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Harnessing water hyacinth potential in hydroponic systems for sustainable sewage treatment

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ABSTRACT

Rapid urbanization and population growth have increased sewage generation, creating major environmental and public health challenges, particularly in regions lacking centralized treatment. Conventional systems are effective but costly and energy-intensive, limiting decentralized deployment. Integrating water hyacinth (*Eichhornia crassipes*) into hydroponic systems offers a low-cost, nature-based alternative for nutrient and organic removal. This review makes three key contributions: (i) it defines a quantitative design–performance envelope linking hydraulic retention time, plant density, and harvesting frequency to treatment efficiency; (ii) it reframes biomass harvesting as a core process control governing net nitrogen and phosphorus removal and root-zone oxygen dynamics; and (iii) it integrates reactor design, biosecurity, and biomass valorization into a unified framework for decentralized sewage treatment. Synthesis of 220 studies shows that controlled floating hydroponic systems typically achieve 50–90% total nitrogen, 60–95% total phosphorus, and 60–95% BOD removal at 7–30 days HRT, driven by coupled plant uptake, rhizosphere nitrification–denitrification, and biofilm adsorption. Pathogen removal is generally limited to 0.5–2 log reductions for indicator bacteria (total and faecal coliforms/*Escherichia coli*), indicating that post-treatment polishing (UV, chlorination, maturation ponds, or wetlands) is required depending on the intended reuse or discharge standard. Performance declines below 15°C without greenhouse protection or hybridization with conventional biological units. Key constraints include seasonal metabolic limitations, hydraulic sensitivity to shock loading, invasive escape risks, and the need for standardized protocols for metal-laden biomass management. Proposed solutions include adaptive harvesting regimes, modular plug-flow layouts, hybrid treatment trains, and biochar production to stabilize contaminants and enable carbon sequestration. Positioned between passive wetlands and energy-intensive membrane systems, water hyacinth hydroponics offers moderate land demand, low energy use (0.02–0.1 kWh m^{-3}), and circular bioeconomy potential for scalable decentralized sewage treatment.

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1. Introduction

Urbanization, population growth, and industrial development have significantly increased sewage generation [1]. In low- and middle-income countries, untreated or inadequately treated sewage is often discharged into water bodies, leading to substantial environmental and public health risks due to the presence of organic matter, nutrients such as nitrogen and phosphorus, heavy metals, and pathogenic microorganisms [2]. These contaminants drive eutrophication, biodiversity loss, and freshwater resource degradation [3]. Although conventional sewage treatment plants, such as biological processes, are widely used to remove these contaminants, the costs of construction and maintenance are often prohibitively high [4]. Therefore, there is a need for alternative, cost-effective, and environmentally sustainable sewage management strategies.

Nature-based solutions, such as constructed wetlands and phytoremediation, are increasingly recognized as sustainable alternatives for sewage treatment by utilizing the synergy between plants, rhizobacteria, and plant exudates to remove pollutants [5]. Among these approaches, integrating aquatic plants into hydroponic systems has shown promise for treating various types of wastewaters, including sewage [6]. Hydroponics, initially developed for growing plants without soil, provides controlled environmental conditions and efficient nutrient absorption, with potential applications in sewage treatment [7]. As reported in Ndulini et al. [8], a hydroponic system can remove organic pollutants and nutrients from sewage with an efficiency of up to 99%.

The water hyacinth, a rapidly growing aquatic plant, has been extensively studied for its potential in hydroponic systems for treating sewage [9]. This plant is distributed globally, especially in tropical and subtropical environments, and is known for its ability to absorb excess nutrients, heavy metals, and organic pollutants from contaminated water [10,11]. Its fibrous root system provides a large surface area for microbial colonization and contaminant adsorption, thereby increasing pollutant removal [12]. Recent research has examined integrating water hyacinth into hydroponic systems to develop closed-loop sewage treatment models that combine nutrient recovery with plant-based remediation [13,14]. Previous studies reported that water hyacinth can remove up to 77.5% of nitrogen [15] and reduce phosphate content by up to 80% without affecting its growth [16]. This indicates that water hyacinth easily grows in contaminated areas, especially where nutrients are plentiful [17]. Additionally, because of its rapid growth and high organic content, some researchers harvest biomass for use in compost, bioenergy, or bioproducts, thereby supporting circular bioeconomy principles [18,19].

The existing literature has extensively covered general phytoremediation and broad nature-based solutions [6,9]. However, most investigations focus on either the biological characteristics and phytoremediation capacity of water hyacinth, the engineering design of hydroponic systems, or pollutant removal efficiencies under specific conditions [7,20]. Few studies have systematically integrated these aspects within the broader context of sewage management. Furthermore, ecological risks, biomass management, and policy or regulatory considerations are frequently addressed in isolation rather than as interconnected elements of a sustainable treatment strategy. As a result, there is a lack of comprehensive analysis linking sewage characteristics, hydroponic system configurations, and opportunities within the circular bioeconomy. This review fills a critical gap by focusing specifically on hydroponic-engineered configurations optimized for sewage treatment. Furthermore, it moves beyond simple pollutant removal metrics to establish a holistic framework that integrates technical performance with risk governance and biomass valorization. By synthesizing these often-fragmented aspects, this review provides a novel, practical roadmap for transforming water hyacinth from an ecological liability into a governable asset within a circular, decentralized sewage infrastructure.

This review analyses the potential of water hyacinth-based hydroponic systems as innovative and sustainable solutions for sewage treatment. It presents an overview of sewage characteristics, the phytoremediation properties of water hyacinth, and the principles underlying hydroponic systems in sewage treatment. The review synthesizes findings from previous studies, highlights successful implementations, addresses limitations and management challenges, and identifies future opportunities for scaling and integration. Ultimately, the paper argues that utilizing water hyacinth in hydroponic configurations can significantly advance decentralized, low-cost, and environmentally sustainable sewage treatment strategies.

This review was compiled using the SCOPUS database (www.scopus.com) by performing 4 sequential selection stages of identification, screening, eligibility, and inclusion [21,22]. The identification phase used the keywords "water hyacinth," "*Eichhornia crassipes*," "hydroponic," "sewage," and "wastewater," restricted to articles published from 2010 to 2026 (the past 15 years). The preliminary identification stages yielded roughly 3128 articles on water hyacinth, 2580 on *Eichhornia crassipes*, 11,088 on hydroponics, 84,758 on sewage, and 259,771 on wastewater. In the screening phase, the dataset was refined by imposing an additional inclusion criterion. Each article had to include at least 2 predefined keywords, with the term "water hyacinth" or "*Eichhornia crassipes*" being obligatory. Records that exhibited less than three keyword matches or did not contain the mandatory term were excluded. Irrelevant and duplicate materials were removed, yielding a total of 522 documents. The remaining records advanced to the eligibility step, during which studies without an explanation of the hydroponic system or a detailed discussion of sewage were removed. A total of 220 publications that satisfied the inclusion criteria were selected for comprehensive evaluation and data extraction in this review article.

2. Overview of sewage

Sewage is a complex mixture of various types of matter, including organic matter, water, nutrients, and contaminants, commonly generated by human activities. Its sources may come from domestic households, commercial buildings, industries, and, in some cases, stormwater runoff. It is estimated that more than 80% of wastewater is discharged into the environment without, or with inadequate, treatment, and this issue is particularly severe in some developing countries, where fewer than 10% of wastewater is treated [23,24]. Sewage characteristics and their environmental impact are summarized in Fig. 1 and discussed further in the following paragraphs.

Untreated or partially treated sewage discharge may be a significant concern for the environment. Wastewater discharged into water bodies with high organic matter loads can increase the biochemical oxygen demand (BOD). This causes oxygen depletion, leading to hypoxia, fish mortality, and degradation of aquatic ecosystem [25]. Another issue is nutrient enrichment, such as nitrogen and phosphorus, which may lead to eutrophication and harmful algal blooms [26]. Both processes would worsen water quality, reduce biodiversity, and disrupt fisheries. Sewage is also a major transport for spreading pathogens, including bacteria, viruses, and other microorganisms. Contaminated water becomes a breeding ground for disease, posing a danger to human health, especially in communities that depend on untreated river water for daily use. Furthermore, sewage from industries or the community often contains heavy metals and other toxic chemicals. These pollutants persist in the environment, bioaccumulate through food chains, and have long-term impacts on human health and on the stability of the ecosystem [27,28].

2.1. Characteristics of domestic and municipal sewage

Wastewater can be considered in terms of contributions from human activities, such as industries and urban development, as well as lifestyles. The composition of wastewater varies depending on the sources. Characteristics of domestic and municipal sewages are summarized in Table 1.

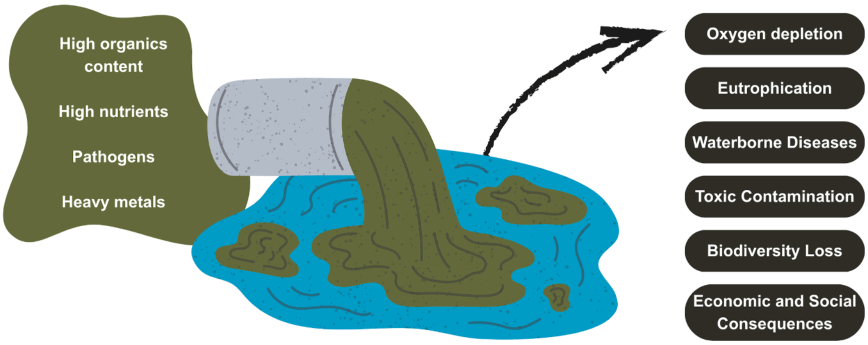


Fig. 1. Schematic representation of sewage composition and its cascading environmental impacts.

Table 1
Characteristics of domestic and municipal sewages.

Feature	Domestic Sewage	Municipal Sewage	Reference (s)
Primary sources	Households (Toilets, kitchens, laundry, bathrooms).	Domestic effluent + commercial, industrial, institutional (hospitals/schools), and stormwater runoff.	-
Composition	Blackwater (faecal matter, urine) and greywater (detergents, food waste, soaps).	Complex mixture of domestic waste + industrial chemicals and urban debris.	[29–31]
Physical appearance	Greyish, turbid, with foul odour slightly higher than ambient temperature.	Highly variable, unstable turbidity and suspended solids, contains grit, sand, and oil.	[32,33]
Organic load	High biodegradable matter with BOD ranged 100–300 mg/L and COD ranged 250–600 mg/L.	Higher COD to BOD ratio (less biodegradable) due to industrial contributions.	[30,34,35]
Chemicals & nutrients	Nitrogen (1.36–133.2 mg/L), Phosphorus (0.03–7.73 mg/L), surfactants, and grease.	Higher concentrations of N and P, includes toxic solvents, heavy metals, pesticides, and pharmaceuticals.	[36,37]
Biological profile	Pathogens (viruses, bacteria, protozoa); *Escherichia coli* used as a faecal indicator.	Same as domestic, plus resistant strains of bacteria/viruses from hospitals and labs.	[38,39]
Environmental impact	Oxygen depletion, nutrient enrichment (algal blooms), and spread of infectious diseases.	All domestic risks + long-term bioaccumulation of toxins/heavy metals in ecosystems.	[40]

3. Common contaminants in sewage and their impact

There is a wide range of pollutants in sewage. Still, the three primary pollutants are considered imperative contaminants due to their environmental persistence and direct effects on human health: nutrients, pathogens, and heavy metals. The respective classes originate from different sources and behave differently when discharged into the environment, thus posing exceptional harm [23,41]. The impacts of common contaminants in sewage are summarized in Table 2.

4. Conventional sewage treatment methods and their limitations

Conventional methods for sewage treatment are intended to reduce the pollutant load before discharging into the environment. The system commonly consists of a multi-staged process involving physical, biological, and chemical procedures that address different types of pollutants or contaminants under each condition [57,58]. Although these methods have been implemented broadly and are operational under certain conditions, the limitations of this technology are gradually becoming apparent, particularly in regions with rapid population growth, limited financial resources, and scarce facilities. The stages of conventional sewage treatment are summarized in Table 3.

