AL-Bahir
Journal for Engineering and Pure Sciences
BJEPS

Volume 6 | Issue 2 Article 2

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Source of Funding

No funding from any organization or individuals in the subject matter or materials discussed this manuscript.

Conflict of Interest

This declaration is not applicable

Data Availability

All data used were mentioned in the manuscript and can be accessed.

Author Contributions

All authors contributed to the study's conception and design. Material preparation was performed by Ali M. Ahmed, Results Analysis was performed by Sabreen L.Kareem and Ali M. Ahmed, and the first draft of the manuscript was written by Ali M.. Finally, technical aspects were done by Sabreen.L. Kareem. All authors read and approved the final manuscript.

REVIEW

Comparative Analysis of Vertical and Horizontal Subsurface Flow Constructed Wetlands for Eutrophication Mitigation

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Abstract

Constructed wetlands (CWs) serve as a sustainable and eco-friendly solution for wastewater treatment, particularly in the removal of eutrophication-causing pollutants. This review focuses on the comparative performance of Vertical Flow (VF) and Horizontal Flow (HF) Subsurface Flow (SSF) systems, assessing their efficiency in removing Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN), and Total Phosphorus (TP). VF systems demonstrate superior pollutant removal, particularly for nitrogen, due to enhanced aeration and efficient oxygenation processes. In addition, their compact design reduces land area requirements, making them advantageous in space-limited applications. Conversely, HF systems are more effective at supporting nutrient gradient development, particularly for phosphorus removal, but they require more land and exhibit slower treatment rates due to limited oxygenation. The review synthesizes current literature on the mechanisms of pollutant removal in these systems, emphasizing the role of phytoremediation plants and microbial interactions. Our analysis underscores that, while both VF and HF systems offer substantial environmental benefits, VF systems consistently outperform HF systems in terms of pollutant removal efficiency and spatial economy. This makes VF systems particularly valuable in settings where land availability is constrained and nitrogen reduction is prioritized. These findings highlight the critical role of VF-SSF systems in advancing wastewater treatment, positioning them as essential components in strategies to mitigate eutrophication and enhance environmental sustainability. Scientifically and academically, future research should focus on optimizing VF system designs, enhancing phosphorus removal, and ensuring resilience across diverse climatic conditions for long-term, global water management solutions.

Keywords: Constructed wetlands, Eutrophication, Sustainability, Subsurface flow, Wastewater

1. Introduction

The global challenge of water scarcity is further exacerbated by inefficient wastewater management, particularly in developing regions where the strain on freshwater resources is most acute [1]. Pollutants originating from agricultural runoff, untreated domestic and industrial discharges, and suboptimal treatment processes significantly degrade water quality, posing serious risks to ecosystems and public health [2]. Extensive research highlights the ongoing decline in global water quality [3], with regions like Iraq, already grappling with water shortages, facing amplified threats due to geopolitical conflicts and reduced precipitation linked to climate change [4]. The rising water demand driven by population growth further intensifies the need for sustainable water resource management. To address these issues, there is a growing imperative to develop alternative water sources, such as the reclamation and reuse of treated wastewater for non-potable purposes, particularly in agriculture [5]. However, concerns regarding sanitation, public health, and environmental risks underscore the need for robust treatment technologies. Constructed wetlands (CWs) have emerged as a promising decentralized wastewater treatment solution, efficiently processing a variety of effluents, including domestic and industrial waste [6]. Beyond their capacity for pollutant

Received 20 December 2024; revised 9 February 2025; accepted 19 February 2025.
Available online 8 April 2025

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https://doi.org/10.55810/2313-0083.1092

removal, CWs provide additional ecological benefits such as habitat creation, groundwater recharge, and carbon sequestration [7]. This paper aims to critically examine the pollutant removal mechanisms and performance of CW systems, with a focus on their role in addressing eutrophication, a leading cause of water quality degradation. By synthesizing current research, this work underscores the importance of CWs in mitigating pollutants, thus supporting the long-term sustainability of water resources and promoting environmentally sound wastewater management practices [8].

