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Harnessing Nature's Power to Cleanse Water Bodies through Phytoremediation of Aquatic Plants

Chandni Asha Syamlal [a] and D. Sayantan [a*]

[a] *Department of Life Sciences, Christ University, Bengaluru - 560029, Karnataka, India.*

Authors' contributions

This work was carried out in collaboration between both authors. Authors CAS and DS designed the study and drafted of the manuscript. Author DS supervised, reviewed and edited. Author CAS wrote original draft preparate, data collected analysis of the manuscript, wrote and edited and prepared of the Table. Both authors read and approved the final manuscript.

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ABSTRACT

The use of plants to remove, detoxify, or immobilize environmental contaminants, a process known as phytoremediation, is an emerging field with significant potential for the sustainable and economical treatment of polluted water bodies. Aquatic plants are uniquely suited for this purpose due to their inherent capabilities to uptake and metabolize a diverse range of pollutants such as heavy metals, pesticides, and organic compounds. Although the method does present challenges, including the length of time for effective cleanup and potential toxin bioaccumulation, innovative advancements in fields like genetic engineering and integrated remediation techniques offer promising avenues to overcome these hurdles. Additionally, the function of phytoremediation in carbon sequestration, paired with potential commercial uses, underscores its role as an essential

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**Corresponding author: Email: sayantan.d@christuniversity.in;*

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tool for sustainable environmental stewardship. Therefore, it's crucial to continue research, encourage policy backing, and foster community participation to fully exploit the benefits of phytoremediation in aquatic settings.

Keywords: Bioaccumulation; heavy metals; pesticides; phytoremediation.

1. INTRODUCTION

Aquatic ecosystems are essential for the well-being of our planet, providing habitat for a wide range of plant and animal species and delivering valuable ecological services[1]. Unfortunately, these delicate environments are increasingly threatened by pollution resulting from human activities such as industrial discharges, agricultural runoff, and urban development [2]. Water pollution poses significant risks to both aquatic life and human health, making the remediation of contaminated water bodies a pressing global concern [3]. Traditional methods of water remediation often involve expensive and energy-intensive processes, which may have limited effectiveness and can potentially introduce additional environmental risks. In recent years, an alternative approach that is more sustainable and environmentally friendly has gained recognition: Phytoremediation [4]. This technique harnesses the natural abilities of plants to remove, degrade, and immobilize pollutants, offering a promising strategy for water pollution management [5]

Phytoremediation capitalizes on the inherent capabilities of aquatic plants to absorb, accumulate, and transform various contaminants, thus restoring water quality and promoting the health of aquatic ecosystems [6]. These plants have unique adaptations that allow them to thrive in water environments, making them well-suited for the remediation of polluted water bodies. The mechanisms underlying phytoremediation by aquatic plants are diverse and include processes such as phytoaccumulation, rhizofiltration, phytostabilization, and phytodegradation [7]. These mechanisms enable plants to uptake and sequester pollutants within their tissues, filter contaminants through their root systems, stabilize pollutants in the soil or sediments, and even break down complex pollutants into less harmful forms. Understanding these processes is crucial for designing effective phytoremediation strategies and selecting suitable plant species for specific types of contaminants [8].

Numerous aquatic plant species have demonstrated their potential for phytoremediation across different categories of pollutants, including heavy metals, organic compounds, nutrients, and pesticides [9]. Species such as water hyacinth, duckweed, water lettuce, and reed have been extensively studied for their efficient pollutant removal capabilities. These plants possess unique traits such as rapid growth rates, extensive root systems, and high tolerance to pollutants, enabling them to effectively cleanse water bodies [10]. Phytoremediation using aquatic plants can be implemented through various approaches, including constructed wetlands, floating treatment wetlands, and natural aquatic ecosystems [11]. These systems can be designed and optimized to maximize the efficiency of pollutant removal while simultaneously promoting biodiversity conservation and the creation of habitats. Successful case studies from around the world highlight the potential of phytoremediation in restoring contaminated water bodies and improving overall water quality [12]. Researchers have investigated various plant species for their ability to absorb heavy metals, organic pollutants, and radioactive elements. Studies have focused on identifying hyperaccumulator plants, which are capable of accumulating high levels of contaminants in their tissues. For example, research has shown that plants like sunflowers, willows, and certain types of grasses can effectively remove heavy metals such as lead, cadmium, and arsenic from contaminated sites. Moreover, previous studies have explored the mechanisms through which plants take up and sequester contaminants. These mechanisms include root absorption, translocation to above-ground parts, and storage in vacuoles. Experiments have also examined the influence of environmental factors such as soil pH, temperature, and microbial interactions on the efficiency of phytoremediation. Overall, these studies highlight the potential of phytoremediation as an environmental friendly and cost-effective approach to pollution cleanup, although challenges remain in optimizing plant selection and site-specific practices.

However, phytoremediation also faces limitations and challenges that must be considered. Factors such as plant species selection, management strategies, and long-term effectiveness require careful attention [13]. Additionally, interdisciplinary collaborations, technological advancements, and knowledge exchange are crucial for advancing the field and optimizing the application of phytoremediation in aquatic environments [14].

In conclusion, phytoremediation using aquatic plants presents a promising approach to addressing water pollution challenges in a sustainable and environmentally friendly manner. By harnessing the natural capabilities of aquatic plants, we can restore contaminated water bodies, safeguard aquatic ecosystems, and protect the well-being of wildlife and human populations [15]. Continued research and the implementation of phytoremediation strategies will contribute to the development of effective and sustainable water management practices worldwide.

2. MECHANISMS OF PHYTOREMEDIATION

Understanding the mechanisms by which aquatic plants remediate pollutants is crucial for designing effective phytoremediation strategies. This section discusses the various processes involved, including phytoaccumulation, rhizofiltration, phytostabilization, and phytodegradation. It also highlights the factors influencing plant uptake and transformation of pollutants. Phytoremediation is a remarkable process that explores the natural abilities of aquatic plants to remediate water pollution. These plants utilize various mechanisms to remove, transform, or immobilize pollutants present in water bodies [16]. The specific mechanisms employed depend on the type of pollutant and the characteristics of the plant species involved. Understanding these mechanisms is vital for effective phytoremediation strategies [17].

