International Journal of Pharmaceutical research and Applications
Volume 11, Issue 3, May-June 2026, pp:920-924 www.ijprajournal.com ISSN: 2456-4494

Use Of Aquatic Plants for Heavy Metal and Dye Removal in Wastewater Systems

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Date of Submission: 10-05-2026 Date of Acceptance: 20-05-2026

Abstract
Industrial wastewater containing heavy metals and synthetic dyes has become a serious environmental concern due to its toxicity, persistence, and ability to accumulate in aquatic ecosystems. Conventional treatment methods are often expensive, energy-intensive, and generate secondary waste, limiting their large-scale applicability. Phytoremediation using aquatic plants has emerged as a sustainable and eco-friendly alternative for wastewater treatment. Aquatic macrophytes such as *Eichhornia crassipes*, *Pistia stratiotes*, *Lemna minor*, and *Salvinia* spp. have demonstrated significant potential in removing heavy metals and dye pollutants through mechanisms such as adsorption, rhizofiltration, phytoaccumulation, enzymatic degradation, and microbial interactions in the rhizosphere. This review critically analyses the efficiency of aquatic plants in pollutant removal, the biological and physicochemical mechanisms involved, and the environmental factors influencing performance. Recent advancements in integrated phytoremediation systems, including nanoparticle-assisted approaches and constructed wetlands, are also discussed. Finally, the challenges associated with scalability, biomass disposal, and seasonal variability are highlighted along with future research directions for sustainable wastewater treatment applications.

Keywords: Phytoremediation, Aquatic macrophytes, Heavy metals, Dye removal

I. Introduction

The rapid expansion of industrial activities has significantly increased the discharge of untreated or partially treated wastewater into natural aquatic systems. Among various pollutants, heavy metals and synthetic dyes are of particular concern due to their toxicity, persistence, and resistance to biodegradation.

Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), and nickel (Ni) are non-degradable and tend to accumulate in sediments and living organisms, leading to biomagnification in the food chain [1].

Synthetic dyes, widely used in textile, paper, leather, and cosmetic industries, contribute significantly to water pollution. It is estimated that a considerable fraction of dyes used in industrial processes is released into wastewater without adequate treatment. These compounds are often complex aromatic structures that resist microbial degradation and persist in aquatic environments, leading to reduced light penetration, oxygen depletion, and toxicity to aquatic organisms [2].

Conventional wastewater treatment techniques such as chemical coagulation, membrane filtration, activated carbon adsorption, and advanced oxidation processes are effective but associated with high operational costs, sludge generation, and energy consumption, making them less sustainable for large-scale applications [3]. As a result, biological approaches such as phytoremediation have gained increasing attention as cost-effective and environmentally friendly alternatives.

Aquatic plants (macrophytes) are particularly effective in phytoremediation due to their ability to grow in contaminated water, high biomass production, and direct interaction with pollutants. These plants not only absorb contaminants but also support microbial communities that enhance degradation processes

II. Classification of Aquatic Plants in Phytoremediation Systems

Aquatic macrophytes are generally classified into floating, submerged, and emergent plants based on their growth habit and interaction with water. Each category plays a distinct role in wastewater treatment systems. Floating plants such as *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), and *Lemna minor* (duckweed) are the most extensively studied due to their rapid growth rate and extensive root systems. These roots remain in direct contact with contaminated water, providing a large surface area for pollutant adsorption and microbial colonization.Submerged plants such as *Ceratophyllumdemersum* and *Hydrilla verticillata* contribute primarily to nutrient uptake and oxygen release into the water column. However, their efficiency in heavy metal removal is comparatively lower due to limited structural biomass and exposure conditions.

Emergent plants such as *Typha latifolia* and *Phragmites australis* are commonly used in constructed wetland systems. These plants stabilize sediments and facilitate pollutant removal through their root-zone interactions, which create favorable conditions for microbial degradation.