2. Overview of eutrophication treatment techniques

Effective treatment of wastewater to address nutrient enrichment, primarily caused by excess nitrogen (TN) and phosphorus (TP), is critical for preventing eutrophication in aquatic ecosystems. Traditional wastewater treatment technologies, such as activated sludge processes and anaerobic digesters, are commonly employed for nutrient removal [9]. These systems excel in reducing organic matter and pathogens but often require significant energy inputs and skilled personnel for precise process control [10]. Additionally, the operational complexity and ongoing maintenance costs associated with these methods limit their applicability, especially in resource-constrained regions [11]. In contrast, constructed wetlands (CWs) offer an ecologically sustainable and cost-effective solution for nutrient removal [12]. CWs leverage the synergistic interactions between hydrophytes plants, substrate materials, and microbial communities to effectively remove TN and TP from wastewater [13]. Within these systems, nitrogen removal occurs through processes such as nitrification-denitrification and plant uptake, while phosphorus is primarily removed through adsorption onto substrates and plant assimilation. CWs demonstrate substantial capacity for reducing nutrient loads, preventing excessive nutrient release into receiving waters, which is a key factor in combating eutrophication [14]. Recent studies indicate that CWs can achieve nutrient removal efficiencies comparable to, or exceeding, conventional systems, but with lower energy requirements and reduced operational complexity [15]. Their ability to treat a variety of wastewater types while simultaneously conserving energy and promoting biodiversity makes CWs an ideal choice for both developed and developing regions. Understanding the specific mechanisms behind TN and TP removal in CWs is essential for optimizing these systems, as highlighted in Table 1, leads to excessive nutrient enrichment, resulting in algal blooms and oxygen depletion in aquatic ecosystems [16].

3. Design and operation

Subsurface Flow (SSF) systems are primarily classified into two types: Horizontal Subsurface Flow (HSSF) and Vertical Subsurface Flow (VSSF) systems. Both systems are designed with porous substrates, typically gravel or sand, which serve as a medium for microbial colonization, essential for the biological degradation of pollutants [26]. In HSSF systems, wastewater flows horizontally through the substrate, creating predominantly anaerobic conditions that facilitate the removal of organic pollutants and nutrients, such as nitrogen and phosphorus. The horizontal flow pattern promotes extended contact time with the substrate, enabling effective filtration and adsorption processes, particularly beneficial for phosphorus removal. Conversely, VSSF systems introduce wastewater at the surface, allowing it to percolate vertically through the substrate. This design enhances aerobic microbial activity by promoting better oxygen diffusion. The alternation between aerobic and anaerobic zones within VSSF systems supports simultaneous biochemical processes, such as nitrification-denitrification, leading to improved removal of Biochemical Oxygen Demand (BOD) and nitrogen compounds. Both SSF systems rely on the complex interactions between the substrate, microbial communities, and the hydraulic flow regime to achieve optimal pollutant removal [27]. The treatment performance of these systems is highly influenced by design parameters, such as substrate composition, hydraulic retention time, and flow direction. A schematic diagram (Fig. 1) illustrates the continuous operation of both HSSF and VSSF systems, highlighting their respective flow pathways and pollutant removal mechanisms. Specifically, it shows (a) the horizontal subsurface flow in HSSF and (b) the vertical subsurface flow in VSSF, with arrows indicating the overall direction of water movement within each system [28].

4. Pollutant removal mechanisms

Constructed wetlands (CWs) designed with Horizontal Subsurface Flow (HSSF) and Vertical Subsurface Flow (VSSF) configurations are employed to maximize pollutant removal, particularly for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN), and Total Phosphorus (TP). Each system relies on

Table 1. Typical Compositions of Untreated Domestic Effluent and Eutrophication-Contributing Pollutants (Pepper et al., 2006).