2.1 Phytoextraction

Phytoextraction is a specific strategy under the umbrella of phytoremediation. In this approach, plants draw out pollutants from the soil through their root system and relocate these substances into their above-ground parts [18]. The primary application of this method is to clean up soil contaminated with heavy metals. Certain plant species, referred to as hyperaccumulators, display an extraordinary capacity to absorb and amass these heavy metals within their tissue. Heavy metals include lead, cadmium, arsenic, and zinc [19]. After these plants have successfully absorbed and concentrated the contaminants, they are then harvested. Following this, the contaminants are extracted from the plant matter and handled in a secure manner [20]. In instances where the pollutants include valuable metals like gold or rare earth elements, a process termed "phytomining" can be applied to recover these metals for potential reuse [21]. A variety of factors can influence the efficiency of phytoextraction. This includes the nature and level of the contaminant, how deep the contaminant is located, the characteristics of the soil, the growth characteristics of the plant, and the plant's capacity to absorb and tolerate the contaminant [22]. Compared to conventional remediation techniques, phytoextraction offers several benefits. It is usually more cost-effective, causes less disruption to the environment, and aligns better with ecological principles [23]. However, it should be noted that phytoextraction is not a quick solution, and may not be suitable for dealing with all types of pollutants or in every environmental context.

2.2 Rhizofiltration

Rhizofiltration is a method of phytoremediation, which uses plants to remove contaminants from soil or water [24]. It specifically involves employing the root system of plants to absorb and filter pollutants, such as heavy metals, organic compounds, and excess nutrients, from contaminated water sources [25]. Rhizofiltration takes advantage of certain plants known as hyperaccumulators, which possess the natural ability to tolerate high levels of toxic substances without being harmed. Examples of hyperaccumulator species include willows, poplars, and water hyacinths, among others. The process of rhizofiltration involves passing contaminated water through a system that [26] contains the roots of hyperaccumulator plants. As the water flows through the roots, the plants take up the pollutants, which can be either stored in their root tissues or transformed into less harmful substances through various biochemical processes. The purified water is then collected and discharged, while the pollutants remain trapped within the plants [27]

Rhizofiltration offers several advantages as a remediation technique. It is cost-effective and environmentally friendly since it relies on natural processes and does not require extensive infrastructure or energy consumption [28].

Moreover, it is applicable to both terrestrial and aquatic environments, making it versatile for different contaminated sites. Additionally, rhizofiltration can be combined with other phytoremediation methods to enhance overall pollutant removal efficiency [29]. The success of rhizofiltration depends on choosing the right hyperaccumulator plants, the contaminant types and concentrations, the specific site conditions. The effectiveness of rhizofiltration may vary based on these factors, and in some cases, additional treatment methods may be necessary to achieve complete remediation [30].

2.3 Phytostabilization

Phytostabilization is an environmental remediation technique employed to stabilize and immobilize contaminants in soil or sediment using plants [31]. It is a form of phytoremediation that aims to reduce the mobility and bioavailability of pollutants, especially heavy metals, and metalloids. Phytostabilization involves selecting specific plant species that can tolerate and accumulate contaminants in their roots and above-ground tissues [32]. These plants, known as metal-tolerant or metal-hyperaccumulating plants, play a crucial role in minimizing the spread of contaminants and mitigating potential risks to human health and the environment [33].

The process of phytostabilization encompasses the following steps:

1. Plant Selection: Appropriate plant species are chosen based on their ability to withstand the contaminants present in the soil or sediment. These plants should possess a strong affinity for absorbing and storing metals in their roots[34].
2. Establishment and Growth: The selected plants are cultivated and established in the contaminated site. They are allowed to grow and develop a robust root system, which is essential for the uptake and containment of contaminants [35].
3. Contaminant Uptake: The plants absorb contaminants primarily through their root systems. They accumulate contaminants in their roots, reducing their movement through the soil and preventing leaching into groundwater[36].
4. Immobilization: Once the plants uptake the contaminants, they are immobilized within the plant tissues. This immobilization occurs through various mechanisms such as complexation, precipitation, or adsorption onto root surfaces [37] .
5. Long-term Stabilization: The planted vegetation helps stabilize the contaminants in place, preventing their dispersion and reducing the risk of exposure. The plants act as a physical barrier, preventing erosion and minimizing the transport of contaminants by wind or water [38].

Phytostabilization offers several advantages as a remediation technique. It is cost-effective, environmentally friendly, and sustainable. It can be implemented in various settings, such as mine tailings, industrial sites, and areas contaminated with heavy metals [24]. Additionally, phytostabilization promotes habitat restoration and biodiversity by establishing vegetation in degraded areas [39]. However, the effectiveness of phytostabilization depends on factors such as plant selection, site conditions, contaminant properties, and long-term maintenance [40]. Achieving significant results may require extended periods; in some cases, combining it with other remediation methods can optimize outcomes. Regular monitoring and management are essential to ensure the ongoing stability and performance of the phytostabilization system [41].

2.4 Phytodegradation

Phytodegradation is a phytoremediation technique that utilizes plants to degrade or break down contaminants in soil, water, or air. It harnesses the inherent ability of certain plant species to metabolize or transform pollutants into less harmful substances through biochemical processes [42].

The process of phytodegradation involves several steps:

1. Plant Selection: Plant species are carefully chosen based on their ability to degrade the specific contaminants of concern. Different plants possess varying capacities to metabolize different types of pollutants [43].
2. Contaminant Uptake: Plants absorb contaminants from the environment, typically through their roots or leaves. The contaminants can enter the plant tissues or be adsorbed onto the plant surfaces [44].
3. Metabolism and Transformation: Once inside the plant, the contaminants undergo

metabolic processes facilitated by enzymes and other biochemical mechanisms. These processes may involve oxidation, reduction, hydrolysis, or other reactions, leading to the breakdown or transformation of the contaminants into less toxic forms [45].

