

## A Review of Phytoremediation and Factors Affecting its Efficiency

<sup>1</sup>Ibrahim Bilqees Onize, <sup>2</sup>Alege Gbenga Olorunshola, <sup>1</sup>Adang Kombe Lucas and <sup>1</sup>Olaomi Adeyemi Afeez

<sup>1</sup>Department of Biology, Federal University Lokoja, Kogi State, Nigeria.

<sup>2</sup>Department of Biotechnology, Federal University Lokoja, Kogi State, Nigeria.

\*Corresponding authors' email: [bilqees.ibrahim@fulokoja.edu.ng](mailto:bilqees.ibrahim@fulokoja.edu.ng)

### ABSTRACT

Due to the environmental and economic advantages, phytoremediation using aquatic macrophytes to reduce heavy metal contamination in aquatic and semiaquatic environments is becoming more widely accepted. In this review, we explore the use of aquatic macrophytes in heavy metal remediation, including the environmental and management factors affecting remediation efficiency, including plant species, metal characteristics, pH, nutrient status, temperature, initial metal concentration, microbial activity, metal speciation, and amendments, and the relative roles of metal uptake, immobilization, translocation, and accumulation in plant tissues. Optimal conditions for metal uptake, immobilization, translocation, and accumulation in plant tissues usually occur under slightly acidic to near-neutral conditions, although the optimal conditions vary for different plant species and target metals. The review compares laboratory and field-based approaches to macrophyte bioremediation. The review also compares laboratory and field-based approaches to macrophyte bioremediation, which provide controlled conditions for evaluating uptake mechanisms, kinetics, tolerance limits, and optimal treatment conditions, and more realistic information on long-term performance under complex environmental conditions, respectively, and it emphasizes that successful application of macrophyte-based phytoremediation requires integration of laboratory findings with pilot- and field-scale validation to improve remediation efficiency, sustainability, and practical application of aquatic macrophyte-based treatment systems.

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### INTRODUCTION

Heavy metal pollution has become a worldwide problem in aquatic ecosystems; toxic elements such as cadmium (Cd), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) are introduced into rivers, lakes, reservoirs, and wetlands by industrial effluents, mining, agricultural runoff, and urban wastewater (Ali *et al.*, 2020). Heavy metals are non-biodegradable, highly persistent, easily bioaccumulated in aquatic biota, and cause serious risks to drinking-water quality, fisheries, and public health (HamaAzizet *et al.*, 2023). Traditional treatment techniques, such as chemical precipitation, ion-exchange, and membrane filtration, are usually energy-intensive, expensive, and produce secondary sludge; therefore, research efforts have focused on developing more environmentally friendly "green" techniques, such as using aquatic macrophytes for phytoremediation (Chandanshive *et al.*, 2020; Choudhary *et al.*, 2022). Environmental and management factors, such as pH, nutrient status, temperature, initial metal concentration, and the use of soil or water amendments, play a significant role in the efficiency of heavy metal phytoremediation in aquatic and semiaquatic systems (Grzegórska *et al.*, 2020; Ali *et al.*, 2020; Sabreena *et al.*, 2022), and these factors interact with plant species traits, microbial activity, and metal speciation to determine whether metals are removed from the water column, immobilized in the rhizosphere, or translocated and accumulated in plant tissues (Motrescu *et al.*, 2026).

### Optimal pH Range for Heavy Metal Phytoextraction in Different Plants

The optimal pH range for heavy metal phytoextraction also varies by plant species and metal type. However, in most non-

hyperaccumulator and aquatic-adapted plants, it ranges from slightly acidic to near-neutral conditions (around pH 5.0–7.0), which is optimal for metal solubility and plant growth (Reeves *et al.*, 2018; Ali *et al.*, 2020; Zunaiddiet *et al.*, 2023), with low pH increasing cationic metal solubility and bioavailability for root uptake, and pH values above about 6.5–7.5 typically precipitating or adsorbing metals, reducing their availability for phytoextraction (Golia *et al.*, 2023; Wang *et al.*, 2023).

