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بررسی نقش نباتات آبی در پاکسازی (فیتورِمدییشن) آب‌های آلوده به فلزات سنگین

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چکیده

برخی از نباتات آبی توانایی قابل‌توجهی در جذب و تجمع فلزات سنگین دارند و از این ویژگی می‌توان به‌عنوان روشی مؤثر برای کاهش آلودگی آب استفاده نمود. در این مقالهٔ مروری، کاربرد نباتات ماکروفیت آبی، به‌ویژه سنبل آبی(*Eichhornia crassipes*)، در پاک‌سازی فلزات سنگین و تصفیهٔ پایدار فاضلاب مورد بررسی قرار گرفته است. بدین منظور، مرور سیستماتیک ۱۱۲ مقالهٔ علمی منتشرشده طی سال‌های ۲۰۱۹ تا ۲۰۲۴ از ۱۲ دیتابیس معتبر انجام شد. نتایج نشان می‌دهد که سنبل آبی قادر است فلز کادمیوم را تا سطح 166.25 قسمت در میلیون (بر اساس وزن خشک) در بافت‌های خود انباشت نماید و هم‌زمان در کاهش غلظت سرب، سیماب، آرسنیک و نیکل نیز نقش مؤثری ایفا کند. افزون بر این، سایر نباتات آبی مانند *Lemna minor*، *Pistia stratiotes* و*Hydrilla verticillata* توانایی قابل‌توجهی در اصلاح و تصفیهٔ فلزات کروم، مس و زینک نشان داده‌اند. هرچند تماس با فلزات موجب بروز تنش‌های فیزیولوژیکی در نباتات می‌شود، این نباتات به‌عنوان گزینه‌هایی کم‌هزینه و سازگار با محیط‌زیست برای تصفیهٔ فاضلاب مطرح می‌باشند.

کلمات کلیدی : ماکروفیت‌های آبی، آلودگی محیط‌زیست، آلودگی فلزات سنگین، تصفیهٔ نباتی، تصفیهٔ فاضلاب

Exploring the Role of Aquatic Macrophytes in Phytoremediation of Heavy Metal-Contaminated Water

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Abstract

Some aquatic plants have a remarkable ability to absorb and accumulate heavy metals, which can be used to reduce water pollution. In this review, we assessed the utilization of aquatic macrophytes, specifically water hyacinth (Eichhornia crassipes), for heavy metal cleanup and sustainable wastewater treatment. After screening 12 databases, including PubMed, Scopus, Web of Science, and ScienceDirect, for the period 2019-2024, we reviewed 112 studies. Bibliometric analysis using VOSviewer (v1.6.18), which revealed the main research trends, citation networks, and thematic clusters. The produced results suggest that (i) the water hyacinth has a high capacity of cadmium accumulation (166.25 ppm dry weight), but is very effective for the removal of lead, mercury, arsenic, and nickel. Other macrophytes, including Lemna *minor*, *Pistia stratiotes*, and *Hydrilla verticillata*, also have a considerable extent of chromium, copper, and zinc removed. While exposure to metals imposes physiological stress, aquatic plants serve as indicators, providing low-cost, eco-friendly phytoremediation agents.

Keywords: Biodiversity, conservation, Cricetidae, Afghanistan, mountain ecosystems

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Introduction

Water is essential for all life, yet its quality is increasingly threatened by contamination of freshwater ecosystems. Heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), and chromium (Cr) are of particular concern due to their toxicity, persistence, and non-biodegradable nature. These pollutants enter aquatic systems mainly through industrial effluents, agricultural runoff, mining activities, and improper waste disposal, posing serious risks to human and ecological health (Singh & Patel, 2025; Ali et al., 2019; Mondou et al., 2021). Conventional wastewater treatment methods—such as chemical precipitation, ion exchange, membrane filtration, and electrochemical processes—can remove contaminants but are often costly, energy-intensive, and may generate secondary pollution (Kumar et al., 2025). These limitations underscore the urgent need for sustainable and eco-friendly alternatives to safeguard freshwater resources.