4. Plant Growth and Maintenance: The plants continue to grow and maintain their metabolic activities, enabling the ongoing degradation of contaminants over time [46].

Phytodegradation offers several advantages as a remediation technique. It is cost-effective, environmentally friendly, and sustainable, as it harnesses natural processes and minimizes the need for extensive infrastructure [47]. Phytodegradation can be applied to various types of contaminants, including organic pollutants, pesticides, petroleum hydrocarbons, and volatile organic compounds [48]. It is adaptable to both terrestrial and aquatic environments. However, the effectiveness of phytodegradation depends on various factors, such as plant selection, contaminant concentration, site conditions, and the availability of essential nutrients and other factors required for plant growth and metabolism [49]. The process of phytodegradation may require time to achieve significant degradation, and its efficacy can be influenced by seasonal variations and climatic conditions. Careful selection of appropriate plant species and regular monitoring of the remediation process is crucial for successful phytodegradation. In some cases, combining phytodegradation with other remediation techniques may be necessary to optimize results and ensure complete remediation [50].

It's important to note that these mechanisms can occur concurrently or sequentially, depending on the specific plant species, pollutant type, and environmental conditions. The effectiveness of phytoremediation in aquatic plants is influenced by factors such as pollutant concentration, plant species selection, growth conditions, and the overall health of the aquatic ecosystem [51]. Understanding and harnessing these mechanisms is crucial for designing and implementing successful phytoremediation strategies using aquatic plants. By leveraging their natural capabilities, we can utilize these plants as powerful tools to combat water pollution and restore the health of aquatic ecosystems [52].

3. AQUATIC PLANT SPECIES FOR PHYTOREMEDIATION

Numerous aquatic plant species have demonstrated their capability to remediate different types of pollutants. This section presents a comprehensive analysis of some commonly studied species, such as water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna spp*.), water lettuce (*Pistia stratiotes)*, and reed (*Phragmites australis*). It examines their unique characteristics, pollutant tolerance, and efficiency in remediating specific contaminants.

4. APPLICATION OF AQUATIC PLANTS IN WATER REMEDIATION

This section explores the practical implementation of phytoremediation using aquatic plants. It discusses the design and optimization of phytoremediation systems, including constructed wetlands, floating treatment wetlands, and natural aquatic ecosystems.[58]. Aquatic plants are highly valuable in water remediation due to their ability to enhance water quality and restore ecosystems. They find application in various ways:

Constructed Wetlands: Aquatic plants are commonly used in constructed wetlands, which are designed to replicate natural wetland environments. By incorporating aquatic plants like cattails, bulrushes, and sedges, along with specific substrate layers, these wetlands treat wastewater or stormwater runoff. As water passes through the wetland, the plants and their root systems aid in the physical, chemical, and biological removal of pollutants [17] .

Phytofiltration: Aquatic plants serve as natural filters in phytofiltration, where they are planted in water bodies or channels [59] They help trap suspended particles, sediment, and absorb nutrients and pollutants. This approach improves water quality by reducing turbidity and removing excess nutrients, heavy metals, and organic compounds [60].

Floating Treatment Wetlands (FTWs): FTWs are floating platforms or rafts that support the growth of aquatic plants. Typically made from recycled materials, these rafts are placed on the water's surface, providing a substrate for aquatic plants to root [61]. The plants' roots extend into the water, absorbing nutrients and pollutants. FTWs offer a cost-effective and scalable solution for improving water quality in ponds, lakes, and other water bodies, especially in areas where traditional wetland construction is challenging [62].

Algal Biofiltration: Certain aquatic plants like water hyacinths and duckweeds are used in algal biofiltration systems. These plants establish a symbiotic relationship with algae, providing a surface area for their attachment and growth [63]. The algae, in turn, aid in nutrient removal by utilizing excess nitrogen and phosphorus. Algal biofiltration systems effectively treat nutrient-rich wastewater, reduce algal blooms, and enhance water quality [64].

Riparian Buffer Zones: Riparian buffer zones are vegetated areas along the banks of rivers, streams, and other water bodies [65]. Aquatic plants, trees, shrubs, and herbaceous species are planted in these zones to act as natural filters and stabilizers. They intercept and absorb pollutants like sediments, nutrients, and pesticides before they reach the water body, safeguarding water quality and preventing erosion [66].

Phytoremediation: Aquatic plants possess the ability to accumulate and metabolize contaminants through a process known as phytoremediation [67]. This approach is particularly valuable for cleaning up contaminated water bodies, including industrial wastewater or polluted lakes. Aquatic plants absorb and break down pollutants like heavy metals, organic compounds, and pesticides, thereby reducing their concentration in the water and sediments [68].

The application of aquatic plants in water remediation offers a versatile and environmentally friendly approach that can be tailored to specific water quality issues [69]. Careful selection of suitable plant species, consideration of site-specific conditions, and ongoing monitoring and management are crucial for successful implementation [70].

5. ADVANTAGES AND LIMITATIONS OF PHYTOREMEDIATION

Phytoremediation offers several advantages over traditional remediation methods. This section explores the ecological, economic, and social benefits of phytoremediation, including its potential for biodiversity conservation and sustainable resource recovery. Additionally, it addresses the limitations and challenges associated with phytoremediation, such as plant species selection, management, and long-term effectiveness.

Table 1. Represents the aquatic species and the types of contaminants they can accumulate

Aquatic Species	Contaminant	Description
Typha latifolia (Common Cattail)	Heavy Metals, Nutrients	Fast-growing and robust, common cattails are used to remove a wide range of contaminants [53].
Phragmites australis (Common Reed)	Heavy Metals, Nutrients, Hydrocarbons	This plant species can tolerate a wide variety of environmental conditions and can be found worldwide. It's used for the removal of nutrients, heavy metals, and some organic compounds [54].
Lemna minor (Duckweed)	Nutrients, Heavy Metals	Duckweed is a small floating plant. It's especially effective at nutrient uptake and is often used in nutrient-rich environments [55].
Pistia stratiotes (Water Lettuce)	Heavy Metals, Nutrients	This free-floating perennial herb can be found in a wide range of climates and has been used to treat water contaminated with heavy metals [7]
Eichhornia crassipes (Water Hyacinth)	Nutrients, Heavy Metals, Organic Compounds	This fast-growing plant is effective at nutrient uptake and is also used in the removal of organic compounds and heavy metals [56].
Azolla filiculoides (Water Fern)	Heavy Metals, Nutrients	This small aquatic fern is known for its ability to absorb heavy metals from the water. It also absorbs nutrients rapidly, making it suitable for nutrient-rich environments [57].