Despite their efficiency in controlled environments, conventional sewage treatment methods face several limitations that limit their application worldwide. Some limitations include high capital and operational expenditures [66,67], environmental footprints [68,69], treatment gaps especially for micropollutants and emerging contaminants [70–72], waste (byproduct) management [73–75], and system resilience [76,77], as summarized in Fig. 2.

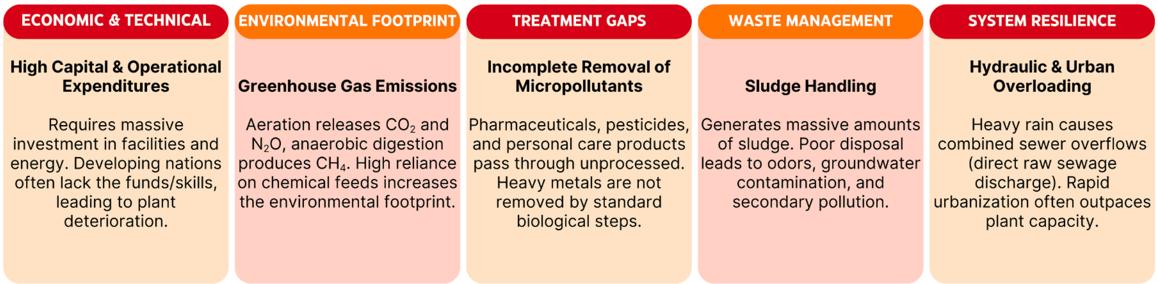
Bridging the gap between the complex characteristics of sewage outlined in Section 2 and the limitation of conventional treatment requires a specific set of design constraints for alternative hydroponic systems. Specifically, the high organic and nutrient loads dictate that

Table 2
The impact of common contaminants in sewage.

Contaminant category	Common examples & forms	Primary sources	Environmental impact	Human health impact
Nutrients	Nitrogen (ammonia, nitrates, nitrites) and phosphorus (orthophosphates, polyphosphates) [42,43]	Human waste, detergents, industrial discharge, food residues, fertilizer runoff.	Eutrophication which triggers algal blooms, causing sunlight blockage, and depletes dissolved oxygen (hypoxia) which can kill aquatic life [44].	Blue baby syndrome (methemoglobinemia), cancers from nitrates, liver/nerve damage from algal toxins (microcystins) [45].
Pathogens	Bacteria: *E. coli, Salmonella, Vibrio cholerae.* Viruses: Hepatitis A, Rotavirus. Protozoa/helminths: *Giardia, Ascaris* [46,47].	Human excreta/faecal matter.	Contaminates water bodies for days or months, serves as a reservoir for infectious disease transmission in the ecosystem [48,49].	Waterborne diseases such as diarrhea, cholera, dysentery, typhoid, and hepatitis A which responsible for around 1.4 million deaths worldwide annually [50,51].
Heavy metals	Lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu) [23,52,53].	Industrial discharge, hospitals, stormwater runoff, household plumbing.	Non-biodegradable & bioaccumulative by entering the food chain, impairs reproduction in aquatic life [53,54], and reduces soil fertility.	Neurological damage (lead/mercury), kidney dysfunction and skeletal disorders (cadmium), organ damage and cancer (chromium) [55,56].

Table 3
Stages of conventional sewage treatment and their limitations.

Stage	Main Processes	Targeted Pollutants	Removal Efficiency	Limitations
Preliminary & primary	Bar screens, grit chambers, sedimentation tanks.	Large solids, sand, heavy inorganic particles, settable matter.	30–40% of BOD and total suspended solids (TSS) [59].	Inadequate for nutrients, dissolved organics, or pathogens [59].
Secondary (biological)	Activated sludge, trickling filters, aeration, microbial degradation.	Biodegradable organic matter (BOD/COD) and some pathogens.	80–95% of organic matter and substantial pathogen reduction [60].	Poor nutrient removal (N & P); sensitive to operational control (oxygen, retention time) [61,62].
Tertiary (advanced)	Chemical precipitation, sand filtration, disinfection (chlorine, UV, ozone).	Residual suspended solids, nutrients (N/P), and persistent pathogens.	Very high removal of residual pollutants, effluent suitable for reuse [63,64].	Energy-intensive, relatively expensive, and complex to operate [64,65].


ECONOMIC & TECHNICAL

High Capital & Operational Expenditures

Requires massive investment in facilities and energy. Developing nations often lack the funds/skills, leading to plant deterioration.

ENVIRONMENTAL FOOTPRINT

Greenhouse Gas Emissions

Aeration releases CO_2 and N_2O, anaerobic digestion produces CH_4. High reliance on chemical feeds increases the environmental footprint.

TREATMENT GAPS

Incomplete Removal of Micropollutants

Pharmaceuticals, pesticides, and personal care products pass through unprocessed. Heavy metals are not removed by standard biological steps.

WASTE MANAGEMENT

Sludge Handling

Generates massive amounts of sludge. Poor disposal leads to odors, groundwater contamination, and secondary pollution.

SYSTEM RESILIENCE

Hydraulic & Urban Overloading

Heavy rain causes combined sewer overflows (direct raw sewage discharge). Rapid urbanization often outpaces plant capacity.

Fig. 2. Limitations of conventional sewage treatment.

hydroponic configurations must optimize hydraulic retention times (HRT) to balance adequate rhizofiltration contact time with the prevention of system stagnation [78]. Unlike conventional systems that can mechanically aerate to manage BOD, hydroponic designs rely on the passive oxygen transport of plant roots and surface reaeration [79], making the surface area-to-depth ratio a critical design limitation. Furthermore, environmental conditions such as temperature and pH stability become governing operational parameters, as treatment efficiency is directly linked to the plant's biological activity rather than purely chemical or mechanical processes [80]. Therefore, the subsequent sections evaluate how water hyacinth-based systems can be engineered to meet these specific operational demands while overcoming the economic and technical barriers of centralized infrastructure.

5. Water hyacinth (*Eichhornia crassipes*): a promising phytoremediator

5.1. Morphological and physiological features

Water hyacinth, scientifically known as Eichhornia crassipes, is a free-floating, perennial aquatic plant characterized by its unique morphological features that promote buoyancy and rapid dispersal in freshwater ecosystems. Its extensive root system, with a surface area of more than 150,000 mm2 per plant, serves as a primary adsorption site for pollutants [81]. Water hyacinth has a vascular ring structure that prevents the translocation of harmful substances into above-ground tissue, thereby increasing its remediation potential [81]. In addition, the presence of spongy aerenchyma tissue in both roots and shoots improves internal oxygen transport and thus supports survival in low-oxygen environments [82]. Morphological characteristics of water hyacinth are depicted in Fig. 3.

Water hyacinths show high efficiency in removing various pollutants, including microplastics, heavy metals, crude oil, and organic contaminants from water [81,83,84]. Its rapid growth and ability to alter water movement contribute to its effectiveness in phytoremediation [85]. In addition to water purification, water hyacinth has been researched for conversion into a sorbent, for potential applications in biofuel production, and as a green fertilizer [86].

Based on its physiological characteristics, water hyacinth is extraordinarily flexible across a wide range of environmental conditions. It has a highly efficient photosynthetic system and can continue to grow even under nutrient-poor or hypoxic conditions by increasing its uptake and accumulation of essential nutrients, especially nitrogen and phosphorus [87,88]. These properties make water hyacinth an environmentally friendly and cost-effective solution for sewage treatment and for restoring aquatic ecosystems.

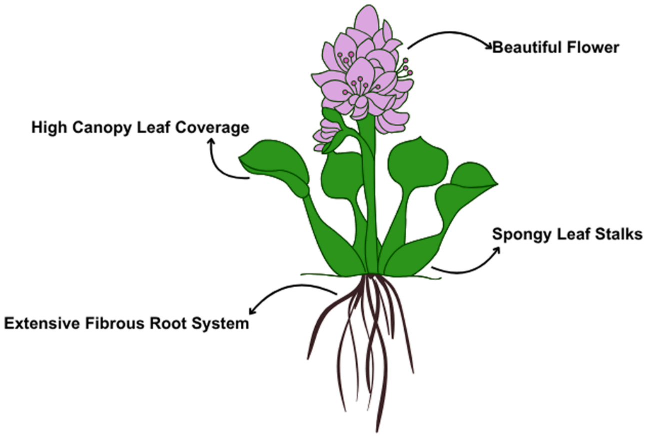


Fig. 3. Morphological features of water hyacinth facilitating phytoremediation.

5.2. Growth requirements and biomass yield

The removal of nitrogen and phosphorus from the aquatic environment provides an additional source of nutrients for water hyacinth, promoting its growth and spread. Results across studies vary widely due to different environmental and experimental conditions. This variability makes it challenging to define a universal nutrient requirement, yet it underscores the strong dependence of water hyacinth on dissolved N and P for sustained growth.

Controlled system studies repeatedly emphasize its ability in phytoremediation. Rezania et al. [89] found optimal growth and nutrient removal at 18 days under stable conditions, with significant reductions in chemical oxygen demand (COD), ammonia, and phosphate under optimal pH (5.3–6.3), temperature, and dissolved oxygen conditions. Water hyacinth demonstrates higher nutrient removal across different system designs. System design also plays a role. Parab et al. [90] reported phosphate and ammonia removal efficiencies of up to 76% and 31%, respectively, influenced by media presence and system design for treating greywater by using water hyacinth. Similarly, Selvaraj & Velvizhi [91] observed high removal efficiencies for nitrate (70.23%), phosphate (63.64%), and sulphate (61.16%), attributed to its dense root system and fibrous tissues, which enhance nutrient absorption and support effective sewage treatment.

Field observations confirm these experimental findings and, at the same time, emphasize the influence of seasonal fluctuations. A Nile Delta study by Eid & Shaltout [92] revealed that water hyacinth biomass peaked in summer, with shoot biomass reaching 887 g DM/m^2 in July and root biomass 235 g DM/m^2 in August, before declining in cooler months. The plant allocated 52% of its biomass to petioles and 24% to roots, with a peak density of 144 individuals/m^2 in May. Growth rates were highest in spring (0.044 g DM/g/day) and lowest in autumn (0.017 g DM/g/day), while factors such as Zn, EC, total N and P, and pH significantly influenced biomass distribution. Overall, these results show that nutrient uptake and water hyacinth growth are influenced not only by system design but also by seasonal and environmental dynamics. Strategic harvesting, optimized pH and temperature management, and control of hydraulic retention time are crucial measures to improve the efficiency of phytoremediation and biomass yield.

5.3. *Ecological risks and management considerations*

Water hyacinth is widely recognized as one of the most destructive aquatic invasive species in tropical and subtropical regions, causing severe ecological and socio-economic impacts. Large-scale infestations have been linked to nutrient imbalance, eutrophication, biodiversity loss, and economic damage, including reduced fisheries, impaired hydropower generation, and disruption of water transport, as documented in systems such as Lake Tana, Lake Victoria, and nutrient-enriched wetlands in China [93–96]. Additional impacts include accelerated sedimentation, increased evapotranspiration, greenhouse gas emissions during biomass decay, and secondary pollution through the release of nutrients and accumulated heavy metals [97,98].

A critical distinction must be made between uncontrolled natural infestations and engineered hydroponic applications. In natural systems, water hyacinth exhibits boom-and-bust dynamics, where unchecked growth ultimately leads to mass decomposition, oxygen depletion, and further eutrophication [99]. In contrast, hydroponic systems function as controlled biological reactors in which plant density, harvesting frequency, and hydraulic conditions are actively regulated [80]. Scheduled harvesting prevents overcrowding and senescence, maintains aerobic root-zone conditions, and enables predictable nutrient and pollutant removal.