Contaminant	Concentration (mg/L)	Description	Eutrophication Relevance	Sources
Total Solids (TS)	Low: 350, Moderate: 720, High: 1200	The total sum concentration of solid particles in wastewater.	Indirect contribution, affecting water clarity and sedimentation.	[17]
Total Dissolved Solids (TDS)	Low: 500, Moderate: 850, High: 1000	The concentration of dissolved substances in the wastewater.	Not directly related to eutrophication.	[18]
Volatile Organic Compounds (VOC)	Low: 105, Moderate: 200, High: 325	Amount of volatile components present in the wastewater.	Indirectly linked, as they can impact microbial activity and oxygen demand.	[19]
Suspended Solids (SS)	Low: 100, Moderate: 220, High: 350	The concentration of suspended solid particles in the wastewater.	Can reduce light penetration, affecting aquatic plant growth, indirectly contributing to eutrophication.	[20]
Biochemical Oxygen Demand (BOD5)	Low: 110, Moderate: 220, High: 400	The amount of oxygen microorganisms require to decompose organic matter over five days.	High BOD leads to oxygen depletion, exacerbating eutrophication by creating hypoxic conditions.	[21]
Total Organic Carbon (TOC)	Low: 80, Moderate: 160, High: 290	Overall concentration of organic carbon compounds in wastewater.	High TOC may stimulate algal blooms and increase oxygen consumption, indirectly contributing to eutrophication.	[22]
Chemical Oxygen Demand (COD)	Low: 250, Moderate: 500, High: 1000	The quantity of oxygen required for the chemical oxidation of contaminants.	High COD promotes oxygen depletion, indirectly exacerbating eutrophication.	[23]
Nitrogen (Total as N)	Low: 20, Moderate: 40, High: 85	Total nitrogen concentration in the form of ammonia, nitrites, and nitrates.	Major contributor to eutrophication, fueling excessive algal growth and nutrient loading in aquatic systems.	[23]
Free Ammonia (NH3)	Low: 12, Moderate: 25, High: 50	The concentration of ammonia present in its free form in wastewater.	Direct contributor to nutrient overloading and eutrophication, promoting algae and aquatic plant overgrowth.	[24]
Phosphorus (Total as P)	Low: 4, Moderate: 15, High: 35	The overall concentration of phosphorus in the wastewater.	Primary driver of eutrophication, leading to algal blooms and ecosystem imbalances when present in excess.	[25]

distinct pollutant removal mechanisms, driven by differences in water flow and the oxygen conditions within the system [30].

4.1. Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)

HSSF systems facilitate wastewater flow horizontally through the substrate in an anaerobic or facultative environment, where organic matter is degraded by anaerobic bacteria. This system effectively reduces Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) by trapping suspended solids and utilizing anaerobic microbial activity, achieving approximately 60 % reduction in BOD and 50 % in COD (Table 2) [31]. However, its efficiency is somewhat limited by the absence of oxygen. In contrast, Vertical Subsurface Flow (VSSF) systems alternate between periods of flooding and draining, creating aerobic and anaerobic conditions that promote more complete organic matter breakdown [32]. The aerobic conditions during the drainage phase enhance microbial degradation of BOD and COD, allowing VSSF systems to achieve reductions of about 80 % for BOD and 75 % for COD (Table 2). Thus, while both systems are effective, VSSF systems demonstrate superior performance in handling higher organic loads due to their dynamic conditions that favor microbial activity [33].

4.2. Nutrient removal (TN and TP)

Nutrient removal in Horizontal Subsurface Flow (HSSF) systems occurs primarily through nitrification and denitrification processes within the substrate [36]. In this system, phosphorus is predominantly removed through adsorption to substrate particles, while nitrogen removal is effective under anaerobic conditions [37]. Nitrification takes place in localized aerobic micro zones, followed by denitrification in anaerobic zones, resulting in the release of nitrogen gas. In contrast, Vertical Subsurface Flow (VSSF) systems promote more efficient nitrogen removal due to their aerobic-anaerobic cycling [38]. During the drainage phase, aerobic nitrification is enhanced, converting

