



Zone-Specific Phytoremediation Strategies for the Restoration of Contaminated Freshwater Lake Ecosystems

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Abstract

Freshwater lakes worldwide face severe contamination from industrial effluents, domestic sewage, agricultural runoff, and urban stormwater, resulting in eutrophication, heavy metal accumulation, hypoxia, and rapid biodiversity loss. Conventional remediation techniques, including dredging and chemical treatments, remain costly, ecologically disruptive, and often unsustainable over the long term. Phytoremediation using aquatic macrophytes offers a promising, low-cost, and nature-based alternative. However, most existing strategies overlook the inherent ecological heterogeneity of lakes by treating them as uniform systems. This review proposes a novel zone-specific phytoremediation framework grounded in the classical ecological zonation of freshwater lakes—littoral, limnetic, profundal, and benthic. Each zone presents distinct physicochemical conditions, contaminant profiles, light availability, oxygen levels, and sediment interactions, necessitating tailored plant interventions. Emergent macrophytes such as *Typha latifolia* and *Phragmites australis* excel in the littoral zone for sediment stabilisation and phytoextraction of metals. Floating species including *Eichhornia crassipes* and *Lemna minor* effectively remove dissolved nutrients and metals in the limnetic zone. Submerged macrophytes like *Hydrilla verticillata* and *Vallisneria spiralis* enhance oxygenation and reduce internal nutrient loading in deeper waters, while rhizosphere-enhanced phytostabilisation targets benthic sediments. Drawing on recent global studies and morphological adaptations of hydrophytes, the framework integrates plant functional traits with lake-specific hydrology and biogeochemistry. It improves contaminant removal efficiency, restores dissolved oxygen balance, minimises secondary pollution risks, and supports biodiversity recovery. Post-harvest management of metal-laden biomass through controlled incineration, phytomining, or secure landfill disposal ensures permanent contaminant removal without re-entry into food chains. This approach is particularly suitable for rapidly urbanising regions in developing countries, including India, where cost-effective and scalable solutions are urgently needed. By aligning remediation with natural ecological gradients, zone-specific phytoremediation represents a resilient, sustainable pathway toward restoring degraded lake ecosystems.

Keywords: Zone-Specific Phytoremediation; Freshwater Lake Restoration; Aquatic Macrophytes; Heavy Metal Remediation; Eutrophication Control; Littoral Zone Management; Rhizofiltration

Introduction

Freshwater lakes serve as critical reservoirs of biodiversity, drinking water, fisheries, and recreational resources, yet they are increasingly stressed by anthropogenic pollution. Industrial discharges, untreated sewage, agricultural fertiliser runoff, and urban stormwater introduce excessive nutrients (nitrogen and phosphorus), heavy metals (Cd, Pb, Cr, Hg, As), organic pollutants, and emerging contaminants. These inputs trigger eutrophication, harmful algal blooms, hypoxia, sediment toxicity, and cascading biodiversity decline (Pereira and Mulligan, 2023).

In India and other developing nations, lakes near urban-industrial hubs—such as those in Telangana and surrounding states—exhibit particularly alarming degradation. Human health risks arise through direct water consumption, irrigation, recreational exposure, and consumption of contaminated fish and livestock products. Chronic lead exposure impairs neurodevelopment and causes hypertension; cadmium leads to renal damage and bone fragility; methylmercury induces severe neurological disorders; and hexavalent chromium is carcinogenic

(WHO, 2022 updates). Aquatic organisms suffer gill damage, oxidative stress, reproductive failure, and biomagnification of toxins up the food chain (Ansari et al., 2020).

Traditional engineering solutions—dredging, chemical precipitation, and mechanical aeration—incur high costs, disturb sediments, and often fail to address internal nutrient cycling. Phytoremediation, the use of plants and associated rhizosphere microbes to extract, stabilise, or degrade contaminants, emerges as an eco-friendly, solar-powered alternative (Salt et al., 1998; Ali et al., 2013). Aquatic macrophytes are especially effective because they cycle rapidly through planting and harvesting cycles without entering human or livestock food chains when properly managed.