Despite decades of intervention, no single management strategy has proven sufficient. Mechanical harvesting is costly and prone to reinfestation, chemical control risks ecological toxicity and secondary pollution, and biological control using weevils is climate-sensitive and slow to respond [100,101]. More sustainable outcomes have been achieved through integrated approaches that combine mechanical, biological, and preventive measures, although implementation is often constrained by fragmented governance, limited data, and weak economic planning [102].

Recent advances highlight the importance of emerging technologies and circular bioeconomy approaches. AI-based detection models, eDNA monitoring, and IoT-enabled surveillance enable early warning and targeted intervention before infestations escalate [103] At the same time, controlled biomass utilization pathways, including biochar, compost, biofuel, and bioplastics, offer opportunities to offset management costs and support local livelihoods, provided that contaminant risks are rigorously managed [97,104]. Biochar production, in particular, shows potential for carbon sequestration and soil improvement, while composting initiatives demonstrate high social acceptance in several regions.

Overall, the evidence indicates that water hyacinth should not be viewed solely as an ecological threat, but as a biological system whose risks and benefits can be strategically balanced. Integrated management combining ecological restoration, nutrient load reduction, digital monitoring, and controlled biomass valorization offers the most sustainable pathway forward. In this context, engineered hydroponic systems provide a framework for harnessing the plant's high productivity while minimizing the environmental instability associated with natural infestations. Comparative synthesis of ecological risks, management strategies, and implications of water hyacinth for hydroponic sewage treatment are tabulated in Table 4.

6. Hydroponic systems in sewage treatment

6.1. *Basic principles and configurations*

Hydroponics is a soilless plant cultivation method in which plants grow in nutrient-rich water rather than traditional soil. The system relies on controlled water circulation, aeration, and nutrient delivery to ensure optimal plant growth. In the context of sewage treatment, hydroponic systems are modified to use sewage or other wastewater streams as nutrient sources [110]. Typical hydroponic configurations include the nutrient film technique (NFT) [111], floating raft systems [112], wick systems [113], and deep-water culture setups [114] (Fig. 4). When adapted for sewage, these systems allow roots to be submerged or in contact with nutrient-laden effluents, enabling plants to absorb contaminants such as nitrogen, phosphorus, heavy metals, and organic compounds. The configuration choice depends on pollutant type, plant species, hydraulic retention time, and available space [115].

6.2. *Advantages over soil-based phytoremediation*

Compared to soil-based phytoremediation systems, hydroponic approaches offer several advantages for sewage treatment. The absence of soil reduces the risks of secondary pollution, such as leaching or contaminant accumulation in sediments [116]. The next advantage is that hydroponics provides better control over environmental conditions, such as nutrient concentration, pH, and oxygenation, leading to more consistent pollutant removal efficiency [117]. Hydroponic setups also require less land area than constructed wetlands or traditional soil-based phytoremediation, making them suitable for urban or space-limited environments [110]. Additionally, hydroponic systems enable faster plant growth rates and easier monitoring of root-zone processes, as roots are directly exposed to the aqueous environment [118].

6.3. *Comparative performance and operational characteristics of hydroponic systems*

To facilitate a systematic comparison of hydroponic approaches applied in sewage treatment, Table 5 summarizes the key performance characteristics and operational attributes of commonly reported system designs. Based on Table 5, it is evident that each hydroponic system design presents distinct advantages and limitations when applied to sewage treatment. These trade-offs highlight the importance of selecting hydroponic designs based on treatment objectives and operational capacity rather than assuming a universally optimal configuration.

A comparative overview of sewage treatment performance across various hydroponic systems and operating conditions is tabulated in Table 6, highlighting how differences in operational parameters influence nutrient and pollutant removal efficiencies. A closer analysis of Table 6 shows that the same system can produce very different performances, whereas other systems can achieve similar removal efficiencies under favorable conditions. This indicates that the hydroponic system

Table 4
Comparative synthesis of ecological risks, management strategies, and implications of water hyacinth for hydroponic sewage treatment.

Ecological Risk	Global Evidence	Implications for Hydroponic Sewage Treatment
Biodiversity loss & habitat degradation	Dense mats reduce habitat quality and fish catch, Lake Victoria and Tana show 65–70% decline in fisheries [98,100,105].	Not directly relevant in hydroponics, but strict containment prevents escape into natural habitats.
Water quality deterioration	Lake Tana invaded areas with pH up to 8.5 vs 6.9, TDS 215 mg/L vs 24 mg/L, EC 4450 mS/cm vs 1110 mS/cm, DO dropped to 1.83 mg/L [106], Acidic pH, high turbidity, and *E. coli* contamination elsewhere [100,107], DO depletion in China [101].	Nutrient uptake is useful in hydroponics but requires scheduled harvesting to prevent decomposition-driven oxygen depletion.
Eutrophication & nutrient cycling disruption	TN up to 2.97%, TP up to 3.94 mg/kg, chlorophyll-a 19.6 mg/L with changing from mesotrophic to eutrophic condition in Lake Tana [106], TP increased 5–10 folds in Lake Tana [100], Algal blooms were also reported [98].	Hydroponics must balance nutrient dosing with harvesting to avoid re-release and secondary eutrophication.
Greenhouse gas emissions	Methane and CO₂ from anaerobic decomposition [97,98].	Managed harvesting + biomass valorization (biochar/biofuel) can minimize emissions and even enable carbon-negative outcomes.
Heavy metal accumulation & bioaccumulation risk	Uptake of Cd, Cu, Pb above FAO/WHO limits [108,109].	Advantageous for sewage polishing, but requires tissue testing, safe valorization (biochar), and exclusion from feed/fertilizer chains.
Mechanical removal	Effective short-term but costly, labor-intensive, and reinfestation-prone [98,100].	In hydroponics, harvesting is designed into system operation, reducing cost and improving control.
Chemical control	Herbicides (glyphosate, 2,4-D) effective but cause oxygen depletion, toxicity, resistance [100,102].	Not suitable in hydroponics, avoidance is essential to maintain effluent safety.
Biological control	*Neochetina weevils* effective but slow, climate-dependent [98,101].	Unnecessary in controlled systems, physical containment replaces need for biocontrol.
Integrated management	Combinations reduced infestations from around 75% to 1% in Lake Tana [98,100,101].	Hydroponics inherently integrates design, harvesting, and valorization with adaptive monitoring strengthens long-term sustainability.
Preventative strategies	Environmental DNA for early detection, nutrient runoff reduction, biosecurity[102,105].	Physical barriers, overflow protocols, and strict monitoring prevent accidental release.
Nutrient management	Reducing watershed nutrient inputs essential to limit WH spread [98,100].	In hydroponics, nutrient dosing and hydraulic retention time must be carefully controlled to balance uptake vs. release.
Biomass valorization	Bioenergy, biochar, compost, bioplastics widely studied [97,102,104].	Hydroponics benefits from valorization but requires standardized contaminant testing and safe end-use protocols.
Valorization risks	Improper reuse can reintroduce metals or pathogens; field validation of large-scale valorization still limited [97,102].	Biomass must be processed under strict QA/QC, valorization options limited to safe outlets (e.g., biochar, controlled biofuel).
Emerging technologies	AI monitoring HydroSpot-YOLO [103], and complements eDNA [103, 105]>91% accuracy.	Enables real-time monitoring of biomass growth and prevents escapes.

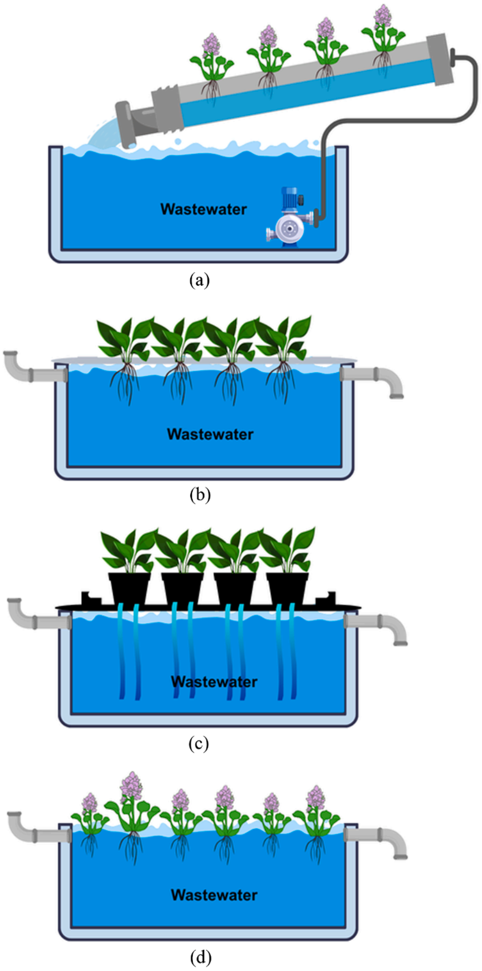


Fig. 4. Schematic of hydroponic configurations (a) nutrient film technique, (b) floating raft systems, (c) wick systems, and (d) deep-water culture adapted for sewage treatment.

type alone does not determine performance. For instance, identical NFT systems treating aquaculture wastewater exhibited nitrate and ammonia removal efficiencies ranging from very low to high values, depending on operating conditions [119,125]. It is also worth noting that the latest available data on sewage treatment using a wick hydroponic system are currently limited; the most recent articles focus only on plant growth.

Among the operational parameters, hydraulic retention time (or flow rate) is the most critical, as longer contact time consistently enhances nitrogen, phosphorus, and organic matter removal by allowing greater interaction among plant roots, associated microbial communities, and pollutants [126]. In addition, plant species selection strongly influenced

Table 5
Comparison of hydroponic system designs for sewage treatment applications.

System type	Nutrient removal efficiency*	Plant growth characteristics	Hydraulic & operational features	Operational robustness	Key limitations	References
Nutrient Film Technique (NFT)	N: 16–83% P: 50% BOD: 68–78%	Rapid shoot growth, limited root submergence	Shallow flowing film, short HRT, high flow sensitivity	Low to moderate	Susceptible to clogging, uneven flow distribution, limited buffering against influent variability	[78,119,120]
Floating Raft Systems	N: 32–94% P: 94% BOD: 41–96% COD: 27–95%	High biomass production, extensive root mats	Long HRT, high root–water contact, passive hydraulics	High	Risk of hypoxia beneath root mats, requires aeration or frequent harvesting	[112,121,122]
Wick Systems	N: 30–60% P: 30–60%	Slow to moderate growth, limited root exposure	Passive nutrient transport via capillary action, minimal flow	Low	Not suitable for high-strength wastewater, limited scalability	[113,123]
Deep-Water Culture (DWC)	N:53–100% P: 17–98% BOD:43–72% COD: 62–85%	Stable biomass growth, fully submerged roots	Large water volume, long HRT, high oxygen demand	Moderate to high	Requires continuous aeration, higher energy input	[114,124]

* Reported removal ranges are drawn from previous studies with different hydraulic retention times, plant species, and operational scales. Values therefore indicate literature-reported envelopes rather than directly comparable performance metrics.

performance, particularly in floating raft systems where macrophytes with extensive root systems demonstrated superior nutrient and organic matter uptake under identical operating conditions. Sewage characteristics and supporting physicochemical conditions, such as pH, temperature, and aeration, further modulated system efficiency but were secondary to HRT and plant-related factors. Overall, the data suggest that optimizing operational parameters, especially retention time and plant selection, is more impactful on treatment efficiency than selecting a specific hydroponic system configuration.

