

Review

Application of Water Hyacinth for Phytoremediation of Ammoniacal Nitrogen

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Abstract

Ammoniacal nitrogen ($\text{NH}_3\text{-N}$) is a major pollutant in municipal, industrial, and agricultural wastewaters and is a key driver of eutrophication and aquatic ecosystem degradation. This review paper assessed the potential of water hyacinth (*Eichhornia crassipes*) as a sustainable phytoremediation option for removing ammoniacal nitrogen from wastewater. This paper focused on the plant's biological characteristics, nutrient uptake pathways, and adaptability to varying environmental conditions. Specific mechanisms examined include direct root uptake of ammonium, internal translocation, and microbial-assisted nitrification and denitrification within the rhizosphere. The influence of pH, temperature, salinity, retention time, and plant density on removal efficiency was also assessed in this study. Across laboratory, pilot, and field-scale studies, water hyacinth achieved ammoniacal nitrogen removal efficiencies ranging from 74% to 97% under favorable conditions, alongside significant reductions in biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (TDS). Integration with constructed wetlands, microbial systems, and hybrid treatment approaches further enhanced nitrogen removal and process stability. This paper also highlighted opportunities for biomass valorization through biogas, bioethanol, and compost production while identifying challenges related to salinity sensitivity and biomass management. Overall, water hyacinth emerges as a cost-effective, nature-based solution for decentralized wastewater treatment, with strong potential to support sustainable water management and circular bioeconomy initiatives.

Keywords: ammoniacal nitrogen; circular bioeconomy; constructed wetlands; *Eichhornia crassipes*; phytoremediation; wastewater treatment; water hyacinth



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1. Introduction

Nitrogen as a water pollutant exists in several forms, including total nitrogen, nitrate, nitrite, organic nitrogen, and ammoniacal nitrogen [1]. Out of these, ammonia is an important part of the biogeochemical N-cycle as well as in biological cycles of organisms, and it is both formed and utilized in these processes [2]. Two chemical forms of ammonia, ionized ammonium (NH_4^+) and unionized ammonia (NH_3), exist in water and are combinedly called total ammonia nitrogen (TAN) [3–5]. The NH_3 to NH_4^+ ratio in water varies with pH, temperature, and different minerals, favoring NH_3 at higher temperatures and pH [4,6,7].

Ammoniacal nitrogen is known to be a water odorant formed during N-containing organic matter decomposition, resulting in the production of black and odorous water (BOW) [8].

One of the most efficient, cost-effective, and environmentally friendly processes for the removal of different pollutants is phytoremediation. It is a natural process where plants help clean and stabilize contaminated soil and water. It involves various methods using vegetation for in situ treatment of soil and water polluted by hazardous substances. Phytoremediation mainly includes five different types of mechanisms for the removal of pollutants, namely (i) phytoextraction, where plants uptake contaminants (e.g., heavy metals or nutrients) and accumulate them in harvestable tissues; (ii) phytostabilization, which immobilizes contaminants in the rhizosphere and reduces their mobility and bioavailability; (iii) phytovolatilization, in which plants absorb contaminants and release them into the atmosphere in volatile forms; (iv) rhizofiltration, where plant roots adsorb or absorb contaminants directly from aqueous media; and (v) phytodegradation, which involves enzymatic breakdown or transformation of organic pollutants within plant tissues or the rhizosphere [9,10]. The characteristics that an ideal phytoremediator should have include high-biomass production, resistance to heavy metal toxicity, a resilient nature, highly efficient absorption, and being unattractive to herbivores [11–14]. Some plants that are efficient phytoremediators include *Eichornia crassipes*, *Medicago sativa* [9], *Lolium perenne*, *Pistia stratiotes* [15], *Ipomoea aquatica*, *Lemna minor*, *Centella asiatica*, *Salvinia minima* [16], and *Chrysopogon zizanioides* [17,18].

1.1. Background on Ammoniacal Nitrogen Pollution

Excessive nitrogen in the aquatic environment seriously damages water supplies and associated industries globally. Except for nitrate and nitrite nitrogen, numerous investigations have demonstrated that ammonia-nitrogen pollution is the most dangerous [19]. At ranges above 0.5 mg/L, both ammonia and ammonium, the two types of ammonia nitrogen found in wastewater, negatively impact biological organisms [19–21]. Unionized ammonia (NH_3) is toxic, as it may readily permeate biological membranes, change intracellular pH, and interfere with critical enzyme processes [4,22]. Excessive free ammonia can suppress microbial activity and nitrifying bacteria in wastewater treatment facilities, which can impact treatment efficacy. Ammonia toxicity in fish and invertebrates can cause gill damage, disruptions in ion and oxygen transport, abnormalities in growth and reproduction, and even death [23,24]. High ammonium ion concentrations can also decrease metazoan populations, boost algae abundance, induce eutrophication, and deplete dissolved oxygen, all of which have an effect on aquatic food webs [25]. A type of inorganic nitrogen known as ammoniacal nitrogen is commonly found as a contaminant in a variety of aquatic habitats, such as municipal sewage, industrial wastewater, and agricultural runoff [26–29]. Conventional techniques like nitrification and denitrification, which remove ammoniacal nitrogen, are expensive and energy intensive [28].

1.2. Environmental Impact and Health Risks

Numerous health and environmental problems can result from high ammoniacal nitrogen levels in water [27]. Algal blooms and hypoxia caused by excess nitrogen can degrade aquatic environments and reduce biodiversity. Water's dissolved oxygen is consumed by ammonia nitrogen. Ammonia nitrogen in drinking water sources will also raise the cost of water treatment as it increases the chlorine requirement, as ammonia reacts directly with chlorine during disinfection to produce chloramines and impose a considerable oxidant demand; breakpoint chlorination may require 8–11 mg Cl_2 per mg $\text{NH}_3\text{-N}$ to achieve a free chlorine residual [30,31]. Furthermore, nitrate, a byproduct of ammoniacal nitrogen, is associated with several illnesses, like gastrointestinal disorders and liver and kidney prob-

lems, which can be hazardous to human health, especially for young children. Municipal wastewater, industrial wastewater, wastewater from livestock and poultry, and landfill leachate are the primary causes of ammoniacal nitrogen pollution in water bodies. The content and concentration of these pollutants vary depending on the source [32].

1.3. Overview of Phytoremediation

Phytoremediation, the use of living plants to remove, transfer, stabilize, or degrade environmental contaminants, has emerged as a cost-effective and environmentally friendly approach to addressing various forms of pollution, including ammoniacal nitrogen [33]. This method provides a sustainable way to clean up the environment by taking advantage of some plants' innate capacity to absorb and retain contaminants. Numerous factors, including the number of pollutants in the growing environment, the age and density of the plants, the plants' genetic compatibility with the contaminants that are accessible, and the reactor design, affect how effective plants are when used for phytoremediation applications [14,18,34]. A phytoremediation system's maximum efficiency can also be attained by controlling several variables, including temperature, time, wastewater loads, pH, and loading rates, among others [35].

1.4. Aquatic Macrophytes for Ammoniacal Nitrogen Removal

Aquatic macrophytes, particularly floating species, have been widely investigated for nutrient-rich wastewater treatment. Species such as *Eichhornia crassipes*, *Pistia stratiotes*, *Trapa natans*, *Azolla pinnata*, *Chrysopogon zizanioides*, and *Typha latifolia* have demonstrated substantial nutrient uptake capacity in laboratory, pilot, and field-scale systems [10,18,36]. These plants were used to treat effluents from paper processing, sugar mills, textile industries, dairy operations, slaughterhouses, pharmaceutical facilities, and other industrial sources [37–42].

Among these species, *Eichhornia crassipes* has received particular attention due to its rapid growth, high biomass yield, and tolerance to nutrient-rich environments. Many studies have demonstrated high ammoniacal nitrogen removal efficiencies in water hyacinth-based systems. However, significant inconsistencies exist in the interpretation of these results. In several cases, ammonium reduction occurs simultaneously with increases in nitrite and nitrate concentrations, indicating the substantial role of microbial nitrification rather than exclusive plant assimilation. Furthermore, removal efficiencies are often compared across studies with markedly different influent concentrations, hydraulic retention times, system configurations, and environmental conditions, without normalization or nitrogen mass balance evaluation.

Previous reviews have largely emphasized overall nutrient removal performance but have not systematically distinguished between plant assimilation, microbial nitrification–denitrification, ammonia volatilization under alkaline conditions, and temporary nitrogen retention through sorption processes. The absence of a mechanistic differentiation and standardized comparative framework has led to potential overestimation of plant-mediated ammoniacal nitrogen removal.

Therefore, a critical synthesis integrating mechanistic analysis and a conceptual nitrogen mass balance approach is required. This study aimed to (i) differentiate plant assimilation from microbial transformation pathways in *Eichhornia crassipes*-based systems, (ii) evaluate the influence of operational parameters on nitrogen dynamics, and (iii) propose a nitrogen mass balance framework to improve interpretation, comparison, and standardization of reported ammoniacal nitrogen removal efficiencies.

2. Water Hyacinth: Botanical and Biological Characteristics

Native to the Amazon Basin, water hyacinth (*Eichhornia crassipes*) is a free-floating aquatic plant that is renowned for its exceptional capacity to multiply quickly and generate large amounts of biomass [26,27,43]. It is a member of the Pontederiaceae family and is a great candidate for wastewater remediation applications since it can grow in extremely contaminated water bodies [44]. The potential of this plant in phytoremediation, specifically in the removal of nutrients such as ammoniacal nitrogen and heavy metals, has been well investigated. Water hyacinth is a viable option for the remediation of ammoniacal nitrogen pollution because of its quick growth rate, high biomass production, and capacity to accumulate pollutants [26,27,45]. According to earlier studies, *E. crassipes* can clean up large amounts of different types of wastewaters from the glass and sugar mill industries, including trace (Cd, Pb, Cr, Pb, Ni), minor (Fe, Zn, Cu), and major (P, N, Ca, Mg) contaminants [37,38].

2.1. Taxonomy and Morphology

Water hyacinth is an aquatic, free-floating plant species that finds its origin in the Amazon Basin of South America [46]. This perennial macrophyte is an herbaceous monocot belonging to the Pontederiaceae family [47,48]. It is characterized by rounded green leaves, bluish lavender-colored flowers that are self-fertile [49], and black–dark purple roots and is accompanied by rhizomes and stolons for propagation [47,48]. There is a presence of air-filled tissues in the leaves as well as in the shoots of the plant, aiding it to float in water due to buoyancy [50]. The plant typically grows to 40 cm but can reach up to 1 m, forming dense mats up to 2 m thick by spreading through stolons [50].