Phytoremediation has emerged as a promising green technology for mitigating heavy metal contamination. This approach harnesses plants' natural capacity to absorb, accumulate, or detoxify pollutants, offering a cost-effective and environmentally sustainable solution. Aquatic macrophytes, including Eichhornia crassipes, Lemna minor, and Typha latifolia, are particularly effective due to their extensive root systems, rapid growth, and ability to tolerate elevated metal concentrations (Edo et al., 2021; Stanikzai et al., 2023; Koul et al., 2022). These species can accumulate metals at levels far exceeding surrounding water, reducing bioavailability and mitigating ecological risks, making them valuable for constructed wetlands and wastewater treatment systems.

Despite these advantages, several knowledge gaps remain. Uptake efficiency varies among species, and environmental factors strongly influence remediation performance. Widespread proliferation of invasive macrophytes may disrupt ecosystems, deplete oxygen, or promote vector-borne diseases (Zhou et al., 2020). Additional contaminants, such as fungicides, ammonia, nitrates, and phosphorus, further complicate water quality management, contributing to eutrophication, algal blooms, and fish kills (Kansal et al., 2025; U.S. Environmental Protection Agency, 2021;

Cheng et al., 2020). Continuous monitoring of physical, chemical, and biological parameters is essential (Chauhan et al., 2025), yet there is limited consensus on selecting optimal plant species and applying them efficiently in constructed wetlands.

The objective of this review is to critically evaluate the potential of aquatic macrophytes in phytoremediation of heavy metal–contaminated water. Specifically, it examines (i) the physiological and biochemical responses of different macrophytes to heavy metal stress, (ii) their uptake and accumulation capacities for various metals, and (iii) their practical applications in constructed wetlands and wastewater treatment. By integrating recent findings, this review aims to identify the most promising plant species, outline current limitations, and suggest future research directions to optimize phytoremediation as a sustainable, scalable approach to improving water quality.

Methods and Materials

A detailed review of research articles published in book chapters and digital journals is provided in this chapter. To highlight contemporary developments in the intriguing topic of water quality and their sustainable management strategies, we focused primarily on articles published over the last five years, from 2019 through 2024. Water quality, the relationship between water and energy, sustainable methods for managing water quality, and cutting-edge sensor technology were the main topics of the search. To collect the data and conduct the analysis in this methodical chapter, we used 112 distinct publications from 12 databases.

Using keywords from the PubMed database, data were examined for bibliometric analysis as previously described. Three distinct matrices, including (i) the strength of the overall link, (ii) the number of published papers, and (iii) the number of citations, were used by the VOS reader 1.6.18 program to filter the datasets. Figure 1 shows a network visualization in which a larger frame size indicates greater dominance, and a larger number of lines indicates stronger networking capability. The larger the frame size relative to the co-occurrence of a keyword in maps, the more often that keyword is used. A network visualization map of the most frequently mentioned terms in 112 publications from 2019 to 2024 is shown in Fig. 1 (Supplementary source 1). This section's primary emphasis is on water quality and sustainable management strategies.