6.4. *Integration with water hyacinth for sewage treatment*

Water hyacinth functions as a high-rate rhizofiltration matrix in hydroponic reactors, maintaining growth under elevated nutrient and organic loading. When added to floating raft hydroponic systems, its extensive root system acts as a biofilter, trapping suspended solids, encouraging microbial colonization, and improving nutrient uptake [110,131,132]. Using water hyacinth in hydroponic sewage treatment has two benefits: it cleans polluted water and provides a renewable biomass source. But it needs to be managed carefully to address concerns about its invasiveness, potential rapid growth, and safe disposal of contaminated biomass. To contextualize the role of hydroponic systems within the broader spectrum of sewage treatment technologies, Table 7 presents a comparative assessment of hydroponic treatment alongside selected nature-based and conventional engineered systems.

Compared with conventional nature-based systems such as constructed wetlands and stabilization ponds, hydroponic systems generally require less land area while achieving comparable nutrient removal efficiencies under controlled operating conditions. However, because Table 7 presents qualitative performance categories rather than first-order rate constants or areal removal rates, no direct kinetic superiority can be inferred. The observed performance advantages are instead attributable to enhanced root–water contact, controlled hydraulics, and intensified rhizosphere microbial activity, which can improve treatment consistency in compact footprints.

In terms of pollutant removal, hydroponic systems often demonstrate similar or higher percentage removal of nitrogen and phosphorus than stabilization ponds, while requiring lower energy input and operational complexity than membrane bioreactors [140]. The cost comparisons presented in Table 7 should also be interpreted as qualitative rankings rather than quantitative economic evaluations. Under typical decentralized conditions, hydroponic systems require limited mechanical equipment and low energy inputs relative to activated sludge and membrane bioreactors, but somewhat greater operational oversight than fully passive stabilization ponds. These comparisons should be interpreted as performance-based rather than rate-based, as differences in hydraulic retention time, influent loading, and reactor configuration across studies preclude a standardized kinetic analysis. Consequently, hydroponic systems are best positioned as an intermediate technology between passive wetlands and highly engineered biological reactors, offering moderate land demand, low energy requirements, and flexible integration into decentralized treatment trains rather than inherently faster reaction kinetics.

7. Mechanisms of sewage pollutant removal by water hyacinth

Pollutant removal mechanisms by water hyacinth are summarized in Fig. 5 and detailed in the following sections.

7.1. *Nutrient uptake*

One of the most critical ways water hyacinths help clean up sewage is by removing nitrogen (N) and phosphorus (P). High levels of these nutrients in water can cause algal blooms, lower dissolved oxygen levels, and accelerate eutrophication [141–143], harming ecosystems and killing fish. Because of this, reducing nutrients is a primary goal of sewage treatment processes. Water hyacinth is highly effective at this because it can take up large amounts of nutrients and grow quickly [144,145].

Ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-), and organic nitrogen compounds from proteins and urea are all common forms of nitrogen in sewage [146,147]. Water hyacinth takes up nitrogen primarily as NH_4^+ and NO_3^-, which it absorbs through root membranes and uses to synthesize amino acids, proteins, and nucleic acids [148]. The plant also helps microbes convert nitrogen in its rhizosphere [149], including nitrifying bacteria (which convert NH_4^+ to NO_3^-) and denitrifying bacteria (which convert NO_3^- to N_2 gas).

Phosphorus in sewage is mainly in the form of soluble orthophosphate (PO_4^{3-}), polyphosphates, and organic phosphorus compounds [150]. Water hyacinth uses phosphorus for structural and metabolic functions, such as the synthesis of ATP, nucleic acids, and phospholipids [151]. Phosphorus can also be trapped in root biofilms, where bacteria take up or precipitate phosphates with cations like calcium, magnesium, and iron. Phosphorus is not lost as a gas during treatment, unlike nitrogen. This means that, to obliterate it, biomass must be harvested regularly to physically remove phosphorus from the system [152]. Under optimal conditions, studies have shown that phosphorus uptake rates can reach 1.1–3.1 g P per m^2 of plant coverage per day [153,154], making it highly competitive with other aquatic macrophytes. It should be noted that reported nutrient removal efficiencies are strongly influenced by biomass harvesting regimes, as harvesting frequency and intensity regulate plant growth dynamics, nutrient uptake capacity, and

Table 6
Performance comparison of hydroponic systems among different systems.

System	Plant Species	Wastewater Type	Wastewater Origin	Scale	Influent Characteristics	Operational conditions	Removal performance	Reference
Municipal/domestic sewage								
Deep-water culture	*Capsicum annuum*	Domestic wastewater	Real	Laboratory	pH: 6.9–8.8 BOD: 65–114 mg/L COD: 94–247 mg/L PO_4-P: 2.6–5.8 mg/L NH_4-N: 24–52 mg/L NO_3-N: 1–67 mg/L	Experimental duration: 90 days Flow rate: 13 L/day	BOD: 42.9% COD: 61.9% PO_4-P: 55.1% NH_4-N: 53.8% NO_3-N: 99%	[126]
Deep-water culture	*Lactuca sativa* L. var. crispa	Domestic wastewater	Artificial	Laboratory	Total N: 126±19 mg/L Total P: 40±3 mg/L	Experimental duration: 35 days Effective volume: 6 L Temperature: 21–22°C Flow: 1.5–3 L/35 days Light conditions: No direct solar radiation	Total N: 95% Total P: 94%	[124]
Wick system	*Ipomoea reptans*	Mixed domestic wastewater	Real	Laboratory	-	Experimental duration: 90 days Effective volume: 520 mL Flow: 1 L/plants	-	[123]
Deep-water culture	*Amaranthus campestris*	Secondary treated sewage	Real	Laboratory	COD: 110.25 mg/L BOD: 40 mg/L Total N: 5.6 mg/L Total P: 0.51 mg/L	Experimental duration: 90 days Effective volume: 7 L Density: 12 plants/unit Flow: 7 L/90 days	COD: 85% BOD: 72.5% Total N: 53.6% Total P: 17.6%	[130]
Deep-water culture	*Lactuca sativa* L. var. crispa	Secondary treated sewage	Real	Pilot	Total N: 110 mg/L Total P: 30 mg/L	Experimental duration: 240 days Effective volume: 185 L Flow rate: 23.5 L/h	Total N: 100% Total P: 78%	[129]
Non-sewage streams								
Nutrient film technique	*Spinacia oleracea*	Aquaculture	Real	Pilot	TAN: 0.12 mg/L NH_3: 0.06 mg/L NO_2-N: 0.15 mg/L NO_3-N: 0.7 mg/L PO_4-P: 0.8 mg/L	Experimental duration: 105 days Effective volume: 100 L Aeration: Continuous Growing medium: Construction gravel Flow rate: 2.9 L/min	TAN: 16% NH_3: 71% NO_2-N: 83% NO_3-N: 71% PO_4-P: 50%	[125]
Nutrient film technique	*Pangasianodon hypophthalmus*	Aquaculture	Real	Pilot	TAN: 0.12 mg/L NH_3: 0.06 mg/L NO_2-N: 0.15 mg/L NO_3-N: 0.7 mg/L PO_4-P: 0.8 mg/L	Experimental duration: 105 days Effective volume: 100 L Aeration: Continuous Growing medium: Construction gravel Flow rate: 2.9 L/min	TAN: 16% NH_3: 71% NO_2-N 83% NO_3-N: 71% PO_4-P: 50%	[120]
Nutrient film technique	*Lactuca sativa* ‘Rex	Aquaculture	Real	Pilot	NO_3-N: 6.5 mg/L	Effective volume: 227.1 L HRT: 4, 8, 12, 16 days	NO_3-N: 10.8%	[78]
Nutrient film technique	*Epiprennum aureum*	Aquaculture	Real	Pilot	NO_3-N: 27.55–28.26 mg/L BOD: 14.66 mg/L	pH: 6.0–6.4 Temperature: 25–27°C HRT: 0.3 h Flow rate: 54 L/h	NO_3-N: 78.28% BOD: 71.07%	[119]
Nutrient film technique	*Codiaeum varigatum*	Aquaculture	Real	Pilot	NO_3-N: 27.55–28.26 mg/L BOD: 14.66 mg/L	pH: 6.0–6.4 Temperature: 25–27°C HRT: 0.3 h Flow rate: 54 L/h	NO_3-N: 71% BOD: 68.62%	[119]
Nutrient film technique	*Syngonium podophyllum*	Aquaculture	Real	Pilot	NO_3-N: 27.55–28.26 mg/L BOD: 14.66 mg/L	pH: 6.0–6.4 Temperature: 25–27°C HRT: 0.3 h Flow rate: 54 L/h	NO_3-N: 70.25% BOD: 78%	[119]
Nutrient film technique	*Tradescantia pallida*	Aquaculture	Real	Pilot	NO_3-N: 27.55–28.26 mg/L BOD: 14.66 mg/L	pH: 6.0–6.4 Temperature: 25–27°C HRT: 0.3 h Flow rate: 54 L/h	NO_3-N: 67.25% BOD: 72%	[119]
Nutrient film technique	*Spinacea oleracia*	Aquaculture	Real	Pilot	NO_3-N: 27.55–28.26 mg/L BOD: 14.66 mg/L	pH: 6.0–6.4 Temperature: 25–27°C HRT: 0.3 h Flow rate: 54 L/h	NO_3-N: 68.62% BOD: 68%	[119]
Nutrient film technique	*Solanum melongena*	Aquaculture	Real	Pilot	NO_3-N: 27.55–28.26 mg/L BOD: 14.66 mg/L	pH: 6.0–6.4 Temperature: 25–27°C	NO_3-N: 42.85% BOD: 70%	[119]

(*continued on next page*)

Table 6 (*continued*)

System	Plant Species	Wastewater Type	Wastewater Origin	Scale	Influent Characteristics	Operational conditions	Removal performance	Reference
Municipal/domestic sewage								
						HRT: 0.3 h Flow rate: 54 L/h		
Floating raft system	*Eichhornia crassipes*	Aquaculture	Real	Laboratory	SS: 64 mg/L COD: 29 mg/L BOD: 18 mg/L NH$_4$-N: 0.036 mg/L Total N: 0.413 mg/L Total P: 0.121 mg/L	Experimental duration: 120 days Effective volume: 1.8 L Density: 9 plants/unit HRT: 14, 21, 28 days	SS: 92.71% COD: 89.9% BOD: 91.5% NH$_4$-N: 93.6% Total N: 67.8% Total P: 94%	[121]
Floating raft system	*Ipomoea aquatica*	Aquaculture	Real	Laboratory	SS: 64 mg/L COD: 29 mg/L BOD: 18 mg/L NH$_4$-N: 0.036 mg/L Total N: 0.413 mg/L Total P: 0.121 mg/L	Experimental duration: 120 days Effective volume: 1.8 L Density: 9 plants/unit HRT: 14, 21, 28 days	SS: 92.6% COD: 89.6% BOD: 93.9% NH$_4$-N: 93.4% Total N: 64.3% Total P: 94.6%	[121]
Floating raft system	*Commelina diffusa*	Aquaculture	Real	Laboratory	SS: 64 mg/L COD: 29 mg/L BOD: 18 mg/L NH$_4$-N: 0.036 mg/L Total N: 0.413 mg/L Total P: 0.121 mg/L	Experimental duration: 120 days Effective volume: 1.8 L Density: 9 plants/unit HRT: 14, 21, 28 days	SS: 92.71% COD: 89.9% BOD: 91.5% NH$_4$-N: 93.6% Total N: 67.8% Total P: 94%	[121]
Deep-water culture	*Lactuca sativa* var. crispa L	Aquaculture	Real	Laboratory	PO$_4$-P: 7–10.9 mg/L NH$_4$-N: 0.05–0.22 mg/L NO$_3$-N: 78–124 mg/L	Experimental duration: 90 days Flow rate: 13 L/day	PO$_4$-P: 97.7% NH$_4$-N: 99% NO$_3$-N: 97.9%	[126]
Floating raft system	*Carex riparia*	Agri-food tertiary wastewater	Real	Pilot	Total N: 9.1±3.4 mg/L	Experimental duration: 210 days Effective volume: 6.5 m^3 Density: 10 plants/m HRT: 7 days	Total N: 32 ±18%	[127]
Floating raft system	*Alternanthera amoena*	Tofu wastewater	Real	Laboratory	-	Experimental duration: 10 days	-	[122]
Floating raft system	*Pistia stratiotes*	Industrial wastewater	Real	Laboratory	COD: 924.66 mg/L BOD: 594.33 mg/L TSS: 842.66 mg/L Cr: 41.19 mg/L	Experimental duration: 60 days Effective volume: 50, 70, 145 L Flow rate: 0.72 m^3/day	COD: 27% BOD: 41% TSS: 85% Cr: 94%	[128]
Floating raft system	*Eichhornia crassipes*	Industrial wastewater	Real	Laboratory	COD: 1222.16 mg/L BOD: 814.7 mg/L TSS: 149 mg/L Cr: 12 mg/L	Experimental duration: 60 days Effective volume: 50, 70, 145 L Flow rate: 0.72 m^3/day	COD: 95% BOD: 96% TSS: 85% Cr: 94%	[128]
Floating raft system	*Typha latifolia*	Industrial wastewater	Real	Laboratory	COD: 583.83 mg/L BOD: 399.33 mg/L TSS: 220.33 mg/L Cr: 10.04 mg/L	Experimental duration: 60 days Effective volume: 50, 70, 145 L Flow rate: 0.72 m^3/day	COD: 48% BOD: 41% TSS: 72% Cr: 33%	[128]

the permanent removal of assimilated nitrogen and phosphorus from the system.

