Sustainable Remediation of Heavy Metal–Contaminated Urban Lake Water Using Aquatic Macrophyte-Based Phytoremediation

Umadevi KM[1], Sharadadevi Kallimani[*1]

[1]Department of Studies in Environmental Science, Davangere University, Karnataka, India – 577007.

Abstract

Urban freshwater systems are increasingly threatened by physicochemical deterioration and heavy metal accumulation, driven by rapid urbanization and wastewater inflows. The present study evaluates the phytoextraction and rhizofiltration potential of three floating aquatic macrophytes—water hyacinth (WH), Pistia stratiotes (PS), and duckweeds (DW)—for improving the water quality of Halasuru Lake, Bengaluru, India. Baseline monitoring revealed elevated dissolved solids, organic pollution loads, microbial contamination, and trace levels of heavy metals, including Cd, Pb, Cr, Hg, Zn, and As. Short-term phytoextraction experiments demonstrated progressive reductions in electrical conductivity, total dissolved solids, alkalinity, hardness, COD, BOD, and pathogenic indicators, with duckweed exhibiting the highest remediation efficiency. Heavy metal concentrations declined systematically, with toxic metals showing significant attenuation. Long-term rhizofiltration conducted over 4 months resulted in approximately 45–50% reductions in major and trace metals, confirming sustained uptake by plant root systems. Comparative performance followed the order DW > PS > WH. The findings establish floating macrophyte-based remediation as a cost-effective, eco-friendly approach for restoring contaminated urban lake systems and highlight duckweed as a highly efficient candidate for large-scale water quality management.

Keywords: Phytoextraction; Rhizofiltration; Heavy metal removal; Aquatic macrophytes; Sustainable water treatment.

1. Introduction

Water is a critical natural resource, indispensable for sustaining terrestrial and aquatic life, and a core component of the hydrological cycle, regulating Earth's ecosystems [1-2]. Conversely, the introduction of pollutants alters the physical, chemical, and biological characteristics of water, thereby degrading its quality and rendering it unsuitable for potable use [3]. Over the past decade, population growth and industrialization have markedly increased demand for sustainable supplies of clean, safe water worldwide. Water resources are becoming increasingly scarce due to the combined effects of population growth, escalating pollution levels, altered climatic patterns, unsustainable consumption practices, and the impacts of climate change and global warming [4]. Unfortunately, sediment accumulation disrupts the ecological balance of aquatic ecosystems, reducing water quality and limiting the long-term usability of water bodies. Aquatic habitats contribute significantly to global environmental sustainability by supporting diverse and ecologically important species [5]. However, increasing metal accumulation in water bodies complicates remediation processes, accelerates water resource degradation, and intensifies the environmental urgency of heavy metal contamination [6]. Major anthropogenic contributors to elevated metal concentrations include industrial effluents, landfill leachate, and agricultural runoff, all of which pose severe risks to aquatic ecosystems. Under natural conditions, heavy metals typically occur in water bodies at trace concentrations; however, prolonged and persistent metal pollution degrades water quality, disrupts the stability of aquatic ecosystems, and threatens the sustainable use of water resources [7-8]. Assessment of heavy metal contamination in aquatic environments requires both measuring dissolved metal concentrations in the water column and evaluating metal accumulation in bottom sediments. Heavy metal contamination in aquatic systems often arises from interactions between natural geochemical processes and anthropogenic activities, leading to the accumulation of metals in both water and bottom sediments [9-10].

A comprehensive analysis of biota, sediments, and water provides essential evidence of pollution levels, as excessive metal loads threaten ecosystem health and human safety. National and international regulatory agencies have established permissible limits for toxic heavy metals to safeguard environmental integrity and public health, recognizing that while trace amounts of certain metals are biologically essential, excessive concentrations pose significant risks [11-12]. Human health is severely threatened when heavy metal concentrations in water exceed regulatory limits, potentially resulting in fatal outcomes. Although conventional mechanical removal methods are often costly, these expenses may be partially mitigated through the beneficial utilization of remediation plants [13]. Consequently, findings reported at the International Water Technology Conference (IWTC-8, 2004, Alexandria, Egypt) highlighted the strong capacity of aquatic macrophytes to absorb heavy metal ions from contaminated waters, thereby stimulating increased interest in the use of aquatic vegetation for pollution mitigation [14].

One of the world’s most aggressive invasive aquatic species is water hyacinth (WH; *Eichhornia crassipes*), a member of the Pontederiaceae family closely related to lily-like plants. It is distinguished by an extensive fibrous root system and erect, curved leaves that enhance nutrient and metal uptake [15]. The species exhibits rapid vegetative expansion via stolon’s emerging from the parent plant, representing the dominant mode of reproduction and population spread. A notable characteristic of WH is its capacity to thrive in highly contaminated environments while progressively removing pollutants from surrounding waters. It exhibits exceptional remediation efficiency for a broad spectrum of contaminants, including organic compounds, heavy metals, nutrients, TSS, and TDS [16].

Furthermore, the plant’s optimal growth rate is closely linked to enhanced metal and nutrient removal efficiency. The exceptional biomass accumulation, pollutant tolerance, and broad-spectrum adsorption capability of Eichhornia crassipes position it as a highly efficient macrophyte for wastewater remediation. It demonstrates bioaccumulation efficiency toward heavy metals—including As, Zn, Hg, Ni, Cu, and Pb-supporting its application in treating industrial and domestic effluents containing hazardous metal contaminants [17-18].