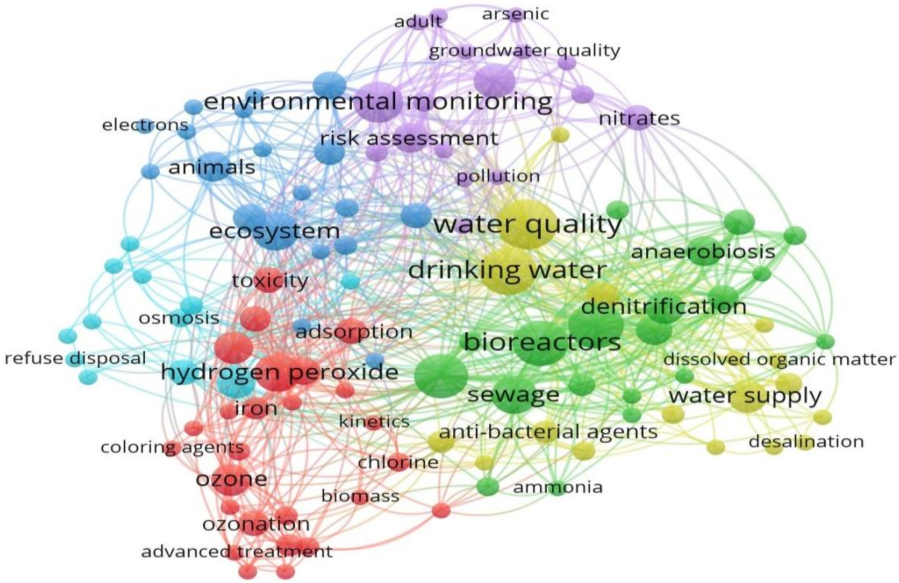

Fig: 1 Network Visualization

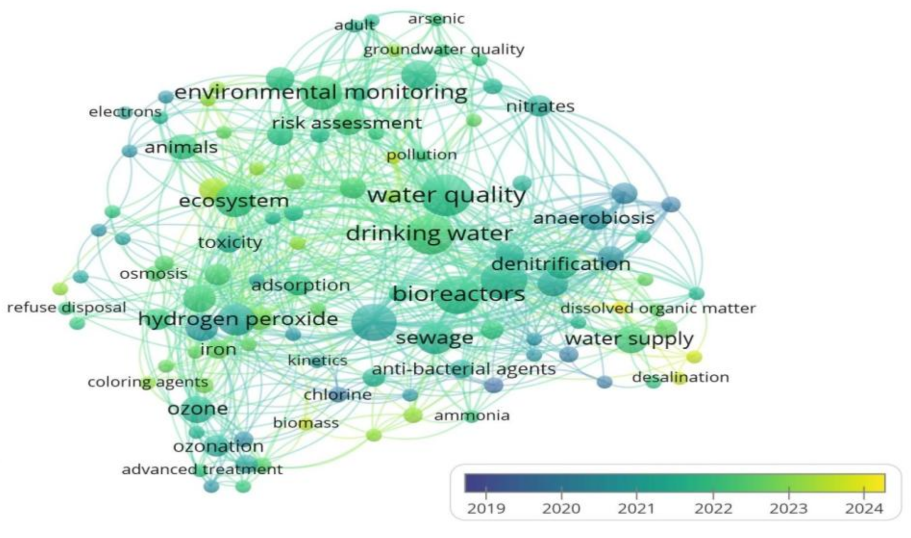

Fig. 2 Bibliometric analysis based on network clustering of 112 published articles from 2019 to 2024 (Supplementary source 1), which have a high match of selected keywords and their citations.

Results

Free-Floating Aquatic Macrophyte Species

These are plants whose leaves float, and their roots are submerged. Several free-floating aquatic plants that have gained recognition for their ability to extract metals from polluted environments include duckweed, water ferns, water hyacinth, water lettuce, and water cress. The capacity of these free-floating aquatic plants to remove heavy metals has been the subject of several investigations (Muthusaravanan et al., 2018; Maine et al., 2001). Additionally, in free-floating aquatic plants, heavy metals are actively moved from the root to other parts of the plant. Direct transmission occurs when a plant's body comes into direct contact with the polluted medium. The higher parts of the plant body are where heavy metals tend to collect during passive transport (Maine et al., 2004). The most widely used free-floating plants for removing heavy metals from wastewater are water lettuce, duckweed, and water hyacinth (Chen et al., 2018).

Submerged Aquatic Plant Species

The main source of metal uptake in submerged aquatic plants is the leaves. The cuticle's passive mobility allows heavy metals to be absorbed. They can extract heavy metals from sediments and water. Well-known submerged plants that are known to accumulate different heavy metals include parrot feather (Myriophyllum spicatum), coontail or hornwort (Ceratophyllum demersum), pondweed (Potamogeton crispus), American pondweed (Potamogeton pectinatus), Mentha Aquatica, and Vallisneria spiralis.