Water hyacinth has significant potential to remove nutrients, but a few factors make it less effective. Changes in temperature throughout the year affect metabolic activity and uptake rates. In colder climates, these processes are less efficient [155]. If not diluted sufficiently or acclimatized, high levels of ammonia can become toxic and prevent plants from growing [156].

7.2. Heavy metal accumulation and detoxification

Water hyacinth exhibits strong phytoremediation potential for heavy metal removal due to its fast growth rate, extensive root system, and physiological capacity for metal uptake. Its fibrous roots act as the primary site for metal accumulation, providing a large surface area for adsorption, ion exchange, and precipitation [157]. Metal ions bind to negatively charged groups such as carboxyl, hydroxyl, and phosphate moieties in root tissues [158]. Some metals are then translocated to stems and leaves, where they are sequestered in vacuoles to reduce toxicity. Additionally, root exudates can alter the chemical speciation of metals, enhancing their solubility and bioavailability for uptake [159]. This multi-pathway mechanism allows water hyacinth to remove both dissolved and suspended forms of metals effectively.

Once internalized, heavy metals can disrupt enzymatic functions, generate reactive oxygen species, and inhibit plant growth. To counteract these toxic effects, water hyacinth employs several detoxification

Table 7
Comparison of hydroponic systems with other sewage treatment technologies utilizing water hyacinth.

Technology	Area requirement	Pollutant removal	Capital cost*	Operational cost*	Key strengths	Key limitations
Hydroponic systems	Low to moderate [80]	Moderate to high rate in nutrients Low to moderate in organics	Low to moderate [80]	Low	Compact, low energy, biomass recovery	Seasonal sensitivity, needs operational control [133]
Free water surface CW (FWS)/ Floating treatment wetland (FTW)	Moderate [134]	Moderate to high rate in nutrients Low to moderate in organics	Low [134]	Low	Simple, passive operation	Large land demand, limited control [135]
Stabilization ponds	Very high [136]	Low to moderate in nutrients Low to moderate in organics	Low [136]	Very low	Robust, low-tech	Large footprint, odour, variable effluent [137]
Membrane bioreactors (MBR) - Hybrid	Very low [138]	Moderate to high in nutrients Moderate to high in organics	Very high [138]	Very high	Excellent effluent quality	Fouling, high energy cost [139]

* Qualitative cost rankings are based on typical infrastructure and energy requirements reported for decentralized systems: stabilization ponds (minimal mechanical equipment), constructed wetlands/hydroponics (low pumping and periodic harvesting), activated sludge (continuous aeration), and membrane bioreactors (aeration plus membrane maintenance). These rankings do not account for site-specific land costs, labor, or regional price variations.

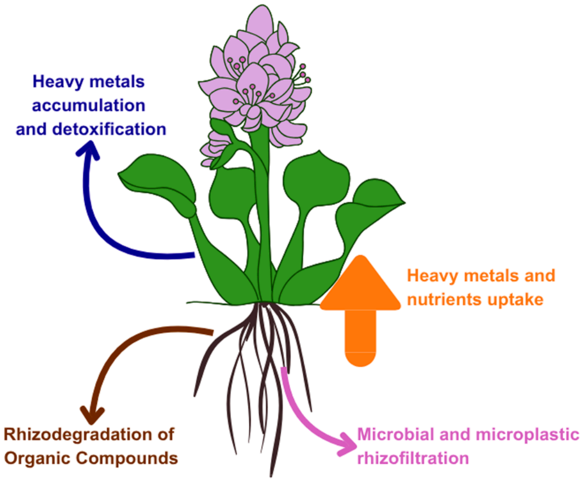


Fig. 5. Pollutant removal and detoxification mechanisms by water hyacinth.

mechanisms [159]. These include binding metals to phytochelatins and metallothioneins, which are low-molecular-weight proteins that chelate and neutralize metal ions [160]. Metals may also be compartmentalized within vacuoles or deposited in cell walls, effectively isolating them from metabolic processes [159]. Additionally, the plant enhances its antioxidant defense system to mitigate oxidative stress caused by metal exposure [161].

7.3. Reduction of organic load and microbial contaminants

In addition to nutrients and metals, sewage is rich in organic matter and pathogenic microorganisms. Water hyacinth contributes to reducing BOD and COD by directly assimilating organic compounds and stimulating microbial degradation in the rhizosphere [160]. The oxygen released by plant roots into the surrounding water creates aerobic microzones that promote the breakdown of organic pollutants by heterotrophic bacteria. Simultaneously, anaerobic zones within root mats facilitate further decomposition of complex organic matter. The extensive root system also physically traps suspended solids, improving water clarity and reducing the microbial load by adsorption and sedimentation. Moreover, studies have shown that water hyacinth can suppress pathogenic bacteria and viruses by encouraging the growth of antagonistic microbial communities in the root zone [162].

8. Case studies and applications

8.1. Reported performance in sewage and wastewater treatment

A comprehensive summary of studies on water hyacinth's capabilities is presented in Table 8. It is highlighting its application in the remediation of a variety of organic and inorganic pollutants. The systems employed in these studies differ in their operating conditions. Some research at a lab scale prioritized the use of nutrient-enriched medium for plant growth. In contrast, other research demonstrated the plant's ability to consume nutrients from real sewage without additional nutrient supplements.

8.2. Comparative treatment efficiency of water hyacinth with other aquatic plants

Aquatic macrophytes are an essential element in phytoremediation processes. Like water hyacinth, there are many types of plants that also demonstrate comparable potential for contaminant removal. Many researchers are exploring various water-based plants, as summarized in Table 9. However, water hyacinth has emerged as the best solution due to its rapid growth, high resistance, and availability [176]. This section will highlight and discuss the comparison of water hyacinth performances with other aquatic plants.

Based on the analysis in Table 9, it can be inferred that water hyacinth offers greater potential than other aquatic plants. This is further supported by the findings of Justin & Olukanni [169], who found that water hyacinth outperformed other plants in terms of organic pollutants such as BOD and COD, as well as microbial contaminants. This is likely due to its long, hanging roots, which provide a larger surface area for absorption and pollutant filtration. In addition, the plant's potential for heavy metal removal further highlights its versatility and makes it a strong candidate for enhancing sewage treatment. This statement has been supported by Batagarawa et al. [181], who found that water hyacinth removed 81.8% of copper, compared to cattail at 79%.

8.3. Insight and lessons from pilot- scale and full-scale implementation

Sewage treatment using water hyacinth is becoming a sustainable solution for contaminant removal at both pilot- and full-scale levels. A few criteria should be considered to ensure optimal system performance, including retention time and design considerations. It has been shown that a retention time of 30 days is sufficient for the effective removal of all organic and inorganic pollutants, with additional time not providing

Table 8
Performance of Water Hyacinth in treating various wastewater.

Wastewater Type	Country	Experimental Conditions	Key Findings	Operational Issue/ Recommendation	Reference
Dairy effluent	Brazil	Mode: Batch HRT: 4 -8 days Exposure time: 52 – 54 days Effective volume: 30 L	BOD, TN, and TP removal of 90%, 58, and 75%, respectively in 4 days HRT system	Consider increasing number of repetitions during analysis due to uncertainty values	[163]
Synthetic wastewater	China	Mode: Batch Exposure time: 14 days Nutrient solution: Hoagland's nutrient Temperature: 26 - 30°C Photoperiod: 12 h light / 12 h dark Initial concentration: 50 mg/L	After 5 days, 62.8% - 77% removal of polyestrene detected via root cap absorption Particle size 0.5 mm or less than that could penetrate root cracks	The performance of the plant by the usage of 50 mg/L as generally used concentration can be validated with real wastewater pollutants concentration.	[164]
Synthetic wastewater	China	Mode: Batch Exposure time: 25 days Nutrient solution: Hoagland's solution Temperature: 18–32 pH: 6.7 Initial concentration: 0.01 - 1.0 mg/L	Removal of sulfadiazine around 83.5% after 25 days High removal via roots Not visible growth inhibitance as concentration increase	Translocation and related mechanism of lower concentration of sulfadiazine throughout the plant since 0.01 mg/L uptake not detected in plant tissue	[165]
Greywater	India	Mode: Continuous Exposure time: 30 days Temperature: 23–25 pH: 7.3 – 7.5	The nutrient removal as below: Ammonium-nitrogen: 63± 10.5% Phosphate: 62±12% COD: 52±5.3% No major visible plant damage	Risk of secondary pollution due to plant biomass Selective harvesting to avoid removal of baby plant with mother plants	[166]
Synthetic industrial wastewater	India	Mode: Batch Exposure time: 7 days Nutrient solution: natural ditch water pH: 6–8 Temperature: 21 °C Initial concentration: 1–5 mg/L Cr(VI)	Removal of Cr(VI) is 29% Better performances under acidic conditions	Limited performances in treating Cr(VI) rich wastewater	[167]
Pulp and paper mill wastewater	India	Mode: Continuous Exposure time: 32 days Initial pH: 7.8	Optimal heavy metal removal can be achieved at 50% effluent concentration where above that, it might damage the growth of the plant Heavy metals that can be removed is cadmium, cuprum, ferrum, chromium, plumbum, manganese and zinc	Further research on mechanism of heavy metal uptake above 50% effluent concentration	[168]
Domestic wastewater	India	pH: 6.14 Temperature: <30°C HRT: 7, 14, 21 days Optimum plant density: 80% of tank surface area	Removal efficiency of BOD, COD, TDS and total coliforms is 97%, 85%,88% and 66% respectively Reduce electrical conductivity by 90%	Periodic harvesting to avoid overgrowth and dead plants Longer HRT does not impact significant removal	[169]
Lake water	India	Mode: Batch hydroponic Exposure time: 13 days Nutrient solution: Hoagland's nutrient pH: 8 Temperature: 30± 1°C Photoperiod: 12:12 light-dark cycle Initial concentration: Phenol (300 mg/mL), Cyanide (30 mg/ mL)	96.4% phenol removal, 92.7% cyanide removal Physiological stress due to pollutants concentration	Long-term translocation studies to track the plant growth	[170]
Lake water with $ZnCl_2$ addition	Indonesia	Mode: Batch Exposure time: 30 days Nutrient Solution: No Photoperiod: Natural light Initial concentration: 50 mg/L	Removal of Zn concentration around 98% recorded at 30 days Occurrence of chlorosis on the day-20	Chlorosis also might occur due to lack of sufficient nutrient since nutrient source are not supplied for the plant	[171]
Lake water with $ZnCl_2$ addition	Indonesia	Mode: Batch Temperature: 25–30°C pH: 5.5–7 Duration: 28 days	Removal efficiency of nitrate, phosphate and BOD recorded at 61.7%, 78.3% and 78.3% respectively Possess large stomata and leaf structure for nutrient storage	Periodic harvesting to avoid overgrowth and dead plants Sensitive to pH or dissolved oxygen fluctuation	[172]
Sewage wastewater	Malaysia	Exposure time: 28 days	Removal as below: COD: 51- 60% BOD: 61–70 % Ammonia: 28–36% TSS: 41–59 % Dissolved oxygen level increase	pH more than 8 inhibited the growth in some ponds	[173]