Despite its promise, most phytoremediation projects deploy uniform plant species across entire water bodies, ignoring lake zonation. Freshwater lakes comprise distinct ecological zones with unique depth, light, oxygen, and contaminant gradients. Treating lakes as homogeneous systems limits efficiency and risks incomplete remediation or secondary pollution from decaying biomass. This review synthesises current knowledge on macrophyte physiology, lake ecology, and recent field studies to propose a scientifically optimised, zone-specific phytoremediation framework. It expands upon earlier concepts by incorporating post-2020 research on littoral restoration, submerged plant oxygenation effects, and integrated microbial–plant interactions, offering a practical roadmap for sustainable lake restoration.

Aquatic Macrophytes Used in Phytoremediation

Metal Uptake and Accumulation Potential

Aquatic hydrophytes demonstrate remarkable capacity to accumulate heavy metals and nutrients, with uptake varying by species, tissue type, and environmental conditions. Table 1 updates and expands earlier compilations with recent data (2020–2025), highlighting concentration ranges in mg kg⁻¹ dry weight.

Table 1. Metal uptake by selected hydrophytes (updated with recent studies)

Plant	Metals	Concentration range (mg kg ⁻¹ DW)	Key Reference(s)
<i>Eichhornia crassipes</i>	Cd, Pb, Cr, Hg, Cu, Zn	Cd: 100–450; Pb: 500–5000; Cr: 200–1500	Mishra and Tripathi (2008); Rezanian et al. (2015); Huynh et al. (2021); Yang (2025)
<i>Pistia stratiotes</i>	Cd, Pb, Cr, Ni	Cd: 80–350; Cr: 150–1200	Rai (2008); Singh et al. (2007)
<i>Lemna minor</i>	Cd, Pb, Ni, Zn	Cd: 50–300; Zn: 300–2000	Zayed et al. (1998); Ceschin et al. (2020)
<i>Ceratophyllum demersum</i>	Cd, Pb, Cr, Cu	Cd: 200–650	Aravind and Prasad (2005); Liu et al. (2018)
<i>Hydrilla verticillata</i>	Cd, Pb, Cr, Zn	Cd: 150–600; Zn: 400–2500	Rai (2008); Ahila et al. (2021)
<i>Typha latifolia</i>	Cd, Pb, Cr, Zn	Cd: 50–300; Zn: 1000–3500	Ye et al. (1997); Bonanno and Giudice (2010); Hejna et al. (2020)
<i>Phragmites australis</i>	Cd, Pb, Zn, Cr	Zn: 1000–4000	Vymazal (2011); Bonanno and Giudice (2010)

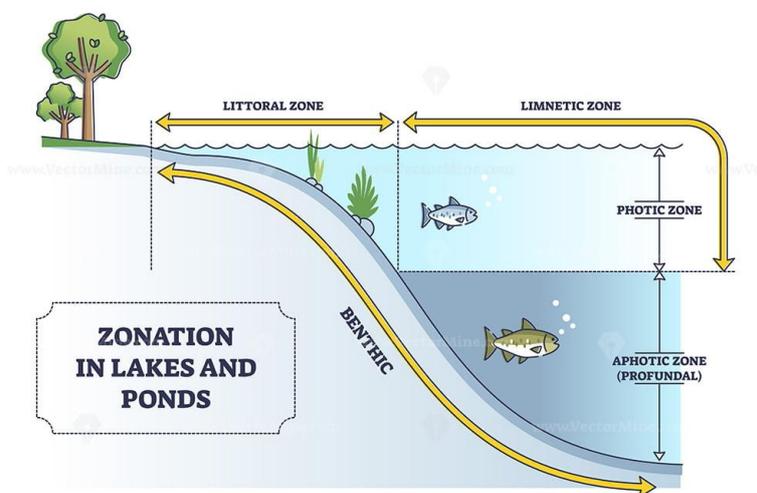


Figure 1. Zonation in lakes and ponds showing littoral, limnetic, photic, benthic, and profundal (aphotic) zones with representative vegetation and organisms.