2.2. Growth and Reproduction

Under ideal circumstances, water hyacinth can double its biomass in as little as 5–15 days, making it famous for its quick growth rate [51]. Water hyacinth seeds can survive for up to 20 years submerged in water under unfavorable conditions (such as low temperatures and low light levels). The plant's effective utilization of resources, ability to adapt to a variety of environmental situations, and extremely effective reproductive strategies, including both sexual and asexual reproduction, are all responsible for its prolific development [27]. The plant reproduces by sexual as well as asexual means, and since a single parent can reproduce quickly via vegetative means, there is rapid growth and spread of the plant in less time [52]. The large populations thus formed due to this rapid growth have interconnected shoots and complex root structures, resulting in the formation of interlocking mats [53].

The spread of the plant is via water currents, winds, or movement by boats and fishing nets, invading freshwater bodies, and the growth accelerates when there is no natural enemy present [54]. The plant can grow in tropical as well as temperate environments in an optimal pH condition of 6–8 and an optimal temperature range of 25–27 °C [55].

The factors that primarily influence the reproduction and growth of water hyacinth are nutrients and temperature. The growth of water hyacinth is limited by high salinity, as seen in the case of coastal areas and estuaries [56]. Environmental disturbances, pH, light availability, and the reproduction system also influence the growth of water hyacinth [57].

2.3. Nutrient Uptake Mechanisms

Water hyacinth is well known for its phytoremediation properties due to its ability to absorb various heavy metals and nutrients from wastewater. Figure 1 shows overall nutrient uptake mechanisms of water hyacinth.

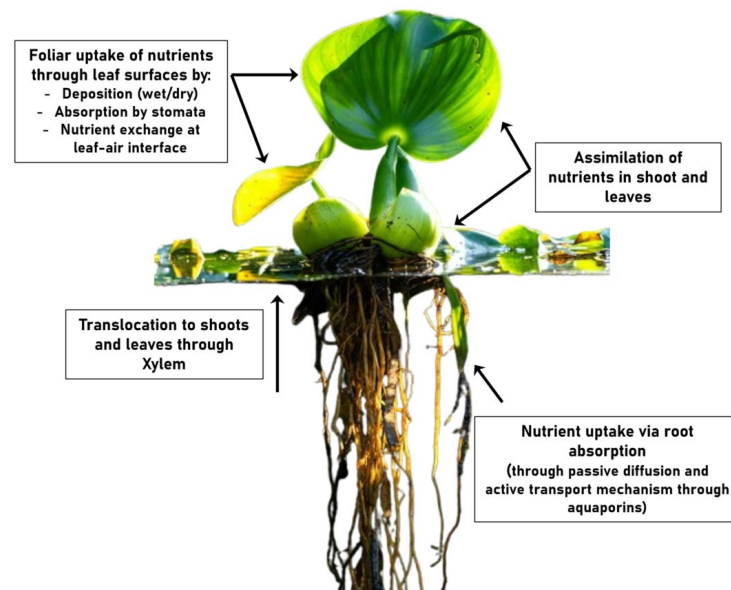


Figure 1. Nutrient uptake mechanisms of water hyacinth (*Eichhornia crassipes*). [Source: AI-based tool (Google Gemini3 image generation tool) used to support visualization and layout development only].

Water hyacinth removes metals from water by the process of root surface adsorption. Studies showed that metals like Cu^{2+} , Hg^{2+} , As(V) , $\text{Fe}^{2+}/\text{Fe}^{3+}$, Mn^{2+} and Zn^{2+} can be removed from water through root adsorption and absorption processes. It was also found that metals like Cu^{2+} , Hg^{2+} , $\text{Fe}^{2+}/\text{Fe}^{3+}$, Mn^{2+} and Zn^{2+} can be removed from water by the process of shoot absorption [58]. The root absorption process in water hyacinth is both by passive uptake and through active diffusion [59]. A study done on organophosphate esters revealed that water hyacinth is capable of nutrient uptake through anion channels and aquaporins by passive diffusion and, at the same time, can also uptake nutrients in the presence of a concentration gradient, proving the active transport capability of the plant. Properties like hydrophilicity also influence the plant uptake mechanism, and hydrophilic substances have higher upward movement and translocation rates, while hydrophobic substances tend to stay in the root cell wall region, showing lower translocation rates.

It was observed that water hyacinth was able to remove 99.5% of hexavalent chromium from a chromite mine area in 15 days [60]. The same study observed an increase in dissolved oxygen (DO) based on the decrease in chemical oxygen demand (COD) by 34% and biochemical oxygen demand (BOD) by 50% in wastewater. The study showed that the bioaccumulation of Cr (VI) was highest in the roots of water hyacinth, followed by the leaves and stems, respectively. The movement of metals from roots to shoots mainly takes place by the process of translocation, which is mainly governed by the root pressure and the transpiration of the leaves. At times, various metals accumulated in the roots due to some physiological barrier preventing the metals from reaching the aerial part of the plant [61,62].

Water hyacinth can also enhance its nutrient uptake capacity when it is in a mycorrhizal association. A study revealed that, with the inoculation of Arbuscular Mycorrhizal Fungi (AMF), the plant could take up higher cadmium (Cd) concentrations [63]. AMF also facilitates the trapping of heavy metals in the root and mycorrhizosphere region, thus preventing the translocation of the heavy metals to the shoot. The study also showed that the growth rate of water hyacinth is higher with AMF inoculation than non-inoculated ones in cadmium concentration within the range of 20 ppm to 50 ppm.

The plant also uptakes nutrients via foliar uptake (uptake by the leaves), which can happen via absorption, deposition (wet or dry), or by substance exchange at the air-leaf

interface [64]. Basipetal migration of substances from leaves to stalks and roots has also been observed in water hyacinth [64].

2.4. Adaptability to Different Water Conditions

The degree of water hyacinth growth depends differently on various water conditions in a water body. In the case of the water body being eutrophic, the rate of water hyacinth proliferation is much higher than that of mesotrophic (intermediate-nutrient conditions) and oligotrophic (low-nutrient conditions) water bodies, and the plant biomass increases in the eutrophic water conditions [65]. A study reported that changes in growth measurements over time declined in low- and medium-nutrient treatments [66]. The leaf nitrogen content and the phosphorus levels increased in high-nutrient growth, and it also enhanced carbon gain, with increased surface area for photosynthesis. The growth of water hyacinth is also influenced by the salinity of water, and for optimum growth of the plant, <2% salinity in water is required. Water having a good quantity of dissolved sulfates, phosphates, and nitrates is favorable for the growth of the plant. Slightly alkaline water (pH 6.5–8.5) is optimal for water hyacinth growth [57].

In an experimental setup of domestic wastewater treatment, water hyacinth reduced BOD by 96%, overall salinity by 15%, and TDS and $\text{NH}_3\text{-N}$ as well within three weeks [67]. In another study of domestic sewage purification with water hyacinth, it was observed that, after a treatment period of 28 days, pungent sewage odor as well as deep yellow color disappeared, allowing for its safe discharge into a stream. The pH value of the sewage was decreased from 8.58 to 7.81, along with a 34% reduction in the color grade, and the turbidity value also decreased from 48.5 to 35.9 NTU [68]. Water hyacinth was also used in the treatment of effluent water from a sago mill, showing high removal efficiencies for COD (86.4–97.2%), ammonia (91.4–97.2%), and phosphorus (80.4–97.2%) in 30 days [69].

Accordingly, studies continually report that water hyacinth has a wide ecological adaptability to variable trophic conditions, salinity, and pH. Indeed, it is very effective in removing organic matter, nutrients, and other pollutants from various aquatic and wastewater environments.

3. Mechanisms of Ammoniacal Nitrogen Removal

3.1. Uptake and Assimilation by Water Hyacinth

Water hyacinth has demonstrated the ability to efficiently absorb and assimilate ammoniacal nitrogen from aqueous environments [27]. The plant's extensive root system and high biomass production contribute to its capacity to remove significant quantities of ammoniacal nitrogen from the water column. The pace of plant growth, culture density, and environmental factors like temperature and solar radiation will all affect how much nitrogen is removed by plant uptake. Both ammonium and nitrate can be absorbed by water hyacinth, although, like many aquatic plants, ammonium is preferred over nitrate even when both ions are present in the wastewater at the same time [70].

3.2. Conversion Processes

In addition to direct uptake, water hyacinth can help reduce the environmental impact of ammoniacal nitrogen pollution by facilitating the nitrification process, which is carried out by specialized bacteria present in the plant's rhizosphere and converts ammoniacal nitrogen into less harmful forms, such as nitrate [71].

3.3. Distinguishing Plant Assimilation and Microbial Transformation

Ammoniacal nitrogen removal in *Eichhornia crassipes*-based systems results from multiple concurrent processes rather than plant assimilation alone. Although water hyacinth

absorbs NH_4^+ through root uptake and incorporates it into biomass, several studies reported a simultaneous increase in nitrite and nitrate concentrations during ammonium decline, indicating active microbial nitrification [72,73]. Nitrification is strongly influenced by dissolved oxygen, pH, temperature, and hydraulic retention time, which regulates the growth and activity of ammonia-oxidizing bacteria [72].

While plant assimilation contributes to nitrogen sequestration, it represents temporary storage unless biomass harvesting is implemented [74]. In contrast, microbial denitrification, when nitrate is reduced to gaseous nitrogen under anoxic conditions, results in permanent nitrogen removal. Therefore, reductions in ammonium concentration alone cannot be interpreted as direct plant-mediated removal. A mechanistic distinction between plant uptake and microbial transformation is essential for accurately evaluating system performance.

Elevated heavy metal concentrations may inhibit nitrifying and denitrifying microorganisms in the rhizosphere, potentially reducing nitrogen transformation efficiency. Metals such as Cd, Cu, and Pb are known to suppress ammonia-oxidizing bacteria. Standardized assays like Organization for Economic Co-operation and Development (OECD) 209:2010 and International Organization for Standardization (ISO) nitrification inhibition tests (ISO 9509:2006) are commonly used to assess such microbial inhibition and should be considered when interpreting treatment performance in mixed-contaminant wastewater [75–77].

3.4. Conceptual Nitrogen Mass Balance in Water Hyacinth Systems

Accurate interpretation of ammoniacal nitrogen removal requires a conceptual nitrogen mass balance framework. In water hyacinth systems, ammonium reduction may result from (i) plant assimilation, (ii) microbial nitrification, (iii) subsequent denitrification, (iv) ammonia volatilization under elevated pH conditions, and (v) temporary retention through sorption to sediments or biofilms.