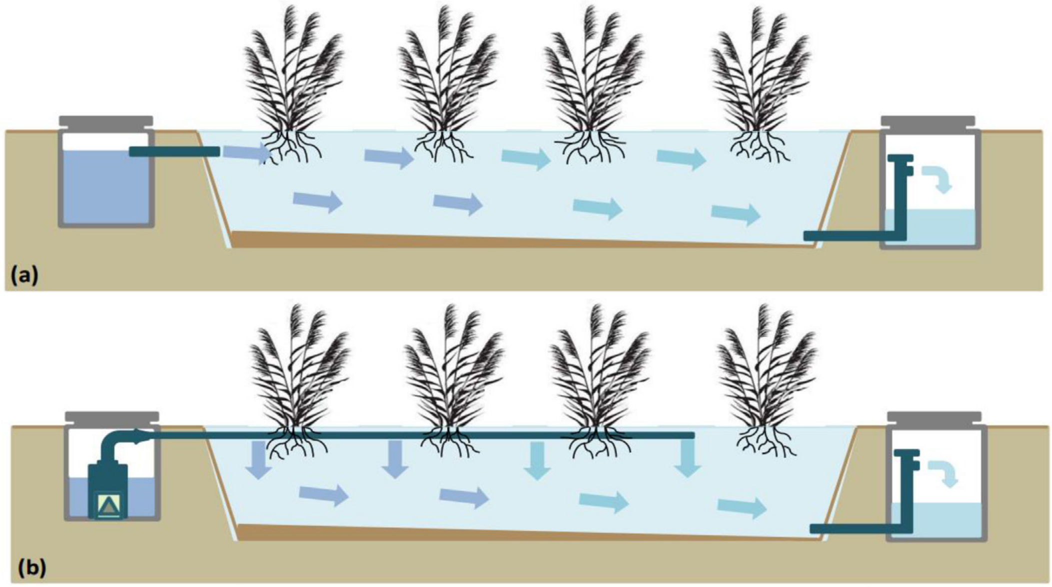

Fig. 1. Schematic diagram illustrating a Continuous Wetland with (a) The Horizontal Subsurface Flow (HSSF). (b) Vertical Subsurface Flow (VSSF), with arrows showing the overall flow direction [29].

Table 2. Comparative reduction of BOD and COD in HSSF and VSSF systems.

System Type	BOD Reduction (%)	COD Reduction (%)	Notes	Sources
HSSF systems	60 %	50 %	Effective in anaerobic conditions but limited by oxygen availability.	[34]
VSSF systems	80 %	75 %	Superior performance due to alternating aerobic and anaerobic conditions.	[35]

ammonium to nitrate, while the subsequent anaerobic phase supports denitrification, effectively removing nitrogen gas. Phosphorus removal in VSSF systems also occurs through adsorption to the substrate; however, the exposure to oxygen may enhance plant uptake as shown in Table 3 [39]. Overall, while both systems rely on similar mechanisms for nutrient removal, VSSF systems demonstrate greater efficiency due to their dynamic flow patterns and improved conditions for microbial and plant interactions [40].

4.3. Pathogen reduction

Pathogen reduction is a crucial aspect of wastewater treatment in constructed wetlands, with distinct processes observed in Horizontal Subsurface Flow (HSSF) and Vertical Subsurface Flow (VSSF) systems [43]. In HSSF systems, pathogens are primarily reduced through sedimentation and microbial activity under anaerobic conditions. While this method is effective to a certain extent, HSSF systems do not achieve the same level of pathogen removal as VSSF systems [44]. In contrast, VSSF systems create aerobic conditions that enhance microbial processes, resulting in superior pathogen removal efficiency as shown in Table 4. This increased microbial activity enables VSSF systems to effectively reduce pathogen loads compared to their HSSF counterparts, highlighting their importance in wastewater treatment [45].

Table 3. Nutrient removal mechanisms in HSSF and VSSF systems.

Nutrient Type	Removal Mechanism	HSSF Systems	VSSF Systems	Sources
Nitrogen	Nitrification and denitrification	60 % under anaerobic conditions	85 % through aerobic-anaerobic cycling	[41]
Phosphorus	Adsorption	70 % through substrate adsorption	80 % with enhanced plant uptake due to oxygen exposure	[42]

Table 4. Pathogen reduction efficiency in HSSF and VSSF systems.

Pathogen Type	Removal Mechanism	HSSF Systems	VSSF Systems	Sources
Total coliforms	Sedimentation and anaerobic activity	50 % reduction	90 % reduction	[46]
E. coli	Sedimentation and anaerobic activity	55 % reduction	92 % reduction	[47]
Enterococci	Sedimentation and anaerobic activity	45 % reduction	88 % reduction	[48]
Pathogenic Protozoa	Sedimentation and microbial activity	40 % reduction	85 % reduction	[49]

5. Ecological functions and key characteristics of VSSF and HSSF wetlands

Vertical Subsurface Flow (VSSF) and Horizontal Subsurface Flow (HSSF) wetlands play pivotal roles in ecosystem health and environmental sustainability, especially within the context of wastewater treatment and nutrient removal [50]. Both systems operate by channeling water through substrates like gravel or sand, facilitating microbial-mediated degradation of contaminants. However, they exhibit distinct flow patterns and pollutant-handling efficiencies, which influence their overall performance in diverse environmental conditions [51].