Roots generally accumulate higher concentrations than shoots due to cell-wall binding and vacuolar sequestration, reducing translocation and enhancing tolerance. Recent studies confirm that *Eichhornia crassipes* can achieve 80–90% removal of nutrients and metals within weeks under optimal conditions (Yang, 2025).

Morphological and Anatomical Adaptations

Hydrophytes possess specialised features that underpin their remediation efficacy. Extensive aerenchyma enables oxygen transport to roots, creating oxidised microzones that promote metal precipitation and microbial degradation. Thin cuticles and high surface-to-volume ratios in submerged species facilitate direct foliar absorption. Fibrous root systems in floating plants maximise rhizofiltration surface area, while rhizomes in emergent species anchor and stabilise sediments (Reddy and DeLaune, 2008; Maranho et al., 2024). Rapid vegetative propagation supports repeated harvesting cycles, maximising biomass removal of contaminants.

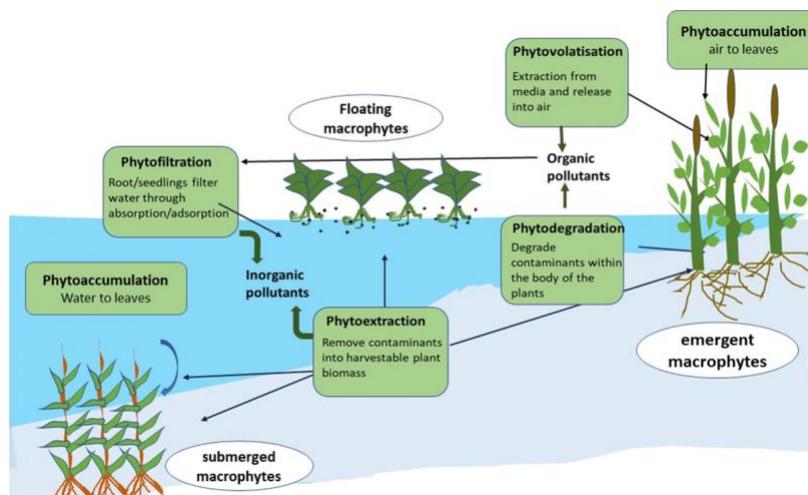


Figure 2. Mechanisms of pollutant removal by different macrophyte types (floating, submerged, emergent) in aquatic systems

Table 2 Morphology, adaptations, and phytoremediation roles of major hydrophytes (expanded)

Plant Type	Example Species	Key Morphological Features	Adaptive Significance	Phytoremediation Role
Free-floating	<i>Eichhornia crassipes</i> , <i>Pistia stratiotes</i> , <i>Lemna minor</i>	Spongy petioles, feathery roots, rapid clonal growth	Buoyancy, high root surface area	Nutrient and metal uptake from water column; easy mechanical harvesting
Submerged	<i>Hydrilla verticillata</i> , <i>Ceratophyllum demersum</i>	Finely dissected leaves, thin cuticle	Direct absorption across entire surface	Dissolved metal and nutrient removal; oxygenation of water column
Rooted floating- leaved	<i>Nelumbo nucifera</i> , <i>Nymphaea</i> spp.	Long petioles, waxy leaves, robust rhizomes	Sediment anchoring	Sediment stabilisation and dual water–sediment metal removal
Emergent	<i>Typha latifolia</i> , <i>Phragmites australis</i>	Aerial stems, extensive rhizomes, aerenchyma	Oxygen transport to roots	Rhizofiltration, sediment stabilisation, microbial stimulation in constructed wetlands

Global Implementation and Lessons Learned

Countries across continents have successfully deployed aquatic macrophytes (Table 3 updated). Recent African and Asian studies emphasise native species to avoid invasiveness risks (Kola et al., 2025). In India, integrated wetland systems using *Typha* and *Eichhornia* treat textile and tannery effluents with >70% metal removal (Ahila et al., 2021). China's large-scale lake restoration programmes combine *Hydrilla* with floating species for eutrophic systems (Pereira and Mulligan, 2023).