(*continued on next page*)

Table 8 (*continued*)

Wastewater Type	Country	Experimental Conditions	Key Findings	Operational Issue/ Recommendation	Reference
Semiconductor sewage	Malaysia	Mode: Batch Exposure: 10 days Photoperiod: 10 h full sunlight Temperature: 28–35 Initial pH: 7.02–7.11	Removal as below: COD: 73% BOD: 73% TSS: 86% TP: 79% NH4: 77% Color: 54% pH dropped due to microbial activities Four plans sufficient for optimum pollutants removal to reduce costing	Exploration on micropollutants removal using the same system Biomass valorization for circular economy	[174]
Synthetic wastewater	Pakistan	Exposure time: 15 days Nutrient solution: Hoagland's solution Initial concentration: 2–8 mg/L (Chromium), 10–40 mg/L (Lithium), 2–8 mg/L combination)	Highest absorption by roots Maximum removal of chromium by roots is 65%, 62% for lithium Effective chromium removal than lithium High concentration effects the growth of the plant	Discussion on how climate influence the removal can be discussed	[175]

significant additional removal [169].

In water hyacinth–based hydroponic systems, harvesting should not be treated merely as a biomass management practice but rather as a critical process control variable that directly governs treatment efficiency and system stability [182]. Regular harvesting determines the net removal of nutrients and contaminants by physically exporting nitrogen, phosphorus, and accumulated pollutants from the system, thereby preventing their re-release through plant senescence and decomposition [183]. Similar to hydraulic retention time and influent loading rates, harvesting frequency and intensity regulate biomass turnover, nutrient uptake kinetics, and oxygen dynamics within the root zone [182].

Evidence from pilot- and full-scale applications indicates that optimized harvesting intervals maintain plants in a high-growth physiological state, maximizing nutrient assimilation and pollutant removal while minimizing risks of clogging, hypoxia, and secondary eutrophication. Excessively long harvesting intervals can reduce treatment performance due to aging biomass, while overly frequent harvesting may limit nutrient uptake capacity by reducing active root surface area [183]. Framing harvesting as an operational control strategy enables predictive system optimization and aligns water hyacinth–based hydroponic treatment with established principles of process engineering. This perspective also facilitates scalability, automation, and integration with real-time monitoring systems, where harvesting decisions can be dynamically adjusted based on biomass accumulation, nutrient removal efficiency, and effluent quality targets [184].

For optimal system performance, pilot- and full-scale systems may require protective coverings, especially in colder regions, to prevent reduced metabolism and nutrient uptake [185]. The relative contributions of plant uptake and microbial processes determine a hydroponic system's ability to maintain treatment standards during low-growth seasons. While reduced temperature and light availability can suppress water hyacinth growth and nutrient assimilation, several studies indicate that treatment performance does not decline proportionally, as microbial nitrification–denitrification and biofilm-mediated processes within the root zone continue to contribute to pollutant removal [186]. Consequently, hydroponic systems often exhibit partial decoupling between plant growth rates and overall treatment efficiency [187].

Nevertheless, sustained compliance with effluent quality standards during prolonged low-growth periods typically requires adaptive operational strategies. These include increased hydraulic retention time, reduced influent loading, supplementary aeration, or integration with upstream primary treatment units. Evidence from pilot-scale systems suggests that while peak nutrient removal efficiencies are achieved during high-growth seasons, baseline treatment performance can be maintained year-round when hydroponic systems are appropriately designed and operated as part of a hybrid treatment train rather than as standalone units.

8.4. Real-World operational constraints

While hydroponic systems offer distinct advantages, their full-scale implementation is bound by significant physical and operational constraints that do not apply to conventional treatment. First, despite being more space-efficient than constructed wetlands, the need for adequate HRT, often up to 40 days for optimal nutrient removal [124], results in a substantial land footprint for municipal flows, potentially limiting application to peri-urban or decentralized settings. Second, these systems are susceptible to hydraulic loading rates; unlike concrete reactors, hydroponic setups lack the buffer capacity to handle sudden hydraulic surges from stormwater runoff [188], which can physically disturb root zones and reduce contact time below adequate levels. Third, climatic dependency remains a critical bottleneck; treatment efficiency is intrinsically linked to plant metabolism, meaning performance drops precipitously in colder months or requires expensive protective infrastructure to maintain activity [186]. To enhance practical applicability, Table 10 summarizes key operational control variables, associated failure modes, underlying mechanisms, and recommended mitigation strategies for WH hydroponic reactors.

9. Challenges and constraints

The challenges and constraints of implementing water hyacinth in a hydroponic system for sewage treatment are summarized in Fig. 6 and discussed further in the following sections.

9.1. Invasiveness and ecosystem management

One big problem with using water hyacinth is that it spreads very quickly. The plant grows quickly, doubling its biomass in just a few days when nutrients are plentiful [81]. This makes it possible for it to spread uncontrolled in open water systems. Water hyacinth can form thick mats that block sunlight, reduce dissolved oxygen levels, and harm aquatic biodiversity if not carefully controlled [189]. Proper handling for controlled farming, physical barriers to keep plants from escaping into natural ecosystems, and systematic harvesting are highly needed [184]. Invasive species management often relies on the assumption of ideal containment; however, physical barriers are prone to failure during extreme weather events like flooding, potentially catalyzing irreversible ecological invasions. Without these protections, adding water hyacinth to sewage treatment could create additional environmental problems.

10. System maintenance and biomass harvesting

Hydroponic systems incorporating water hyacinth require continuous monitoring and regular maintenance to remain effective [114].

Table 9
Performance of other floating plant species in treating pollutants.

Plant Species	Operating Conditions	Removal Efficiency	Advantages	Limitation	Reference
Lemna minor (duckweed)	Temperature: 25± 1°C Light regime: 16 h light/ 8 h dark pH: 5.8 Duration: 7 days	Arsenic accumulation increases with addition of chelating agents As(V) and As(III)	Mobilization of As from Fe plaques Uptake of beneficial nutrient like phosphorus and iron	Non-biodegradable of chelating agents	[177]
	Temperature: 20.6 °C pH: 6 & 8 Duration: 7 days Initial concentration: 1–5 mg/L Cr(VI)	Highest removal efficiency at 85% within day-3	Rapid uptake High bioconcentration factor (BCF) factor	Rapid growth resulting in frequent harvesting Require shallow water depth for effective rot contact	[167]
	pH: 6.14 Temperature: <30°C HRT: 7, 14, 21 days Optimum plant density: 80% of tank surface area	Removal efficiency of nitrogen, TSS and phosphorus is 91%, 94% and 83% respectively	Suitable for tropical climate	Possess smaller root system that inhibit organic pollutants removal	[169]
Pistia stratiotes (water lettuce)	Temperature: 20.6 °C pH: 6 & 8 Duration: 7 days Initial concentration: 1–5 mg/L Cr(VI)	Average removal efficiency is 81% Rapid removal detected after day 4 Better performance in acidic conditions	High bioconcentration factor (BCF) factor Function well in acidic conditions	Inhibitance in plant growth after day 4	[167]
	Temperature: 24–28°C Photoperiod: 12:12 light-dark pH: 5.4–5.8 Duration: 12 for Ni(II) and 18 days for Cr(III) Initial conc: 0.75–5 mg/L for Ni(II) and 1.25–5 mg/L for Cr (III)	Removal efficiency up to 77.5% and 70.8% for highest concentration	Effective for low metal concentration High bioaccumulation and bioconcentration potential	Chlorosis effect at high concentration Low performance in real wastewater due to toxic impacts	[178]
	pH: 6.14 Temperature: <30°C HRT: 7, 14, 21 days Optimum plant density: 80% of tank surface area	Removal efficiency of TSS and phosphorus is 96% and 94% respectively	Easy to cultivate Suitable for tropical climate	Less effective for nitrogen removal Frequent harvesting to avoid overgrowth	[169]
Typha latifolia (cattail)	pH: 7.2 Duration: 28 days	8.7% pH reduction that is within permissible limit The efficiency of removal as below: Turbidity: 96.6% Sulphate: 96% Nitrate: 0.28% Total phosphorus: 85.8% COD: 82.7% BOD: 40.5% Copper: 79.3% Lead: 88% Zinc: 78.9% Oil and grease: 64.10% Coliform: 35.5%	Effective in pollutants removal	Total phosphorus level exceeds permissible limits	[179]
Ipomoea aquatica (water spinach)	Temperature: 25–30°C pH: 5.5–7 Duration: 28 days	Removal efficiency of nitrate, phosphate and BOD recorded at 57.8%, 74.2% and 8.8% respectively	High selective absorption for nitrate and phosphate Easy to adapt	Possess lower biomass production	[172]
Myriophyllm spicatum (spiked watermilfoil)	Temperature: 16–30°C Duration: 36 days Initial concentration: 228.4 mg/L nitrate	Removal efficiency of nitrate is 83.3%	Offer habitat for microbial communities	Production of biomass and dry weight are less significant	[180]
Lemna gibba	Temperature: 16–30°C Duration: 36 days Initial concentration: 228.4 mg/L nitrate	Removal efficiency of nitrate is 86.3%	Source of organic fertilizer Significant biomass production	Low dissolved oxygen in dense environment	[180]

Overgrown plants can block systems, slow water flow, and limit oxygen transfer, reducing their effectiveness at removing pollutants [189]. Periodic biomass harvesting is essential not only to maintain system stability but also to ensure the permanent removal of nutrients and contaminants stored in plant tissues. However, handling large amounts of biomass is difficult because it must be collected, moved, and stored. Also, if the biomass contains heavy metals or pathogens, improper handling could worsen pollution. Creating sustainable end-uses, such as producing bioenergy, composting, or converting it into biochar, can help address some of these problems, but more infrastructure and funding are usually needed [190,191].

Ensuring the safety of harvested biomass requires rigorous processing to neutralize biological and chemical hazards. Thermal treatments, particularly pyrolysis for biochar production, offer a reliable method for pathogen destruction while simultaneously stabilizing carbon [192]. For agricultural applications, thermophilic composting is necessary to inactivate pathogens, though it must be carefully monitored to prevent metal mobilization [193]. Furthermore, to validate product safety, leaching tests and compliance with regulatory standards are essential to ensure that heavy metals remain sequestered and do not re-enter the environment through soil amendments or construction materials [194]. The absence of universally established safety protocols for these specific by-products remains a significant operational constraint.

Table 10
Operational control variables, associated failure modes, and mitigation strategies.