1. **Water Filtration**: The vertical water movement characteristic of VSSF wetlands enhances oxygenation and fosters more active microbial degradation of organic matter and nutrients such as nitrogen (N) and phosphorus (P). In contrast, the horizontal flow in HSSF wetlands prolongs water retention time, allowing for extended substrate contact, which promotes the adsorption and filtration of pollutants, particularly phosphorus. This difference highlights the spatial influence of flow on pollutant removal efficiency in these systems (refer to Table 5 for specific pollutant removal rates) [52].
2. **Treatment Efficiency**: VSSF wetlands demonstrate superior efficacy in the removal of organic matter and nitrogen, driven by enhanced aeration and the promotion of aerobic microbial processes, particularly nitrification. Conversely, HSSF wetlands exhibit greater efficiency in phosphorus removal, as extended hydraulic retention times facilitate phosphorus adsorption onto substrate materials [53]. The flow dynamics in HSSF systems, which allow for nutrient gradient development, provide a stronger phosphorus sequestration capacity compared to the more oxygen-rich VSSF systems [54].
3. **Biodiversity Support**: While both VSSF and HSSF wetlands support essential plant and microbial communities, fostering nutrient cycling, HSSF wetlands provide a more stable environment for plant root systems, which in turn supports greater microbial diversity. The intermittent flow regime in VSSF systems may limit habitat availability for aquatic organisms but supports robust microbial activity, which is critical for nutrient removal. The ecosystem services provided by each system thus vary based on habitat stability and microbial functional diversity [55].
4. **Carbon Sequestration**: Both wetland types contribute to carbon sequestration but through different mechanisms. In VSSF systems, carbon sequestration occurs mainly via the accumulation of plant biomass, whereas in HSSF wetlands, carbon is stored primarily within the substrate through the accumulation of organic matter. This distinction between plant-based versus substrate-based carbon capture is essential for understanding long-term carbon storage potential in constructed wetlands [56].

Both VSSF and HSSF wetlands offer substantial benefits for wastewater treatment. VSSF systems

Table 5. Comparative performance of Vertical Subsurface Flow (VSSF) and Horizontal Subsurface Flow (HSSF) wetlands in ecological functions and treatment efficiency.

Ecological Function	VSSF Wetlands	HSSF Wetlands	sources
Water filtration (Removal efficiency)	- Nitrogen: 80–95 % - Phosphorus: 40–55 % - BOD: 85–98 %	- Nitrogen: 50–70 % - Phosphorus: 70–85 % - BOD: 60–75 %	[60]
Treatment efficiency	- Organic matter removal: 90–98 % - Nitrification efficiency: 85–95 %	- Phosphorus adsorption: 75–85 % - Sedimentation rate: 65–80 %	[61]
Biodiversity support	- Microbial diversity: 70–80 % - Plant root Habitat: Limited	- Microbial diversity: 85–95 % - Plant root Habitat: High	[62]
Carbon sequestration	- Biomass accumulation: 3–5 kg/m^2/yr - Carbon stored in biomass: 70–80 %	- Organic matter accumulation: 4–6 kg/m^2/yr. - Carbon stored in substrate: 85–90 %	[63]
Retention time	- Short (1–3 days)	- Longer (3–7 days)	[64]

excel in nitrogen and organic matter removal due to enhanced aeration and efficient microbial activity [57]. HSSF systems, on the other hand, are more effective for phosphorus removal due to extended substrate contact and slower flow rates [58]. Both systems are integral to improving water quality and enhancing sustainable wastewater management practices, as illustrated by their respective pollutant removal efficiencies (see Table 5 for comparison). Future research should focus on optimizing these systems for site-specific pollutant challenges, particularly in relation to the balance between nitrogen and phosphorus removal [59].

