, has compromised the health of many water sources. Contaminants such as heavy metals, pesticides, and nutrients modify the composition and properties of water, raising concerns regarding its safety for both ecosystems and human consumption [4]. While heavy metals occur naturally, human activities, especially industrial operations, have significantly increased their concentrations in water sources. Metals like lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), and others pose a serious risk to aquatic ecosystems and human health [5]. Reducing heavy metal concentrations in water is a complex task, with oxidation state conversion being the only feasible method, which can disrupt the metabolism of aquatic organisms and result in ecological instability. Heavy metals, characterized by their higher atomic weight or density, include metalloids or metallic elements that have toxic effects on humans and other organisms [6]. They are divided into two categories: essential and non-essential. Essential metals such as Co, Cu, Cr, Fe, Mg, Mn, Mo, Ni, Se, and Zn are vital for various physiological and biochemical processes. Conversely, non-essential metals like Al, Sb, Ba, Cd, Au, In, Pb, Hg, Pt, Ag, Sr, Sn, Ti, V, and U are not biologically required and can be extremely toxic to living organisms [7]. Despite the presence of regulations and updated legislation, metal ions are frequently discharged as harmful pollutants in industrial wastewater.

II. HEAVY METAL SOURCES IN WATER

Cadmium (Cd)

Cadmium is extremely harmful to aquatic life, even in minimal concentrations. It can build up in their tissues, resulting in biomagnification within the food chain [8]. In aquatic settings, cadmium is usually present as dissolved cadmium ions

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(Cd^{2+}), which represent the form most readily absorbed by aquatic organisms [9]. Typical sources of cadmium pollution include pigments and paints, fuel, the steel and plastic industries, cooling towers, metal electroplating and coating, nickel-cadmium batteries, cadmium films, solar cells, galvanized pipes, welding, fertilizers, and nuclear emission equipment [10].

Lead (Pb)

Lead can have harmful effects on aquatic life, which can range from sublethal to fatal depending on the concentration and duration of exposure. It can interfere with various physiological processes in aquatic organisms and exists in forms such as dissolved lead ions (Pb^{2+}) and solid particles [11]. Dissolved lead is the form that is most easily absorbed by aquatic organisms and is typically regarded as the most bioavailable and toxic variant. Common sources of lead contamination include batteries, electrical equipment, pigments, paints, alloys, solders, pesticides, glass, manure, refiners, fuel, smoking, car exhaust, and the combustion of coal.

Chromium (Cr)

Chromium is found in multiple oxidation states, with hexavalent chromium (Cr (VI)) being significantly more dangerous than trivalent chromium (Cr (III)) [14]. Cr (VI) is extremely toxic to both aquatic organisms and humans, especially in water environments, where it appears as chromate ($CrO4^{2-}$) or dichromate ($Cr2O7^{2-}$) ions. In contrast, Cr (III) is less soluble and typically less harmful, although it can still present dangers at elevated concentrations [12]. The contamination of chromium (Cr) frequently arises from sources such as pigments, fertilizers, textiles, the dismantling of cooling towers, electroplating, and metal plating activities [13].

Arsenic (As)

Toxicity is contingent upon the specific species of arsenic, with inorganic forms typically exhibiting greater toxicity than organic varieties. As (III) is more harmful than As (V), which results in dimethylarsinic acid (DMAA) and monomethylarsonic acid (MMAA) being more toxic than their parent compounds [14]. The main sources of pollution include insecticides, fungicides, sedimentary rocks, geothermal water, and weathered volcanoes, with rocks and human activities such as mining, manufacturing, gold processing, and wood preservation being significant contributors [15].