Duckweed (DW) commonly forms dense mats on the surface of stagnant or slow-moving freshwater bodies, consisting of minute, free-floating aquatic plants. Taxonomically, it belongs to the family Araceae and is classified under the subfamily Lemnoideae [19]. Comprising approximately 40 species distributed across 5 genera-*Wolffia, Wolffiella, Spirodela, Lemna, and Landoltia*—this group of aquatic macrophytes is commonly referred to as water lentils. These fast-growing plants are globally widespread and predominantly inhabit ponds, canals, and drainage channels [20]. DW exhibits remarkable environmental adaptability, tolerating a broad pH range of approximately 3.5–10.5 and temperatures between 7 and 35

°C. This broad physiological tolerance enables duckweed species to perform effectively in phytoremediation applications, even under conditions of variable pH, temperature, and nutrient availability [21-22]. The high contaminant uptake capacity of DW extends to heavy metals, agrochemicals, organic and inorganic pollutants, and wastewater-derived nutrients. Their accelerated biomass expansion enables rapid surface coverage, limiting algal blooms and fungal growth within aquatic systems [23]. DW facilitates nitrogen attenuation in marine environments by promoting ammonium assimilation and stimulating microbial denitrification. Furthermore, systematic harvesting of accumulated biomass substantially improves the removal performance for COD, BOD, TN, TSS, and NH_3–N, contributing to sustained nutrient load reduction and overall water quality enhancement [24].

Pistia stratiotes L., a member of the Araceae family, is a free-floating freshwater macrophyte widely distributed across lentic and low-flow aquatic environments, including ponds, lakes, and slow-moving streams. The species has light-green, velvety leaves measuring 10–20 cm in length and up to 20 cm in width, with fine, whitish trichomes on the abaxial (lower) leaf surface. Beneath the floating rosette, a dense, feathery root system extends into the water column, facilitating efficient nutrient and contaminant uptake [25]. The ecological resilience of *Pistia stratiotes* is reflected in its broad tolerance to temperature and pH fluctuations. Although vegetative propagation via stolon formation predominates, reproductive cycles also involve seed production, with dormant seeds persisting in submerged substrates until environmental triggers, such as rainfall, stimulate germination [26]. The phytoremediation efficiency of *Pistia stratiotes* is associated with rapid biomass turnover and elevated contaminant assimilation rates. Its capacity to attenuate organic load (BOD, COD), nutrient fractions (TKN, NH_3, NO_2^-, NO_3^-, PO_4^{3-}), and dissolved oxygen imbalances underscores its applicability in wastewater treatment systems. Comparative studies indicate superior Zn and Hg uptake relative to WH, attributed to enhanced bioaccumulation dynamics and a higher surface-area-to-biomass ratio [27].

The present investigation was designed to assess the effectiveness of floating aquatic macrophytes in restoring the physicochemical, microbiological, and heavy metal quality of polluted urban lake water through combined phytoextraction and rhizofiltration processes. Surface water from Halasuru Lake was systematically characterized for key water quality parameters, including pH, EC, TDS, alkalinity, hardness, major ions, COD, BOD, microbial indicators, and a broad spectrum of heavy metals using standardized analytical protocols.

Short-term phytoextraction experiments were conducted using water hyacinth, water lettuce, and duckweed to evaluate immediate improvements in water quality under controlled natural conditions. Subsequently, long-term rhizofiltration was performed at monthly intervals to monitor sustained heavy metal removal efficiency over four months.

The specific objectives of the study were to:

- Quantify baseline physicochemical, microbial, and heavy metal contamination levels in urban lake water
- Evaluate the short-term phytoextraction efficiency of selected aquatic macrophytes
- Assess long-term rhizofiltration performance for toxic and significant metal attenuation
- Compare remediation efficiencies among plant species
- Establish an eco-sustainable remediation strategy for polluted freshwater ecosystems

2. Materials and Methods

2.1. Halasuru Lake

Halasuru Lake, situated in central Bengaluru, Karnataka, is one of the city's prominent freshwater lakes and serves as an essential urban water body supporting local ecological functions. Originally developed as a traditional irrigation reservoir, the lake has been subjected to significant environmental stress due to rapid urban expansion. In recent years, untreated domestic sewage, urban stormwater runoff, and anthropogenic discharges have substantially degraded water quality, leading to elevated organic matter levels, nutrient enrichment, and eutrophication. The continuous inflow of municipal wastewater and surface runoff further suggests the accumulation of inorganic pollutants, particularly heavy metals, within the water column and bottom sediments. These conditions make Halasuru Lake a suitable site for assessing contamination levels and evaluating the phytoremediation potential of aquatic macrophytes to improve water quality and mitigate metal pollution.

2.2. Study Area and Sample Collection

Surface water samples were collected from Halasuru Lake, Bengaluru, Karnataka, India, following standard environmental sampling protocols. Samples were obtained using pre-cleaned high-density polyethylene (HDPE) bottles (1 L) for physicochemical and heavy metal analyses, while sterile plastic containers (250 mL) were used for microbiological assessment. All collected samples were preserved under controlled conditions, transported promptly to the laboratory, and analyzed within the recommended holding periods to ensure data accuracy and reliability.

2.3. Physicochemical Characterization of Water Samples

The physicochemical properties of surface water collected from Halasuru Lake were systematically evaluated to assess overall water quality. Parameters, including pH, turbidity, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, total hardness, major ions (chloride, calcium, magnesium, sulfate, and silica), as well as organic pollution indicators such as chemical oxygen demand (COD) and biological oxygen demand (BOD), were determined using standardized analytical procedures. All analyses were conducted in accordance with protocols recommended by the Bureau of Indian Standards (IS 3025 series). The pH was measured using a calibrated digital pH meter, while EC and TDS were determined using conductivity and TDS meters, respectively. COD was quantified by the dichromate reflux method, and BOD was determined by the five-day incubation method. Other chemical constituents were analyzed using titrimetric and spectrophotometric techniques as prescribed in standard methods. The obtained values were benchmarked against permissible limits specified in IS 10500:2012 to evaluate suitability for potable and environmental quality.

2.4. Physico-Chemical Characterization of Lake Water

The physicochemical properties of water samples collected from Halasuru Lake were analyzed following standardized protocols prescribed by the Bureau of Indian Standards. Turbidity was quantified by nephelometry, and color was assessed by visual inspection. The pH was measured with a calibrated digital pH meter, and electrical conductivity was measured with a portable conductivity meter. Total dissolved solids (TDS) were estimated through gravimetric analysis. Alkalinity and total hardness were determined using standard titrimetric procedures. Chloride content was analyzed by argentometric titration, whereas calcium and magnesium concentrations were measured using ethylenediaminetetraacetic acid (EDTA) complexometric methods. Sulfate concentration was quantified employing turbidimetric analysis. Organic pollution indicators, including chemical oxygen demand (COD) and biological oxygen demand (BOD), were evaluated using the dichromate reflux method and five-day incubation technique, respectively.