Nitrification converts NH_4^+ to NO_3^- but does not remove total nitrogen; permanent removal occurs only if denitrification produces gaseous nitrogen species [72]. Moreover, free ammonia formation at higher pH may inhibit nitrifiers and contribute to physicochemical nitrogen loss. Environmental parameters such as dissolved oxygen, pH, and hydraulic retention time, therefore, determine the relative contribution of each pathway.

Accordingly, assessment of treatment efficiency should consider ammonium, nitrate, total nitrogen, and biomass nitrogen accumulation simultaneously. A generalized nitrogen cycle scheme is presented in Figure 2 to illustrate the interaction between plant assimilation and microbial transformation processes in macrophyte-based systems.

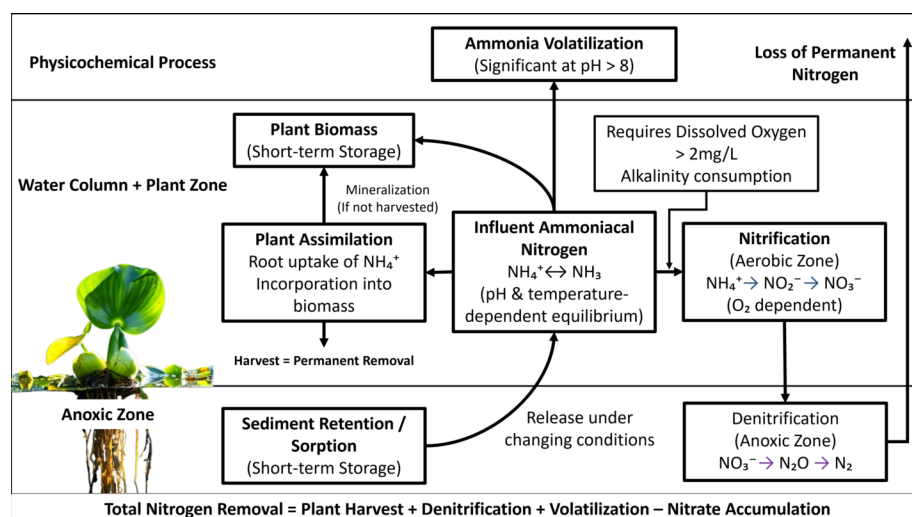


Figure 2. Schematic diagram of nitrogen cycle in macrophyte-based systems.

3.5. Impact on Nitrogen Cycle

The integration of water hyacinth into aquatic ecosystems can have a positive influence on the overall nitrogen cycle. The plant's ability to absorb and transform ammoniacal nitrogen ($\text{NH}_3\text{-N}$) can help to maintain a balanced distribution of nitrogen species, reducing the risk of eutrophication and other detrimental environmental effects.

Figure 3 shows mechanism of ammoniacal nitrogen removal by water hyacinth. It primarily assimilates $\text{NH}_3\text{-N}$ through direct root uptake, converting it into amino acids such as glutamine and arginine that contribute to biomass development [1]. This uptake preference positions water hyacinth as an efficient first-line scavenger for $\text{NH}_3\text{-N}$, only resorting to nitrate absorption when ammoniacal nitrogen becomes scarce [70]. Moreover, the plant's aerenchyma tissue facilitates oxygen transfer to the rhizosphere, promoting microbial nitrification and denitrification processes essential for complete nitrogen cycling. Microbial interactions lead to the conversion of $\text{NH}_3\text{-N}$ into nitrites, nitrates, and ultimately inert nitrogen gas through denitrification, identified as the dominant removal pathway, accounting for up to 81.9% of total nitrogen loss in constructed wetlands [78]. This synergistic interplay of plant uptake and microbial transformation not only mitigates eutrophication but also sustains long-term nutrient balance in aquatic ecosystems.

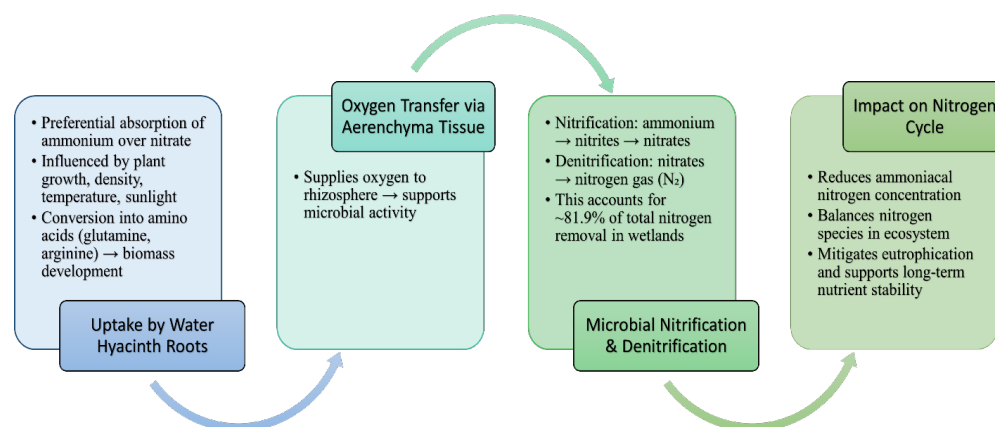


Figure 3. Mechanism of ammoniacal nitrogen removal by water hyacinth (*Eichhornia crassipes*).

In real wastewater matrices, xenobiotic organic pollutants (e.g., pharmaceuticals, pesticides, industrial organics) can directly affect nitrogen transformation pathways by inhibiting or altering nitrifying and denitrifying microorganisms and, in some cases, are co-transformed by ammonia-oxidizing microbes [79]. These micropollutants are also taken up and adsorbed by *Eichhornia crassipes* (primarily in roots with variable translocation to shoots), which can induce physiological stress and change plant nutrient uptake efficiency [80]. Finally, xenobiotics can shift rhizospheric microbial community composition and reduce nitrification/denitrification rates (sometimes causing nitrite accumulation), so interpretation of $\text{NH}_3\text{-N}$ removal in complex wastewaters must consider coupled plant–microbe–pollutant interactions [81].

4. Effectiveness of Water Hyacinth in Ammoniacal Nitrogen Phytoremediation

Several studies were performed on the role and efficiency of water hyacinth in ammoniacal nitrogen phytoremediation (Table 1). A study was conducted to observe the phytoremediation potential of water hyacinth in wastewater [82]. Using three different samples (river water, detention pond, and WTP effluent), various parameters were evaluated, with ammoniacal nitrogen being one of them. The river water sample had the highest ammonia nitrogen concentration of 5.5 mg/L, while the WTP effluent and detention pond

had an initial ammonia nitrogen concentration of 1.75 mg/L and 1.25 mg/L, respectively. After treatment of the samples for a period with water hyacinth, the concentration of ammonia nitrogen for river water was found to be 0.14 mg/L after 14 days, while in the case of WTP effluent and the detention pond, it was 0.33 mg/L and 0.54 mg/L respectively on the 2nd day of the treatment. The removal efficiency was highest for the river sample (96.91%), followed by pond water (95.20%) and WTP effluent (94.29%), respectively. Out of the different types of nitrogen, the degree of ammonia nitrogen removal was the largest. It was also noticed that, due to fluctuations in water level owing to rainfall, there may be modifications in the microbial community of water, which could also significantly affect the nitrogen removal process. The decrease in ammonia nitrogen was accompanied by a corresponding increase in both nitrite as well as nitrate concentrations. It was evident that ammonia was converted into nitrite and then successively into nitrate through the process of nitrification. For complete removal of nitrates as well, further treatment like denitrification is necessary along with the phytoremediation process. The study also showed a significant reduction in pH, TSS, phosphorus, COD, BOD, and *E. coli* as well, thereby highlighting the effectiveness of water hyacinth in phytoremediation. A similar reduction in ammoniacal nitrogen was observed in a study at the Skudai River, Malaysia [83]. It was observed in the study that a higher plant density of water hyacinth resulted in better absorption of ammoniacal nitrogen. The setup had three containers having six, eight, and ten water hyacinth plants, respectively, where in 9 days, all three containers showed reductions in $\text{NH}_3\text{-N}$ from 12 mg/L to less than 4 mg/L. The container with 10 plants showed the highest reduction rate due to a higher number, leading to better absorption and an accelerated process. It was also observed that the concentration of $\text{NH}_3\text{-N}$ stabilized, but after 9 days, it increased slightly due to the nitrification process. The increase in ammonia is also due to a decrease in water level, increasing nitrification, inadequate management in removing dried leaves of the plant, and algal presence in the setup after the 9-day study period.

Various parameters affect the $\text{NH}_3\text{-N}$ removal capacity of water hyacinths, such as pH, retention time, salinity, and macrophyte density, and the relationship between these factors is a key aspect to understanding the ideal conditions of $\text{NH}_3\text{-N}$ removal (Table 2). The equilibrium distribution between NH_4^+ and free NH_3 is strongly pH- and temperature-dependent, with the fraction of toxic, volatile NH_3 increases exponentially above pH 8 [4]. Another study analyzed several combinations of different variables by response surface methodology (RSM) to understand their combined effect on $\text{NH}_3\text{-N}$ removal [84]. Even with a shorter retention time, high $\text{NH}_3\text{-N}$ removal (>80%) could be achieved if the pH is higher than 8, as higher pH leads to faster ammonia volatilization. With low levels of pH (pH less than 4), water hyacinth shows less $\text{NH}_3\text{-N}$ removal efficiency. There is also higher $\text{NH}_3\text{-N}$ removal in low saline and high macrophyte density conditions at a fixed neutral pH over a period of 8 days. It was also observed that, even in high saline conditions, $\text{NH}_3\text{-N}$ removal could be done efficiently if the stress is compensated by a significantly higher macrophyte density. In the case of a fixed pH and low saline conditions, higher retention time in a high macrophyte density condition boosts the $\text{NH}_3\text{-N}$ removal. While observing the interactive effect of salinity and retention time at a fixed pH and macrophyte density, higher salinity was observed to be the dominant factor that negatively influenced the $\text{NH}_3\text{-N}$ removal. The plant was observed to develop negative biomass along with dead and wilted parts over time in high salinity conditions, which lead to a decrease in $\text{NH}_3\text{-N}$ removal. In a higher pH condition, $\text{NH}_3\text{-N}$ removal would increase but would simultaneously decrease the density of the plant, thus showing its insignificant effect in $\text{NH}_3\text{-N}$ removal in alkaline conditions. Overall, the optimum condition for $\text{NH}_3\text{-N}$ removal of almost 77.48% could be achieved by combining the interaction of all the factors at a pH

of 8.51 and salinity of 0 g NaCl/L, with a macrophyte density of 21.39 g/L in a retention time of 8.47 days.