Phytoremediation with aquatic plants provides an eco-friendly and cost-efficient approach to detoxifying contaminated water. Here are some benefits of this process [71]:

1. Economical: Unlike conventional remediation methods such as pump and treat or excavation, phytoremediation incurs a lower cost. It does not require complex machinery or significant manual labor [72].
2. Eco-conscious: This technique is entirely natural, not introducing any additional harmful substances to the environment [73].
3. On-site treatment: Aquatic plants can neutralize pollutants directly within the contaminated water body. This avoids the hazardous and expensive process of moving contaminated materials to a separate treatment location [74] .
4. Visual Improvement: Phytoremediation can revitalize a polluted water body, enhancing its overall visual appeal and transforming it into a more pleasant environment [75].
5. Enhanced Biodiversity: The process promotes biodiversity by providing new habitats for various wildlife species [76] .
6. Secondary Pollutants Control: Aquatic plants can absorb secondary pollutants such as nitrates, phosphates, and heavy metals, preventing further water quality deterioration [77].
7. Carbon Capture: Plants naturally absorb CO_2, aiding in the fight against climate change [78]
8. Flexible Application Various aquatic plants can be used depending on the specific contaminants present, such as oil, pesticides, heavy metals, or organic pollutants[79].
9. Long-lasting Solution: After being introduced, these plants can proliferate and offer continued remediation benefits over an extended duration [80]
10. Biomass Utilization: The plant biomass harvested after the process can potentially be converted into bioenergy, adding further environmental and economic gains [81].

Despite these benefits, it's essential to understand that phytoremediation is not a quick remedy. It requires more time than traditional methods, and its effectiveness varies depending on the type of pollutant [82]. Additionally, careful management is needed when introducing non-native plant species for phytoremediation to prevent potential ecological disruptions.

Phytoremediation with aquatic plants, while having several advantages, comes with its set of challenges:

1. Slow Process: Compared to conventional remediation methods, phytoremediation is often slower, needing multiple growth cycles to detoxify a site thoroughly, depending on the contamination level and nature[83] .
2. Limited Reach: Plants can only cleanse pollutants within the zone of their roots, restricting their effectiveness in scenarios of deep-seated contamination [84].
3. Specificity in Pollutant Uptake: Plants differ in their capacity to absorb or degrade certain contaminants, implying that not all aquatic plants can handle all kinds of pollutants effectively [85] .
4. Bioaccumulation Risk: The potential for toxic substances to accumulate within plant tissues can create a hazard for animals that consume these plants or if the plants are discarded without proper care [86] .
5. Requires Maintenance: Keeping the plants healthy and ensuring their effectiveness in absorbing pollutants necessitates regular maintenance, including monitoring and potential application of fertilizers or pest control [87] .
6. Risk of Invasive Species: Plants introduced for phytoremediation, particularly non-native species, could become invasive and disrupt local ecosystems [88] .
7. Seasonal Impact: Seasonal changes, such as temperature fluctuations and variations in light, can affect plant growth and metabolism, influencing phytoremediation efficiency [89].
8. Recontamination Possibility: If not correctly managed and harvested after they have absorbed pollutants, plants can pose a risk of recontamination [90] .
9. Unfit for Certain Sites: Some polluted sites may be inhospitable for plant growth due to harsh conditions such as extreme pH levels, high salinity, or excessive toxicity [91].
10. Not Effective for All Contaminants: Phytoremediation might not work effectively for all pollutants, especially non-biodegradable substances [92] .

Despite these issues, with proper management and understanding of its constraints, phytoremediation can still be a beneficial environmental remediation tool.

6. FUTURE PERSPECTIVES OF PHYTOREMEDIATION

Phytoremediation, the practice of using plants to remediate polluted environments, has shown a great deal of potential for sustainable, economical, and environmentally sound remediation [96]. As we cast our eyes to the future, we can envisage several promising advancements in this area:

1. Genetic Alterations: With the progression of genetic engineering and plant biology, we might see the development of plant species tailored specifically to absorb, degrade, or neutralize certain pollutants. This can significantly amplify the efficacy of phytoremediation and extend its reach to deal with a broader array of pollutants [93].
2. Multidisciplinary Approaches: Merging phytoremediation with other remediation tactics, like biochar application, microbial remediation, or nanotechnology, could potentially improve its efficacy. This multidisciplinary approach could help tackle some of the phytoremediation's limitations and establish more comprehensive remediation strategies [94].
3. Contribution to Climate Change Mitigation Given their ability to sequester carbon, plants used in phytoremediation could contribute to climate change mitigation efforts [95]. As climate change concerns escalate, the role of phytoremediation in capturing carbon and enhancing soil health may become progressively important [96].
4. Sophisticated Monitoring and Data Analysis: Emerging technologies could allow for more accurate monitoring of phytoremediation processes and the application of advanced data analysis techniques to optimize these processes [97]. This could assist in maximizing the effectiveness of phytoremediation and foster a deeper understanding of the factors that drive its success [98].
5. Policy and Regulation: As our comprehension of phytoremediation's benefits expands, we might witness more policy and regulatory backing for its usage [99]. This could entail initiatives to encourage phytoremediation, guidelines for its implementation, and standards for tracking its effectiveness [100].
6. Commercial Applications Potential commercial uses of phytoremediation, like producing biofuel from plants involved[101] in remediation, could become a key area of growth. This could make phytoremediation not only an environmental solution but also a commercially feasible one [101]].
7. Education and Community Involvement Enhancing awareness about the advantages of phytoremediation and involving communities in its execution can play a crucial role in endorsing its use. This could encompass educational programs, community-led phytoremediation projects, and citizen science endeavors [102].
8. Ongoing Research There will be a need for additional research to investigate the potential ecological impacts of phytoremediation, establish best practices for its application, and pinpoint the most effective plant species for various types of pollutants [103].

