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RESEARCH ARTICLE

Phytoremediation for Water Quality Improvement: A Sustainable Strategy for Pollutant Mitigation in the North China Plain

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ABSTRACT - Phytoremediation is a financially feasible and ecologically sound methodology that capitalizes on the inherent qualities of plants to mitigate and remediate environmental pollutants arising from diverse sources. These pollutants include heavy metals, nutrients, antibiotics, pesticides, as well as other emerging contaminants. This synthesis encompasses a scoping review of phytoremediation, elucidating its fundamental techniques and removal effectiveness. Through a comprehensive examination of existing research, the optimal plant-based remediation scheme for addressing the water quality concerns of Baiyangdian has been identified, demonstrating significant potential for sustainable water resource management in the region.

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1. INTRODUCTION

Aquatic environments play a fundamental and irreplaceable role in the sustenance of human existence and well-being [1], [2]. They provide vital resources and services that contribute to the preservation of biodiversity, while also serving as crucial drivers for pivotal economic domains including agriculture, transportation, and energy generation [3], [4]. Nevertheless, the impacts of human activities encompassing land utilization, industrialization, urbanization, and alterations to the natural topography impose a multitude of stresses and pressures upon aquatic ecosystems [5], [6]. Given the myriad challenges confronting water bodies on a global scale, the international community has proactively formulated precise policy aims to guarantee their preservation and protection [7]. Significantly, under the United Nations' 2030 Agenda for Sustainable Development, encapsulated within its 17 Sustainable Development Goals (SDGs), two goals are dedicated to the pivotal cause of sustainable water governance [8]. These objectives serve to underscore the critical importance of enacting sustainable water policies in pursuit of these overarching aspirations [9].

The adequacy of naturally occurring freshwater resources seems increasingly inadequate in satisfying the continuously expanding requirements, resulting in a pronounced disjunction between the availability and utilization of water. Concurrently, the unregulated discharge of untreated wastewater gives rise to noteworthy ecological hazards [10], [11]. Conversely, the treatment of wastewater offers a prospect to actualize sustainable water governance and harmonize biogeochemical cycles, thereby fostering the adoption of a circular economy paradigm [12]. With escalating water demands persisting within industrial and agricultural domains, the reclamation of wastewater has surfaced as the singular pragmatic recourse to contend with this escalating necessity [13], seeking to ameliorate the mounting requisites for water resources and temper the exacerbation of water quality degradation [14]. In addition to conventional wastewater treatment methods, Phytoremediation represents an economically viable green technology, characterized by its cost-effectiveness and concomitant ecological and aesthetic benefits, have gained global recognition as sustainable approaches to wastewater treatment and quality enhancement [15], [16].

As plants utilize solar energy and their inherent physiological mechanisms, they require minimal additional energy input and generate no secondary pollutants, rendering it a cost-effective and environmentally friendly novel green ecological technology [17], [18]. So, phytoremediation aligns with China’s “Ecological Civilization” policy, which prioritizes low-cost, nature-based solutions for water security. Moreover, the application of phytoremediation can sequester carbon from the environment, as plant photosynthesis reduces atmospheric carbon dioxide levels and stores carbon within their biomass [19], [20]. Looking ahead, the scope of phytoremediation will extend beyond the singular removal of specific pollutants from the environment [21], [22]. It will encompass the remediation of complex pollution matrices within the entire ecosystem, aiming to achieve optimal ecological and societal advantages while simultaneously restoring the quality and functionality of resources [23].

Based on the problems described previously, this study aims to compile pertinent accounts and findings pertaining to phytoremediation. Through the utilization of diverse online search engines to retrieve published literature, it conducts a comprehensive review and synthesis of research outcomes associated with the subject of phytoremediation, with a particular emphasis on their suitability for addressing pollution in BaiyangDian lake.

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2. REMOVAL EFFICIENCY OF VARIOUS POLLUTANTS

In recent years, there has been extensive research into the efficacy of phytoremediation technology for the removal of various pollutants. Subsequent sections provide a compendium of recent studies elucidating the removal efficacy of diverse plant species in relation to different pollutants present within the environment.