Post-harvest management remains critical: harvested biomass undergoes drying, controlled incineration (500–800°C), and either phytomining for valuable metals or secure landfill disposal/vitrification to prevent re-release (McGrath and Zhao, 2003; Chaney et al., 2007). Composting is avoided to eliminate biomagnification risks.

Ecological Zonation of Freshwater Lakes

Freshwater lakes exhibit four primary zones, each with distinct conditions supporting specific macrophyte communities and contaminant dynamics.

Littoral Zone (0–2 m depth): High light, rooted vegetation, sediment–water interface. Dominant pollutants: sediment-bound metals and nutrients. Processes: phytoextraction, stabilisation (Fujibayashi et al., 2020). Suitable plants: *Typha latifolia*, *Phragmites australis*, *Vetiveria zizanioides*.

Limnetic Zone (open surface to light penetration depth): Dissolved nutrients, algal blooms. Plants: floating and submerged species. Direct uptake and competition reduce eutrophication (Reddy and DeBusk, 1984).

Profundal Zone (below light penetration): Low oxygen, sediment deposition. No rooted plants, but detritus influences redox and metal speciation. Submerged species introductions or aeration can mitigate internal loading (Carpenter and Lodge, 1986).

Benthic Zone (sediment layer): Root–sediment interactions. Mechanisms: phytostabilisation, rhizosphere oxidation, microbial precipitation of insoluble sulphides and hydroxides (Gadd, 2010).

Table 3 Selected countries using aquatic macrophytes for phytoremediation (updated 2020–2025)

Country	Primary Species	Main Applications	Recent Reference
India	<i>Eichhornia</i> , <i>Typha</i> , <i>Pistia</i>	Industrial effluents, lake restoration	Ahila et al. (2021)
China	<i>Eichhornia</i> , <i>Hydrilla</i>	Eutrophic lakes, mining wastewater	Yang (2025)
USA/Canada	<i>Typha</i> , <i>Phragmites</i> , <i>Lemna</i>	Constructed wetlands, mine drainage	Vymazal (2011) updated applications
Brazil	<i>Eichhornia</i> , <i>Salvinia</i>	Agricultural runoff	Recent FTW studies
Europe (Germany, Netherlands)	<i>Phragmites</i> , <i>Typha</i>	Municipal wastewater polishing	Maranho et al. (2024)
South Africa/Australia	<i>Phragmites</i> , <i>Typha</i>	Acid mine drainage	Kola et al. (2025)

This zonation necessitates targeted interventions rather than blanket planting.

Zone-Specific Phytoremediation Approaches

Littoral Zone: Emergent Macrophyte Phytoextraction and Stabilisation

Plant *Typha*, *Phragmites*, and *Vetiver* to stabilise shores, reduce erosion, and immobilise metals via root plaques. Efficiencies reach 40–90% for nutrients and high metal sequestration in roots (Vymazal, 2011; Fujibayashi et al., 2020).

Limnetic Zone: Floating and Submerged Macrophyte Nutrient Stripping

Deploy *Eichhornia crassipes*, *Lemna minor*, *Pistia stratiotes*, and *Hydrilla* for rapid N/P uptake (up to 80%) and metal bioaccumulation. Controlled harvesting prevents mat formation and oxygen depletion (Rezania et al., 2015; Pereira and Mulligan, 2023).

Profundal and Benthic Zones: Oxygenation and Rhizosphere-Enhanced Immobilisation

Introduce tolerant submerged species or use sediment capping combined with deep-rooted emergents. Root oxygen release oxidises sediments, precipitating metals and suppressing anaerobic P release (Sand-Jensen et al., 1982; Liu et al., 2018). Microbial augmentation further enhances transformation.