These advancements could position phytoremediation as an essential strategy in our toolbox for dealing with environmental pollution, contributing to sustainable and resilient communities in the future.

7. CONCLUSION

Phytoremediation using aquatic plants

- Promising and effective method for addressing water pollution and contamination.

-Environmental Benefits

- Utilizes natural abilities of aquatic plants to eliminate, break down, or immobilize pollutants.
- Restores water quality and ecosystems.

Versatility

- Selection of different aquatic plants based on specific contaminants and site conditions.
- Targets removal of heavy metals, organic compounds, nutrients, and radioactive substances.

Cost-effectiveness

- More economical than traditional remediation methods.
- Minimal infrastructure and energy input required, making it sustainable and viable.

Additional Benefits

- Creates habitats and food sources for aquatic organisms.
- Contributes to biodiversity conservation.

- Enhances the aesthetic value of water bodies.
- Provides protective buffers against erosion and improves shoreline stability.
- Mitigates impacts of floods and stormwater runoff.

Success Factors

- Careful selection of plant species and consideration of site-specific conditions.
- Monitoring pollutant concentrations and remediation duration.
- Long-term monitoring and management for sustained effectiveness.

Overall Potential

- Sustainable, cost-effective, and environmentally friendly solution for water pollution remediation.
- Harnessing nature's power to restore and preserve water body health for future generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

Details of the AI usage are given below:

1. ChatGPT Version 3.5.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Rodrigues-Filho JL, et al. From ecological functions to ecosystem services: Linking coastal lagoons biodiversity with human well-being. Hydrobiologia. 2023;850(12–13):2611–2653.
2. Akhtar N, Syakir Ishak MI, Bhawani SA, Umar K. Various natural and anthropogenic factors responsible for water quality degradation: A review. Water. 2021;13(19):2660.
3. Hojjati-Najafabadi A, Mansoorianfar M, Liang T, Shahin K, Karimi-Maleh H. A review on magnetic sensors for monitoring of hazardous pollutants in water resources. Sci. Total Environ. 2022;824:153844.
4. Khellaf N, Djelal H, Amrane A. An overview of the valorization of aquatic plants in effluent depuration through phytoremediation processes. Appl. Microbiol. 2022;2(2):309–318.
5. Naha A, et al. A hypothetical model of multi-layered cost-effective wastewater treatment plant integrating microbial fuel cell and nanofiltration technology: A comprehensive review on wastewater treatment and sustainable remediation. Environ. Pollut. 2023;323:121274.
6. Nattrass MP. Evaluation of constructed wetlands for phytoremediation of selenium-impacted waters. search.proquest.com; 2020. Available:https://search.proquest.com/openview/50f376b10edf2d861996e80fa165efc7/1.pdf?pq-origsite=gscholar&cbl=18750&diss=y
7. Pang YL, Quek YY, Lim S, Shuit SH. Review on phytoremediation potential of floating aquatic plants for heavy metals: A promising approach. Sustain. Sci. Pract. Policy. 2023;15(2):1290.
8. Singh BSM, Singh D, Dhal NK. Enhanced phytoremediation strategy for sustainable management of heavy metals and radionuclides. Case Studies in Chemical and Environmental Engineering. 2022;5: 100176.
9. Zhou Y, Stepanenko A, Kishchenko O, Xu J, Borisjuk N. Duckweeds for phytoremediation of polluted water. Plants. 2023;12(3). DOI: 10.3390/plants12030589
10. Hussain I, et al. Effect of metals or trace elements on wheat growth and its remediation in contaminated soil. J. Plant Growth Regul. 2023;42(4):2258–2282.
11. Nasrollahzadeh M, Sajjadi M, Iravani S, Varma RS. Green-synthesized nanocatalysts and nanomaterials for water treatment: Current challenges and future