2.1 Heavy Metals

Numerous heavy metals currently pose environmental hazards on a global scale, contributing to adverse repercussions on human health [24], [25]. Owing to their enduring presence within the environment for extended durations, often spanning hundreds to thousands of years, these metals engender detrimental consequences for both human and animal well-being [26], [27]. In the context of employing plants for heavy metal remediation, a multitude of factors exert an influence on the efficacy of phytoremediation[28], [29]. These factors encompass the chemical and physical characteristics of water, exudates originating from plants and microorganisms, metal bioavailability, as well as the inherent capacity of plants to engage in processes such as "uptake, accumulation, translocation, sequestration, and detoxification of metals" [30], [31]. The selection criteria for the plants used in phytoremediation are that they should be highly metal tolerant and have a short life cycle, broad distribution, large biomass, and large transport factor (Table 1) [32].

Table 1. List of selected aquatic and terrestrial plants used in the phytoremediation of various heavy metals, including their removal efficiency and translocation factor

Heavy metals	Plants	Percentage removal (%)	Translocation factor (TF)	References
Zn	*Phragmites karka*	69.20	0.89	[33]
	Arundo donax	66.00	0.68	
As	*Phragmites karka*	46.00	0.37	
	Arundo donax	32.00	0.20	
Cd	*Lemna gibba*	95.00	0.87	[34]
	Pistia stratiotes	84.40	0.41	
Cr	*Lemna gibba*	92.00	0.63	
	Pistia stratiotes	88.00	0.74	
Pb	*Sargassum fusiforme*	99.46	/	[35]
	Enteromorpha prolifera	100.00		
Mn	*Sargassum fusiforme*	95.73	/	
	Enteromorpha prolifera	98.17		
Hg	*Lemna minor*	68–94	/	[36]
	Salvinia natans	61–91		
Ni	*Alocasia puber*	95.60	0.17	[37]

2.2 Nutrients

In this section, Table 2 provide a comprehensive compilation of existing references documenting the utilization of aquatic plant species within the domain of wastewater phytoremediation targeting nutrient removal. Additionally, the increased suitability of free-floating aquatic plants for phytoremediation is attributed to their ready availability, robust yield, and the convenience associated with their cultivation, stocking, and subsequent harvest [38], [39].

Table 2. Common aquatic plant species employed in nutrient phytoremediation, along with recorded removal efficiencies

Country	Plants	Removal efficiency	References
Italy	*Phragmites australis* (Constructed wetland)	COD 68%, TSS 80%, TN 49%, TP 47%	[47]
Indonesia	*dan Heliconia,Typha Latifolia, Cyperus papyrus* (Constructed wetland)	COD 51.1%	[48]
Iran	*Arundo donax, Cortaderia selloana, Phragmites australis* (Local species)	BOD_5 88.9%, COD 86.0%, TSS 92.2%, PO_4-P 63.5%, NH_4^+-N 66.5%, NO_3-N 65.7%	[49]
Mexico	*Agapanthus africanus*	BOD_5 90 ± 5%, COD 90 ± 5%	[50]
Cuba	*Typha domingensis*	COD 94%	[51]
Ethiopia	*Phragmites karka*	Nitrogen 96%	[52]

China	*Ipomoea aquatica*	NH_4^+-N 75.8%, NOx-N 66.1%, TN 70.3%, TP 86%	[53]

The potential of aquatic plants in entrapment of nutrients is harnessed for the purpose of addressing eutrophication within environments such as lakes, ponds, and constructed wetlands [40], [41]. Nitrogen and phosphorous predominantly contribute to eutrophication, often serving as limiting factors for primary growth within most freshwater ecosystems [42], [43]. Furthermore, the recovery of nitrogen and phosphorous from wastewater is regarded as a significant innovation with the potential to cultivate bioresource feedstocks suitable for the synthesis of fertilizers, phosphates, biogas, biofuels, and other valuable resource feedstock derived from wastewater [44], [45]. Specifically, Municipal wastewater is a hidden source of nitrogen and phosphorous. Phosphorous recovery from municipal wastewater can address 15–20% of the world's demand [46].