Mechanisms of Pollutant Uptake

Mechanisms include: (i) rhizofiltration/adsorption on root surfaces; (ii) active transport via membrane proteins; (iii) intracellular chelation by phytochelatins; (iv) vacuolar sequestration; and (v) rhizosphere microbial transformations (Cobbett and Goldsbrough, 2002; Ali et al., 2013; Maranho et al., 2024). Submerged species additionally utilise foliar uptake. These processes operate differently across zones, explaining the superiority of the zoned approach.

Application, Advantages and Comparative Analysis

Zone-specific deployment optimises each plant's traits to zone conditions, yielding higher overall efficiency, better oxygen balance, stronger biodiversity support, and lower secondary pollution risk compared with single-species strategies (see expanded comparative table below).

Comparative Analysis

Parameter	Uniform Single-Species Approach	Zone-Specific Multi-Plant Strategy
Ecological fit	Limited to one zone's conditions	Matched to depth, light, redox gradients
Metal & nutrient removal	Moderate (surface-focused)	High (water column + sediment)
Sediment stabilisation	Weak	Strong (littoral emergents)
Oxygen dynamics	Risk of depletion	Balanced via submerged + emergent species
Biodiversity	Low (monoculture)	High (habitat heterogeneity)
Long-term resilience	Moderate	Superior (mimics natural gradients)

Recent meta-analyses confirm macrophytes improve lake water quality across latitudes when properly sited (Song et al., 2019). Limitations include potential invasiveness (*Eichhornia* in tropical climates) and seasonal die-back; these

are mitigated by native species selection and scheduled harvesting. Integration with constructed wetlands at inflows enhances performance (Kola et al., 2025).

Expected Outcomes

Implementation is projected to reduce water-column metals by 60–90%, nutrients by 70–85%, increase dissolved oxygen, decrease algal blooms, stabilise sediments, and restore native biodiversity within 2–3 years. Periodic harvesting ensures permanent contaminant export. Monitoring protocols using bioindicators and water-quality indices will verify success.

Discussion

The zone-specific framework addresses key shortcomings of traditional phytoremediation by respecting ecological complexity. Recent studies on littoral macrophyte restoration (Fujibayashi et al., 2020) and shallow-lake practices (Pereira and Mulligan, 2023) validate the approach. Challenges remain—species selection must consider local climate, invasiveness risk, and metal speciation—but advances in microbial consortia and native germplasm screening offer solutions. In rapidly urbanising regions like India, this low-cost strategy aligns with national missions for lake rejuvenation and circular economy principles. Future research should quantify long-term carbon sequestration, economic valuation via phytomining, and climate-change resilience.

Conclusion

Uniform single-species phytoremediation provides partial benefits but cannot fully restore heterogeneous lake ecosystems. The proposed zone-specific multi-plant strategy—deploying emergent, floating, submerged, and rhizomatous macrophytes according to littoral, limnetic, profundal, and benthic characteristics—offers a comprehensive, ecologically aligned, and highly efficient solution. By harnessing plant functional diversity and natural gradients, it achieves superior contaminant removal, sediment stabilisation, oxygenation, and biodiversity recovery while remaining cost-effective and sustainable. Widespread adoption, supported by community participation and adaptive monitoring, can revitalise contaminated freshwater lakes globally and secure these vital ecosystems for future generations.