Emergent Aquatic Plant Species

The soil in which these plants thrive has a water table that is 0.5 meters below the surface. Different emergent plants have different capacities for bioconcentrating the bulk of metals from water and sediments in their underground roots. Additionally, certain emergent plants use their aerial parts to distribute the metal burden. The weight of metals is also distributed by plants in their aerial parts. For instance, the leaves of smooth cordgrass absorb heavy metals (Hempel et al., 2008). However, the heavy metal weight is primarily carried by the roots of ordinary reeds (Ha & Anh, 2017). In these plants, detoxification and heavy metal sequestration take place at the cellular level (Wang et al., 2017). The most promising emergent aquatic plants for phytoremediation of heavy metals (HMs) like Cd, Fe, Pb, Cr, Zn, Ni, and Cu are cattail, bulrush, common reed, and smartweed (Srivastava et al., 2025).

Phytoremediation Potential of Aquatic Macrophytes for Heavy Metal-Contaminated Wastewater

Aquatic plants naturally absorb pollutants and heavy metals (Peng et al., 2008). Aquatic plants are the most effective and economical method of eliminating various heavy metals and other pollutants (Ali et al., 2013; Guittonny-Philippe et al., 2015). Constructed wetlands with aquatic plants have been widely used for wastewater treatment worldwide (Gorito et al., 2017; Mesa et al., 2015). For phytoremediation to be successful, aquatic plant species that accumulate heavy metals must be chosen carefully (Åström & Greger, 2003; Galal et al., 2018). The ability of aquatic plants to purify polluted areas worldwide has earned them an impressive reputation over the years (Gopal, 2003; Gorito et al., 2017). Because of the extensive root systems they produce, aquatic plants are the best option for preventing pollution buildup in their roots and shoots (Said et al., 2015). The slow growth and cultivation of aquatic plants may limit the increasing need for phytoremediation (Mousavi-Kouhi, 2025).

Furthermore, this drawback is offset by the numerous benefits this wastewater treatment process offers. From ancient times to the present, the water hyacinth (Eichhornia crassipes) has been a crucial phytoremediation agent for pollutants such as lead, mercury, cobalt, nickel, arsenic, and cadmium. It grows fast without any special needs. Water hyacinth can remove a wide range of heavy metals, though other marine plants are also beneficial. Water hyacinth (*Eichhornia crassipes*) was found to be an effective remediator of contaminated water containing metals, including cadmium, arsenic, and mercury. This reduced the potential environmental risk posed by untreated wastewater.

Table 1. Heavy metal removal efficiency of macrophytes

Macrophytes	Plant species	Heavy metal eliminated	References
Macrophytes that float freely in water	*Nasturtium ocinale, Spirodelaintermedia Pistiastratoites, Eichhornia crassipes,*	Ni, Cr, As, Pb	(Zarcinas et al., 2004)
Aquatic Macrophytes Under Water	*Ceratophyllum demersum, Myriophyllum spicatum Mentha aquatica, Vallisneria spiralis, Potamogeton pectinatus, Potamogeton Crispus, Myriophyllum spicatum, Ceratophyllum demersum L.*	Zn, Cr, Fe, Cu, Cd, Ni, Hg	(El-Khatib et al., 2014)
New Aquatic Macrophytes	*Typha latifolia, Polygonum hydropiperoides, Scirpus spp, Spartina alterniflora,*	Cd, Fe, Pb, Cr, Zn, Ni, Cu	(Sahibin et al., 2002)