Water hyacinth effectively absorbs and transforms ammonium (NH_4^+) into other forms of nitrogen, such as nitrate and nitrite [8]. In different concentrations of black and odorous water containing ammonia and other pollutants, it was observed, after a 10-day cultivation, by Fourier transform infrared (FT-IR) spectroscopy that water hyacinth showed characteristic peaks of ammonium, nitrate, and nitrite in the root structure, highlighting the absorption characteristics of water hyacinth. It was also observed that, in the FT-IR spectroscopy of the stem, the peak of NH_4^+ was reduced, signifying its conversion into nitrate and nitrite, and in the further FT-IR analysis of the leaf, a minimal concentration of nitrite and ammonia was observed, and nitrate was seen in the highest concentration in the leaves due to faster conversion of other N-ions into nitrates. The entire migration route of the nitrogen species was from roots to leaves via the stem. Further, on an analysis of the same parameters after a 20-day cultivation, the analysis showed a very low presence of NH_4^+ and NO_2^- , confirming weak absorption in roots, followed by weak migration in the stem, and slight concentration of NO_3^- in the leaves. This highlights that the absorption and remediation abilities of water hyacinth decrease with higher retention time. However, in the same study, two other plants, *Acorus calamus* and *Canna indica*, were observed to be more efficient than water hyacinth for the entire study period.

However, the direct comparison of the removal efficiency of ammoniacal nitrogen across different studies (Table 3) is inherently challenged by the significant variability in influent ammoniacal nitrogen concentration, hydraulic retention time (HRT), macrophyte density, environmental factors, and operational scale (laboratory, pilot, or full-scale). In fact, removal efficiency is usually given as a percentage reduction only, without providing normalized performance data such as volumetric removal rate ($\text{mg NH}_3\text{-N L}^{-1} \text{ day}^{-1}$), areal removal rate ($\text{g NH}_3\text{-N m}^{-2} \text{ day}^{-1}$), or biomass-specific removal rate ($\text{mg NH}_3\text{-N g}^{-1} \text{ dry biomass day}^{-1}$). In fact, the lack of normalization of removal efficiency makes quantitative comparisons across studies difficult. It may lead to an overemphasis on differences in removal efficiency that are actually due to differences in loading rate or retention time rather than phytoremediation potential per se.

Table 1. Ammoniacal nitrogen removal efficiencies of aquatic macrophytes under varied treatment conditions.

Study	Macrophyte	Duration/HRT	Influent $\text{NH}_3\text{-N}$ (mg/L)	Effluent $\text{NH}_3\text{-N}$ (mg/L)	Removal (%)	System Context	Mechanistic Indications	Key Notes
[15]	<i>Pistia stratiotes</i>	14 days	12.14	3.49	71.25 ± 5.8	Mixed wastewater	Likely assimilation + adsorption	Also reduced Cu (76.7%) and TDS (22.6%)
	<i>Ipomoea aquatica</i>	8 days	10.2	0.28	97.3	Batch system	High uptake; short HRT suggests strong assimilation	Best $\text{NH}_3\text{-N}$ removal among tested species
[16]	<i>Salvinia minima</i>	8 days	10.2	1.03	89.9	Batch	Likely assimilation	Better COD removal
	<i>Lemna minor</i>	8 days	10.2	2.00	80.4	Batch	Surface assimilation dominant	—
	<i>Centella asiatica</i>	8 days	10.2	2.13	79.1	Batch	Likely assimilation	—
[85]	<i>Canna lily</i>	18 weeks	—	—	45.65–100	Constructed wetland	Variable; influenced by flooding and decay	NH_3 increase during weeks 14 and 18
[8]	<i>Eichhornia crassipes</i>	20 days	24 (first 10 d)	~8 (first 10 d)	>80 (first phase)	Comparative plant study	Likely assimilation; efficiency declined over time	Inferior to <i>A. calamus</i> and <i>C. indica</i>
	<i>Acorus calamus</i> / <i>Canna indica</i>	20 days	24	<2	>90	Rooted emergent system	Likely sustained uptake	Better long-term performance
[86]	<i>Eichhornia crassipes</i>	14 days	4.20 ± 0.10	3.1	74	Wastewater	Assimilation + possible microbial role	Best phosphate removal (98%)

Table 1. Cont.

Study	Macrophyte	Duration/HRT	Influent NH ₃ -N (mg/L)	Effluent NH ₃ -N (mg/L)	Removal (%)	System Context	Mechanistic Indications	Key Notes
[87]	<i>Eichhornia crassipes</i>	1 month	2.5	<0.01	~99	Aquaculture water	Likely assimilation; low loading	65% plant survival
[41]	<i>Eichhornia crassipes</i>	2 months	TKN: 42.2	—	30.8	Pond system	Lower NH ₃ -N removal vs. duckweed	Better COD removal

Table 2. Factors affecting the efficiency of ammoniacal nitrogen removal by water hyacinth.

Factor	Optimal Range/Condition	Impact on Efficiency
Water Temperature	25–30 °C	Enhances metabolic activity and nutrient uptake; growth slows below 15 °C
pH Level	6.0–8.0	Neutral to slightly alkaline pH supports optimal growth and NH ₃ -N uptake
Ammoniacal Nitrogen (NH ₃ -N)	100–150 mg/L (optimal); >200 mg/L (toxic)	High NH ₃ -N boosts uptake but may inhibit growth if excessive
Salinity	<1.66% NaCl	High salinity causes chlorosis and necrosis, limiting plant survival
Plant Age	Young plants preferred	Younger roots have higher oxygen release and nutrient absorption capacity
Harvest Frequency	Every 2–3 weeks (varies by system)	Prevents decay and nutrient release; maintains optimal biomass productivity
Sunlight Availability	High solar radiation	Boosts photosynthesis and biomass growth; rainy seasons reduce efficiency
Retention Time	8–44 days (depending on wastewater type)	Longer retention improves NH ₃ -N removal but may slow throughput
Nutrient Load	Moderate nutrient levels	Excessive nutrients may cause toxicity; balanced load supports steady uptake
Water Depth	14–15 cm (recommended)	Prevents anaerobic conditions and odor; supports aerobic microbial activity

Table 3. List of various case studies showing ammoniacal nitrogen removal efficiency by water hyacinth.

Sl. No.	Case Study	Water Type/Location	Scale	Duration/Retention Time	NH ₃ -N Removal Efficiency	Reference
1.	Domestic wastewater	Pond effluent (India)	Laboratory	24 days	67% removal	[88]
2.	Domestic wastewater	Institutional WWTP (Malaysia)	Pilot	21 days	85% removal	[74]
3.	Municipal wastewater	City effluent (Tanzania)	Pilot	44 days	81% removal	[78]
4.	Polluted river	Waigang River (China)	Field	1 year	From 5.2 mg/L to 3.5 mg/L (48.6% removal)	[89]
5.	Polluted river	Waigang River (China)	Field	3 years	86.5% removal	[90]

5. Benefits and Limitations

5.1. Environmental and Economic Benefits

Water hyacinth (*Eichhornia crassipes*) has demonstrated remarkable efficacy in the phytoremediation of ammoniacal nitrogen (NH₃-N), offering significant environmental and economic benefits. Its fast growth, large biomass, and extensive root systems make it ideal for absorbing nutrients, particularly nitrogenous compounds, from aquatic systems. Multiple studies confirm its ability to reduce ammonium, nitrate, and nitrite by over 95% in controlled experiments, demonstrating a highly efficient nutrient uptake potential [91]. Economically, water hyacinth systems are relatively low-cost compared to conventional wastewater treatment methods, such as nitrification–denitrification, ion exchange, or membrane filtration (Table 4). These traditional approaches often require significant energy

inputs, chemical reagents, and sophisticated infrastructure, which can be financially burdensome, especially for low- and middle-income regions. In contrast, phytoremediation using water hyacinth offers a low-input, eco-friendly alternative [84]. Furthermore, water hyacinth grows abundantly in tropical and subtropical climates without the need for fertilizers or pesticides, making it readily available and self-sustaining.

Table 4. Comparison of water hyacinth with conventional wastewater treatment methods.

Treatment Method	Efficiency for NH ₃ -N Removal	Advantages	Limitations	Relative Performance of Water Hyacinth	References
Nitrification–Denitrification (Activated Sludge)	80–95%	Reliable and consistent; controlled biological process	High energy demand; chemical inputs; skilled operation required	Water hyacinth achieves comparable removal (81–97%) under optimized conditions but with lower operational cost and slower kinetics	[1,28,84]
Ion Exchange/Adsorption Systems	85–95%	Rapid and selective removal	Expensive resins; regeneration waste	Water hyacinth provides a low-cost, low-maintenance alternative but offers less precise process control	[1]
Membrane Bioreactors (MBR)	90–99%	High precision; compact design	Membrane fouling; high maintenance and energy cost	Water hyacinth may serve as pre-treatment to reduce nutrient loading prior to MBR application	[28]
Constructed Wetlands (Rooted Macrophytes)	70–95%	Sustainable; low energy requirement	Large land area required; limited hydraulic capacity	Integration with floating water hyacinth can enhance nitrogen removal via combined assimilation and microbial processes	[10,18]
Chemical Precipitation/ Air Stripping	60–80%	Rapid removal; suitable for high concentrations	Chemical sludge production; pH adjustment required	Water hyacinth avoids chemical sludge generation but requires longer retention times	[84]
Water Hyacinth (<i>Eichhornia crassipes</i>)	77–97% (system-dependent)	Low cost; minimal energy input; biomass valorization potential	Slower treatment rate; requires harvesting; performance depends on environmental conditions	—	[1,84,91]

The application of water hyacinth in real-world scenarios has shown promising results. For example, in a municipal wastewater pilot plant, water hyacinth achieved an NH₃-N removal efficiency of 81% and 85% over retention periods of 44 and 21 days, respectively, depending on influent concentrations and plant density [1]. These results are not limited to synthetic systems; validation experiments using real semiconductor effluents revealed an NH₃-N removal efficiency of 77.48% under optimized conditions (pH 8.51, 8.47 days retention time, and plant density of 21.39 g/L) [84].

Besides its purification potential, harvested water hyacinth biomass can be converted into value-added products. An experimental study reported successful conversion into bioethanol (yielding 0.09 mL/mL culture) and nutrient-rich vermicompost with a microbial nitrogen content ranging from 104.4 to 254.9 µg/g and a germination index of 84.3%, demonstrating its potential in circular bioeconomy applications [91]. These co-benefits reduce environmental waste and offer alternative energy and agricultural solutions.