Heavy metal concentrations were determined using inductively coupled plasma–optical emission spectroscopy (ICP-OES), and results were expressed in mg L^{-1}.

2.5. Heavy Metal Quantification

The concentrations of trace and heavy metals in surface water collected from Halasuru Lake were determined using advanced instrumental analytical techniques. The target metals analyzed included aluminum (Al), arsenic (As), boron (B), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), selenium (Se), and zinc (Zn). Prior to instrumental measurement, water samples were acidified and subjected to appropriate digestion procedures in accordance with established laboratory standard operating protocols to ensure complete solubilization of metal species. Quantitative results were reported in milligrams per liter (mg L^{-1}).

2.6. Microbiological Assessment of Lake Water

The microbiological quality of surface water from Halasuru Lake was evaluated using standard culture-based techniques to determine key indicator organisms. Total viable bacterial counts were quantified and expressed as colony-forming units per milliliter (CFU mL^{-1}). Additionally, total coliforms and *Escherichia coli* were enumerated and reported as CFU per 100 mL to assess fecal contamination. These microbial indicators provided insight into biological pollution levels and overall water safety status.

2.7. Experimental Framework for Phytoextraction Evaluation

The phytoextraction study was systematically designed to assess the remediation efficiency of three floating aquatic macrophytes—water hyacinth (WH), water lettuce (PS), and duckweed (DW)—in improving the physicochemical, microbiological, and heavy metal quality of lake water. Surface water collected from Halasuru Lake served as the contaminated medium for treatment experiments.

2.7.1. Baseline Monitoring and Sampling Protocol

Surface water samples were obtained at predetermined intervals using pre-cleaned polyethylene containers to ensure contamination-free collection. Prior to the introduction of macrophytes, baseline characterization was performed to establish initial pollution levels. Key physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), alkalinity, hardness, major ionic species (Cl^-, Ca^{2+}, Mg^{2+}, SO_4^{2-}), chemical oxygen demand (COD), and biological oxygen demand (BOD) were analyzed.

Microbial indicators, including total bacterial count, total coliforms, and Escherichia coli, were quantified to assess biological contamination. In parallel, heavy metal concentrations—including Al, As, B, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Se, and Zn—were determined to define the initial metal burden prior to phytoremediation treatment.

2.7.2. Phytoextraction Experimental Setup

Three separate treatment reactors were configured to evaluate the remediation performance of each aquatic macrophyte species independently. The experimental units consisted of:

- WH system – water hyacinth introduced into contaminated lake water
- PS system – water lettuce introduced
- DW system – duckweed introduced

Each treatment unit contained identical volumes of lake water and equivalent initial plant biomass to maintain experimental consistency and comparability across systems. No external aeration or chemical additives were applied. The setups were kept under natural photoperiod conditions at ambient temperature to replicate field-like environmental conditions and ensure realistic phytoremediation performance.

2.8. Contamination sources of Halasuru Lakes

Halasuru Lake, situated in a densely urbanized zone of central Bengaluru, is influenced by both point and non-point contamination sources, although management interventions have moderated severe degradation compared to highly stressed lakes. The primary source of contamination is inflow of untreated or partially treated domestic wastewater through stormwater drains, particularly during peak flow and monsoon periods, contributing elevated concentrations of total nitrogen, total phosphorus, BOD, and COD, thereby promoting eutrophic tendencies. Urban runoff from surrounding residential roads and commercial establishments transports suspended particulates, hydrocarbons, construction debris, microplastics, and heavy metals such as lead, cadmium, chromium, nickel, zinc, and copper into the lake basin. Shoreline anthropogenic activities, including improper solid waste disposal and littering, introduce biodegradable organic matter and plastic residues, increasing oxygen demand and localized contamination. Sediment accumulation over time has resulted in internal nutrient loading, where phosphorus release under low-oxygen conditions can sustain algal and macrophyte growth even when external inputs decline. Atmospheric deposition from vehicular emissions further adds nitrogen oxides and particulate-bound metals. Despite periodic desilting and aeration measures, these cumulative inputs contribute to moderate eutrophication and require continuous inflow regulation, sediment management, and water quality monitoring to maintain ecological balance.

2.9. Investigation of Macrophytes diversity in Halasuru Lakes

Halasuru Lake demonstrates a comparatively structured and ecologically balanced macrophyte community with moderate species diversity and better spatial distribution. Although free-floating species such as Eichhornia crassipes, Lemna minor, and Pistia stratiotes are present, their distribution is largely localized and does not form extensive continuous mats as observed in Hebbal Lake. Rooted floating macrophytes such as Nelumbo nucifera are more prominent and contribute to habitat heterogeneity, aesthetic value, and microhabitat formation for aquatic fauna. Submerged species including Hydrilla verticillata are relatively better represented due to improved light penetration and lower surface obstruction. Emergent vegetation such as Typha angustifolia is distributed along shallow margins, enhancing shoreline stabilization, nutrient sequestration, and sediment filtration. The comparatively controlled abundance of invasive species suggests moderated nutrient enrichment, possibly influenced by periodic lake management interventions such as desilting and aeration. Ecologically, Halasuru Lake appears to be in a mesotrophic-to-moderately eutrophic transitional stage, supporting greater ecological resilience and biodiversity retention compared to Hebbal Lake. Nevertheless, sustained surveillance of nutrient inputs, seasonal biomass dynamics, and invasive spread is essential to prevent ecological deterioration and maintain long-term ecosystem functionality.

