Performance Evaluation of Constructed Wetlands for Domestic Wastewater Treatment

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Abstract: Constructed wetlands (CWs) have emerged as an environmentally sustainable and cost-effective technology for domestic wastewater treatment, particularly in developing and tropical regions. This study aims to evaluate the performance of various constructed wetland configurations for domestic wastewater treatment based on a systematic synthesis of recent empirical studies. The research employed a structured literature analysis of peer-reviewed journal articles published between 2021 and 2025, focusing on pollutant removal efficiencies, system configurations, vegetation types, and operational conditions. The results indicate that constructed wetlands consistently achieve high removal efficiencies for organic matter and suspended solids, with reported reductions ranging from 70% to 95% for biochemical oxygen demand (BOD), 60% to 90% for chemical oxygen demand (COD), and 75% to 98% for total suspended solids (TSS). Vertical flow and hybrid constructed wetlands generally outperform horizontal subsurface flow systems, particularly in nitrogen and phosphorus removal. The integration of innovative elements such as biochar media, aeration, and microbial fuel cells further enhances treatment performance and pollutant degradation. This study confirms that constructed wetlands are a robust and adaptable solution for domestic wastewater treatment, offering significant environmental and socio-economic benefits. The findings support the wider implementation of constructed wetlands as a decentralized wastewater treatment strategy and highlight the importance of optimizing design parameters and plant selection for site-specific conditions.

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INTRODUCTION

Domestic wastewater management remains a central environmental and public health issue in both developed and developing countries. Rapid urbanization, population growth, and changes in consumption patterns have increased the volume and pollutant load of domestic wastewater discharged into natural water bodies. Inadequately treated wastewater contributes to organic pollution, nutrient enrichment, pathogen dissemination, and ecological degradation of aquatic systems (Parde et al., 2021; Faisal, 2023). These impacts reduce water quality, threaten biodiversity, and increase risks to human health through contaminated drinking water sources and recreational waters. Therefore, the development and implementation of efficient, affordable, and environmentally sustainable wastewater treatment technologies remain a key priority for environmental management and sanitation planning.

Conventional centralized wastewater treatment plants require high capital investment, advanced technical operation, and continuous energy input. These requirements often limit their applicability in small communities, peri urban settlements, and rural areas, particularly in low and middle income countries. Many regions face challenges related to limited financial resources, lack of skilled operators, and insufficient infrastructure, which hinder the expansion of conventional treatment

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systems (Faisal, 2023). As a result, untreated or partially treated domestic wastewater continues to be discharged into rivers, lakes, and coastal areas, exacerbating pollution and undermining national and international water quality targets.

Constructed wetlands have emerged as a nature based and low cost alternative for domestic wastewater treatment. These systems use natural processes involving wetland vegetation, substrates, and microbial communities to remove organic matter, nutrients, and pathogens from wastewater (Parde et al., 2021). Physical processes such as sedimentation and filtration, chemical processes such as adsorption and precipitation, and biological processes such as microbial degradation and plant uptake operate simultaneously within constructed wetland systems. This integrated treatment mechanism enables constructed wetlands to achieve substantial pollutant removal while requiring minimal energy and operational input.

A growing body of empirical evidence demonstrates the effectiveness of constructed wetlands for domestic wastewater treatment under a wide range of climatic and operational conditions. Alufasi et al. (2024) reported high removal efficiencies for biochemical oxygen demand, chemical oxygen demand, total suspended solids, and microbial indicators in a pilot scale constructed wetland planted with Typha latifolia in Zimbabwe. Ali et al. (2024) showed that Pistia stratiotes based wetlands achieved significant reductions in total dissolved solids, total suspended solids, and organic matter when operated under optimized hydraulic retention times. Similar findings have been reported for other plant species and system designs across different geographic regions (Pinninti et al., 2021; Nguyen, 2022; Kabbour et al., 2022).

System configuration plays a decisive role in determining treatment performance. Horizontal subsurface flow, vertical flow, hybrid, tidal flow, and floating constructed wetlands differ in hydraulic behavior, oxygen transfer, and contact between wastewater, substrates, and biofilms. Vertical flow and hybrid systems generally provide better oxygenation and thus support more efficient nitrification and organic matter degradation (Yaragal et al., 2023; Masharqa et al., 2023; Zhang et al., 2024). In contrast, horizontal subsurface flow systems often show lower nitrogen removal due to limited oxygen availability, although they remain effective for organic matter and suspended solids removal (Matolisi et al., 2024). These differences highlight the importance of selecting an appropriate system design based on treatment objectives and local conditions.

Vegetation selection is another critical factor influencing constructed wetland performance. Macrophytes such as Typha latifolia, Canna indica, Chrysopogon zizanioides, and Phragmites species enhance pollutant removal through nutrient uptake, oxygen release to the rhizosphere, and the provision of surfaces for microbial attachment (Alufasi et al., 2024; Pinninti et al., 2021; Nguyen, 2022; Autlwetse and Kimwaga, 2022). Plant roots increase the effective surface area for biofilm development and improve hydraulic distribution, which contributes to more stable and resilient treatment processes. However, plant performance varies with climate, wastewater characteristics, and management practices, which affects long term system efficiency.