References

- Ahila KG, et al. (2021) Phytoremediation potential of freshwater macrophytes for treating dye-containing wastewater. *Sustainability* 13(1):329. DOI: 10.3390/su13010329.
- Ali H, Khan E and Sajad MA (2013) Phytoremediation of heavy metals—Concepts and applications. *Chemosphere* 91(7):869–881. DOI: 10.1016/j.chemosphere.2013.01.075.
- Ansari AA, Naeem M, Gill SS, et al. (2020) Phytoremediation of contaminated waters: An eco-friendly technology based on aquatic macrophytes application. *Egyptian Journal of Aquatic Research* 46(4):371–376. DOI: 10.1016/j.ejar.2020.06.003.
- Aravind P and Prasad MNV (2005) Cadmium–zinc interactions in *Ceratophyllum demersum*. *Plant Physiology and Biochemistry* 43:1029–1036.
- Bonanno G and Giudice RL (2010) Heavy metal bioaccumulation by *Phragmites australis*. *Ecotoxicology and Environmental Safety* 73:1322–1330.
- Carpenter SR and Lodge DM (1986) Effects of submerged macrophytes on ecosystem processes. *Aquatic Botany* 26:341–370.
- Ceschin S, Crescenzi M and Iannelli MA (2020) Phytoremediation potential of *Lemna minuta* and *Lemna minor*. *Environmental Science and Pollution Research* 27:15806–15814. DOI: 10.1007/s11356-020-08045-3.
- Chaney RL, et al. (2007) Phytomining. In: *Phytoremediation*. Springer.
- Cobbett C and Goldsbrough P (2002) Phytochelatins and metallothioneins. *Annual Review of Plant Biology* 53:159–182.
- Fujibayashi M, et al. (2020) Effects of restoration of emergent macrophytes on the benthic environment of the littoral zone of a eutrophic lake. *Ecological Engineering* 155:105960. DOI: 10.1016/j.ecoleng.2020.105960.
- Gadd GM (2010) Metals, minerals and microbes. *Microbiology* 156:609–643.
- Hejna M, et al. (2020) Bioaccumulation of heavy metals. *Chemosphere* 241:125018.
- Huynh AT, et al. (2021) A small-scale study on removal of heavy metals. *Processes* 9:182.
- Kola E, et al. (2025) A review of macrophyte phytoremediation in Africa. *International Journal of Environmental Analytical Chemistry*. DOI: 10.1080/03067319.2025.2470315 (in press).
- Liu L, et al. (2018) Effects of water regime on *Ceratophyllum demersum*. *Journal of Freshwater Ecology* 33(1):1–15.

- Maranho LT, et al. (2024) Morphophysiological adaptations of aquatic macrophytes. *Plants* 13:2870. DOI: 10.3390/plants13202870.
- McGrath SP and Zhao FJ (2003) Phytoremediation. *Advances in Agronomy*.
- Mishra VK and Tripathi BD (2008) Concurrent removal. *Bioresource Technology* 99:7091–7097.
- Pereira AC and Mulligan CN (2023) Practices for eutrophic shallow lake water remediation. *Water* 15(12):2270. DOI: 10.3390/w15122270.
- Rai PK (2008) Heavy metal pollution. *Environmental Monitoring and Assessment* 152:407–426.
- Reddy KR and DeBusk WF (1984) Growth characteristics. *Economic Botany* 38:229–239.
- Reddy KR and DeLaune RD (2008) *Biogeochemistry of Wetlands*. CRC Press.
- Rezania S, et al. (2015) Water hyacinth for phytoremediation. *Ecological Engineering* 74:285–293.
- Salt DE, Smith RD and Raskin I (1998) Phytoremediation. *Annual Review of Plant Physiology and Plant Molecular Biology* 49:643–668.
- Sand-Jensen K, et al. (1982) Oxygen release from roots. *Oikos* 38:349–354.
- Song Y, et al. (2019) Effects of macrophytes on lake-water quality across latitudes: a meta-analysis. *Global Change Biology*.
- Vymazal J (2011) Plants used in constructed wetlands. *Hydrobiologia* 674:133–156.
- Yang H (2025) The dual nature of water hyacinth. *Environmental Advances*. DOI: 10.1016/j.envadv.2025.100002.
- Ye ZH, et al. (1997) Lead uptake. *Environmental Pollution* 95:131–137.
- Zayed A, et al. (1998) Phytoaccumulation. *Journal of Environmental Quality* 27:715–721.

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