2.3 Antibiotics

In the previous century, the discovery and utilization of antibiotics elevated human life expectancy and markedly reduced mortality rates attributed to bacterial infections. However, antibiotics exert adverse effects on the environment, particularly by fostering the emergence of antibiotic-resistant bacteria (ARBs), which poses a significant menace to human health [54]. The World Health Organization has identified antibiotic resistance as one of the foremost perils to human health. An increasing body of research has been dedicated to investigating the efficacy of phytoremediation in addressing antibiotics in both human and livestock settings. Table 3 provides an overview of recent studies that have examined the utilization of phytoremediation for the removal of antibiotics from wastewater. By scrutinizing the chemical structure, physicochemical attributes, and prior research pertaining to these antibiotics, it has been ascertained that both phytoremediation and bioremediation, specifically employing enzymatic degradation, exhibit potential as viable approaches for the efficacious mitigation of antibiotics within wastewater treatment [55]. In light of the aforementioned investigations, the efficacy demonstrated by the hydroponic uptake of antibiotics by plants and the microbial enzymatic degradation of antibiotics underscores the viability of biological treatment modalities. Constructed wetlands and floating treatment wetlands, as examples, could emerge as economically feasible alternatives for municipalities aiming to modernize their wastewater treatment practices, particularly in the context of antibiotics removal.

Table 3. Summary of antibiotic removal efficiencies using various macrophytes in phytoremediation studies

Antibiotic	Plants	Removal efficiency	References
Sulfamethoxazole	*Phalaris arundinacea*	99.7%	[56]
Sulfamethoxazole	*Cattail*	26–33 %	[57]
Ciprofloxacin	*Vetiver grass*	60–94 %	[58]
Sulfadiazine	*Acorus calamus*	26.42–64.93	[59]
Tetracyclines (tetracycline, oxytetracycline, chlortetracycline)	*Myriophyllum aquaticum*	88 %, 83 %, and 99 %	[60]
Sulfamethoxazole	*Acorus calamus*	98	[61]

2.4 Herbicide

On a global scale, approximately 64% of agricultural land is deemed susceptible to pesticide contamination [62], a with a staggering 2.5 billion hectares being afflicted by the presence of multiple chemical compounds [63]. Predominantly, the category exerting the most pronounced influence comprises herbicides, which represent the most extensively employed class of pesticides [64]. Numerous plant species exhibit the capacity to diminish residual herbicides within soil matrices, concurrently facilitating safeguarding measures for watercourses [65] and enhancing water purification processes [66]. A substantial body of research endeavors in the realm of phytoremediation has been undertaken and documented in recent years, as evidenced by the compilation in Table 4. Aquatic organisms have been suggested as candidates for the removal of residual herbicide substances from water bodies [67]. For certain categories of pollutants, such as herbicides, the utilization of "remediation islands" enclosed by containment barriers can be advised to mitigate the unregulated proliferation of aquatic phytoremediation plant species. [68] These islands can subsequently be removed upon completion of the remediation process [69].

Table 4. Common plant species used for herbicide phytoremediation, highlighting the targeted compounds and removal performance

Herbicide	Plants	Removal efficiency	References
Terbuthylazine	*Typha latifolia*	23.0	[70]
Glyphosate	*Salvinia biloba*	100.0	[71]
Atrazine	*Eichhornia crassipes*	79.0	
Atrazine	*Potamogeton crispus*	91.0	[72]