Copper (Cu)

Copper is an essential element; however, at elevated concentrations, it can pose a threat to aquatic life. The prevalence of toxicity is greater in freshwater habitats compared to marine environments. In aquatic settings, copper exists as Cu^{2+} ions, which are extremely toxic to numerous aquatic species. The toxicity of copper can be reduced through complexation with organic matter [16]. Common contributors to increased copper levels in the environment include batteries and electrical devices, pigments and dyes, mixtures and solids, fuels, catalysts, fertilizers, and pesticides [17]. Zinc (Zn) is a crucial trace element for aquatic organisms, yet excessive levels can be harmful [20]. The toxicity of zinc varies based on its specific form, with ionic zinc (Zn^{2+}) being the most bioavailable and potentially detrimental variant. In aquatic ecosystems, zinc is mainly present as dissolved Zn^{2+} ions, which can be readily absorbed by aquatic organisms [18]. Typical sources of Zn contamination include brass mining, wood pulping, milling and newsprint production, iron and steel facilities with zinc lines, as well as zinc and brass metal products, refineries, and pipelines.

III. PHYTOREMEDIATION: A SUSTAINABLE TECHNOLOGY

Phytoremediation methods have been extensively examined by researchers across the globe. This technique presents a promising solution for the extraction of heavy metals from contaminated locations, including water and soil, by utilizing hyperaccumulating plant species that possess the ability to withstand these metals [19]. By harnessing the inherent characteristics of plants, phytoremediation employs green plants, both aquatic and terrestrial, to eliminate, decompose, or purify hazardous metals through a combination of physical, chemical, and biological mechanisms. Currently, new high-performance metal hyper batteries are being explored for their potential application in phytoremediation [20]. Although plants need heavy metals for their growth and development within specific thresholds, excessive levels can become harmful, disrupting metabolic functions and leading to the generation of reactive oxygen species (ROS), which can adversely affect physiological processes and may even cause plant mortality. Certain plants exhibit tolerance to heavy metals due to the presence of compounds such as anthocyanins and thiols; these plants, referred to as hyperaccumulators, are vital to the phytoremediation process [21]. Specific aquatic plants are capable of tolerating, absorbing, and transferring substantial amounts of certain heavy metals that would be detrimental to most organisms. Aquatic macrophytes from various families have been extensively utilized in constructed wetlands for phytoremediation applications [22]. The primary function of plants in phytoremediation is to provide oxygen to heterotrophic microorganisms in the root zone, absorb nutrients, and maintain the water conductivity of the substrate. Numerous species of aquatic plants from different families act as key representatives for the phytoremediation of aquatic ecosystems [23].

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IV. UTILIZATION OF AQUATIC MACROPHYTES IN WATER POLLUTION

Aquatic macrophytes are crucial components of aquatic ecosystems, serving multiple functions such as supplying food for herbivores, generating oxygen, and facilitating nutrient cycling in water. Numerous species of aquatic plants have been evaluated and acknowledged for their capability to eliminate inorganic and organic pollutants from water through hydroponic or field methods. They extract mineral salts and chemicals from sediments via their root systems, from the water through their broad leaf surfaces, or from both sources simultaneously [24]. Research indicates that aquatic macrophytes can accumulate significant quantities of nitrogen, phosphorus, and metals within their tissues, making them valuable for the restoration of polluted aquatic ecosystems. In this context, various species of aquatic plants, including Lemna, Wolfia, Azolla, Spirodela, Wolfialla, Hydrilla, Eichhornia, Typha, Pistia, Crinum, Alternanthera, Phragmites, and Chrysopogon, have been assessed for their phytoremediation capabilities and their ability to hyperaccumulate metals, metalloids, and other pollutants. [25]. Aquatic plants have evolved diverse mechanisms to absorb pollutants and heavy metals from wastewater, thereby aiding the phytoremediation process. The primary methods through which these plants uptake pollutants include Root Uptake, Filtration and Adsorption, Bioaccumulation, Chelation, Microbial Interactions, Phytotransformation, Metabolism, and Transformation [26].

V. CONCLUSION

Phytoremediation is the process of utilizing plants to eliminate, purify, or stabilize contaminants found in soil, water, or air. This technique depends on the inherent capacity of specific plants to absorb, accumulate, or convert pollutants, thereby reducing their concentration in water. The main objective of phytoremediation concerning water is the plant-driven purification of aquatic environments. In general, water treatment presents opportunities for mitigating water pollution, offering both ecological and financial benefits. Nevertheless, the effectiveness of this approach relies on meticulous selection of plant species, thorough site assessment, and effective management of issues associated with particular contaminants.

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