5.2. Challenges and Limitations

Despite its benefits, the use of water hyacinth for phytoremediation presents multiple challenges. Water hyacinth is known to multiply rapidly up to 50 kg/m², leading to the obstruction of waterways, reduced light penetration, and decreased oxygen levels, ultimately harming aquatic ecosystems [91]. Its proliferation can displace native flora and fauna, demanding careful monitoring and regular harvesting to maintain ecological balance. Maintenance is another significant issue. Improper management can result in decaying biomass, which may reintroduce nutrients into the water column, thereby reversing the remediation process.

Phytoremediation using water hyacinth also demands adequate surface area and favorable climatic conditions. The plant thrives in tropical environments but is sensitive to cold, salinity, and extreme pH values. It was evident that salinity levels exceeding 2.5 g NaCl/L resulted in phytotoxic effects, such as leaf chlorosis, twisting, and necrosis, drastically reducing biomass and nitrogen uptake [84]. Additionally, acidic conditions (pH < 5) inhibited plant growth and nitrogen assimilation due to physiological stress and nutrient imbalance.

Another logistical challenge is biomass disposal. Since the plant may accumulate not only nutrients but also heavy metals and other contaminants, careless disposal can lead to environmental recontamination. Strategies such as composting, anaerobic digestion, or controlled incineration are required to manage biomass safely [91].

5.3. Potential for Large-Scale Implementation

The potential for large-scale implementation of water hyacinth in phytoremediation is promising but context dependent (Table 5). In developing countries with abundant aquatic weeds and inadequate wastewater treatment systems, integrating phytoremediation into decentralized infrastructure could be transformative.

In long-term studies, extensive water bodies have been remediated effectively using water hyacinth. For instance, a year-long phytoremediation project in a eutrophic lake covering 10.5 km² demonstrated substantial reductions in NH₃-N concentration, with biomass periodically harvested to prevent saturation [1]. In another case, a three-year riverine project covering 5000 m² of water surface achieved 86.5% NH₃-N removal using 90% plant coverage and systematic harvesting.

Research-driven optimization using response surface methodology (RSM) has made scalability more feasible. Studies showed that, even with fluctuating influent concentrations and weather conditions, performance remained consistent when process parameters were carefully tuned [84]. Innovations such as automated harvesting systems and integrated multi-stage treatment (e.g., combining water hyacinth with sedimentation or filtration units) can further enhance viability.

However, large-scale application requires strong institutional frameworks and policy backing. Guidelines must address environmental risks, safe biomass handling, and system maintenance. Moreover, integrating community participation in biomass harvesting and reuse (e.g., compost production or biofuel generation) could improve public acceptance and economic sustainability. For better scalability and comparability, future large-scale applications should measure ammoniacal nitrogen removal using standardized volumetric or areal performance metrics like mg NH₃-N L⁻¹ day⁻¹ or g NH₃-N m⁻² day⁻¹, which would facilitate more robust analysis of treatment efficiency.

Table 5. Viability of large-scale implementation of water hyacinth for wastewater treatment.

Aspect	Details and Examples	References
Environmental Benefits	Efficient removal of ammoniacal nitrogen (NH ₃ -N), nitrate, and nitrite (>95% under controlled conditions). Reduction in nutrient pollution in wastewater and improvement of water quality in lakes, rivers, and industrial effluents.	[1,91]
Economic Benefits	Low-cost alternative compared to conventional nitrification–denitrification systems; minimal energy, chemical, and infrastructure requirements. Harvested biomass can be converted into bioethanol (0.09 mL/mL culture) and nutrient-rich vermicompost.	[84,91]
Key Challenges and Limitations	Rapid proliferation (up to 50 kg/m ²) may obstruct waterways, reduce light penetration and dissolved oxygen, and displace native species. Decaying biomass can reintroduce nutrients if not harvested. Performance is sensitive to climatic conditions; salinity > 2.5 g NaCl/L and pH < 5 induce phytotoxic stress and reduce nitrogen uptake. Biomass may accumulate contaminants, requiring safe disposal through composting, anaerobic digestion, or controlled incineration.	[84,91]

Table 5. Cont.

Aspect	Details and Examples	References
Real-World Performance	Municipal wastewater treatment achieved 81–85% NH ₃ -N removal over 21–44 days depending on influent concentration and plant density. Semiconductor effluent treatment achieved 77.48% NH ₃ -N removal under optimized conditions (pH 8.51, 8.47 days retention, 21.39 g/L plant density).	[1,84]
Large-Scale Implementation Potential	Suitable for decentralized wastewater treatment in developing regions. Long-term remediation projects demonstrated substantial NH ₃ -N reduction in a 10.5 km ² eutrophic lake and 5000 m ² riverine system (86.5% removal with systematic harvesting). Performance stability enhanced through response surface methodology (RSM) optimization and integration with multi-stage systems.	[1,84]
Requirements for Large-Scale Success	Strong institutional frameworks, environmental monitoring, regulated biomass harvesting and safe reuse strategies (composting, bioenergy generation), and community participation are essential for sustainable implementation.	[91,92]

6. Advances and Innovations

6.1. Integration with Other Remediation Technologies

Trends in *Eichhornia crassipes*-based treatment systems include the integration of such processes with other complementary biological and physicochemical processes for enhanced removal of ammoniacal nitrogen (Table 6). Notwithstanding the nutrient removal capacity and resistance to complex wastewater composition of the water hyacinth, its efficiency is highly sensitive to hydraulic retention time, oxygen concentration, and system design.

In integrated systems, the dense root system of *E. crassipes* contributes to the development of biofilm and enhances oxygen transfer across the water–root interface, thus facilitating microbial nitrification. At the same time, anoxic microhabitats in sediments and root tissues can facilitate denitrification, thus enabling permanent nitrogen removal. These plant–microbe interactions can enhance overall nitrogen conversion processes, apart from plant assimilation [93].

Hybrid phytoremediation systems have also demonstrated the potential to reduce co-occurring wastewater variables. For example, the treatment of coir retting wastewater using *E. crassipes* demonstrated progressive removals of nitrate, sulphate, total suspended solids (TSS), and biochemical oxygen demand (BOD), with the removal efficiency increasing with increasing retention times [94]. Although these findings indicate improvements in wastewater treatment, they also underscore the importance of optimal hydraulic retention time and design for efficient nitrogen removal.

In addition, plant exudates and rhizosphere interactions facilitate microbial growth associated with nitrogen cycling. This suggests that the removal of ammoniacal nitrogen in macrophyte-based systems involves both plant assimilation and microbial processes [93].

Table 6. Integrated wastewater treatment approaches involving water hyacinth and their pollutant removal performance.

Integration Type	Mechanism and Synergistic Advantage	Key Pollutants Removed	Removal Efficiency	Outcome and Benefit	References
Water Hyacinth + Constructed Wetland	Rhizosphere oxygenation enhances microbial nitrification–denitrification; combined plant–microbe action stabilizes the nitrogen cycle	- NH ₃ -N - nitrate - nitrite - BOD - COD	85–95% N removal 90–95% COD/BOD reduction	Improved nutrient and organic load removal, which reduces eutrophication	[78,94]
Water Hyacinth + Microbial Biofilms	Biofilm formation on roots supports nitrifiers and denitrifiers; faster conversion of NH ₄ ⁺ → NO ₃ [−] → N ₂	- NH ₃ -N - nitrite - nitrate	80–90% total nitrogen	Boosted microbial nitrogen cycling and stability under variable loads	[93,95]

Table 6. Cont.

Integration Type	Mechanism and Synergistic Advantage	Key Pollutants Removed	Removal Efficiency	Outcome and Benefit	References
Water Hyacinth + Physicochemical Treatment	Adsorption via hydroxyl, carbonyl, and carboxyl groups; acts as a polishing stage post-coagulation or filtration	- Heavy metals (Cd, Pb, Cr) - residual NH ₃ -N - TSS	70–90% metal and nutrient removal	Reduced toxicity, lower effluent TSS, improved water clarity	[59,96]
Water Hyacinth + Anaerobic Digestion	Biomass used as feedstock for methane generation; digestate reused as fertilizer	- Biomass residues - organic matter	58% CH ₄ in the produced biogas	Circular bioeconomy: renewable energy and nutrient recycling	[91,93]
Water Hyacinth + Multi-Stage Hybrid System (e.g., with <i>Canna indica</i> / <i>Acorus calamus</i>)	Sequential plant use: <i>E. crassipes</i> for rapid uptake, rooted macrophytes for long-term polishing	- NH ₃ -N - phosphate - COD	>95% N and P removal in optimized systems	High resilience, long-term sustainability	[8,84]

6.2. Policy and Management Strategies

Effective implementation of *Eichhornia crassipes* systems requires careful biomass management to ensure sustained ammoniacal nitrogen removal. Since plant assimilation represents temporary nitrogen storage, periodic harvesting is essential to prevent nitrogen re-release during senescence. Ex situ systems provide greater operational control compared to unmanaged infestations, allowing optimization of hydraulic loading and retention time.

Beyond pollutant removal, harvested biomass presents opportunities for resource recovery. Due to its favorable C/N ratio (20–30:1) and high organic matter content, *E. crassipes* has been investigated as a substrate for biogas production, producing methane-rich gas streams suitable for energy recovery [93]. Such valorization strategies can enhance the sustainability of nitrogen treatment systems by coupling nutrient removal with bioenergy generation.

Control of excessive water hyacinth proliferation remains an important management consideration. Biological agents such as *Neochetina* sp. and fungal pathogens were employed previously to regulate overgrowth in natural systems [93]. While primarily used for invasive management, these strategies highlight the need for balanced biomass control in engineered treatment applications.

In the context of nutrient pollution mitigation, macrophyte-based systems contribute to broader water quality improvement goals, including those aligned with the United Nations Sustainable Development Goal 6 on clean water and sanitation [92]. However, effective deployment requires integrating biomass harvesting, operational control, and nitrogen mass balance considerations to ensure long-term treatment efficiency.

7. Conclusions

The presence of a highly developed root system, fast growth, and high biomass make water hyacinth very effective in nitrogen uptake through root absorption, microbial-assisted nitrification–denitrification, and foliar assimilation. This study clearly showed that water hyacinth is an efficient and sustainable macrophyte for NH₃-N removal from various sources of wastewater. The removal efficiency of NH₃-N by water hyacinth is in the range of 74–97%, and a significant reduction in BOD, COD, and TDS can be achieved under favorable conditions of pH 6–8 and temperature 25–30 °C. However, as some other macrophytes like *Canna indica* and *Acorus calamus* gave better performance than water hyacinth after longer or high salinity exposures, the overall performance of water hyacinth remains favorable in rapid treatment systems with short retention periods. Further integration with microbial and physicochemical processes enhances its performance by adding support to resource recovery via bioethanol, compost, or biogas production.