Table 1: Classification of Aquatic Plants and Their Phytoremediation Role

Plant Type	Example Species	Primary Function	Target Pollutants
Floating	*Eichhornia crassipes*, *Pistia stratiotes*	Adsorption, accumulation	Heavy metals, dyes
Submerged	*Hydrilla*, *Ceratophyllum*	Oxygenation, nutrient uptake	Nutrients, low metals
Emergent	*Typha*, *Phragmites*	Wetland stabilization	Metals, organics

3. Mechanisms of Heavy Metal Removal

The removal of heavy metals by aquatic plants involves multiple interconnected mechanisms. The first step is adsorption, where metal ions bind to negatively charged functional groups on root surfaces such as carboxyl, hydroxyl, and phosphate groups. This passive process is influenced by pH, ionic strength, and metal concentration.Following adsorption, metals are taken up into plant tissues through membrane transport systems in a process known as phytoaccumulation. Once inside the plant, metals are translocated via xylem vessels and distributed to shoots and leaves.

The rhizosphere also plays a crucial role in enhancing metal uptake. Root exudates modify the chemical environment, increasing metal solubility and availability, while associated microbial communities facilitate redox transformations that influence metal mobility [4].

Table 2: Mechanisms Involved in Heavy Metal Removal

Mechanism	Description	Biological Location	Role in Removal
Adsorption	Surface binding of ions	Root surface	Initial capture
Rhizofiltration	Filtration through roots	Rhizosphere	Metal immobilization
Phytoaccumulation	Uptake into tissues	Xylem transport	Internal storage
Sequestration	Detoxification	Vacuoles	Toxicity reduction

4. Mechanisms of Dye Removal in Aquatic Plant Systems

Synthetic dyes present a complex challenge in wastewater treatment due to their aromatic structures, high molecular stability, and resistance to biodegradation. Unlike heavy metals, dyes require a combination of physicochemical adsorption and biochemical transformation for effective removal. Aquatic plants remove dyes through three major pathways: surface adsorption, enzymatic degradation, and microbially mediated breakdown in the rhizosphere.

Initially, dye molecules are removed through adsorption onto plant surfaces, particularly roots. This occurs via weak interactions such as van der Waals forces, hydrogen bonding, and hydrophobic interactions. The efficiency of adsorption is strongly influenced by dye structure, charge, and solubility. Cationic dyes tend to show higher affinity for negatively charged plant root surfaces compared to anionic dyes [5].

The second mechanism involves enzymatic degradation, where plant-produced enzymes such as peroxidases, laccases, and azoreductasescatalyze the breakdown of complex dye molecules. These enzymes oxidize chromophoric groups, leading to decolorization and structural breakdown of dyes into simpler, less toxic compounds. This biochemical transformation is particularly important for azo dyes, which contain -N=N- bonds that are resistant to natural degradation processes [6].

The third and highly significant pathway is rhizosphere-assisted microbial degradation. The root zone of aquatic plants supports diverse microbial communities capable of degrading organic pollutants. These microorganisms utilize dyes as carbon or nitrogen sources, breaking them down through oxidative and reductive pathways. The synergistic interaction between plant roots and microbes significantly enhances overall dye removal efficiency [7].

Table 3: Mechanisms of Dye Removal in Aquatic Plants

Mechanism	Process Description	Key Agents	Outcome
Adsorption	Binding of dye molecules to roots	Root biomass	Initial removal
Enzymatic degradation	Oxidation/reduction reactions	Laccase, peroxidase	Dye breakdown
Microbial degradation	Biodegradation by bacteria	Rhizobacteria	Mineralization
Phytotransformation	Internal metabolic conversion	Plant enzymes	Detoxification

5. Factors Affecting Phytoremediation Efficiency

The efficiency of aquatic plant-based wastewater treatment systems is governed by several environmental, biological, and operational parameters. One of the most critical factors is pH, which influences both metal speciation and dye ionization, thereby affecting uptake and adsorption efficiency. Acidic conditions generally enhance heavy metal mobility, whereas neutral pH conditions favor optimal plant growth and metabolic activity [8].