6. Site selection of constructed wetlands to mitigate nutrient enrichment

The selection of appropriate sites for constructed wetlands aimed at mitigating nutrient enrichment, particularly controlling high concentrations of nitrogen (N) and phosphorus (P), is a complex process requiring the integration of multiple environmental and geographic factors. Effective site selection involves compiling and analyzing detailed maps, such as topographic, geological, aerial imagery, soil surveys, and hydrological maps, to optimize the removal efficiency of N and P [65]. Key factors include climatic conditions, rainfall patterns, geographical landscape, surface water dynamics, and soil composition, all of which contribute to the wetland's nutrient-loading capacity. Proximity to pollution sources like agricultural fields or urban areas with high nutrient runoff is essential for reducing transportation costs and maximizing efficiency [66]. Utilizing natural slopes further minimizes earthwork, thus reducing construction expenses. Additionally, watershed size and its effect on water retention time must be considered to ensure the wetland can effectively process nutrient loads [67]. Artificial wetlands with vertical flow systems (VF) offer an economical advantage over horizontal flow (HF) systems, as they depend on depth rather than longitudinal area, thus requiring less land [68]. The compact design of VF wetlands reduces land-use requirements while maintaining high removal efficiencies, particularly for nitrogen and phosphorus. A comparison of VF and HF systems, shown in Table 6, reinforces this point with scientific data demonstrating the cost-effectiveness of vertical systems [69]. Geographic Information Systems (GIS) and remote sensing (RS) further enhance site evaluation by offering precise environmental mapping, nutrient monitoring, and land-use forecasting. This integrated approach ensures that wetlands are located in optimal areas, balancing environmental conservation with agricultural productivity to address nutrient enrichment in ecosystems [70].

7. Literature review

Numerous studies have evaluated the performance of different constructed wetland (CW) systems, providing valuable insights into their pollutant removal efficiencies and operational effectiveness. The following studies are arranged chronologically and highlight significant findings in the context of CW applications [81]:

Jan Vymazal, 2007: In constructed wetlands (CWs), nitrogen removal involves various processes such as volatilization, nitrification, denitrification, and plant uptake, but only a few effectively eliminate total nitrogen. Removal rates vary from 40 % to 55 %, with loads between 250 and 630 g N m^{-2} yr^{-1}. Vertical flow wetlands effectively remove ammonia-N, while horizontal flow wetlands facilitate denitrification. Phosphorus removal relies on processes like sorption and plant uptake, achieving 40 %–60 % removal under specific conditions. Harvesting emergent vegetation can enhance nitrogen and phosphorus removal, particularly in lightly loaded systems.

Yaqian Zhao, 2013: This study explores the integration of microbial fuel cells (MFCs) within

Table 6. Key factors in site selection for constructed wetlands to mitigate nutrient enrichment (N and P control).

Factor	Role in Mitigating Nutrient Enrichment	Sources
Topographic map	Identifies suitable wetland locations with natural slopes for optimizing water flow and nutrient retention.	[71,72]
Geological map	Determines soil characteristics that influence the wetland's ability to adsorb phosphorus and retain nitrogen.	[73,74]
Hydrological map	Assesses water flow patterns and sources, essential for calculating nutrient retention times and preventing eutrophication.	[75,76]
Proximity to pollution sources	Ensures the wetland is positioned near areas with high nutrient concentrations for efficient nitrogen and phosphorus capture.	[77,78]
Natural slope utilization	Minimizes earthworks by leveraging the natural terrain to optimize water flow and nutrient cycling.	[79,80]

constructed wetlands (CWs) to enhance wastewater treatment while generating electrical energy. Two 3.7 L CW-MFC systems were developed: System 1 operated in batch mode, achieving an average COD removal of 71.5 % with a peak power density of 12.83 $\mu W/m^2$; System 2 functioned in continuous upward flow mode with air diffusion, yielding a 76.5 % COD removal from swine wastewater and a peak power density of 9.4 mW/m^2. The aeration of the cathode significantly improved System 2's performance.