### General pH Trends for Phytoextraction

Studies in terrestrial and semiaquatic systems indicate that pH values of approximately 4.5–6.0 typically favor higher metal uptake across a range of metals, as metal ions are more soluble and less bound to soil or sediment phases (Adamczyk-Szabela *et al.*, 2022; Zhao *et al.*, 2024). Experiments with *Helianthus tuberosus* cultivated in soils from mining sites showed the highest phytoextraction efficiency for Fe, Mn, Zn, Cd, and Ni at pH values between 4.0 and 6.0, with the greatest metal concentrations in roots and shoots occurring at slightly acidic conditions (Grzegórska *et al.*, 2020; Daniel *et al.*, 2023). Experiments with the Cd-accumulating plant *Sedum alfredii* similarly found that pH 5.5 was optimal for both plant growth and Cd uptake, with uptake declining rapidly as pH approached neutrality (Hou *et al.*, 2018; Hu *et al.*, 2023; Li *et al.*, 2025). On the other hand, for many of the aquatics or wetland macrophytes that are employed in constructed wetlands and phytofiltration, the optimal pH for phytoextraction is often slightly higher, at around pH 6.0–7.0, because these plants are adapted to more stable, well-buffered, near-neutral waters; at this pH, cationic metals like Zn<sup>2+</sup> and Cu<sup>2+</sup> are sufficiently soluble for uptake, but

micronutrient availability and photosynthetic performance are also optimal, allowing for high biomass production that is essential for efficient phytoextraction (Meihua *et al.*, 2022; Hausaet *et al.*, 2026).

### Species-specific Optimal pH Ranges

The ideal pH range is not the same for all plants and there are reports of species-specific "windows" for metal uptake: for example, for *Helianthus tuberosus* (Jerusalem artichoke) used for the phytoextraction of Fe, Mn, Zn, Cd, and Ni, the pH 4.0–6.0 range gave the highest metal accumulation in roots and shoots, with maximum yields of Fe, Mn, and Zn at approximately pH 5.0–5.5 (Grzegórskaet *et al.*, 2020; Daniel *et al.*, 2023). For the Cd-hyperaccumulating species *Sedum alfredii*, maximum Cd uptake and biomass production was at pH 5.5, with uptake decreasing at both lower and higher pH (Hou *et al.*, 2018; Hu *et al.*, 2023). For example, in studies of common herbs and medicinal plants (such as basil, dandelion, and lemon balm) grown in soil, Mn, Cu, and Zn uptake by roots increased as pH decreased from 8.5 to about 4.7, but photosynthetic efficiency and overall plant growth were greatest at pH 6.0, indicating that the optimal pH for both metal uptake and plant performance occurs around slightly acidic conditions (Adamczyk-Szabelaet *et al.*, 2022; AL-Huqail et *al.*, 2023; Adamczyk-Szabelaet *et al.*, 2024; Ben *et al.*, 2025). Most mesocosm and constructed-wetland studies suggest that pH 6.0–7.0 is optimal for growth and phytoextraction of Cd, Pb, Zn, and Cu by aquatic macrophytes such as *Eichhornia crassipes*, *Pistia stratiotes*, *Lemna minor*, and *Typha latifolia*. More acidic conditions (below pH 5.5) can increase metal toxicity and decrease biomass, and more alkaline conditions (above pH 7.5) significantly decrease metal bioavailability (Justin *et al.*, 2022; Abdullahi *et al.*, 2024; Rodrigues *et al.*, 2026).