The outcome of this critical review has clearly shown that water hyacinth can assist in managing wastewater sustainably because it will provide an economic and ecological alternative to other conventional modes of treatment methods. Its application fits well into

concepts of integrated water resource management and circular bioeconomy, especially in those areas where advanced treatment infrastructure is still lacking. Its production under controlled conditions in constructed wetlands or floating systems could remove much of the nutrient loading with a minimum of ecological risk, provided regular harvesting and safe disposal or reuse of biomass to prevent re-release of nutrients. Its integration into other macrophytes or microbial systems in such a way enhances long-term stability while supporting balanced ecosystem functioning in aquatic environments.

Water hyacinth can be effectively and safely applied in an engineered system that is regularly monitored to prevent uncontrolled proliferation. Protocols on biomass collection, valorization, and methods of valorization, such as composting, bioethanol, or biogas production, shall be developed with a view to supporting the circularity of resources. Hybrid treatment systems in which phytoremediation is combined with microbial or physicochemical methods for enhanced pollutant removal must be favored by policymakers. The regulatory framework must address design standards, monitoring frequency, ecological safety, and effluent discharge norms. Further studies should focus on enhancing salinity and pH stress tolerance of the plant, optimizing retention time, and testing long-term performance of the plant under field conditions. Community participation must be fostered in cultivation and biomass utilization aspects for sustainability and local ownership of the wastewater management programs.

Water hyacinth offers a practical, natural solution for the removal of ammoniacal nitrogen from aquatic systems. It is highly suitable for decentralized and small-scale approaches to wastewater treatment owing to its low operational cost, high nutrient removal efficiency, and adaptability in tropical climate conditions. Ecological control, sustainable biomass management, and institutional support are required for its successful implementation. With a well-regulated policy framework, water hyacinth can play a useful contributory role in improving water quality, enhancing the circular bioeconomy, and providing options toward long-term environmental sustainability.

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References

1. Ting, W.H.T.; Tan, I.A.W.; Salleh, S.F.; Wahab, N.A. Application of Water Hyacinth (*Eichhornia crassipes*) for Phytoremediation of Ammoniacal Nitrogen: A Review. *J. Water Process Eng.* **2018**, *22*, 239–249. [\[CrossRef\]](#)
2. Edwards, T.M.; Puglis, H.J.; Kent, D.B.; Durán, J.L.; Bradshaw, L.M.; Farag, A.M. Ammonia and Aquatic Ecosystems—A Review of Global Sources, Biogeochemical Cycling, and Effects on Fish. *Sci. Total Environ.* **2024**, *907*, 167911. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Francis-Floyd, R.; Watson, C.; Petty, D.; Pouder, D.B. *Ammonia in Aquatic Systems*; IFAS University of Florida (UF)/Institute of Food and Agricultural Sciences (IFAS): Gainesville, FL, USA, 2009; Volume 16, pp. 1–4.
4. Emerson, K.; Russo, R.C.; Lund, R.E.; Thurston, R.V. Aqueous Ammonia Equilibrium Calculations: Effect of PH and Temperature. *J. Fish. Res. Board Can.* **1975**, *32*, 2379–2383. [\[CrossRef\]](#)
5. Boyd, C.E. Determination of Total Ammonia Nitrogen and Chemical Oxygen Demand in Fish Culture Systems. *Trans. Am. Fish. Soc.* **1979**, *108*, 314–319. [\[CrossRef\]](#)
6. Kent, D.B. *Simulating Changes in the Distribution of Ammonium and Ammonia Versus Physical and Chemical Conditions Using PHREEQC with Applications to Toxicity to Fish*; US Geological Survey (USGS): Reston, VA, USA, 2023.
7. Shammass, N.K. Interactions of Temperature, pH, and Biomass on the Nitrification Process. *Water Pollut. Control Fed.* **1986**, *58*, 52–59.
8. Huangfu, S.; Zhou, F.; Zheng, X.; Zhang, X.; Hu, L. Removal of Ammonia Nitrogen from Black and Odorous Water by Macrophytes Based on Laboratory Microcosm Experiments. *RSC Adv.* **2023**, *13*, 3173–3180. [\[CrossRef\]](#)
9. Paz-Alberto, A.M.; Sigua, G.C. Phytoremediation: A Green Technology to Remove Environmental Pollutants. *Am. J. Clim. Change* **2013**, *2*, 71–86. [\[CrossRef\]](#)
10. Roychowdhury, A.; Mukherjee, P.; Panja, S.; Datta, R.; Christodoulatos, C.; Sarkar, D. Evidence for Phytoremediation and Phytoexcretion of NTO from Industrial Wastewater by Vetiver Grass. *Molecules* **2021**, *26*, 74. [\[CrossRef\]](#)
11. Adesodun, J.K.; Atayese, M.O.; Agbaje, T.A.; Osadiaye, B.A.; Mafe, O.F.; Soretire, A.A. Phytoremediation Potentials of Sunflowers (*Tithonia diversifolia* and *Helianthus annuus*) for Metals in Soils Contaminated with Zinc and Lead Nitrates. *Water Air Soil Pollut.* **2010**, *207*, 195–201. [\[CrossRef\]](#)
12. Sakakibara, M.; Ohmori, Y.; Ha, N.T.H.; Sano, S.; Sera, K. Phytoremediation of Heavy Metal-Contaminated Water and Sediment by *Eleocharis acicularis*. *CLEAN Soil Air Water* **2011**, *39*, 735–741. [\[CrossRef\]](#)
13. Shabani, N.; Sayadi, M.H. Evaluation of Heavy Metals Accumulation by Two Emergent Macrophytes from the Polluted Soil: An Experimental Study. *Environmentalist* **2012**, *32*, 91–98. [\[CrossRef\]](#)
14. Roychowdhury, A.; Datta, R.; Sarkar, D. Heavy Metal Pollution and Remediation. In *Green Chemistry: An Inclusive Approach*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 359–373. [\[CrossRef\]](#)
15. Apritama, M.R.; Wayan, I.; Suryawan, K.; Afifah, A.S.; Septiariva, I.Y. Phytoremediation of Effluent Textile WWTP for NH₃-N and Cu Reduction Using *Pistia stratiotes*. *Plant Arch.* **2020**, *20*, 2384–2388.
16. Aziz, N.I.H.A.; Hanafiah, M.M.; Halim, N.H.; Fidri, P.A.S. Phytoremediation of TSS, NH₃-N and COD from Sewage Wastewater by *Lemna minor* L., *Salvinia minima*, *Ipomea aquatica* and *Centella asiatica*. *Appl. Sci.* **2020**, *10*, 5397. [\[CrossRef\]](#)
17. Roychowdhury, A.; Sarkar, D.; Datta, R. Remediation of Acid Mine Drainage-Impacted Water. *Curr. Pollut. Rep.* **2015**, *1*, 131–141. [\[CrossRef\]](#)
18. Roychowdhury, A.; Sarkar, D.; Datta, R. A Combined Chemical and Phytoremediation Method for Reclamation of Acid Mine Drainage-Impacted Soils. *Environ. Sci. Pollut. Res.* **2019**, *26*, 14414–14425. [\[CrossRef\]](#)
19. Fu, Q.; Zheng, B.; Zhao, X.; Wang, L.; Liu, C. Ammonia Pollution Characteristics of Centralized Drinking Water Sources in China. *J. Environ. Sci.* **2012**, *24*, 1739–1743. [\[CrossRef\]](#)
20. Clément, B.; Merlin, G. The Contribution of Ammonia and Alkalinity to Landfill Leachate Toxicity to Duckweed. *Sci. Total Environ.* **1995**, *170*, 71–79. [\[CrossRef\]](#)
21. Wang, W. Ammonia Toxicity to Macrophytes (Common Duckweed and Rice) Using Static and Renewal Methods. *Environ. Toxicol. Chem.* **1991**, *10*, 1173–1177. [\[CrossRef\]](#)
22. Liu, Y.; Ngo, H.H.; Guo, W.; Peng, L.; Wang, D.; Ni, B. The Roles of Free Ammonia (FA) in Biological Wastewater Treatment Processes: A Review. *Environ. Int.* **2019**, *123*, 10–19. [\[CrossRef\]](#)
23. Zhang, T.X.; Li, M.R.; Liu, C.; Wang, S.P.; Yan, Z.G. A Review of the Toxic Effects of Ammonia on Invertebrates in Aquatic Environments. *Environ. Pollut.* **2023**, *336*, 122374. [\[CrossRef\]](#)
24. Parvathy, A.J.; Das, B.C.; Jifiriya, M.J.; Varghese, T.; Pillai, D.; Rejish Kumar, V.J. Ammonia Induced Toxic-Physiological Responses in Fish and Management Interventions. *Rev. Aquac.* **2023**, *15*, 452–479. [\[CrossRef\]](#)
25. Yan, L.; Mu, X.; Han, B.; Zhang, S.; Qiu, C.; Ohore, O.E. Ammonium Loading Disturbed the Microbial Food Webs in Biofilms Attached to Submersed Macrophyte *Vallisneria spiralis*. *Sci. Total Environ.* **2019**, *659*, 691–698. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Munive-Olarte, A.; Rosano-Ortega, G.; Schabes-Retchkiman, P.; Martínez-Gallegos, M.; El Kassis, E.; González-Pérez, M.; Pacheco-García, F. Assessment of Biomass of Leaves of Water Hyacinth (*Eichhornia crassipes*) as Reducing Agents for the Synthesis of Nanoparticles of Gold and Silver. *Int. J. Adv. Eng.* **2017**, *3*, 239822. [\[CrossRef\]](#)