perspectives. J. Hazard. Mater. 2021; 401:123401.
12. Uddin M, et al. An overview on water quality, pollution sources, and associated ecological and human health concerns of the lake water of megacity: A case study on Dhaka city lakes in Bangladesh. Urban Water J. 2023;20(3):261–277.
13. Panis B, Nagel M, Van den Houwe I. Challenges and prospects for the conservation of crop genetic resources in field Genebanks, in *In vitro* Collections and/or in Liquid Nitrogen. Plants. 2020; 9(12).
DOI: 10.3390/plants9121634
14. Hou D, Bolan NS, Tsang DCW, Kirkham MB, O'Connor D. Sustainable soil use and management: An interdisciplinary and systematic approach. Sci. Total Environ. 2020;729:138961.
15. Nadow NO, Dorrian-Bak HB, Maloney E. Leveraging earth law principles to protect ocean rights: Safeguarding intrinsic value and well-being for communities and the environment; 2023.
Available at SSRN 4439568,
Available:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4439568
16. Akash S, Sivaprakash B, Raja VCV, Rajamohan N, Muthusamy G. Remediation techniques for uranium removal from polluted environment - Review on methods, mechanism and toxicology. Environ. Pollut. 2022;302:119068.
17. Yaashikaa PR, Kumar PS, Jeevanantham S, Saravanan R. A review on bioremediation approach for heavy metal detoxification and accumulation in plants. Environ. Pollut. 2022;301:119035.
18. Christian E, Beniah I. Phytoremediation of polluted waterbodies with aquatic plants: Recent progress on heavy metal and organic pollutants. Preprints; 2019.
DOI: 10.20944/preprints201909.0020.v1
19. Obasi PN, Akudinobi BB. Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. Applied Water Science. 2020; 10(7):184.
20. Liu Y, Wu T, White JC, Lin D. A new strategy using nanoscale zero-valent iron to simultaneously promote remediation and safe crop production in contaminated soil. Nat. Nanotechnol. 2021;16(2):197–205.
21. Gawroński S, Łutczyk G, Szulc W, Rutkowska B. Urban mining: Phytoextraction of noble and rare earth elements from urban soils. Arch. Environ. Prot. 2023;24–33.
22. Opare O, Mirkouei A. Environmental and economic assessment of a portable e-waste recycling and rare earth elements recovery process. ASME 2021 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. 2021;V005T05A007.
23. Ur Rehman Z, Junaid MF, Ijaz N, Khalid U, Ijaz Z. Remediation methods of heavy metal contaminated soils from environmental and geotechnical standpoints. Sci. Total Environ. 2023;867: 161468.
24. Bhat SA, et al. Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. Chemosphere. 2022;303:134788.
25. Saxena G, Bharagava RN. Bioremediation of industrial waste for environmental safety: Industrial waste and its management. 2020;1.
26. Sharma P, et al. Engineered microbes as effective tools for the remediation of polyaromatic aromatic hydrocarbons and heavy metals. Chemosphere. 2022;306: 135538.
27. Gedik K, Eryaşar AR, Gözler AM. The microplastic pattern of wild-caught Mediterranean mussels from the Marmara Sea. Mar. Pollut. Bull. 2022;175:113331.
28. Bethoux O. Hydrogen fuel cell road vehicles and their infrastructure: An option towards an environmentally friendly energy transition. Energies. 2020;13(22): 6132.
29. Kanwar VS, Sharma A, Srivastav AL, Rani L. Phytoremediation of toxic metals present in soil and water environment: A critical review. Environ. Sci. Pollut. Res. Int. 2020;27(36):44835–44860.
30. Kaleekkal NJ, Mural PKS, Vigneswaran S, Ghosh U. Sustainable technologies for water and wastewater treatment. CRC Press; 2021.
31. Bakshe P, Jugade R. Phytostabilization and rhizofiltration of toxic heavy metals by heavy metal accumulator plants for sustainable management of contaminated industrial sites: A comprehensive review. Journal of Hazardous Materials Advances. 2023;10:100293.

32. Mengistu GT, Sahilu G, Mulat W, Amare E. Assessment of native plants for their potential to remove trace metals around Legadembi tailings dam, Southern Ethiopia. Environ. Sci. Pollut. Res. Int. 2023;30(19):55615–55624.
33. Patel M, Kumari A, Parida AK. Arsenic tolerance mechanisms in plants and potential role of arsenic hyperaccumulating plants for phytoremediation of arsenic-contaminated soil. In Plant Ecophysiology and Adaptation under Climate Change: Mechanisms and Perspectives II: Mechanisms of Adaptation and Stress Amelioration M. Hasanuzzaman, Ed., Singapore: Springer Singapore. 2020;137–162.
34. Naeem M, Aftab T, Ansari AA, Gill SS, Macovei A. Hazardous and trace materials in soil and plants: sources, effects, and management. Academic Press; 2022.
35. Pidlisnyuk V, et al. Phytotechnologies for Site Remediation. In Phytotechnology with Biomass Production, CRC Press. 2021;5–36.
36. Meena VS. Role of Rhizospheric microbes in soil: volume 1: Stress management and agricultural sustainability. Springer; 2018.
37. Haak MR, Indraratne SP. Soil amendments for vanadium remediation: A review of remediation of vanadium in soil through chemical stabilization and bioremediation. Environ. Geochem. Health; 2023.
DOI: 10.1007/s10653-023-01498-8
38. Kostić O, Mitrović M, Pavlović P. Impact of weathering and revegetation on pedological characteristics and pollutant dispersion control at coal fly ash disposal sites. In Advances in Understanding Soil Degradation E, Saljnikov, Mueller L, Lavrishchev A, Eulenstein F, Eds., Cham: Springer International Publishing. 2022; 473–505.
39. Austin AT, Ballaré CL. Attackers gain the upper hand over plants in the face of rapid global change. Curr. Biol. 2023;33 (11):R611–R620.
40. Shackira AM, Puthur JT. Phytostabilization of heavy metals: Understanding of principles and practices. In Plant-Metal Interactions. Srivastava S, Srivastava AK, Suprasanna P. Eds., Cham: Springer International Publishing. 2019;263–282.
41. Kumar A, Das SK, Nainegali L, Reddy KR. Phytostabilization of coalmine overburden waste rock dump slopes: Current status, challenges, and perspectives. Bull. Eng. Geol. Environ. 2023;82(4):130.
42. Reddy M, Shende SN, PSD. Environmental protection: Critical perspectives in science and literature. Tredition; 2021.
43. Kurade MB, Ha YH, Xiong JQ, Govindwar SP, Jang M, Jeon BH. Phytoremediation as a green biotechnology tool for emerging environmental pollution: A step forward towards sustainable rehabilitation of the environment. Chem. Eng. J. 2021;415:129040.
44. Karalija E, et al. Interplay of plastic pollution with algae and plants: Hidden danger or a blessing? J. Hazard. Mater. 2022;438:129450.
45. Varjani SJ, Parameswaran B, Kumar S, Khare SK. Biosynthetic technology and environmental challenges. Springer; 2017.
46. Naing AH, Kim CK. Abiotic stress-induced anthocyanins in plants: Their role in tolerance to abiotic stresses. Physiol. Plant. 2021;172(3):1711–1723.
47. Alprol AE, Mansour AT, Abdelwahab AM, Ashour M. Advances in green synthesis of metal oxide nanoparticles by marine algae for wastewater treatment by adsorption and Photocatalysis techniques. Catalysts. 2023;13(5):888.
48. Mfarrej MFB, et al. Floating Treatment Wetlands (FTWs) is an innovative approach for the remediation of petroleum hydrocarbons-contaminated water. J. Plant Growth Regul. 2023;42 (3):1402–1420.
49. Mondal S, Mukherjee SK, Hossain ST. Exploration of Plant Growth Promoting Rhizobacteria (PGPRs) for heavy metal bioremediation and environmental sustainability: Recent advances and future prospects. In Modern Approaches in Waste Bioremediation: Environmental Microbiology MP. Shah, Ed., Cham: Springer International Publishing. 2023; 29–55.
50. Tshangana CS, Muleja AA, Kuvarega AT, Malefetse TJ, Mamba BB. The applications of graphene oxide quantum dots in the removal of emerging pollutants in water: An overview. Journal of Water Process Engineering. 2021;43:102249.
51. Ansari AA, Naeem M, Gill SS, AlZuaibr FM. Phytoremediation of contaminated waters: An eco-friendly technology based on aquatic macrophytes application. Egypt. J. Aquat. Res. 2020;46(4):371–376.