Ranbin Liu, 2015: This paper reviews the integration of constructed wetlands (CWs) with other treatment technologies to enhance wastewater treatment efficiency, especially in response to stricter discharge standards and effluent reuse demands. While CWs are low-cost and easy to operate, they may fall short of meeting new guidelines as standalone systems. The review highlights various combinations aimed at improving organic and nutrient removal, eliminating persistent organics and heavy metals, and recovering energy. It also discusses future development directions and challenges for integrated treatment technologies, offering a framework for further research in this area.

Shibao Lu, 2016: This study evaluates the effectiveness of various fillers in constructed wetlands for treating rural household sewage. It compares four substrates—maifanite, steel slag, bamboo charcoal, and limestone—using the same plant species across constructed wetland systems. Results indicate that the theoretical maximum adsorption capacities rank as follows: maifanite > steel slag > bamboo charcoal > limestone. The removal efficiencies were significant, with effluent quality meeting the Class A standards of the "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plants" (GB18918-2002). The choice of medium is crucial for optimizing constructed wetland performance.

Qijun Ni, 2020: This study compared pilot-scale vertical-flow constructed wetlands (VFCW) and horizontal-flow constructed wetlands (HFCW) for treating eutrophic water. Increased influent loads led to lower dissolved oxygen (DO) levels and reduced removal efficiencies for chemical oxygen demand (COD), total nitrogen (TN), NH4+-N, and organic nitrogen, but did not significantly affect NO3−-N and total phosphorus (TP) removal. VFCWs showed higher DO concentrations, enhancing atmospheric reoxygenation. While both systems had similar removal capacities for TN, NO3−-N, and TP, VFCWs excelled in degrading COD and organic nitrogen. Enzymatic activities were higher in VFCWs, correlating positively with DO levels.

Ikrema Hassan, 2021: This critical review examines constructed wetlands (CWs) as an eco-friendly technology for wastewater treatment across various sectors, including municipal, petroleum refinery, agricultural drainage, and acid mine drainage. It highlights advancements in microbiology relevant to CWs over the past three decades, addressing types, contaminants, removal mechanisms, degradation pathways, challenges, and opportunities. The manuscript proposes guidelines for standardizing key design aspects and offers insights into the current state of CW technology, including performance metrics to unify the CW community. Furthermore, it outlines emerging trends and suggests future research and development directions in the field.

Ali M. Ahmed, 2024: This study investigates the phytoremediation potential of *Lemna minor* in a vertical subsurface flow system at the Al-Muamirah facility in Babylon, Iraq. From October 31, 2023, to March 14, 2024, the system treated wastewater, evaluating BOD, COD, TN, TP, and TSS. The average influent flow rate was 0.05278 m^3/day with a 5-day detention time for most parameters, extending to 8 days for nitrates. *Lemna minor* achieved removal efficiencies of 93.26 % for BOD, 84.87 % for COD, 70.58 % for TN, 71 % for TP, and 83.73 % for TSS, while the VF basin demonstrated lower removal rates.

Shentan Liu, 2024: This paper reviews the advantages and challenges of constructed wetlands (CWs) as a green wastewater treatment technology, noting issues such as low purification capacity in cold climates, plant vulnerability, clogging risks, greenhouse gas emissions, land area requirements, and management inadequacies. Recommended solutions include thermal insulation, aeration, and effluent recirculation to enhance pollutant removal in colder temperatures. The study advocates for selecting suitable plant species and monitoring methods to assess clogging. It also emphasizes controlling greenhouse gas emissions through various management practices and suggests establishing a CW database for standardized operations and efficient design.

These case studies collectively illustrate the diverse operational efficiencies of CW configurations. Our research aims to build upon these findings by providing a comprehensive review of the integration of wetland operations, focusing specifically on the roles of design and environmental factors in optimizing pollutant removal. By synthesizing existing literature and identifying gaps, this work contributes to a deeper understanding of how various CW configurations can be effectively utilized in different contexts, ultimately enhancing their application in sustainable wastewater management.