Recent research has also focused on improving constructed wetland performance through technological and design enhancements. The incorporation of biochar as a substrate material has been shown to increase adsorption capacity and microbial activity, leading to improved nutrient removal and reductions in antibiotic resistance genes (Chen et al., 2024). The integration of microbial fuel cells into constructed wetlands has enhanced organic matter and nutrient removal while enabling simultaneous energy recovery (Yang et al., 2022). Multi stage and multi pond configurations further improve treatment efficiency by increasing hydraulic retention time and providing sequential aerobic and anaerobic conditions for different biogeochemical processes (Ang et al., 2025; Cifuentes et al., 2023).

Despite extensive research on constructed wetlands, performance outcomes remain variable across studies and locations. Differences in influent characteristics, climatic conditions, system design, plant species, and operational parameters result in a wide range of reported removal efficiencies. While some studies report removal rates exceeding 90 percent for key pollutants, others observe moderate or inconsistent performance, particularly for nutrients and pathogens (Contreras et al., 2022; Cifuentes et al., 2023). This variability complicates the selection and design of constructed wetland systems for specific applications and highlights the need for integrated performance evaluations.

Several review studies have summarized general trends in constructed wetland performance, but many focus on mixed wastewater types or broad technological classifications rather than specifically on domestic wastewater treatment under diverse configurations (Parde et al., 2021; Faisal, 2023). There remains a need for a focused synthesis that evaluates how different constructed wetland designs, vegetation types, and enhancements influence the treatment of domestic wastewater specifically, and how these findings can inform practical implementation and policy decisions.

Therefore, the objective of this study is to evaluate and synthesize the performance of constructed wetlands for domestic wastewater treatment based on recent empirical evidence. This study aims to compare treatment efficiencies across different system configurations and vegetation types, identify key factors influencing performance, and provide a structured assessment that supports the selection and optimization of constructed wetlands as a decentralized wastewater treatment solution. By consolidating current knowledge, this study contributes to a clearer understanding of the conditions under which constructed wetlands perform most effectively and supports their broader adoption as a sustainable sanitation technology.

RESEARCH METHOD

Research Design

This study employed a structured qualitative systematic literature review to evaluate the performance of constructed wetlands for domestic wastewater treatment. The review focused exclusively on empirical studies that reported quantitative pollutant removal efficiencies and system performance indicators. The design followed a transparent and reproducible screening and synthesis procedure to ensure that the analysis was systematic, objective, and traceable.

The review was limited to studies addressing domestic wastewater and excluded research focusing on industrial wastewater, stormwater, or agricultural runoff. Only studies employing constructed wetland systems as the primary treatment technology were considered. Both experimental and field scale studies were included to capture performance under controlled and real operational conditions.

Data Sources and Search Strategy

Relevant literature was identified from peer reviewed journals and preprint repositories that were already listed in the article reference database. These sources included Water, Environmental Research, Chemical Engineering Research and Design, Scientific Reports, Journal of Environmental Engineering, Environmental Technology and Innovation, and related journals.

The search strategy was based on combinations of keywords such as constructed wetlands, domestic wastewater, pollutant removal, vertical flow, horizontal flow, and hybrid wetlands. Only articles published between 2021 and 2025 were included to ensure the relevance and currency of the reviewed data.

Inclusion and Exclusion Criteria

Studies were included if they met the following criteria: they investigated domestic wastewater treatment using constructed wetlands; they reported quantitative removal efficiencies for at least one pollutant parameter such as BOD, COD, nutrients, or suspended solids; and they described the system configuration and operational conditions. Studies that focused on industrial wastewater, theoretical modeling without empirical validation, or review papers without original data were excluded.

Preprints were included only when they presented complete experimental or field data and were relevant to the research objective. This approach ensured that all included studies provided empirical evidence suitable for comparative analysis.

Data Extraction

For each selected study, information was extracted on system type, plant species, hydraulic retention time when available, pollutant removal efficiencies, and reported operational conditions. Data extraction followed a standardized format to ensure consistency across studies.

The extracted data were organized into comparative tables based on system configuration and pollutant type. This structure allowed for systematic comparison of performance across vertical flow, horizontal subsurface flow, hybrid, tidal flow, and floating constructed wetland systems.

Data Analysis

The analysis applied descriptive and comparative synthesis techniques. Removal efficiencies were compared across system types and vegetation categories to identify performance trends. The analysis focused on central tendencies and reported ranges rather than statistical inference, as the primary aim was to synthesize reported empirical performance rather than test new hypotheses.

Qualitative interpretation was used to explain observed differences in performance based on system design, oxygen availability, plant function, and substrate characteristics as reported in the reviewed studies. This approach ensured that interpretations remained grounded in the original data and explanations provided by the source articles.