Saflufenacil	*Pistia stratiotes*	95.0	[73]
Saflufenacil	*Egeria densa*	83.0	

2.5 Emerging Contaminants

Emerging contaminants refer to a category of pollutants that have gained attention due to their identification, presence, and potential environmental and health impacts, even though they were not previously considered significant. These contaminants often include a diverse range of synthetic and natural substances, such as steroid hormones, pharmaceuticals and personal care products (PPCPs), radiation and so on. Steroids constitute a subset of emerging organic contaminants that have garnered attention for their potential role as endocrine-disrupting chemicals [74]. Research indicates that even at exceedingly low concentrations ranging from 0.1 to 0.5 ng/L, steroids have demonstrated the capacity to elicit deleterious impacts on both flora and fauna [75]. Among the various types of plant species, *Typha angustifolia, Phragmites australis, Typha latifolia, Ceratophyllum demersum, Hydrilla verticillate, Myriophyllum verticillatum Vallisneria natans, Potamogeton crispus, Trapa bispinosa, and Nymphaea tetragona* are are the most commonly used macrophytes in treating steroids in constructed wetlands system [76], [77]. Many researchers used *Phragmites australis* due to its high removal efficiency toward the micropollutants [78].

The contamination of water by pharmaceutical and personal care products (PPCPs) has garnered increasing global attention due to their significant ecotoxicological implications and adverse effects on human health[79]. These pharmaceutical and personal care products (PPCPs) are discharged into the environment through various pathways, including industrial wastewater generated during manufacturing, hospital effluents, domestic sewage, aquaculture runoff from agricultural activities, and livestock waste. The hydrophobic and persistent nature of PPCPs contributes to their heightened tendency for bioaccumulation across different trophic levels, ultimately resulting in their biomagnification within food chains, including human populations [80]. Many plants are used to treat PPCPs in wastewater, commonly used species were *Typha angustifolia, Typha latifolia, Phragmites australis, Phalaris arundinacea, Juncus effusus, Scirpus lacustris, and Scirpus californicus* [81], [82]. In summary, the translocation of PPCPs from roots to upper tissues is facilitated by osmosis and the transpiration-cohesion-adhesion mechanism. The physicochemical attributes of PPCPs play a pivotal role in governing their uptake and subsequent migration to other tissue compartments [83].

The sources of radionuclides are nuclear power plants, Radioactive waste, nuclear explosions and radioisotopes [84] As a consequence of the Fukushima nuclear incident, substantial releases of radionuclides (^{133}Xe, ^{85}Kr, ^{131}I, ^{133}I, ^{134}Cs and ^{137}Cs) resulted in the contamination of both marine and terrestrial ecosystems [85], [86]. Moreover, starting from August 24, 2023, nuclear contaminated water of Fukushima was discharged directly to the ocean, which will affect the whole world with the circulation of the ocean. The radionuclide contamination imposes a serious hazard, especially to ecology[87]. This requires us to focus on preventing the impact of nuclear radiation. Some plants have been shown to have potential roles in absorbing or mitigating radioactive substances, such as *Vetiveria zizanioides* (^{137}Cs;^{90}Sr; U) [88], *Callitriche stagnalis*, *Typha latifolia* (U) [89], *Eichhornia crassipes* (^{137}Cs;^{60}Co) [90], *Hypnum plumaeforme* (^{210}Po;^{210}Pb) [91], *Helianthus annuus* (^{137}Cs;^{90}Sr;^{125}I;^{226}Ra; U) [92]. Phytoremediation of radionuclides is a rapidly developing field that attracts attention worldwide [93].

3. RECOMMENDED PHYTOREMEDIATION POTENTIAL FOR STUDY WATER

Baiyang Lake (shown in Figure 1), the largest shallow lake in the North China Plain, located in Xiongan New Area, known as the "Kidney of North China" and the "Pearl of North China", assuming a pivotal role in the cultivation of aquatic products and the enhancement of ecological environments. The aquatic vegetation of Baiyang Lake Wetland primarily comprises hydrophytic vascular plants and floating plants. Prominent species within this context encompass *Phragmites australis, Nelumbo nucifera, Typha orientalis, Potamogeton pectinatus, and Ceratophyllum demersum* [94]. In recent years, scholars have conducted investigations into the pollution status of Baiyang Lake, as documented in Table 5.