3. Results and Discussion

3.1. Variation in Physicochemical Parameters During Phytoextraction

Progressive improvement in water quality parameters was observed across all three phytoextraction systems over the monitoring period shown in Table 1. Turbidity and color consistently remained below detectable limits (<1.0 NTU), indicating effective stabilization of suspended matter throughout treatment. The pH values gradually shifted toward near-neutral conditions, decreasing from 7.9 to 7.6 in the WH system, while PS and DW remained stable at around 7.7, suggesting buffering effects from macrophyte metabolism. Electrical conductivity (EC) and total dissolved solids (TDS) declined continuously, with DW exhibiting the highest reduction efficiency, reflecting enhanced ionic uptake and sedimentation. Total alkalinity and hardness decreased markedly, indicating the removal of bicarbonate and divalent cations via plant absorption and precipitation [28]. Chloride and sulfate concentrations also declined progressively, further confirming the effectiveness of pollutant attenuation. Organic pollution indicators followed a clear downward trend. COD decreased from 6.2 to 5.9 mg L^{-1} in WH and to 5.26 mg L^{-1} in DW, while BOD declined from 3.8 to 3.1 mg L^{-1}, demonstrating improved biodegradability and oxygen balance. Among the species, duckweed consistently performed best at reducing dissolved solids and organic loads [29].

3.2. Microbiological Quality Improvement

Significant microbial reduction was achieved across all treatment units. Total bacterial counts declined from 21 to 19.9 CFU mL^{-1} in WH, 19 to 18.6 CFU mL^{-1} in PS, and 17 to 14.8 CFU mL^{-1} in DW. Coliform populations showed pronounced decreases, particularly in the DW system, where values dropped from 230 to 197 CFU/100 mL. Escherichia coli levels were reduced most effectively by duckweed, reaching 91.5 CFU/100 mL by the end of treatment. These reductions can be attributed to nutrient depletion, root-associated microbial competition, and the release of antimicrobial phytochemicals by macrophytes. The results confirm phytoremediation as an efficient biological polishing step for microbial contamination [30].

3.3. Heavy Metal Removal Efficiency

All monitored heavy metals showed systematic declines in concentration throughout the treatment period. Aluminum and arsenic levels decreased steadily, with DW achieving the lowest residual concentrations (Al: 0.0108 mg L^{-1}; As: 0.010 mg L^{-1}).

Toxic metals such as cadmium, chromium, mercury, and lead showed notable removal:

- Cd decreased from 0.0033 to 0.0022 mg L^{-1} in DW
- Pb reduced from 0.030 to 0.018 mg L^{-1}
- Hg dropped from 0.0045 to 0.0031 mg L^{-1}

Zinc, initially present at elevated levels (2.27 mg L^{-1}), declined to 1.98 mg L^{-1} in DW, representing the highest overall metal attenuation among treatments. The enhanced removal by duckweed is likely due to its high surface-area-to-biomass ratio, rapid nutrient uptake kinetics, and efficient bioaccumulation pathways [31].

3.4. Comparative Phytoextraction Performance

Overall remediation efficiency followed the consistent trend:

DW > PS > WH

Duckweed exhibited:

- Highest reductions in EC, TDS, COD, and BOD
- Maximum microbial suppression
- Superior heavy metal uptake

Water lettuce demonstrated moderate efficiency, while water hyacinth showed comparatively slower pollutant removal despite higher biomass. This performance hierarchy reflects differences in root morphology, metabolic activity, and contaminant bioavailability at plant–water interfaces [32].

3.5. Environmental Implications

The study confirms that floating macrophytes can significantly improve water quality in a polluted urban lake through combined physicochemical stabilization, microbial suppression, and metal sequestration. Duckweed, in particular, emerges as a highly efficient low-cost phytoremediation agent suitable for large-scale application in contaminated freshwater systems. Implementation of such nature-based solutions offers a sustainable alternative to energy-intensive conventional treatment technologies, contributing to improved water security and ecosystem rehabilitation in rapidly urbanizing regions [33].

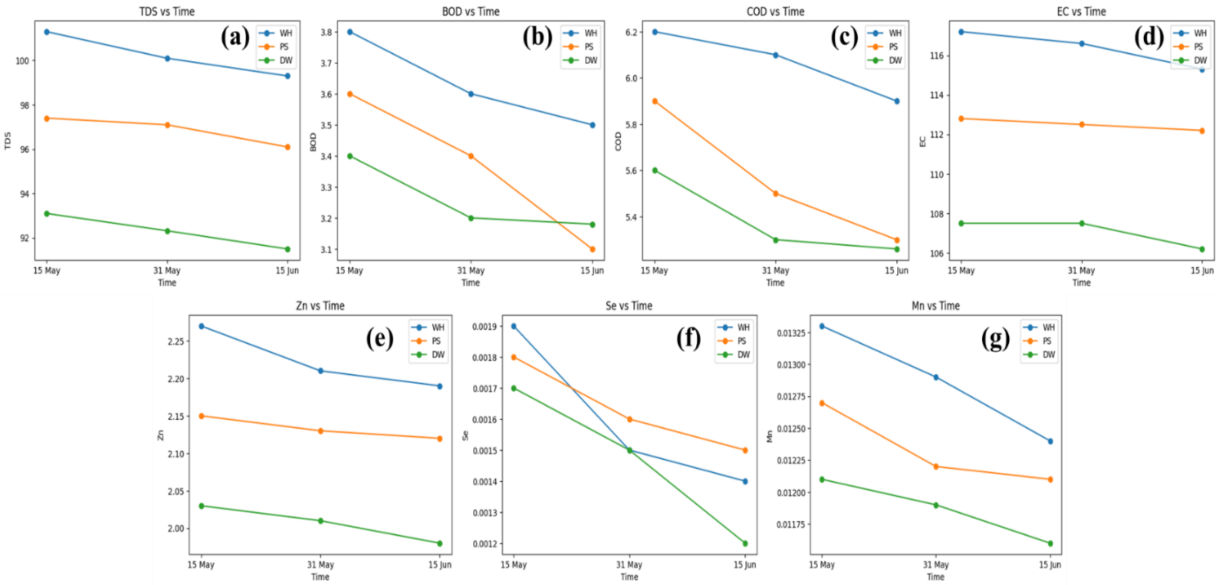


Fig. 1. Time-dependent variation of (a) TDS, (b) BOD, (c) COD, (d) EC, (e) Zn, (f) Se, and (g) Mn during phytoextraction using WH, PS, and DW.