### Acidic Versus Neutral–Alkaline Conditions

Metal toxicity, along with aluminum ( $Al^{3+}$ ) and  $H^+$  toxicity, can cause stress to plants, inhibiting root elongation and nutrient uptake, thereby limiting the phytoextraction capacity of plants at pH < 5.0 (Rahman *et al.*, 2018; Ofocet *et al.*, 2023). However, at pH > 7.5, Zn, Cu, and Pb are frequently found in insoluble hydroxides, carbonates, or strongly adsorbed to Fe/Mn oxides and organic matter, lowering their solution-phase concentration and their availability for root uptake (Aguirre Gómez *et al.*, 2023; Chen *et al.*, 2024). Therefore, from a practical phytoremediation perspective, researchers recommend adjusting pH to the target species and metal pair, but in general slightly acidic conditions (pH 5.0–6.5) are optimal for maximizing metal uptake, while near-neutral pH (6.5–7.0) often provides the best compromise between uptake and plant health, especially in aquatic and constructed-wetland systems (Yan *et al.*, 2020; Sharma *et al.*, 2023; Di Stasio *et al.*, 2025). In field applications, pH is commonly adjusted such as liming or organic amendments to move contaminated media into these optimal ranges prior to and during phytoextraction treatments.

### Studies on Macrophyte Bioremediation

Both field and laboratory studies can be used to investigate the potential of macrophytes to remove or stabilize heavy metals and organic pollutants, but there are important differences between these approaches in control, scalability, and real-world applicability (Carolina *et al.*, 2023; Olubukola *et al.*, 2025; Khan *et al.*, 2025; Rodrigues *et al.*, 2026). Laboratory experiments provide highly controlled conditions in which metal uptake kinetics, species-specific responses, and the impact of individual factors like pH, metal

concentration, and nutrient status can be precisely quantified, while field studies reflect the complexity of natural or engineered ecosystems with their hydrological variability, microbial communities, and interactions among multiple contaminants and biological components. (Peterson *et al.*, 2019; Lorena *et al.*, 2022; Li *et al.*, 2025; Hamid *et al.*, 2026).

### Controlled Conditions in Laboratory Studies

In lab-based macrophyte bioremediation studies, heavy metals or organic pollutants are usually added to artificial aqueous media or sterilized sediments at known concentrations, and experiments are conducted under controlled temperature, light, and pH in mesocosms, hydroponic systems, or batch reactors (Salam *et al.*, 2024; Khan *et al.*, 2025; Aljabriet *et al.*, 2025). These conditions allow researchers to determine uptake kinetics (initial adsorption rates, equilibrium times, and bioconcentration factors) for metals such as Cd, Pb, Zn, Cu, and Ni in species such as *Eichhornia crassipes*, *Pistia stratiotes*, *Lemna minor*, and *Ceratophyllum demersum* (Aguirre Gómez *et al.*, 2023; Chen *et al.*, 2024). This involves the isolation of the effects of a single environmental variable, such as pH, salinity, or nutrient amendments, from confounding effects of weather, flow dynamics, or competing biota (Yin *et al.*, 2025; Akkachaet *et al.*, 2025). Set species-specific tolerance limits and hyperaccumulation thresholds, including critical toxicity concentrations that cause growth inhibition, chlorosis, or lowered biomass (Bhat *et al.*, 2025; Hernández *et al.*, 2026). Given this level of control, laboratory studies are well suited for screening candidate macrophytes, comparing strains or genotypes, and optimizing parameters such as contact time, hydraulic loading, and amendment dosage prior to scaling to field systems (Govindwaret *et al.*, 2020; Kumar *et al.*, 2022).

### Ecological Complexity in Field Studies

Field trials on macrophyte bioremediation typically use natural wetlands, lakes, rivers, or constructed wetlands in which macrophytes are grown under ambient hydrological and climatic conditions (Rai *et al.*, 2018; Pavlikovaet *et al.*, 2025), which give data about long-term metal retention and ecosystem-scale removal efficiency, including the impact of seasonal flow variation, rainfall, and sediment resuspension on metal redistribution and plant performance (Chu *et al.*, 2021; Ghosh *et al.*, 2026). Interactions between macrophytes, microbial communities, and other biota (e.g., plankton, benthic fauna, and riparian vegetation) that can affect nutrient cycling, metal speciation, and overall remediation outcomes (Munyai *et al.*, 2023; Różańska-Boczulaet *et al.*, 2025; Isaac *et al.*, 2026). The sustainability and economic feasibility of macrophyte-based systems is also heavily dependent on practical considerations such as plant establishment, competition, herbivory, and harvesting logistics, which are challenging to replicate in the laboratory (Khan *et al.*, 2024; Liu *et al.*, 2025; Donald *et al.*, 2025). For instance, field trials of constructed wetlands with *Typha latifolia*, *Phragmites australis*, and *Cyperus papyrus* have shown significant reductions in Cd, Pb, Zn, and As loads over several seasons, but also indicate that metal partitioning between water, sediment, and plant biomass varies with hydrology and vegetation density (Hamad *et al.*, 2020; Alao *et al.*, 2022; Zinicovscaiaet *et al.*, 2025).