Table 2. Common macrophytes' reactions to wastewater containing heavy metals

opular name	botanical name	Macrophyte types	Reaction to heavy metals	References
Hornwort	*Ceratophyllum demersum L.*	Underwater Aquatic Macrophytes	As malondialdehyde levels rose, the plants' protein and photosynthetic pigment concentrations fell.	((Ansari, Naeem, Gill, & AlZuaibr, 2020)
Water Hyacinth	*Eichhornia crassipes*	Free-Floating Macrophytes	can endure a highly contaminated environment and produces biomass at an enormous rate.	(Jafari, 2010)
Hydrilla	*Hydrilla verticillata*	Free-Floating Macrophytes	The test plants' chlorophyll and carotenoid content showed a steady decline.	(Sayanthanet al., 2023)
Narrow quillwort	*Isoetes sinensis*	Free-Floating Macrophytes	The membrane structure in chloroplasts was disturbed, the grana lamella shrank, the stroma lamella loosened, and the starch grains shrank.	(Ding, Li, Han, Chi, Zhang, & Liu, 2015)
Duck Weed	*Lemna minor*	Free-Floating Macrophytes	They can withstand temperatures between 7 and 350 °C and high pH levels (3.5 to 10.5).	(Rai, Tripathi, Vajpayee, Pandey, Ali, & Gupta, 2003)

The study found that water hyacinth had the highest cadmium uptake (166.25 ppm) and the lowest mercury uptake (0.032 ppm) per dry weight of water hyacinth. A separate study found that, compared with arsenic and mercury, water hyacinth (Eichhornia crassipes) absorbs the most cadmium

from sewage water. According to a study on the use of aquatic plants to purify water, floating plants such as Salvinia molesta and Azolla pinnata are effective at removing chromium from water, making them an appropriate option for purifying contaminated water. The robust growth of Azolla pinnata and its expanding biomass enhanced root-zone activity, thereby increasing the plant's capacity to absorb metals from the water (Goala et al., 2025).
It has been reported that water lettuce is effective at filtering and purifying municipal wastewater (Suman et al., 2018). The vegetation acts as a hyperaccumulator, efficiently absorbing and storing trace metals such as Cr, Cu, Fe, Mn, Ni, Pb, and Zn, thereby helping reduce metal contamination through its bioconcentration capacity (Lu et al., 2011). Pistia stratiotes is a popular plant found worldwide because it can withstand a wide range of climates. It thrives in temperatures between 15 and 35 °C (Nagajyoti et al., 2010). Scientific investigations have shown that Hydrilla verticillata effectively removes chromium (Cr) and cadmium (Cd) from aquatic environments, demonstrating its high metal-absorption capacity and potential for water remediation (Mandal and Bera, 2025). In this study, four aquatic plant species—*Saccostrea cucullata, Alternanthera sessilis, Pistia stratiotes*, and *Lemna minor*—were used in hydroponics under laboratory settings to test the viability of Pb phytoremediation potentials via phytoextraction mechanisms.

All plant species exhibited rapid growth, extensive root development, high biomass production, and significant tolerance to lead (Pb), as well as the capacity to accumulate Pb. The accumulation of Pb was highest in Saccostrea cucullata, followed by *Alternanthera sessilis, Pistia stratiotes*, and *Lemna minor* (Das et al., 2021).

Discussion

This study provides the first systematic, geographically verified record of three Cricetidae species in Afghanistan, revealing that the country's mountain and semi-arid landscapes support a more structured, ecologically specialized rodent fauna than previously documented. The main finding is the clear ecological and morphological differentiation among *Cricetulus migratorius*, *Ellobius fuscocapillus*, and *Microtus transcaspicus*, each occupying distinct habitats ranging from peri-urban plains to deep soils and alpine meadows. This spatial and functional separation suggests that Cricetidae rodents are key contributors to ecosystem stability across Afghanistan's highly heterogeneous environments.

The morphological patterns observed in this study reflect strong adaptation to local ecological conditions. The robust skull, wide interorbital region, and large cheek pouches of *C. migratorius* indicate specialization for seed storage and burrowing in dry, open habitats, supporting its role as a granivore and soil-disturbing species in agricultural landscapes. Similarly, the cylindrical body, reduced eyes and ears, and compact skull of *E. fuscocapillus* reflect extreme adaptation to subterranean life, where mobility through dense soils and energy-efficient feeding on roots and tubers are critical for survival. In contrast, the lighter body form and distinctive molar pattern of *M. transcaspicus* are consistent with grazing and surface activity in high-altitude grasslands, where rapid reproduction and mobility are advantageous.