27. Mishra, V.K.; Tripathi, B.D. Accumulation of Chromium and Zinc from Aqueous Solutions Using Water Hyacinth (*Eichhornia crassipes*). *J. Hazard. Mater.* **2009**, *164*, 1059–1063. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Yogeve, U.; Gross, A. Reducing Environmental Impact of Recirculating Aquaculture Systems by Introducing a Novel Microaerophilic Assimilation Reactor: Modeling and Proof of Concept. *J. Clean. Prod.* **2019**, *226*, 1042–1050. [\[CrossRef\]](#)
29. Mitsch, W.J.; Day, J.W.; Zhang, L.; Lane, R.R. Nitrate-Nitrogen Retention in Wetlands in the Mississippi River Basin. *Ecol. Eng.* **2005**, *24*, 267–278. [\[CrossRef\]](#)
30. White, G.C. Chlorination and Dechlorination: A Scientific and Practical Approach. *J. AWWA* **1968**, *60*, 540–561. [\[CrossRef\]](#)
31. Lytle, D.A.; Williams, D.; Muhlen, C.; Riddick, E.; Pham, M. The Removal of Ammonia, Arsenic, Iron and Manganese by Biological Treatment from a Small Iowa Drinking Water System. *Environ. Sci.* **2020**, *6*, 3142–3156. [\[CrossRef\]](#)
32. Ahmed, F.N.; Lan, C.Q. Treatment of Landfill Leachate Using Membrane Bioreactors: A Review. *Desalination* **2012**, *287*, 41–54. [\[CrossRef\]](#)
33. Macek, T.; Francová, K.; Kochánková, L.; Lovecká, P.; Ryslavá, E.; Rezek, J.; Surá, M.; Triska, J.; Demnerová, K.; Macková, M. Phytoremediation: Biological Cleaning of a Polluted Environment. *Rev. Environ. Health* **2004**, *19*, 63–82. [\[CrossRef\]](#)
34. Kumar, M.; Singh, R. Assessment of Pollutant Removal Processes and Kinetic Modelling in Vertical Flow Constructed Wetlands at Elevated Pollutant Loading. *Environ. Sci. Pollut. Res.* **2019**, *26*, 18421–18433. [\[CrossRef\]](#)
35. Varma, M.; Gupta, A.K.; Ghosal, P.S.; Majumder, A. A Review on Performance of Constructed Wetlands in Tropical and Cold Climate: Insights of Mechanism, Role of Influencing Factors, and System Modification in Low Temperature. *Sci. Total Environ.* **2021**, *755*, 142540. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Hualpa-Cutipa, E.; Acosta, R.A.S.; Sangay-Tucto, S.; Beingolea, X.G.M.; Gutierrez, G.T.; Zababurú, I.N. Recent Trends for Treatment of Environmental Contaminants in Wastewater: An Integrated Valorization of Industrial Wastewater. In *Integrated Environmental Technologies for Wastewater Treatment and Sustainable Development*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 337–368. [\[CrossRef\]](#)
37. Singh, J.; Kumar, V.; Kumar, P.; Kumar, P.; Yadav, K.K.; Cabral-Pinto, M.M.S.; Kamyab, H.; Chelliapan, S. An Experimental Investigation on Phytoremediation Performance of Water Lettuce (*Pistia stratiotes* L.) for Pollutants Removal from Paper Mill Effluent. *Water Environ. Res.* **2021**, *93*, 1543–1553. [\[CrossRef\]](#)
38. Kumar, V.; Singh, J.; Kumar, P.; Kumar, P. Response Surface Methodology Based Electro-Kinetic Modeling of Biological and Chemical Oxygen Demand Removal from Sugar Mill Effluent by Water Hyacinth (*Eichhornia crassipes*) in a Continuous Stirred Tank Reactor (CSTR). *Environ. Technol. Innov.* **2019**, *14*, 100327. [\[CrossRef\]](#)
39. Adelodun, A.A.; Olajire, T.; Afolabi, N.O.; Akinwumiju, A.S.; Akinbobola, E.; Hassan, U.O. Phytoremediation Potentials of *Eichhornia crassipes* for Nutrients and Organic Pollutants from Textile Wastewater. *Int. J. Phytoremediat.* **2021**, *23*, 1333–1341. [\[CrossRef\]](#)
40. Goala, M.; Yadav, K.K.; Alam, J.; Adelodun, B.; Choi, K.S.; Cabral-Pinto, M.M.S.; Hamid, A.A.; Alhoshan, M.; Ali, F.A.A.; Shukla, A.K. Phytoremediation of Dairy Wastewater Using *Azolla Pinnata*: Application of Image Processing Technique for Leaflet Growth Simulation. *J. Water Process Eng.* **2021**, *42*, 102152. [\[CrossRef\]](#)
41. Alam, R.; Ullah Khan, S.; Basheer, F.; Haq Farooqi, I. Nutrients and Organics Removal from Slaughterhouse Wastewater Using Phytoremediation: A Comparative Study on Different Aquatic Plant Species. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1058*, 012068. [\[CrossRef\]](#)
42. Shikha, S.; Gauba, P. Phytoremediation of Industrial and Pharmaceutical Pollutants. *Recent Adv. Biol. Med.* **2016**, *02*, 113. [\[CrossRef\]](#)
43. Wani, R.A.; Ganai, B.A.; Shah, M.A.; Uqab, B. Heavy Metal Uptake Potential of Aquatic Plants through Phytoremediation Technique—A Review. *J. Bioremediat. Biodegrad.* **2017**, *8*, 2. [\[CrossRef\]](#)
44. Mustafa, H.M.; Hayder, G. Recent Studies on Applications of Aquatic Weed Plants in Phytoremediation of Wastewater: A Review Article. *Ain Shams Eng. J.* **2021**, *12*, 355–365. [\[CrossRef\]](#)
45. Ma, T.; Zhang, W.; Fan, H.; Huang, L.; Xu, Q.; Ma, G.; Zhou, G.; Meng, Y.; Sun, J.; Qiu, J.; et al. Study on Phytoremediation for Heavy Metal Contaminated Sediments by Hydrophytes. *E3S Web Conf.* **2020**, *143*, 02020. [\[CrossRef\]](#)
46. Hill, M.P.; Coetzee, J.A. Integrated Control of Water Hyacinth in Africa. *EPPO Bull.* **2008**, *38*, 452–457. [\[CrossRef\]](#)
47. Patel, S. Threats, Management and Envisaged Utilizations of Aquatic Weed *Eichhornia crassipes*: An Overview. *Rev. Environ. Sci. Biotechnol.* **2012**, *11*, 249–259. [\[CrossRef\]](#)
48. Gettys, L.A.; Tipping, P.W.; Della Torre, C.J., III; Sardes, S.N.; Thayer, K.M. Can Herbicide Usage Be Reduced by Practicing IPM for Waterhyacinth (*Eichhornia crassipes*) Control? In *Proceedings of the Florida State Horticultural Society*; Florida State Horticultural Society: Alexandria, VA, USA, 2014; Volume 127, pp. 213–216.
49. Degaga, A.H. Water Hyacinth (*Eichhornia crassipes*) Biology and Its Impacts on Ecosystem, Biodiversity, Economy and Human Well-Being. *J. Nat. Sci. Res.* **2019**, *9*, 24–30. [\[CrossRef\]](#)
50. Gaurav, G.K.; Mehmood, T.; Cheng, L.; Klemeš, J.J.; Shrivastava, D.K. Water Hyacinth as a Biomass: A Review. *J. Clean. Prod.* **2020**, *277*, 122214. [\[CrossRef\]](#)