Fig. 1 presents the time-dependent evolution of key water-quality parameters and selected heavy-metal concentrations during phytoextraction using WH, PS, and DW. A consistent decrease in contaminant levels was observed across all treatments, confirming effective remediation performance. As illustrated in Fig. 1(a), total dissolved solids (TDS) in the WH system decreased from 101.3 to 99.3 mg L^{-1}, while PS reduced TDS from 97.4 to 96.1 mg L^{-1}, and DW exhibited the highest reduction from 93.1 to 91.5 mg L^{-1} over the treatment period. Similarly, electrical conductivity (EC) declined steadily (Figure 1d), from 117.2 to 115.3 µS cm^{-1} in WH, 112.8 to 112.2 µS cm^{-1} in PS, and 107.5 to 106.2 µS cm^{-1} in DW, reflecting effective ionic uptake by macrophytes [34-35]. Organic pollution indicators showed marked improvement. As shown in Fig. 1(b), BOD decreased from 3.8 to 3.5 mg L^{-1} in WH, 3.6 to 3.1 mg L^{-1} in PS, and 3.4 to 3.18 mg L^{-1} in DW. Correspondingly, COD (Figure 1c) declined from 6.2 to 5.9 mg L^{-1} in WH, 5.9 to 5.3 mg L^{-1} in PS, and 5.6 to 5.26 mg L^{-1} in DW, indicating enhanced degradation of organic matter and improved oxygen balance. Heavy metal concentrations also exhibited continuous attenuation (Figures 1e–1g). Zinc (Zn) levels decreased from 2.27 to 2.19 mg L^{-1} in WH, 2.15 to 2.12 mg L^{-1} in PS, and 2.03 to 1.98 mg L^{-1} in DW. Selenium (Se) declined from 0.0019 to 0.0014 mg L^{-1} in WH, 0.0018 to 0.0015 mg L^{-1} in PS, and 0.0017 to 0.0012 mg L^{-1} in DW. Similarly, manganese (Mn) concentrations were reduced from 0.0133 to 0.0124 mg L^{-1} in WH, 0.0127 to 0.0121 mg L^{-1} in PS, and 0.0121 to 0.0116 mg L^{-1} in DW [36-37]. Overall, duckweed consistently achieved the most significant reductions in physicochemical parameters and heavy metals, followed by water lettuce and water hyacinth. This superior performance is attributed to rapid biomass turnover, extensive surface contact with contaminated water, and duckweed's efficient bioaccumulation mechanisms [38-39].

Table 1. Changes in physicochemical characteristics, microbial quality, and heavy metal levels of lake water over time during phytoextraction treatment with WH, PS, and DW.

Sr. No.	Parameters	15 May 2025			31 May 2025			15 Jun 2025		
		WH	PS	DW	WH	PS	DW	WH	PS	DW
1	Turbidity	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
2	Colour	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
3	pH-Value	7.9	7.7	7.7	7.8	7.7	7.7	7.6	7.7	7.7
4	Taste	-	-	-	-	-	-	-	-	-
5	Odour	-	-	-	-	-	-	-	-	-
6	EC	117.2	112.8	107.5	116.6	112.5	107.5	115.3	112.2	106.2
7	TDS	101.3	97.4	93.1	100.1	97.1	92.32	99.3	96.1	91.5
8	Total Alkalinity, as $CaCO_3$	46.5	44.1	42.0	45.2	43.8	41.0	44.1	42.1	38.3
9	P- Alkalinity, as $CaCO_3$	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
10	Total Hardness, as $CaCO_3$	31.6	29.8	28.1	30.3	29.5	26.5	29.3	27.1	24.67
11	Cl	94.2	91.6	87.3	93.1	91.1	84.2	92.3	90.06	81.34
12	Ca	41.9	39.6	37.8	41.7	39.2	35.2	40.7	38.1	31.45
13	Mg	14.2	13.5	12.7	14.1	13.1	12.5	13.8	12.08	11.09
14	Reactive Silica, As SiO_2	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
15	SO_4	64.7	61.3	58.6	63.2	61.2	57.3	63.1	59.1	56.2
16	COD	6.2	5.9	5.6	6.1	5.5	5.3	5.9	5.3	5.26
17	BOD	3.8	3.6	3.4	3.6	3.4	3.2	3.5	3.1	3.18
18	Total Bacterial Count	21	19	17	20.3	18.9	16.5	19.9	18.6	14.8
19	Coliform	270	250	230	255	248	210	160	245	197
20	Escherichia coli	110	100	94	102	100	93.2	101	100	91.5
Heavy Metals (mg/L)										
21	Aluminium (Al)	0.0128	0.0119	0.0112	0.0123	0.0112	0.0110	0.0123	0.011	0.0108
22	Arsenic (As)	0.0124	0.0116	0.0109	0.0121	0.0113	0.0101	0.0119	0.0109	0.01
23	Boron (B)	0.266	0.252	0.240	0.263	0.251	0.239	0.261	0.249	0.229
24	Cadmium (Cd)	0.0033	0.0031	0.0029	0.0031	0.0029	0.0027	0.0031	0.0027	0.0022
25	Calcium (Ca)	39.7	37.9	36.2	38.4	37.2	36.1	37.2	36.8	35.3

26	**Chromium (Cr)**	0.041	0.039	0.037	0.039	0.031	0.035	0.039	0.032	0.032
27	**Copper (Cu)**	0.0247	0.0235	0.0223	0.0243	0.0231	0.0221	0.0241	0.0229	0.0219
28	**Iron (Fe)**	0.0265	0.0251	0.0238	0.0262	0.0249	0.0235	0.0261	0.0249	0.0231
29	**Lead (Pb)**	0.030	0.028	0.026	0.027	0.025	0.021	0.022	0.021	0.018
30	**Magnesium (Mg)**	20.2	19.0	17.8	20.1	18.9	16.2	20.1	18.6	15.8
31	**Manganese (Mn)**	0.0133	0.0127	0.0121	0.0129	0.0122	0.0119	0.0124	0.0121	0.0116
32	**Mercury (Hg)**	0.0045	0.0042	0.0039	0.0039	0.0038	0.0034	0.0038	0.0036	0.0031
33	**Selenium (Se)**	0.0019	0.0018	0.0017	0.0015	0.0016	0.0015	0.0014	0.0015	0.0012
34	**Zinc (Zn)**	2.27	2.15	2.03	2.21	2.13	2.01	2.19	2.12	1.98