Operational variable	Case	Common failure mode	Mechanism	Practical mitigation
Hydraulic retention time (HRT)	Too short	Low N/P/BOD removal	Insufficient root–water contact and incomplete nitrification–denitrification	Increase reactor volume, use modular plug-flow layout, reduce hydraulic loading
	Too long without harvesting	Hypoxia, biomass decay, nutrient re-release	Dense root mats restrict oxygen transfer, senescent tissue mineralizes N and P	Implement scheduled harvesting (7–21 d), maintain surface coverage ≤70–80%
Harvesting	Infrequent	Declining removal efficiency, clogging	Aging biomass reduces uptake kinetics and blocks flow paths	Treat harvesting as a process control variable, monitor biomass density
	Over-harvesting	Reduced treatment performance	Loss of active root surface and microbial biofilm	Maintain minimum plant coverage and staged harvesting
Organic loading	Too high	Anaerobic conditions, odor, methane production	Oxygen demand exceeds passive root-zone oxygenation	Pre-settling or primary treatment, supplemental aeration in high-load zones
Hydraulic loading	Shock (storm inflow)	Biomass washout, short-circuiting	Physical disturbance of root mats and reduced HRT	Install equalization tank, flow baffles, overflow bypass
Temperature	Low (<15°C)	Reduced nutrient uptake, slower kinetics	Suppressed plant metabolism and microbial activity	Greenhouse covering, hybridization with biological units, seasonal operation
Plant density	Excessive (>80% coverage)	Light limitation, hypoxia beneath mats	Reduced reaeration and internal shading	Maintain optimal spacing, periodic thinning
Biomass control	Metal-laden influent	Secondary contamination risk during reuse	Metal accumulation in tissues	Route biomass to biochar/controlled disposal, avoid feed/fertilizer use
Polishing	Lacking	Inadequate pathogen removal	Limited log reduction of indicator bacteria	Add UV, chlorination, maturation pond, or wetland polishing depending on discharge standard

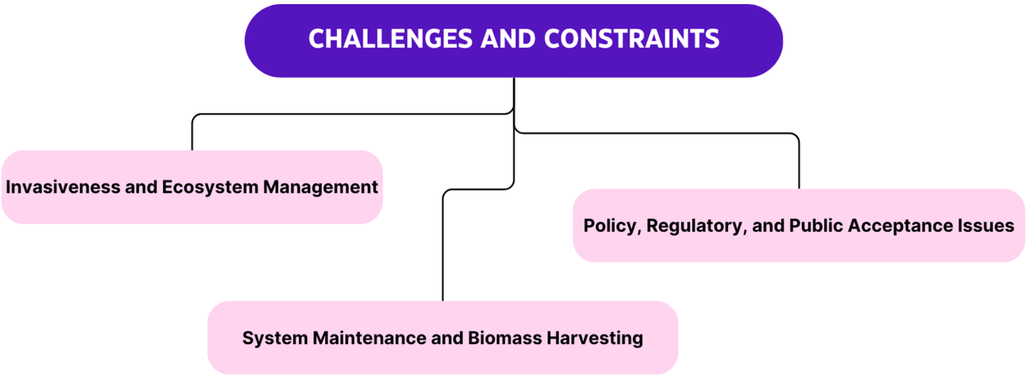


Fig. 6. Challenge and constraints of water hyacinth implementation in sewage treatment.

10.1. Policy, regulatory, and public acceptance issues

Policy and regulatory frameworks also affect the use of water hyacinth-based sewage treatment, along with technical and environmental issues. In many places, water hyacinth is legally considered an invasive weed, and there are strict rules against growing it, even for controlled treatment systems [156]. Policymakers might not want to support large-scale use of the plant because it has a history of harming the environment and the economy. Also, public perceptions can make it harder to get people to accept it. People in communities often view water hyacinth as a nuisance, a source of neglect, or a form of pollution rather than a possible resource. Unlike conventional systems using chemical disinfection, the pathogen-removal efficiency of water hyacinth is biologically variable and may not consistently meet strict effluent discharge standards without supplemental treatment [193]. To address these problems, rules and regulations must strike a balance between protecting the environment and enabling the use of biomass in a circular bioeconomy. Public awareness campaigns and demonstration projects can also be critical in changing public perceptions to ensure that treating sewage with water hyacinth is a long-term, creative solution.

11. Future perspectives and opportunities

11.1. Coupling with aquaponics or constructed wetlands

Aquaponics, which combines fish farming with growing plants without soil, is a promising approach for using water hyacinth-based sewage treatment. This method uses aquaculture effluent as a nutrient-rich water source for aquaponic systems [112,195]. Water hyacinth acts as a biofilter, removing excess nutrients and organic matter before being recirculated to fish tanks or edible crops. After a particular cycle of the aquaponic system, the aquaculture effluent can be combined with sewage and further treated in a constructed wetland supplemented with water hyacinth [137,196]. This two-stage setup not only makes the water cleaner but also makes the system more resilient by reducing the risk of nutrient overload and disease outbreaks in aquaponics. Also, the biomass from harvested water hyacinth can be used as animal feed, compost, or a bioenergy feedstock, supporting the principles of a circular bioeconomy [197]. Careful planning is needed to prevent fish and crop production from coming into direct contact with sewage effluents, where food safety standards must be strictly followed (Fig. 7).

The combination of hydroponics with aquaponics or constructed wetlands offers multiple advantages. These include enhanced pollutant removal efficiency through complementary mechanisms, diversification of outputs such as fish, crops, and biomass, and improved ecological sustainability [133]. Such integrated systems align with circular bioeconomy principles by converting waste streams into valuable products and services. Moreover, they provide flexible, decentralized solutions suitable for peri-urban and rural communities where centralized sewage treatment infrastructure may be lacking [198,199]. Despite these benefits, challenges remain in terms of design complexity, cost of initial setup, and regulatory approval, particularly when integrating

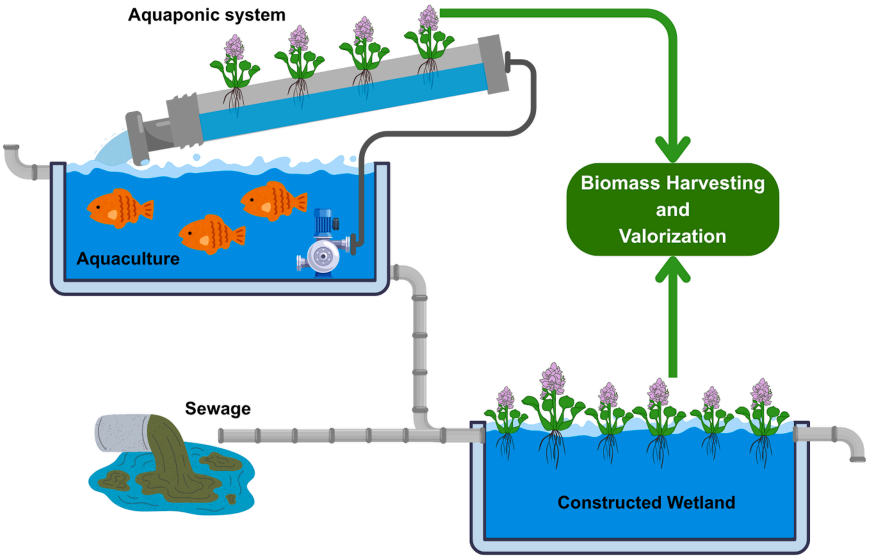


Fig. 7. Integrated circular model coupling aquaponic and phytoremediation with water hyacinth.

sewage-derived water into systems linked to food production.

11.2. Circular economy potential: biomass valorization

According to Rezania et al. [89], attempts to control the uncontrolled spread of water hyacinth have not been fully effective. The best way to manage the plant in a way that is good for the environment is to view its biomass as valuable within a circular bioeconomy framework rather than a mere nuisance [132]. Water hyacinth has been investigated for numerous applications, including bioenergy generation, hydrogen production, sewage treatment for heavy metals and inorganic pollutants, organic fertilizer production, integration into building materials such as concrete, and as a feedstock for animal nutrition [200,201], as summarized in Table 11.

11.3. Research gaps and recommendations for implementation

Although water hyacinth demonstrates significant promise for sewage treatment and resource valorization, several research gaps remain that hinder its widespread adoption. These gaps are technical, environmental, and socio-economic in nature, requiring a holistic research agenda to ensure sustainable implementation as summarized in Fig. 8.

11.3.1. Current research gaps

Many studies show that water hyacinth is effective at phytoremediation, but few examine how this invasive species affects ecosystems in the long term when used in treatment systems. There are still questions about the unintended release of propagules, how organisms adapt genetically to stressful environments, and the dangers of secondary invasions when systems are abandoned or not properly managed [209]. Most studies concentrate on short-term or pilot-scale trials, yielding insufficient evidence regarding the long-term stability, resilience, and seasonal efficacy of water hyacinth-based systems.

Research indicates that integrating water hyacinth into aquaponics or constructed wetlands improves treatment efficiency; however, investigations into system design parameters, such as plant density, hydraulic retention time, biomass harvesting intervals, and integration with microbial communities, remain incomplete [210]. Pilot-to-full-scale demonstrations are still rare, making it hard to know how to scale up from lab experiments.

Further, studies have shown that harvested water hyacinth can be turned into bioenergy, compost, animal feed, and concrete admixtures. However, these ideas are still mainly in the experimental or pilot stage. There aren't many comprehensive techno-economic assessments (TEA) and life-cycle analyses (LCA) yet, which makes it hard for us to fully understand how sustainable and cost-effective these applications really are [211,212]. Current research frequently emphasizes laboratory performance over system-wide feasibility, overlooking essential factors such as supply chain logistics, energy balance, market demand, and environmental trade-offs [213]. The lack of comparative cost-benefit analyses between water hyacinth-based systems and traditional sewage treatment technologies hinders both policy development and private sector investment. Decision-makers are still hesitant to support large-scale deployment because they lack robust economic data and integrated environmental accounting. Consequently, subsequent research should emphasize multidisciplinary assessments that integrate technical performance, environmental impact, and socio-economic feasibility to validate the utilization of water hyacinth as a legitimate element of the circular bioeconomy and sustainable sewage management systems.

To advance hydroponic sewage treatment systems from experimental concepts to practical implementation, coordinated efforts across research, demonstration, and governance domains are urgently required. Future experimental studies should focus on systematically evaluating key operational parameters, including hydraulic retention time, nutrient loading rates, plant density, and harvesting regimes, to establish robust performance benchmarks under controlled conditions. Particular attention should be given to mass balance analyses and contaminant accumulation in plant tissues to inform safe biomass handling and reuse.

Beyond laboratory-scale investigations, pilot-scale implementations under real sewage conditions are essential to assess long-term system stability, seasonal variability, and operational resilience. Such pilots should compare different hydroponic configurations and generate empirical data to support engineering design, cost assessment, and scalability. Current research on the use of water hyacinth has focused chiefly on how well it performs in removing pollutants, converting biomass, and improving systems. There hasn't been enough research on governance frameworks, policy incentives, and regulatory barriers [214,215]. This imbalance makes it hard for scientific breakthroughs to be put into practice in the real world. Existing policies, on the other hand, often view water hyacinth solely as an ecological threat. This leads to strict rules that make it hard to use it in a controlled way for good reasons.

Even though more people are paying attention to the technical and environmental benefits of water hyacinth-based systems, social

Table 11
Utilization of water hyacinth biomass after wastewater treatment.