### Differences in Metal Removal Patterns

Laboratory experiments typically report higher apparent percent removals per unit plant biomass because contaminant levels are initially high, particle settling is reduced, and metal–plant interactions are not diluted by large volumes of

water or heterogeneous sediments (Wang *et al.* 2024; Asim *et al.* 2024; Hussein *et al.*, 2025; Solomon *et al.*, 2026). On the other hand, field studies often show lower percentage removals but higher absolute mass removal because of larger system volumes, greater biomass, and longer exposure times (Robinson *et al.* 2025; Poonia *et al.* 2025; Tenza *et al.* 2025). In addition, natural redox gradients, organic-matter content, and microbial activity in the field are important factors for metal speciation and immobilization in sediments or re-mobilization during anoxic events (Wang *et al.*, 2022; Pratibha *et al.*, 2025; Jones *et al.*, 2025), processes that are rarely duplicated in short-term lab experiments, which may overestimate bioavailability and plant uptake for some metals and overestimate the risk of metal transfer to higher trophic levels, whereas field data may better reflect the long-term stability and ecological safety of macrophyte-mediated bioremediation (Acharya *et al.*, 2023; Mohamed *et al.*, 2025; Rodrigues *et al.*, 2026).

### Bridging Lab and Field for Practical Implementation

Recent reviews stress that successful macrophyte bioremediation entails a systematic scaling from laboratory screening to pilot- and field-scale validation (Narendra *et al.*, 2024; Curiel-Alegre *et al.*, 2025; Ostovaret *et al.*, 2025; Motrescu *et al.*, 2026). While laboratory studies provide the mechanistic underpinning of optimal pH ranges, metal tolerance thresholds, and uptake mechanisms, field trials test the robustness of these findings under real-world variability and inform the design of engineered systems such as floating treatment wetlands, subsurface-flow constructed wetlands, and in situ macrophyte-planting schemes (Kumar *et al.*, 2022; Sharma *et al.*, 2023; Zhao *et al.*, 2024; Lina *et al.*, 2025; Mohammed *et al.*, 2025). However, in practice, researchers are more inclined to use a hybrid research strategy, which combines lab-derived kinetic models and species-specific parameters that are calibrated with field monitoring data, along with management practices, such as harvesting frequency, planting density, and substrate amendments, which are optimized based on both controlled and field-based observations (Getahun *et al.*, 2024; Raizza *et al.*, 2024; Junyeet *et al.*, 2025), which makes the macrophyte bioremediation models more predictive and increases the probability that macrophytes that have been proven to be effective in the laboratory will also perform well in the field.

### CONCLUSION

Phytoremediation using aquatic macrophytes is a promising alternative, environmentally friendly method for removing heavy metals from aquatic systems. The efficacy of metal uptake is highly dependent on pH, plant species, metal characteristics, nutrient status, and other environmental conditions, with slightly acidic to near-neutral conditions generally providing a suitable balance between metal bioavailability and plant growth, although optimal pH varies among species and metals. Laboratory studies are useful to elucidate uptake mechanisms. Laboratory studies can identify tolerance limits, and optimal treatment conditions, while field studies can provide a more realistic assessment of long-term effectiveness under complex environmental conditions. Thus, macrophyte bioremediation will need to integrate controlled laboratory research with pilot- and field-scale validation for successful application, and the management of plant density, harvesting, pH, and other environmental factors will be critical to improving remediation efficiency and the sustainability and practical application of macrophyte-based treatment systems.

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