52. Abell R, et al. Freshwater biodiversity conservation through source water protection: Quantifying the potential and addressing the challenges. Aquat. Conserv. 2019;29(7):1022–1038.
53. Shiryaev G, Maleva M, Borisova G, Tripti, Voropaeva O, Kumar A. Phytomitigation potential and adaptive responses of helophyte *Typha latifolia L*. to copper smelter-influenced heavily multi-metal contamination. Environ. Sci. Pollut. Res. Int; 2023.
DOI: 10.1007/s11356-023-25973-y
54. Milke J, Gałczyńska M, Wróbel J. The importance of biological and ecological properties of Phragmites Australis (Cav.) Trin. Ex Steud. In Phytoremendiation of Aquatic Ecosystems—The Review. Water. 2020;12(6):1770.
55. Mahapatra S, Samal K, Dash RR. Waste Stabilization Pond (WSP) for wastewater treatment: A review on factors, modelling and cost analysis. J. Environ. Manage. 2022;308:114668.
56. Kamusoko R, Jingura RM. Phytoremediation potential of non-edible biofuel plants: Physic nut (Jatropha curcas), Castor Bean (*Ricinus communis*) and Water Hyacinth (*Eichhornia crassipes*). Bioenergy Crops; 2022.
DOI:10.1201/9781003043522-4/phytoremediation-potential-non-edible-biofuel-plants-physic-nut-jatropha-curcas-castor-bean-ricinus-communis-water-hyacinth-eichhornia-crassipes-reckson-kamusoko-raphael-jingura
57. Herath BM, et al. Soil Heavy Metal absorption potential of *Azolla pinnata* and *Lemna gibba* with arbuscular mycorrhizal fungi in Rice (*Oryza sativa L*.) Farming," Sustain. Sci. Pract. Policy. 2023;15(5):4320.
58. Sharma R, Vymazal J, Malaviya P. Application of floating treatment wetlands for stormwater runoff: A critical review of the recent developments with emphasis on heavy metals and nutrient removal. Sci. Total Environ. 2021;777:146044.
59. Meitei MD, Prasad MNV. Potential of *Typha latifolia L*. for phytofiltration of iron-contaminated waters in laboratory-scale constructed microcosm conditions. Applied Water Science. 2021;11(2):47.
60. Palakkeel Veetil D, Arriagada EC, Mulligan CN, Bhat S. Filtration for improving surface water quality of a eutrophic lake. J. Environ. Manage. 2021;279:111766.
61. Samal K, Kar S, Trivedi S. Ecological floating bed (EFB) for decontamination of polluted water bodies: Design, mechanism and performance. J. Environ. Manage. 2019;251:109550.
62. Shen S, Li X, Lu X. Recent developments and applications of floating treatment wetlands for treating different source waters: A review. Environ. Sci. Pollut. Res. Int. 2021;28(44):62061–62084.
63. Zhang B, Wu L, Shi W, Zhang Z, Lens PNL. A novel strategy for rapid development of a self-sustaining symbiotic algal-bacterial granular sludge: Applying algal-mycelial pellets as nuclei. Water Res. 2022;214:118210.
64. Glibert PM, Berdalet E, Burford MA, Pitcher GC, Zhou M. Global ecology and oceanography of harmful algal blooms. Springer; 2018.
65. Blankenberg AGB, Skarbøvik E. Phosphorus retention, erosion protection and farmers' perceptions of riparian buffer zones with grass and natural vegetation: Case studies from South-Eastern Norway. Ambio. 2020;49(11): 1838–1849.
66. Zhu X, et al. Reductions in water, soil and nutrient losses and pesticide pollution in agroforestry practices: A review of evidence and processes. Plant Soil. 2020;453(1):45–86.
67. Huang D, et al. Phytoremediation of poly- and perfluoroalkyl substances: A review on aquatic plants, influencing factors, and phytotoxicity. J. Hazard. Mater. 2021;418: 126314.
68. Banerjee A, Cardozo S, Khuntia SP, Upadhyay AK. Chapter 19 - Phytoremediation of pharmaceutical wastes. In Phytoremediation RA, Bhat FMP, Tonelli GH, Dar, Hakeem K., Eds., Academic Press. 2022;387–414.
69. Lustenberger S, Castro-Muñoz R. Advanced biomaterials and alternatives tailored as membranes for water treatment and the latest innovative European water remediation projects: A review. Case Studies in Chemical and Environmental Engineering. 2022;5:100205.
70. Chatterjee S. Site assessment, suitability, and strategy references for in-situ phytoremediation: a case study of Asansol-pandabeswar mining region. Suitability, and Strategy References for In-Situ Phytoremediation: A Case Study of Asansol-Pandabeswar Mining Region.