Application	Research Objective / Description	Experiment Setup / Conditions	Results	Reference
Production of Animal Feed	To test the role of water hyacinth in purifying nutrient-rich wastewater and its effects on the ducks' feed intake, egg laying performance and egg quality.	• Each duck of the experimental group was fed only • 50 g per day of freshwater hyacinth. For each group, we • recorded the feed intake quantity, the egg-laying quantity • and the total egg weight.	- The average daily feed intake and the egg-laying ratio in the test group were 5.86% and 9.79% higher, respectively, than in the control group; The egg weight in the test group was 2.36% higher than in the control group ($P < 0.05$), but the feed conversion ratios were almost the same. The eggshell thickness - Strength was among the egg qualities significantly increased in ducks fed with water hyacinth.	[202]
Production of Bioenergy	To test practical solutions to improve biogas yield during the anaerobic digestion of WH biomass. Increasing the WH (whole plant) solid content through sun drying.	• Experiments carried out in a two-stage process unit which consists of an Anaerobic Leach Bed Reactor (ALBR) and an Up-flow Anaerobic Sludge Blanket Reactor (UASB) for 12 days. • Sun drying to increase the solid content of WH biomass. • Co-digestion of WH with food waste and sewage activated sludge.	- WH biomass solid contents increased to 40% after 6 hours sun drying. - Biogas yield (140 mL/g VS) increased by 14% with a higher biogas methane (75%) content. - Co-digestion of WH with food waste is 400 mL biogas/g VS higher compared with co-digestion of WH with sewage activated sludge 150 mL/g VS.	[203]
Production of Bioenergy	To analyze and compare biogas production from cow manure, sewage sludge, kitchen waste and WH through anaerobic co-digestion.	• 2 set of batch materials were prepared. WH were cut and mashed with cow manure and sewage sludge into a paste. Kitchen waste mixed with cow manure. • 1 L of anaerobic digester with a loading of 100 g/L with 1.5% NaOH was added in the digester. • Volume of the gas produced was captured and measured by water displacement method.	- The production of 1 L batch of WH, cow manure and sewage sludge produced 812 mL biogas with 65% of methane content. - Kitchen waste and cow manure mixture produced 335 mL biogas with 60% of methane content. Both gases are obtained after 800 hours operation.	[204]
Production of Concrete (Superplasticizer)	To evaluate the effectiveness of using a bio-admixture as partial replacement for Auramix 400 chemical superplasticizer in SCC production. Water hyacinth extract was used as superplasticizer. Mechanical properties of the concrete were determined.	• Dried WH was then cut into 5 mm size and grind into fine powder. Then 500 g of WH powder was soaked in 30 ml ethanol for 24 hours. The WH extract was then filtered and used for experiments. • Both coarse and fines aggregates were blended in 30:60 proportion by percentage weight of total aggregates. • The Water hyacinth extract was added as 0, 10, 15, 20, 25 percentage replacement of Auramix 400 as the superplasticizer.	- WH extract has tested on slump flow test and T500; the results show WH is suitable as superplasticizer in a SCC mix. - WH extract shows higher flowrate ability and filing ability when it retards the hydration and hardening process making the concrete to flow longer. - Water permeability increased with an increase in the amount of water hyacinth extract. - The optimum superplasticizer replacement was found to be 20%.	[205]
Production of Fertilizer	To determine whether Rhizobium inoculants and WH composts are compatible options for plant growth promotion and pest suppression in beans.	• The experiment was carried in a randomized block design comprising with fertilizer factor with six levels: no fertilizer (Non), diammonium phosphate fertilizer (DAP), water hyacinth compost only (H), water hyacinth compost+molasses (H+Mol), water hyacinth compost+effective microbes (H+EM), and water hyacinth compost+cattle manure culture (H+CMC).	- Plants were large in size with short development period when grown with the composts, especially H+CMC and H+EM. - Those grown with H+EM had the lowest A. fabae population. Yields in WH compost were improved. - The commercial Rhizobium inoculant is predominantly compatible with WH compost formulations containing effective microbes and cattle manure culture, which could enhance tolerance of bean plants to aphids and possibly to anthracnose disease.	[206]
Production of Hydrogen	To investigate the H_2 production potential from Co-fermentation of water hyacinth and beverage wastewater in powder and pellet form. Pig slurry was used as seed inoculum.	• WH was sun-dried and powdered to 0.8 mm-mesh size. Beverage wastewater also was dried in an air-bath oven, then powdered to 0.8 mm-mesh size similar to WH powder. • Batch H2 production experiments were performed in serum • bottles with anaerobic head space. • Gas samples were taken using a gas tight syringe to • analysis the biogas production and composition during fermentation.	- Batch co-fermentation results showed peak biogas production of 105.5 mL and H2 production of 55.6 mL at the combination ratio of 1.6 g WH and 2.4 g BW in pellet form. - With the same ratio in pellet form, the maximum H2 production 542 mL H2/L -d, maximum specific H2 production 869 mL H2/g VSS-d and H2 yield 13.65 mL/g feedstock were obtained, and were 88, 88 and 34% higher than its powder form.	[207]
Wastewater Treatment (Heavy Metal Removal)	Using WH shoot powder to remove chromium and copper from tannery effluent from drain.	• The shoot of WH was dried under sunlight for 72 hours, then further dried in oven at 70 ± 5 °C for 48 hours and grind by mortar. • Tannery effluent was flowed vertical down through filtering column packed with WH shoot powder.	- WH root powder adsorbent capacity for Chromium and Copper was found 99.98% and 99.96% for standard solution and 98.83% and 99.59% for tannery effluent.	[208]

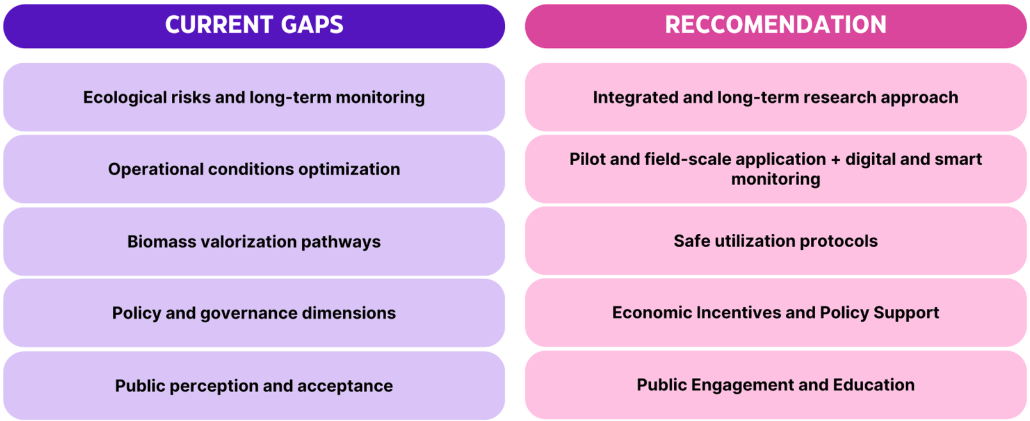


Fig. 8. Current gaps and recommendations for the implementation of water hyacinth in sewage treatment plants.

acceptance remains a largely overlooked aspect [216]. There is not much known about how people feel about using these systems, especially when the end products, like organic fertilizers, animal feed, or aquaponic crops, could end up back in the food chain. People are often concerned about safety, cleanliness, and contamination, especially when sewage or invasive species are involved. These perceptions, regardless of their scientific validity, can profoundly influence the adoption and marketability of products derived from water hyacinth. Cultural and psychological factors also play a role in acceptance in many situations [217].

11.3.2. *Recommendations for implementation*

Subsequent research should employ interdisciplinary, systems-oriented frameworks that integrate perspectives from environmental science, engineering, economics, and the social sciences to thoroughly evaluate water hyacinth-based systems [162]. This is the only way to get a complete picture of their ecological, economic, and social effects, rather than looking at each one separately.

To advance hydroponic sewage treatment systems from experimental concepts to practical implementation, coordinated efforts across research, demonstration, and governance domains are urgently required [218]. Future experimental studies should focus on systematically evaluating key operational parameters, including hydraulic retention time, nutrient loading rates, plant density, and harvesting regimes, to establish robust performance benchmarks under controlled conditions. Particular attention should be given to mass balance analyses and contaminant accumulation in plant tissues to inform safe biomass handling and reuse [219].

Beyond laboratory-scale investigations, pilot-scale implementations under real sewage conditions are essential [213] to assess long-term system stability, seasonal variability, and operational resilience. Such pilots should compare different hydroponic configurations and generate empirical data to support engineering design, cost assessment, and scalability. Adding digital tools such as sensors, automation, and remote monitoring systems can make the system even more reliable and valuable. Smart sensors can monitor water quality parameters such as pH, nutrient concentration, and dissolved oxygen, while automated feedback controls can optimize aeration, flow regulation, and harvesting schedules [220–222]. This digital integration not only makes the system more stable but also reduces environmental risks associated with excessive growth or nutrient release [223]. Also, researchers, policymakers, and operators can share data in real time using Internet of Things (IoT) platforms. This makes it easier to make decisions based on evidence and adapt management.

To ensure that harvesting, moving, and processing water hyacinth biomass are safe and environmentally friendly, standardized rules are needed [224]. These rules are essential for preventing this invasive species from spreading out of control and for ensuring that biomass valorization is safe, traceable, and effective. If there aren't standard procedures, people could reintroduce viable plant fragments into natural waterways through improper procedures, making control efforts less effective and creating another environmental problem.

In parallel, policymakers should offer tax breaks, subsidies, or carbon credits to encourage businesses and communities to use hyacinth-based sewage solutions and create comprehensive policy frameworks that set standards for the safe growing, storage, and handling of water hyacinth biomass after it is harvested [219]. Making rules for risk assessment, setting up certification systems for treated effluents and products made from them, and giving people incentives like subsidies, tax credits, or public-private partnerships [225,226] to use them in a way that is good for the environment are highly suggested.

Lastly, awareness campaigns and stakeholder meetings are significant for clarifying any confusion and demonstrating the value of turning an invasive pest into a helpful resource. As discussed earlier, these problems can't be solved solely by adjusting technology [227]. Scientists, regulators, and end users need to be able to communicate clearly, identify risks, and trust one another [228]. Public education campaigns that focus on the environmental and economic benefits of safe reuse, along with demonstration projects that show how to do it safely, could help change how people think [229]. Also, social research on what motivates people to act and how to get people involved in their communities is essential to improving technical studies. Policymakers and project developers can make interventions that are more sensitive to local conditions if they understand how cultural norms, local knowledge, and socioeconomic conditions affect acceptance.

12. Conclusion

The use of water hyacinth in hydroponic systems is a promising, natural way to treat sewage in an environmentally friendly manner. This review demonstrates that hydroponic systems employing water hyacinth can achieve substantial pollutant removal efficiencies under controlled conditions. Reported studies indicate nitrogen and phosphorus removal efficiencies typically range from approximately 50–90%, depending on influent loading, hydraulic retention time, and biomass harvesting regimes. Reductions in biochemical oxygen demand and chemical oxygen demand of 40–80% have been observed, highlighting the potential of hydroponic treatment systems as practical secondary or polishing steps for sewage treatment.

Across the reviewed literature, strong correlations emerge between treatment performance and operational parameters. Hydroponic systems are operationally driven rather than configuration-driven. Higher nutrient removal efficiencies are consistently associated with moderate hydraulic retention times, optimized plant density, and regular biomass harvesting that maintains plants in active growth phases. Conversely, prolonged retention times without harvesting often lead to diminished performance due to biomass senescence and nutrient re-release. These findings underscore harvesting frequency and system hydraulics as key process control variables governing treatment stability and efficiency.

Collectively, these quantitative trends confirm that water hyacinth–based hydroponic systems are not merely ecological interventions but can function as engineered treatment units with predictable performance. By linking removal efficiencies to controllable operational parameters, this review highlights the feasibility of optimizing these systems for decentralized sewage treatment, particularly in regions with limited conventional infrastructure. Seasonal variability remains a key design consideration, reinforcing the need for hybrid system configurations to ensure year-round treatment reliability. Future efforts should focus on translating these quantitative relationships into design guidelines and performance standards to support wider adoption.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT and Grammarly to refine the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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CRediT authorship contribution statement

Setyo Budi Kurniawan: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Funding acquisition, Data curation, Conceptualization. **Azimah Ismail:** Resources. **Azmi Ahmad:** Writing – original draft. **Junaidah Buhari:** Writing – original draft. **Suriya Vathi Subramanian:** Writing – original draft. **Siti Rozaimah Sheikh Abdullah:** Supervision, Resources, Project administration, Funding acquisition. **Muhammad Fauzul Imron:** Writing – original draft, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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