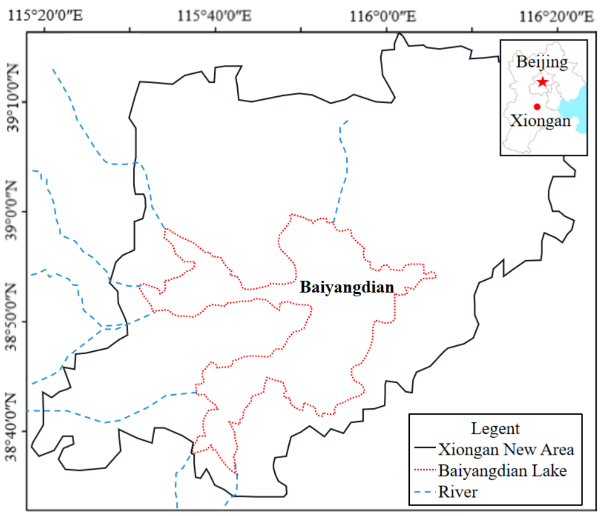

Figure 1. Geographical location of Baiyangdian Lake in the North China Plain, illustrating its catchment and inflow sources

Table 5. Summary of pollution levels in Baiyangdian Lake based on water, sediment, and soil sample analysis

	Pollution	Concentration	References
Water	COD	7.53-594.40 mg/L	[95]
	TP	0.012-0.610 mg/L	
	TN	0.501-3.463 mg/L	
	NH_4^+-N	0.228-0.726 mg/L	
Surface sediment	TOC	14.4-136.82g/kg	[96]
	TN	0.72-10.57g/kg	
	TP	0.46-1.38g/kg	
Surface sediment	As	3.71-28.6 mg/kg	[97]
	Hg	0.015-0.225 mg/kg	
	Cr	29-253.5 mg/kg	
	Ni	18.7-134.5 mg/kg	
	Cu	14.4-255.5 mg/kg	
	Zn	46.1-408.5 mg/kg	
	Cd	0.11-4.13 mg/kg	
	Pb	15.5-486 mg/kg	
Surface soil	As	4.44-28.60mg/kg	[98]
	Hg	9.75-567.50μg/kg	
	Cr	37.70-118.00 mg/kg	
	Cd	0.08-0.56 mg/kg	
	Pb	11.60-65.70 mg/kg	
	Ni	15.30-59.30 mg/kg	
	Cu	8.19-204.50 mg/kg	
	Zn	35.20-459 mg/kg	
	N	170.00-3580.00 mg/kg	
	P	489.10-3746.30 mg/kg	
Water	Phthalate esters (PAEs)	1.215-3.014 μg/L (October) 1.384-3.399 μg/L (May)	[99]
Surface water	Pesticides	0.00025-3.53μg/L	[100]
Soil		0.00279-647 μg/kg	

Considering the prevailing pollution status of Baiyangdian Lake and the comprehensive analysis of phytoremediation conducted above, the strategic implementation of phytoremediation within the inflow region of the lake is advocated. Take the Fu River (shown in Figure 2), which flows into Baiyangdian Lake, for example. The combined wetland system of horizontal underflow and ecological buffer pond has been used to reduce the pollution of organic and nutrient elements in river water.

Figure 2. Schematic diagram of the Fu River Estuary Wetlands on the western side of Baiyangdian Lake, showing the layout of the horizontal subsurface flow and ecological buffer pond system

Considering that the water quality entering the wetland is of low pollution, a horizontal subsurface flow-ecological buffer pond system has been implemented to remove typical pollutants from the river water. The treatment capacity of this system is 250,000 m³/day. Aquatic plants selected for the combined system are common species native to Baiyangdian lake. Efforts should be made to use physical methods and leverage existing material factors within the local ecosystem, avoiding the introduction of new species or chemical substances to prevent secondary damage. The horizontal subsurface flow constructed wetland serves as the primary sewage purification unit in this treatment process, demonstrating a significant advantage in the removal of nitrogen and phosphorus. It is particularly conducive to denitrification reactions. This type of wetland is characterized by its high tolerance to pollution loads and hydraulic loads, with minimal odor and mosquito issues during the summer. Due to the subsurface water flow, the horizontal subsurface flow constructed wetland is less sensitive to temperature fluctuations.