4. Heavy metal reduction using the Rhizofiltration method in a 1 Month Interval time

Rhizofiltration conducted at monthly intervals resulted in a substantial and progressive reduction in heavy metal concentrations in lake water, as shown in Table 2. Toxic metals such as Cd, Pb, Cr, Hg, and As exhibited removal rates of 45–50% within 4 months of treatment. Primary metals, including Ca, Mg, Fe, and Zn, also showed consistent attenuation, indicating effective ionic uptake by plant root systems. Among the macrophytes, duckweed achieved the highest removal efficiency, followed by water lettuce and water hyacinth. These findings confirm rhizofiltration as a sustainable and efficient strategy for long-term heavy metal remediation [40-41].

4.1. Overall Heavy Metal Reduction Trends

Monthly monitoring revealed substantial progressive declines in metal concentrations across all rhizofiltration systems. From August to November 2025, consistent attenuation was observed for both trace toxic metals and major nutrient-associated elements, confirming the sustained removal capacity of aquatic macrophyte root systems. For aluminum (Al), concentrations decreased from 0.023 to 0.01176 mg L^{-1} in WH, 0.020 to 0.0102 mg L^{-1} in PS, and 0.018 to 0.00918 mg L^{-1} in DW, indicating approximately 48–49% reduction over four months [42]. A similar decreasing pattern was evident for boron (B), which declined from 0.41 to 0.2091 mg L^{-1} in WH, 0.32 to 0.1632 mg L^{-1} in PS, and 0.21 to 0.1071 mg L^{-1} in DW. Major cations, such as calcium (Ca), were efficiently removed, with concentrations decreasing from 47.9 to 24.43 mg L^{-1} in WH, 51.3 to 26.16 mg L^{-1} in PS, and 42.6 to 21.73 mg L^{-1} in DW, resulting in nearly 50% removal efficiency. These results demonstrate stable long-term rhizofiltration performance [43].

4.2. Behavior of Toxic Heavy Metals

Highly toxic metals showed rapid and continuous reduction during treatment. Cadmium (Cd) decreased from 0.002 to 0.00102 mg L^{-1} in WH, 0.002 to 0.00102 mg L^{-1} in PS, and 0.001 to 0.00051 mg L^{-1} in DW, confirming enhanced uptake by plant roots. Lead (Pb) concentrations dropped from 0.009 to 0.00456 mg L^{-1} in WH, 0.008 to 0.00408 mg L^{-1} in PS, and 0.006 to 0.00306 mg L^{-1} in DW, corresponding to approximately 49–50% reduction. Mercury (Hg) showed pronounced removal, decreasing from 0.0006 to 0.000306 mg L^{-1} in WH, 0.0005 to 0.000255 mg L^{-1} in PS, and 0.0003 to 0.000153 mg L^{-1} in DW. Chromium (Cr) also followed a strong downward trajectory, reducing from 0.028 to 0.01428 mg L^{-1} in WH, 0.030 to 0.0153 mg L^{-1} in PS, and 0.022 to 0.01122 mg L^{-1} in DW [44-45].

4.3. Removal of Major Metals and Nutrient-Associated Elements

Iron (Fe) concentrations exhibited a steady decline from 0.25 to 0.1275 mg L^{-1} in WH, 0.22 to 0.1122 mg L^{-1} in PS, and 0.18 to 0.0918 mg L^{-1} in DW, reflecting approximately 50% sequestration. Magnesium (Mg) decreased substantially, from 24.6 to 12.55 mg L^{-1} in WH, 21.1 to 10.76 mg L^{-1} in PS, and 18.7 to 9.54 mg L^{-1} in DW, further demonstrating nutrient uptake and ionic stabilization. Zinc (Zn), initially present at elevated concentrations, showed significant attenuation from 3.7 to 1.887 mg L^{-1} in WH, 3.1 to 1.581 mg L^{-1} in PS, and 2.4 to 1.224 mg L^{-1} in DW, confirming effective rhizofiltration of essential yet potentially toxic trace metals [46-47].

4.4. Comparative Rhizofiltration Efficiency

Across all metals studied, removal efficiency consistently followed the order:

DW > PS > WH

Duckweed-based systems achieved the lowest residual metal concentrations at every sampling period, reflecting superior root-surface area exposure and rapid ion adsorption. Water lettuce showed intermediate performance, while water hyacinth demonstrated slower yet stable removal kinetics.

This comparative behavior underscores the influence of morphological and physiological factors on rhizofiltration efficiency.

4.5. Mechanisms Governing Rhizofiltration

The observed metal reduction can be attributed to multiple synergistic processes:

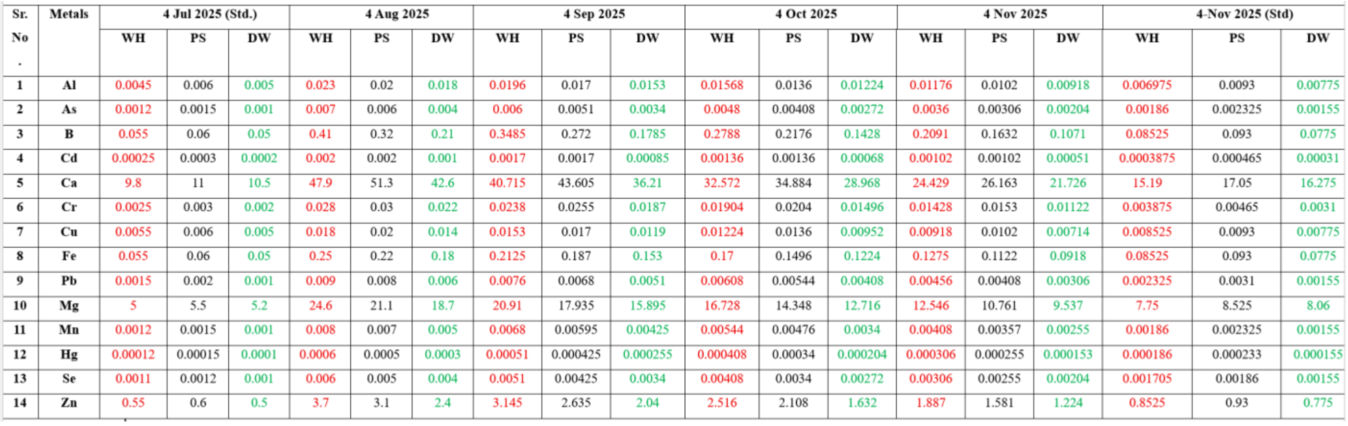
- Adsorption of metal ions onto negatively charged root surfaces
- Active bioaccumulation within root tissues
- Chelation by root-exuded organic compounds
- Precipitation near rhizosphere microenvironments

The continuous decrease across months indicates sustained uptake rather than short-term saturation effects.

4.6. Environmental Significance

The rhizofiltration approach demonstrated long-term stability in heavy metal removal, with nearly a 50% reduction in both toxic and primary metals within 4 months. This highlights its suitability as a low-cost, eco-friendly remediation strategy for contaminated freshwater systems. The superior performance of duckweed further supports its application in large-scale wastewater polishing units and urban lake restoration programs.

Table 2. Time-dependent reduction of heavy metal concentrations (mg L^{-1}) in lake water during Rhizofiltration using WH, PS, and DW.



Sr. No.	Metals	4 Jul 2025 (Std.)			4 Aug 2025			4 Sep 2025			4 Oct 2025			4 Nov 2025			4-Nov 2025 (Std)		
		WH	PS	DW	WH	PS	DW	WH	PS	DW	WH	PS	DW	WH	PS	DW	WH	PS	DW
1	Al	0.0045	0.006	0.005	0.023	0.02	0.018	0.0196	0.017	0.0153	0.01568	0.0136	0.01224	0.01176	0.0102	0.00918	0.006975	0.0093	0.00775
2	As	0.0012	0.0015	0.001	0.007	0.006	0.004	0.006	0.0051	0.0034	0.0048	0.00408	0.00272	0.0036	0.00306	0.00204	0.00186	0.002325	0.00155
3	B	0.055	0.06	0.05	0.41	0.32	0.21	0.3485	0.272	0.1785	0.2788	0.2176	0.1428	0.2091	0.1632	0.1071	0.08525	0.093	0.0775
4	Cd	0.00025	0.0003	0.0002	0.002	0.002	0.001	0.0017	0.0017	0.00085	0.00136	0.00136	0.00068	0.00102	0.00102	0.00051	0.0003875	0.000465	0.00031
5	Ca	9.8	11	10.5	47.9	51.3	42.6	40.715	43.605	36.21	32.572	34.884	28.968	24.429	26.163	21.726	15.19	17.05	16.275
6	Cr	0.0025	0.003	0.002	0.028	0.03	0.022	0.0238	0.0255	0.0187	0.01904	0.0204	0.01496	0.01428	0.0153	0.01122	0.003875	0.00465	0.0031
7	Cu	0.0055	0.006	0.005	0.018	0.02	0.014	0.0153	0.017	0.0119	0.01224	0.0136	0.00952	0.00918	0.0102	0.00714	0.008525	0.0093	0.00775
8	Fe	0.055	0.06	0.05	0.25	0.22	0.18	0.2125	0.187	0.153	0.17	0.1496	0.1224	0.1275	0.1122	0.0918	0.08525	0.093	0.0775
9	Pb	0.0015	0.002	0.001	0.009	0.008	0.006	0.0076	0.0068	0.0051	0.00608	0.00544	0.00408	0.00456	0.00408	0.00306	0.002325	0.0031	0.00155
10	Mg	5	5.5	5.2	24.6	21.1	18.7	20.91	17.935	15.895	16.728	14.348	12.716	12.546	10.761	9.537	7.75	8.525	8.06
11	Mn	0.0012	0.0015	0.001	0.008	0.007	0.005	0.0068	0.00595	0.00425	0.00544	0.00476	0.0034	0.00408	0.00357	0.00255	0.00186	0.002325	0.00155
12	Hg	0.00012	0.00015	0.0001	0.0006	0.0005	0.0003	0.00051	0.000425	0.000255	0.000408	0.00034	0.000204	0.000306	0.000255	0.000153	0.000186	0.000233	0.000155
13	Se	0.0011	0.0012	0.001	0.006	0.005	0.004	0.0051	0.00425	0.0034	0.00408	0.0034	0.00272	0.00306	0.00255	0.00204	0.001705	0.00186	0.00155
14	Zn	0.55	0.6	0.5	3.7	3.1	2.4	3.145	2.635	2.04	2.516	2.108	1.632	1.887	1.581	1.224	0.8525	0.93	0.775