8. Conclusions

The comparative analysis of Vertical Subsurface Flow (VSSF) and Horizontal Subsurface Flow (HSSF) constructed wetlands (CWs) highlights their distinct capabilities in pollutant removal, emphasizing their relevance in sustainable wastewater management. VSSF systems excel in nitrogen removal due to their optimal oxygen supply and short flow distances, which facilitate efficient nitrification processes early in treatment. However, their capacity for denitrification can be limited under certain operational conditions, affecting overall nitrogen removal. On the other hand, HSSF systems are highly effective in organic matter degradation and nutrient removal, benefiting from long flow paths that establish nutrient gradients conducive to both nitrification and denitrification. The formation of humic acids within the HSSF matrix further enhances nitrogen and phosphorus removal, offering consistent performance across various climates. Importantly, VSSF systems, which rely on depth rather than longitudinal surface area, as in HSSF systems, are more space-efficient, making them more economical in terms of land use. This advantage can be observed in the data presented in Table 7, where VSSF systems demonstrate comparable pollutant removal efficiencies to HSSF systems, despite occupying less physical area. This makes VSSF systems preferable for urban or land-limited applications. However, HSSF systems, despite requiring more land and complex hydraulic designs to maintain uniform oxygen distribution and flow, remain superior for organic matter and nutrient removal. In summary, the choice between VSSF and HSSF systems should be guided by the specific environmental context and treatment objectives. VSSF systems are ideal for compact designs and efficient nitrification, while HSSF systems provide enhanced organic and nutrient removal. Both systems reinforce the adaptability of constructed wetlands as effective solutions for modern wastewater management.

Table 7. Comparative analysis of Vertical Subsurface Flow (VSSF) and Horizontal Subsurface Flow (HSSF) constructed wetland systems.

Parameter	Vertical Subsurface Flow (VSSF)	Horizontal Subsurface Flow (HSSF)
Pollutant removal	Nitrogen removal: Efficient due to optimal oxygen supply and short flow distances, which enhance nitrification. Denitrification: Limited capacity, affecting overall nitrogen removal efficiency.	Organic matter degradation: Superior due to long flow paths that establish nutrient gradients. Nitrogen removal: Strong denitrification due to extended flow paths and organic matrix. Phosphorus removal: Enhanced by humic acid formation.
Land use	More economical, as it depends on depth rather than longitudinal area, making it space-efficient.	Requires significant land area for proper wastewater flow and oxygen distribution due to reliance on longitudinal surface area.
Hydraulic design	Simple and compact design. Oxygen supply: High oxygen availability due to vertical flow, improving nitrification.	Complex design needed to ensure uniform oxygen distribution across the system. Long flow paths require careful hydraulic control.
Treatment efficiency	BOD/COD removal: Moderate. Nitrogen removal: High nitrification, limited denitrification.	BOD/COD removal: High efficiency due to extended treatment time. Nitrogen removal: Efficient through both nitrification and denitrification.
Operational context	Ideal for urban or land-limited applications due to space efficiency.	Suitable for rural or larger land areas with available space, offering better nutrient and organic matter removal.
Climatic performance	May require additional aeration in cold climates to maintain oxygen levels for nitrification.	Performs well across diverse climates due to robust nitrogen and phosphorus removal, but requires more maintenance in cold climates.
Environmental context	Best suited for sites where land is scarce but depth is feasible.	Preferred for larger sites with available land and where maximum nutrient removal is required.
Overall strengths	Compact design, highly effective in nitrification, and efficient land use.	Superior organic matter and nutrient removal, high denitrification capacity.
Limitations	Limited denitrification and reliance on aeration to sustain treatment in colder climates.	Large land requirements, complex hydraulic design for effective oxygen distribution.

Source of Funding

No funding from any organization or individuals in the subject matter or materials discussed this manuscript.

Conflict of Interest

This declaration is not applicable.

Ethical Approval

This declaration is not applicable.

Data Availability

All data used were mentioned in the manuscript and can be accessed.

Author Contributions

All authors contributed to the study's conception and design. Material preparation was performed by Ali M. Ahmed, Results Analysis was performed by Sabreen L.Kareem and Ali M. Ahmed, and the first draft of the manuscript was written by Ali M.. Finally, technical aspects were done by Sabreen.L. Kareem. All authors read and approved the final manuscript.

Acknowledgment

The funding sources supporting this research have been appropriately acknowledged in accordance with funder policies. If any specific grant ID or funding body needs to be explicitly mentioned, please indicate the necessary details, and we will ensure compliance with journal requirements.

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