Temperature plays a key role in regulating enzymatic activity and microbial metabolism in the rhizosphere. Higher temperatures generally increase reaction kinetics; however, excessive heat may inhibit plant growth and reduce system stability. Similarly, light intensity directly influences photosynthetic efficiency, which in turn affects biomass production and pollutant uptake capacity.

The initial concentration of pollutants is another important factor. At low concentrations, plants can efficiently uptake contaminants, but at higher concentrations, toxicity effects may inhibit growth and reduce remediation efficiency. Additionally, hydraulic retention time (HRT) determines the contact duration between pollutants and plants; longer HRT generally improves removal efficiency but reduces system throughput [9].

The presence of symbiotic microbial communities significantly enhances phytoremediation performance. These microbes assist in pollutant degradation, nutrient cycling, and root growth promotion, creating a synergistic system that improves overall efficiency.

6. Constructed Wetlands and Engineered Phytoremediation Systems

Constructed wetlands are engineered systems that mimic natural wetland processes to treat wastewater using aquatic plants, soil, and microbial interactions. These systems are widely recognized as one of the most effective large-scale applications of phytoremediation.

Constructed wetlands are generally classified into surface flow wetlands and subsurface flow wetlands. Surface flow systems allow water to flow above the substrate, while subsurface systems involve water flowing through a porous medium such as gravel or sand. Subsurface systems are more efficient in pollutant removal due to increased contact between wastewater and root zones.

Aquatic plants such as *Typha latifolia*, *Phragmites australis*, and *Eichhornia crassipes* are commonly used in these systems due to their high tolerance to pollutants and ability to support microbial communities.

Constructed wetlands provide multiple treatment processes simultaneously, including sedimentation, filtration, adsorption, plant uptake, and microbial degradation. They are particularly effective for treating municipal wastewater, agricultural runoff, and industrial effluents with moderate pollutant loads [10].

Table 4: Comparison of Wetland Types in Wastewater Treatment

System Type	Flow Pattern	Efficiency	Advantages	Limitations
Surface flow wetlands	Above substrate	Moderate	Low cost, simple design	Evaporation losses
Subsurface flow wetlands	Through media	High	Better control, higher efficiency	Higher setup cost

7. Recent Advances in Aquatic Plant-Based Remediation

Recent developments in phytoremediation have focused on enhancing efficiency through integration with advanced technologies. One emerging approach is nanoparticle-assisted phytoremediation, where nanoparticles such as ZnO, TiO_2, and Fe_3O_4 are used to enhance adsorption and catalytic degradation of pollutants. These nanoparticles increase reactive surface area and improve redox reactions, leading to higher pollutant removal efficiency [11].

Another important advancement is the development of plant–microbe synergistic systems, where genetically or naturally selected microbial strains are introduced into the rhizosphere to enhance biodegradation capabilities. These systems significantly improve dye degradation rates and heavy metal stabilization.

Additionally, genetic engineering of aquatic plants is being explored to enhance metal transporter proteins, antioxidant systems, and stress tolerance mechanisms. Such modifications can significantly increase pollutant uptake capacity and survival in highly contaminated environments.

8. Limitations of Phytoremediation Systems

Despite their advantages, aquatic plant-based systems face several limitations. The most significant constraint is slow treatment rate, which makes them less suitable for high-volume industrial effluents without pre-treatment. Seasonal variations in temperature and light can also affect plant growth and system stability.

Another major challenge is the disposal of contaminated biomass, as harvested plants contain accumulated heavy metals and toxic compounds. Improper disposal can lead to secondary environmental contamination. Additionally, extreme pollutant concentrations may lead to phytotoxic effects, inhibiting plant growth and reducing treatment efficiency.

9. Future Perspectives

Future research in phytoremediation should focus on improving scalability, efficiency, and economic viability. Integration of phytoremediation with advanced oxidation processes, microbial fuel cells, and nanotechnology can significantly enhance system performance.

Development of circular economy models, where harvested plant biomass is converted into bioenergy, biofertilizers, or bioplastics, can improve sustainability and economic feasibility. Furthermore, life cycle assessment studies are needed to evaluate long-term environmental impacts and optimize system design for industrial applications.

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