Available:https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4436188
71. Garg S, Roy A. Chapter 18 - Phytoremediation: An alternative approach for removal of dyes. In Phytoremediation RA, Bhat FMP, Tonelli G, Dar H, Hakeem K. Eds., Academic Press. 2022;369–386.
72. Malik JA. Advances in bioremediation and phytoremediation for sustainable soil management: Principles, monitoring and remediation. Springer; 2022.
73. Jadhav DA, Pandit S, Gajalakshmi S, Shah MP. Scaling up of microbial electrochemical systems: From reality to scalability. Elsevier; 2022.
74. El Din Mahmoud A, Fawzy M, Khan NA. Artificial intelligence and modeling for water sustainability: Global challenges. CRC Press; 2023.
75. Rocha CS, Rocha DC, Kochi LY, Carneiro DNM, Dos Reis MV, Gomes MP. Phytoremediation by ornamental plants: A beautiful and ecological alternative. Environ. Sci. Pollut. Res. Int. 2022;29(3): 3336–3354.
76. Thomsen MS, et al. Heterogeneity within and among co-occurring foundation species increases biodiversity. Nat. Commun. 2022;13(1):581.
77. Huang F, et al. Research and engineering application of bypass combined artificial wetlands system to improve river water quality. Journal of Water Process Engineering. 2022;48:102905.
78. Sadatshojaei E, Wood DA, Rahimpour MR. Potential and challenges of carbon sequestration in soils. Applied Soil Chemistry. Wiley. 2021;1–21.
DOI: 10.1002/9781119711520.ch1
79. Mariana M, et al. Recent trends and future prospects of nanostructured aerogels in water treatment applications. Journal of Water Process Engineering. 2022;45: 102481.
80. Liang J, et al. Long-lasting performance of high-flux perovskite membrane for catalytic degradation of organic pollutants. Appl. Catal. B. 2023;327:122440.
81. Edgar VN, Fabián FL, Mario PCJ, Ileana VR. Coupling plant biomass derived from phytoremediation of potential toxic-metal-polluted soils to bioenergy production and high-value by-products—A review. NATO Adv. Sci. Inst. Ser. E Appl. Sci. 2021; 11(7):2982.
82. Saravanan A, et al. Effective water/wastewater treatment methodologies for toxic pollutants removal: Processes and applications towards sustainable development. Chemosphere. 2021;280: 130595.
83. Ahmed SF, et al. Heavy metal toxicity, sources, and remediation techniques for contaminated water and soil. Environmental Technology and Innovation. 2022;25:102114.
84. Kumar P, et al. Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. Sci. Total Environ. 2021; 784:147058.
85. Su F, et al. Removal of total nitrogen and phosphorus using single or combinations of aquatic plants. Int. J. Environ. Res. Public Health. 2019;16(23).
DOI: 10.3390/ijerph16234663.
86. Islam MS, Ahmed MK, Idris AM, Phoungthong K, Habib MA, Mustafa RA. Geochemical speciation and bioaccumulation of trace elements in different tissues of pumpkin in the abandoned soils: Health hazard perspective in a developing country. Toxin Rev. 2022;41(4):1124–1138.
87. Fahad S, et al. Agroforestry systems for soil health improvement and maintenance. Sustain. Sci. Pract. Policy. 2022;14(22): 14877.
88. Prabakaran K, Li J, Anandkumar A, Leng Z, Zou CB, Du D. Managing environmental contamination through phytoremediation by invasive plants: A review. Ecol. Eng. 2019;138:28–37.
89. Da Cunha Cruz Y, Scarpa ALM, Díaz AS, Pereira MP, De Castro EM, Pereira FJ. Influence of seasonal variation to the population growth and ecophysiology of Typha domingensis (Typhaceae). J. Plant Res; 2023.
DOI: 10.1007/s10265-023-01468-2.
90. Alfeus A, Gabriel NN. Applications of aquatic plants in the remediation of aquaculture wastewater: an opportunity for African aquaculture. In Emerging Sustainable Aquaculture Innovations in Africa NN, Gabriel, Omoregie E, Abasubong KP. Eds., Singapore: Springer Nature Singapore. 2023;327–339.
91. Valliere JM, Wong WS, Nevill PG. Preparing for the worst: Utilizing stress-tolerant soil microbial communities to aid ecological restoration in the

anthropocene. Ecological Solutions; 2020. Available:https://besjournals.onlinelibrary.wiley.com/doi/abs/10.1002/2688-8319.12027

92. Sharma J, Sharma S, Soni V. Toxicity of malachite green on plants and its phytoremediation: A review. Regional Studies in Marine Science. 2023;62: 102911.
93. Grohmann L, et al. Detection and identification of genome editing in plants: Challenges and opportunities. Front. Plant Sci. 2019;10:236.
94. Rajput VD, et al. Nanotechnology in the restoration of polluted soil. Nanomaterials (Basel). 2022;12(5). DOI: 10.3390/nano12050769
95. Chauhan NS, Gill SS. The impact of nanoparticles on agriculture and soil. Elsevier; 2023.
96. Kumar S, et al. Pulse-based cropping systems for soil health restoration, resources conservation, and nutritional and environmental security in rainfed agroecosystems. Front. Microbiol. 2022; 13:1041124.
97. Aragona M, et al. New-generation sequencing technology in diagnosis of fungal plant pathogens: A dream comes true? J Fungi (Basel). 2022;8(7). DOI: 10.3390/jof8070737
98. Zhang Y, et al. Control and remediation methods for eutrophic lakes in the past 30 years. Water Sci. Technol. 2020;81(6): 1099–1113.
99. Das A, Ghosh A. Vision Net Zero: A review of decarbonisation strategies to minimise climate risks of developing countries. Environ. Dev. Sustainability; 2023. DOI: 10.1007/s10668-023-03318-6
100. Canadian Parks Council, Principles and Guidelines for Ecological Restoration in Canada's Protected Natural Areas. National Parks Directorate Parks Canada Agency; 2008.
101. Chaney RL, Li YM, Brown SL, Homer FA. Improving metal hyperaccumulator wild plants to develop commercial phytoextraction systems: Approaches and progress. Phytoremediation of; 2020. DOI:10.1201/9780367803148-7/improving-metal-hyperaccumulator-wild-plants-develop-commercial-phytoextraction-systems-approaches-progress-rufus-chaney-yin-ming-li-sally-brown-faye-homer-minnie-malik-scott-angle-alan-baker-roger-reeves-mel-chin.
102. Olabi AG, set al. Role of microalgae in achieving sustainable development goals and circular economy. Sci. Total Environ. 2022;158689.
103. Pandey VC, Mahajan P, Saikia P, Praveen A. Fiber crop-based phytoremediation: Socio-economic and environmental sustainability. Elsevier; 2022.

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