These findings are consistent with previous studies of Cricetidae ecology in Central and Southwest Asia, where *C. migratorius* is known to dominate semi-arid agroecosystems, *Ellobius* species act as ecosystem engineers in compact soils, and *Microtus* species function as keystone prey in alpine food webs (Davidson et al., 2012; Shenbrot et al., 2016; Burgin et al., 2018). However, unlike neighboring regions, Afghanistan has lacked verified distribution and morphological data, making this study the first to confirm these ecological roles within its national boundaries. The restriction of *E. fuscocapillus* to undisturbed soils in Punjab District and of *M. transcaspicus* to Bamyan's alpine meadows suggests a higher degree of habitat specificity than reported in some Central Asian populations, possibly reflecting Afghanistan's extreme topographic and climatic gradients.

The ecological interpretation of these findings highlights the importance of Cricetidae rodents as drivers of soil processes, vegetation dynamics, and trophic stability. Burrowing by *C. migratorius* and *E. fuscocapillus* enhances soil aeration, water infiltration, and nutrient cycling, reducing erosion and increasing plant productivity in fragile landscapes (Whitford & Kay, 1999; Alhajeri & Schenk, 2022). Meanwhile, *M. transcaspicus* supports predator populations in alpine ecosystems, helping maintain food-web balance (Burgin et al., 2018). The presence of these species therefore indicates the presence of functioning ecosystems, making them valuable bioindicators in Afghanistan's post-conflict environment (Ostrowski et al., 2021).

Despite its contributions, this study has limitations. The sample size was small, and karyological analyses were constrained by specimen availability and preservation quality, limiting the ability to detect fine-scale genetic variation. In addition, sampling was restricted to Bamyan, Kabul, and the Punjab District, leaving large areas of eastern and northeastern Afghanistan unexplored. These constraints mean that the full distributional range and population connectivity of these species remain unresolved.

Future research should use non-invasive genetic tools, such as DNA barcoding, to examine population structure and dispersal across fragmented habitats (Frankham, 2010). Expanding surveys into remote and conflict-affected regions such as Nuristan, combined with remote-sensing-based habitat mapping, would allow identification of biodiversity hotspots and guide conservation planning under Afghanistan's ecological recovery framework (Ostrowski et al., 2021).

Conclusion

Aquatic macrophytes are practical, sustainable tools for mitigating heavy metal contamination in freshwater systems. This review highlights that fast-growing species such as *Eichhornia crassipes*, *Lemna minor*, and *Pistia stratiotes* can bioaccumulate metals, reduce BOD and COD, and improve overall water quality, making them suitable for large-scale application in constructed wetlands and wastewater treatment systems. For water managers, incorporating macrophyte-based phytoremediation into existing treatment strategies offers a cost-effective and practical complement to conventional technologies. However, remediation efficiency depends on species selection, pollutant type, and environmental conditions, emphasising the need for site-specific design and careful management. Future research should focus on optimising native and non-invasive species with high metal uptake, improving cultivation and biomass management, exploring plant–microbe interactions to enhance remediation efficiency, and evaluating long-term ecological impacts. Addressing these areas will strengthen the use of macrophytes as scalable, nature-based solutions for heavy metal pollution and sustainable water management.

AUTHOR CONTRIBUTIONS

The study was conceptualized, and Khalid Stanikzai wrote the first manuscript. Dr. Avnish Chauhan supervised and analyzed the data. Javidullah Iqbal worked with all authors to write the manuscript. The final version of the manuscript was reviewed and approved by all authors.

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CONFLICT OF INTEREST STATEMENT

The authors affirm that they have no conflicts of interest regarding this manuscript.

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