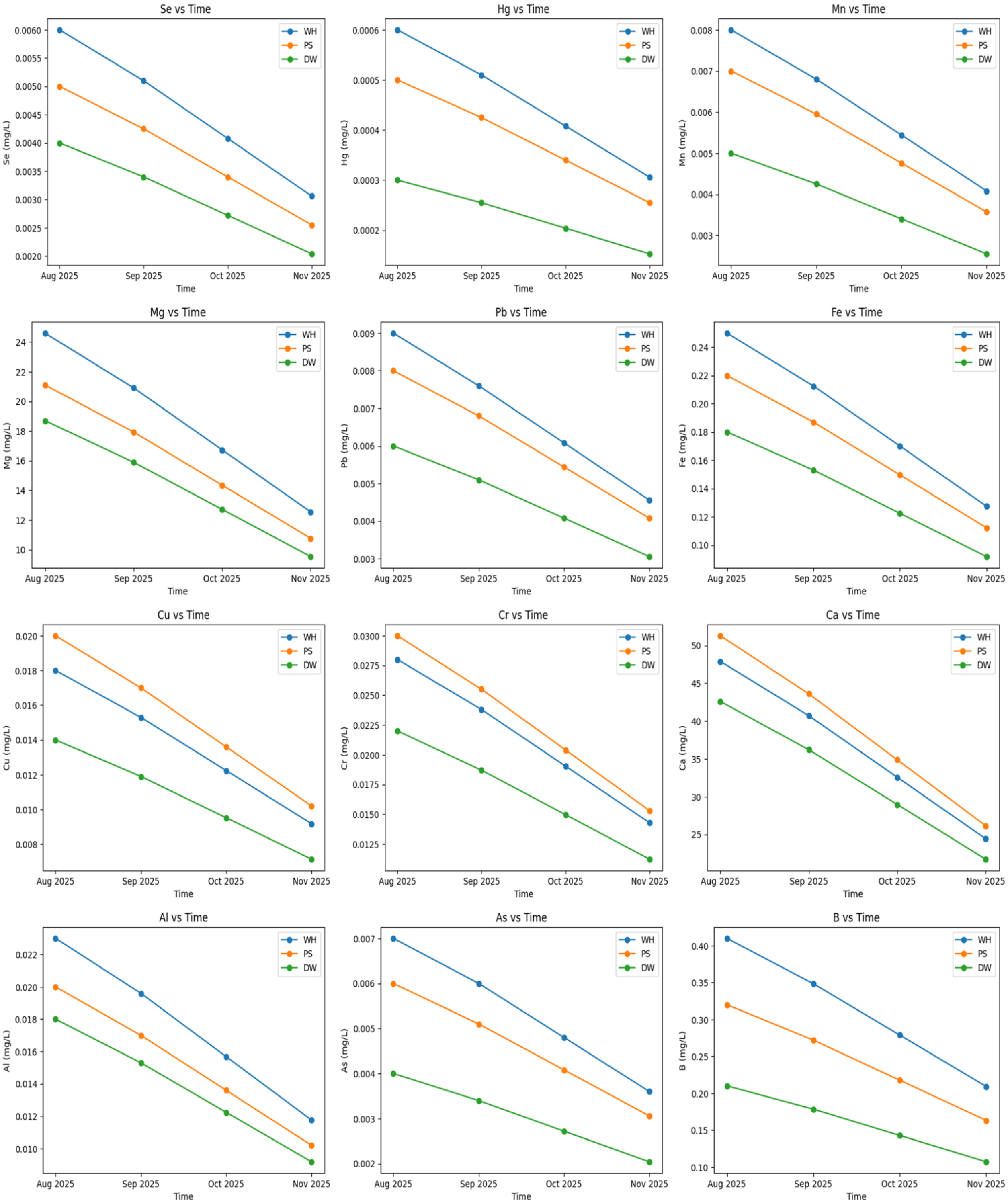


Fig. 2. Monthly variation in heavy metal concentrations (Se, Hg, Mn, Mg, Pb, Fe, Cu, Cr, Ca, Al, As, and B) during rhizofiltration using WH, PS, and DW from August to November 2025.

Fig. 2 illustrates the temporal decline of multiple heavy metals during rhizofiltration using WH, PS, and DW. Across all monitored elements—including Se, Hg, Mn, Mg, Pb, Fe, Cu, Cr, Ca, Al, As, and B- a consistent decreasing trend was observed from August to November 2025, confirming sustained metal uptake by aquatic macrophytes. Toxic metals, including mercury, arsenic, selenium, lead, cadmium, chromium, and manganese, exhibited nearly linear reductions over time, indicating continuous adsorption and bioaccumulation at plant root interfaces. For instance, Hg decreased from approximately 0.0006 to 0.0003 mg L^{-1} in WH and from 0.0003 to 0.00015 mg L^{-1} in DW, while Mn declined from about 0.008 to 0.004 mg L^{-1} in WH and to nearly 0.0025 mg L^{-1} in DW. Primary metals and nutrient-associated elements, including calcium, magnesium, iron, copper, boron, and aluminum, also showed substantial attenuation, with Ca decreasing from ~48 to ~24 mg L^{-1} in WH and from ~43 to ~22 mg L^{-1} in DW, reflecting substantial ionic sequestration [48-50]. Among the treatment systems, duckweed consistently achieved the lowest residual concentrations, followed by water lettuce and water hyacinth. The comparative efficiency trend (DW > PS > WH) highlights the roles of high surface-area root systems, rapid biomass turnover, and duckweed's enhanced metal-binding capacity in driving superior rhizofiltration performance.

Conclusion

The present study demonstrates the strong potential of floating aquatic macrophytes as sustainable bio-remediation agents for improving urban lake water quality. Progressive reductions in dissolved solids, organic pollution indicators, microbial populations, and heavy metal concentrations confirmed the effectiveness of phytoextraction as a rapid natural purification process. Duckweed consistently outperformed water lettuce and water hyacinth, achieving the highest removal of EC, TDS, COD, BOD, and toxic metals. Long-term rhizofiltration further validated the stability and persistence of metal uptake mechanisms, with approximately 45–50% reductions in both trace poisonous metals (Cd, Pb, Cr, Hg, As) and major elements (Ca, Mg, Fe, Zn) over four months. The sustained decline indicates effective adsorption, bioaccumulation, and rhizosphere-mediated sequestration processes without early saturation effects.

Overall remediation efficiency followed the trend:

Duckweed > Water lettuce > Water hyacinth

The combined phytoextraction–rhizofiltration approach offers a low-cost, environmentally friendly alternative to conventional wastewater treatment technologies and is highly suitable for urban lake restoration programs. The superior performance of duckweed highlights its potential for large-scale deployment in contaminated freshwater bodies to enhance water security, ecological stability, and public health protection.

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