51. Guna, V.; Ilangovan, M.; Anantha Prasad, M.G.; Reddy, N. Water Hyacinth: A Unique Source for Sustainable Materials and Products. *ACS Sustain. Chem. Eng.* **2017**, *5*, 4478–4490. [\[CrossRef\]](#)
52. Rakotoarisoa, T.; Waeber, P.; Richter, T.; Mantilla-Contreras, J. Water Hyacinth (*Eichhornia crassipes*), Any Opportunities for the Alaotra Wetlands and Livelihoods? *Madag. Conserv. Dev.* **2015**, *10*, 128–136. [\[CrossRef\]](#)
53. Mitchell, D.S. Surface-Floating Aquatic Macrophytes. In *The Ecology and Management of African Wetland Vegetation*; Denny, P., Ed.; Geobotany; Springer: Dordrecht, The Netherlands, 1985; Volume 6, pp. 109–124.
54. Edwards, D.; Musil, C.J. *Eichhornia crassipes* in South Africa—A General Review. *J. Limnol. Soc. S. Afr.* **1975**, *1*, 23–27. [\[CrossRef\]](#)
55. Sharma, V.; Prasanna, R.; Hossain, F.; Muthusamy, V.; Nain, L.; Das, S.; Shivay, Y.S.; Kumar, A. Priming Maize Seeds with Cyanobacteria Enhances Seed Vigour and Plant Growth in Elite Maize Inbreds. *3 Biotech* **2020**, *10*, 154. [\[CrossRef\]](#)
56. Mangas-Ramírez, E.; Elías-Gutiérrez, M. Effect of Mechanical Removal of Water Hyacinth (*Eichhornia crassipes*) on the Water Quality and Biological Communities in a Mexican Reservoir. *Aquat. Ecosyst. Health Manag.* **2004**, *7*, 161–168. [\[CrossRef\]](#)
57. Gaikwad, R.P.; Gavande, S. Major Factors Contributing Growth of Water Hyacinth in Natural Water Bodies. *Int. J. Eng. Res.* **2017**, *6*, 304. [\[CrossRef\]](#)
58. Newete, S.W.; Erasmus, B.F.N.; Weiersbye, I.M.; Byrne, M.J. Sequestration of Precious and Pollutant Metals in Biomass of Cultured Water Hyacinth (*Eichhornia crassipes*). *Environ. Sci. Pollut. Res.* **2016**, *23*, 20805–20818. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Lao, Z.L.; Wu, D.; Li, H.R.; Liu, Y.S.; Zhang, L.W.; Feng, Y.F.; Jiang, X.Y.; Wu, D.W.; Hu, J.J.; Ying, G.G. Uptake Mechanism, Translocation, and Transformation of Organophosphate Esters in Water Hyacinth (*Eichhornia crassipes*): A Hydroponic Study. *Environ. Pollut.* **2024**, *341*, 122933. [\[CrossRef\]](#)
60. Saha, P.; Shinde, O.; Sarkar, S. Phytoremediation of Industrial Mines Wastewater Using Water Hyacinth. *Int. J. Phytoremediat.* **2017**, *19*, 87–96. [\[CrossRef\]](#) [\[PubMed\]](#)
61. Rahman, M.A.; Hasegawa, H.; Ueda, K.; Maki, T.; Rahman, M.M. Arsenic Uptake by Aquatic Macrophyte *Spirodela polyrrhiza* L.: Interactions with Phosphate and Iron. *J. Hazard. Mater.* **2008**, *160*, 356–361. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Bose, S.; Vedamati, J.; Rai, V.; Ramanathan, A.L. Metal Uptake and Transport by *Typha angustata* L. Grown on Metal Contaminated Waste Amended Soil: An Implication of Phytoremediation. *Geoderma* **2008**, *145*, 136–142. [\[CrossRef\]](#)
63. Gunathilake, N.; Yapa, N.; Hettiarachchi, R. Effect of Arbuscular Mycorrhizal Fungi on the Cadmium Phytoremediation Potential of *Eichhornia crassipes* (Mart.) Solms. *Groundw. Sustain. Dev.* **2018**, *7*, 477–482. [\[CrossRef\]](#)
64. Li, H.; Lao, Z.; Liu, Y.; Feng, Y.; Song, A.; Hu, J.; Liao, Z.; Zhang, L.; Liu, M.; Liu, Y.; et al. Uptake, Accumulation, and Translocation of Organophosphate Esters and Brominated Flame Retardants in Water Hyacinth (*Eichhornia crassipes*): A Field Study. *Sci. Total Environ.* **2023**, *874*, 162435. [\[CrossRef\]](#)
65. Roopnarain, A.; Adeleke, R.; Makofane, R.; Obi, L.; Lubinga, M. *The Potential of Water Hyacinth (Eichhornia crassipes) from Hartbeespoort Dam in Biogas and Soil Ameliorant Production, as a Solution to Water Weed Challenges*; Water Research Commission: Pretoria, South Africa, 2018.
66. Bownes, A. Evaluation of a Plant-Herbivore System in Determining Potential Efficacy of a Candidate Biological Control Agent, *Cornops aquaticum* for Water Hyacinth, *Eichhornia crassipes* Core. Doctoral Dissertation, Rhodes University, Grahamstown, South Africa, 2008.
67. Rezaia, S.; Ponraj, M.; Fadhil Md Din, M.; Chelliapan, S.; Md Sairan, F. Effectiveness of *Eichhornia crassipes* in Nutrient Removal from Domestic Wastewater Based on Its Optimal Growth Rate. *Desalin. Water Treat.* **2016**, *57*, 360–365. [\[CrossRef\]](#)
68. Alade, G.A.; Ojoawo, S.O. Purification of Domestic Sewage by Water-Hyacinth (*Eichhornia crassipes*). *Int. J. Environ. Technol. Manag.* **2009**, *10*, 286–294. [\[CrossRef\]](#)
69. Nash, D.A.H.; Abdullah, S.R.S.; Hasan, H.A.; Idris, M.; Muhammad, N.F.; Al-Baldawi, I.A.; Ismail, N.I. Phytoremediation of Nutrients and Organic Carbon from Sago Mill Effluent Using Water Hyacinth (*Eichhornia crassipes*). *J. Eng. Technol. Sci.* **2019**, *51*, 573–584. [\[CrossRef\]](#)
70. Reddy, K.R.; Tucker, J.C. Productivity and Nutrient Uptake of Water Hyacinth, *Eichhornia crassipes* I. Effect of Nitrogen Source. *Econ. Bot.* **1983**, *37*, 237–247. [\[CrossRef\]](#)
71. Prosser, J.I. Autotrophic Nitrification in Bacteria. *Adv. Microb. Physiol.* **1990**, *30*, 125–181. [\[CrossRef\]](#)
72. Strotmann, U.J.; Windecker, G. Kinetics of Ammonium Removal with Suspended and Immobilized Nitrifying Bacteria in Different Reactor Systems. *Chemosphere* **1997**, *35*, 2939–2952. [\[CrossRef\]](#)
73. Bhattacharya, R.; Mazumder, D. Kinetic Study on Nitrification of Ammonium Nitrogen-Enriched Synthetic Wastewater Using Activated Sludge. *Water Sci. Technol.* **2020**, *81*, 62–70. [\[CrossRef\]](#)
74. Rezaia, S.; Din, M.F.M.; Taib, S.M.; Dahalan, F.A.; Songip, A.R.; Singh, L.; Kamyab, H. The Efficient Role of Aquatic Plant (Water Hyacinth) in Treating Domestic Wastewater in Continuous System. *Int. J. Phytoremediat.* **2016**, *18*, 679–685. [\[CrossRef\]](#)
75. Strotmann, U.; Durand, M.J.; Thouand, G.; Eberlein, C.; Heipieper, H.J.; Gartsier, S.; Pagga, U. Microbiological Toxicity Tests Using Standardized ISO/OECD Methods—Current State and Outlook. *Appl. Microbiol. Biotechnol.* **2024**, *108*, 454. [\[CrossRef\]](#)
76. OECD. Test No. 209: Activated Sludge, Respiration Inhibition Test (Carbon and Ammonium Oxidation). In *OECD Guidelines for the Testing of Chemicals*; Section 2; OECD Publishing: Paris, France, 2010. [\[CrossRef\]](#)

77. ISO 9509:2006; Water Quality—Toxicity Test for Assessing the Inhibition of Nitrification of Activated Sludge Microorganism. ISO: Geneva, Switzerland, 2006.
78. Mayo, A.W.; Hanai, E.E. Modeling Phytoremediation of Nitrogen-Polluted Water Using Water Hyacinth (*Eichhornia crassipes*). *Phys. Chem. Earth* **2017**, *100*, 170–180. [\[CrossRef\]](#)
79. Fernandez-Fontaina, E.; Gomes, I.B.; Aga, D.S.; Omil, F.; Lema, J.M.; Carballa, M. Biotransformation of Pharmaceuticals under Nitrification, Nitrataion and Heterotrophic Conditions. *Sci. Total Environ.* **2016**, *541*, 1439–1447. [\[CrossRef\]](#)
80. Madikizela, L.M. Removal of Organic Pollutants in Water Using Water Hyacinth (*Eichhornia crassipes*). *J. Environ. Manag.* **2021**, *295*, 113153. [\[CrossRef\]](#)
81. Pániková, K.; Weigelhofer, G.; Bílková, Z.; Malá, J. Denitrification Assays for Testing Effects of Xenobiotics on Aquatic Denitrification and Their Degradation in Aquatic Environments. *Water* **2023**, *15*, 2536. [\[CrossRef\]](#)
82. Kasmuri, N.; Malik, S.A.A.; Yaacob, Z.; Miskon, M.F.; Ramli, N.H.; Zaini, N. Application of Water Hyacinth in Phytoremediation of Wastewater. *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1135*, 012008. [\[CrossRef\]](#)
83. Nazri, M.A.A.; Zainol, M.R.R.M.A.; Riwayat, A.I.; Zin, M.H.M. Reducing Ammoniacal Nitrogen through Aquatic Plant Absorption (Water Hyacinth) at Skudai River. *AIP Conf. Proc.* **2020**, *2291*, 020064. [\[CrossRef\]](#)
84. Ting, W.H.T.; Tan, I.A.W.; Salleh, S.F.; Abdul Wahab, N. Ammoniacal Nitrogen Removal by *Eichhornia crassipes*-Based Phytoremediation: Process Optimization Using Response Surface Methodology. *Appl. Water Sci.* **2020**, *10*, 80. [\[CrossRef\]](#)
85. Guevarra, N.G.; Cuevas, D.G.; Pescos, C.J.; Sibal, A.; Carrillo, L. Performance Evaluation of Pilot Phyto-Vortex Integrated System in the Reduction of Wastewater Pollutants. *IOP Conf. Ser. Earth Environ. Sci.* **2024**, *1372*, 012052. [\[CrossRef\]](#)
86. Nizam, N.U.M.; Hanafiah, M.M.; Noor, I.M.; Karim, H.I.A. Efficiency of Five Selected Aquatic Plants in Phytoremediation of Aquaculture Wastewater. *Appl. Sci.* **2020**, *10*, 2712. [\[CrossRef\]](#)
87. Mustaqim, M.; Mustasar, M.; Akmal, Y.; Wahyuni, M.; Fajri, T.I.; Ritaqwin, Z. Reducing Ammonia Levels in Catfish Cultivation Water Using Several Aquatic Plants. *DEPIK* **2022**, *11*, 295–298. [\[CrossRef\]](#)
88. Anandha Varun, R.; Kalpana, S. Performance Analysis of Nutrient Removal in Pond Water Using Water Hyacinth and Azolla with Papaya Stem. *Int. Res. J. Eng. Technol.* **2015**, *2*, 444–448.
89. Wang, H.; Zhang, H.; Cai, G. An Application of Phytoremediation to River Pollution Remediation. *Procedia Environ. Sci.* **2011**, *10*, 1904–1907. [\[CrossRef\]](#)
90. Hu, C.; Ou, Y.; Zhang, D.; Zhang, H.; Yan, C.; Zhao, Y.; Zheng, Z. Phytoremediation of the Polluted Waigang River and General Survey on Variation of Phytoplankton Population. *Environ. Sci. Pollut. Res.* **2012**, *19*, 4168–4175. [\[CrossRef\]](#)
91. Punitha, A.M.; Priyatharshini, C.J.; Alghmd, M.A.; Al Farraj, D.A.; Elshikh, M.S.; Ali, M.A.; Arokiyaraj, S.; Hamlin, S.R. Water Hyacinth: A Sustainable Resource for Water Phytoremediation, Ethanol Production, Soil Nutrient Improvement, and the Dynamics of Microbial C and N in Vermicompost. *BioResources* **2025**, *20*, 1614. [\[CrossRef\]](#)
92. United Nations. *Sustainable Development Goal 6 Synthesis Report 2018 on Water and Sanitation*; United Nations: New York, NY, USA, 2018.
93. Monroy-Licht, A.; Carranza-Lopez, L.; De la Parra-Guerra, A.C.; Acevedo-Barrios, R. Unlocking the Potential of *Eichhornia crassipes* for Wastewater Treatment: Phytoremediation of Aquatic Pollutants, a Strategy for Advancing Sustainable Development Goal-06 Clean Water. *Environ. Sci. Pollut. Res.* **2024**, *31*, 43561–43582. [\[CrossRef\]](#)
94. Mol, R.; Murugesan, A.G. Phytoremediation of Nutrients from the Coir Retting Westwater by Water Hyacinth, *Eichhornia crassipes*. *Pollut. Res.* **2022**, *41*, 1282–1287. [\[CrossRef\]](#)
95. Mohebi, Z.; Nazari, M. Phytoremediation of Wastewater Using Aquatic Plants, A Review. *J. Appl. Res. Water Wastewater* **2021**, *8*, 50–58. [\[CrossRef\]](#)
96. Nandiyanto, A.B.D.; Ragadhita, R.; Hofifah, S.N.; Al Huseaeni, D.F.; Al Huseaeni, D.N.; Fiandini, M.; Luckiardi, S.; Soegoto, E.S.; Darmawan, A.; Aziz, M. Progress in the Utilization of Water Hyacinth as Effective Biomass Material. *Environ. Dev. Sustain.* **2024**, *26*, 24521–24568. [\[CrossRef\]](#)

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