Extensive planting of emergent plants such as reeds is possible within the wetland. Reed fields not only enhance the wetland's pollutant removal efficiency but also add aesthetic value to the landscape. The horizontal subsurface flow constructed wetland is designed in two stages, with each stage covering an area of 41 hectares, divided into 514 units. Each wetland unit has an area of 0.08 hectares and dimensions of 40 meters in length, 20 meters in width, and 1.2 meters in depth. Given the relatively low dissolved oxygen content in the outflow from the horizontal subsurface flow constructed wetland, an ecological buffer pond is established downstream. This buffer pond serves to regulate and further oxygenate the wetland outflow. Considering factors such as ecological restoration and landscape aesthetics, the pond is planted with emergent, submerged, and floating-leaved plants, according to varying water depths. This not only enhances the scenic beauty of the river mouth but also promotes biodiversity.

During seasons other than winter, floating-leaved plants such as water lilies are planted to enhance the wetland's aesthetic appeal. In winter, cold-tolerant plants are used to ensure the buffer pond maintains a certain level of pollutant removal efficiency. The ecological buffer pond is cost-effective, simple to operate, and has low operating costs while providing significant ecological benefits. The pond is designed with an area of 21 hectares, divided into 10 rectangular units, each measuring 210 meters in length and 100 meters in width, with an effective water depth of 1.2 meters. Submerged plants dominate the pond, covering 60% of the water surface area. The water quality improvements include reductions of approximately 80% in NH_3-N, 70% in TP, 50% in TN, and 40% in COD, meeting IV standards of GB3838-2002. The Fu River Estuary Wetlands can serve as a model for the ecological restoration of Baiyangdian and can be promoted for application to other rivers flowing into the lake.

Besides phytoremediation of the inflowing rivers to Baiyangdian lake, additional measures should be implemented: maintaining ecological water levels, strictly adhering to ecological red lines, and improving the policy of converting farmland back to wetlands. The goal is to restore the normal functioning of the Baiyangdian lake ecosystem through effective water supplementation, pollution control, and biodiversity protection. Recommendations are also made to prevent secondary pollution from restoration projects, provide ecological compensation for converting farmland back to wetlands, and establish a solid legal and policy framework for the wetland restoration efforts. Furthermore, an in-depth engagement in comprehensive environmental management and ecological restoration for Baiyangdian Lake is advised. This encompasses robust implementation of projects for ecological water replenishment and water conservation, establishment of a collaborative watershed governance mechanism, and a concerted effort to craft an enchanting ecological ambiance for Baiyangdian lake.

4. CONCLUSION

This paper has provided a comprehensive overview of the mechanistic underpinnings of phytoremediation, along with its effectiveness in addressing various pollutants such as heavy metals, nutrients, antibiotics, pesticides, and other emerging contaminants. Considering the existing pollution scenario in Baiyangdian Lake, the strategic implementation of phytoremediation within the inflow region of the lake is advocated. Moreover, the integration of phytoremediation with plant management is suggested, as this amalgamation is poised to yield more expansive benefits encompassing economic, environmental, and societal dimensions. Future research should focus on long-term monitoring of system performance under seasonal variations, optimizing plant combinations for multi-contaminant removal, and exploring the co-benefits of carbon sequestration and biodiversity enhancement.

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AUTHOR CONTRIBUTIONS

Baiyang Jiang: Data curation, Writing- Original draft preparation.

Shu Ing Doh: Co-Supervision, and Validation.

Suryati Sulaiman: Writing- Reviewing and Editing.

Abdul Syukor Abdul Razak: Supervision.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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