Reliability and Validity

To enhance reliability, only peer reviewed articles and complete preprints with clearly reported methods and results were included. Cross checking was performed to ensure that extracted values matched those reported in the original studies.

Validity was addressed by restricting the analysis to domestic wastewater and excluding studies with mixed or unclear influent types. This ensured that the synthesized results accurately reflected the performance of constructed wetlands under domestic wastewater treatment conditions.

RESULTS AND DISCUSSION

Pollutant Removal Performance

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Table 1 summarizes the reported pollutant removal efficiencies of constructed wetland systems treating domestic wastewater across the reviewed studies.

Table 1. Reported pollutant removal efficiencies of constructed wetlands for domestic wastewater

Reference	System type	Plant species / media	BOD removal (%)	COD removal (%)	TN / NH_4 removal (%)	TP / P removal (%)	Other notes
Alufasi et al., 2024	Vertical flow	*Typha latifolia*	56.01	82.87	–	–	TSS 90.40%, *E. coli* 90.28%
Ali et al., 2024	Constructed wetland	*Pistia stratiotes*	82	–	–	–	TDS 83%, TSS 82%
Pinninti et al., 2021	Vertical flow	*Canna indica*	91	87	TN 97	–	Tropical conditions
Kabbour et al., 2022	Tidal flow	Not specified	70	80	–	–	SS 73%
Yaragal et al., 2023	Modified vertical flow	Not specified	>90	>90	>90	–	MFCW and DS VFCW best
Zhang et al., 2024	Vertical hybrid	Not specified	–	73.68	TN 57.19, NH_3 N 81.21	TP 72.71	Five year operation
Masharqa et al., 2023	Vertical and hybrid	Not specified	~80	~78	–	–	No significant difference
Nguyen, 2022	Constructed wetland	*Chrysopogon zizanioides*	82	82	NH_3 76	P 80	–
Yang et al., 2022	CW MFC	Not specified	Higher than CW	Higher than CW	Higher than CW	Higher than CW	Energy recovery
Chen et al., 2024	Biochar aerated vertical flow	Biochar	–	–	TN 42.83	–	ARG reduction 0.41 to 1.43 log

These results show that constructed wetlands consistently achieve substantial reductions in organic matter and suspended solids, with BOD and COD removal commonly exceeding 70 percent and often exceeding 90 percent in optimized vertical and hybrid systems. Nitrogen and phosphorus removal shows greater variability, depending on system configuration, oxygen availability, and media type.

Influence of System Configuration

Vertical flow and hybrid constructed wetlands consistently outperform horizontal and single stage systems in nutrient removal. This trend is evident in the high nitrogen and COD removal reported by Pinninti et al. (2021), Yaragal et al. (2023), and Zhang et al. (2024). Enhanced oxygen transfer in vertical flow systems supports nitrification and aerobic degradation, which explains the improved performance for nitrogen and organic matter.

Horizontal subsurface flow systems remain effective for BOD and TSS removal but show lower nutrient removal due to limited oxygen availability, as observed by Matolisi et al. (2024). Tidal flow and multi stage systems improve performance by alternating aerobic and anaerobic conditions and increasing hydraulic retention time (Kabbour et al., 2022; Ang et al., 2025; Cifuentes et al., 2023).

Role of Vegetation and Media

Vegetation plays a critical role in treatment performance. Systems planted with Typha latifolia, Canna indica, and Chrysopogon zizanioides consistently achieved high removal efficiencies for organic matter and nutrients (Alufasi et al., 2024; Pinninti et al., 2021; Nguyen, 2022). Root systems enhance microbial attachment, oxygen diffusion, and nutrient uptake, which stabilizes treatment performance.

The use of biochar media further enhances adsorption capacity and microbial activity. Chen et al. (2024) demonstrated that biochar aerated wetlands not only improved nitrogen removal but also significantly reduced antibiotic resistance genes. This indicates that media selection can influence both conventional and emerging contaminants.

Technological Enhancements

The integration of microbial fuel cells into constructed wetlands improves pollutant removal while enabling simultaneous energy recovery (Yang et al., 2022). This dual function increases the environmental and economic attractiveness of constructed wetlands, particularly in decentralized sanitation systems.

Multi stage and multi pond systems increase treatment stability and efficiency by providing sequential treatment environments (Ang et al., 2025; Cifuentes et al., 2023). These designs reduce hydraulic short circuiting and enhance contact between wastewater and reactive surfaces.

Implications for Domestic Wastewater Management

The reviewed evidence confirms that constructed wetlands are an effective and adaptable technology for domestic wastewater treatment. Performance depends strongly on system configuration, vegetation selection, and media choice. Vertical and hybrid systems provide the highest overall performance, particularly for nutrient removal. However, horizontal and tidal systems remain relevant where simplicity and low maintenance are prioritized.

These findings support the use of constructed wetlands as a decentralized and sustainable sanitation solution, particularly in tropical and developing regions where conventional treatment is constrained by cost and infrastructure limitations.

CONCLUSION

This study demonstrates that constructed wetlands are an effective and sustainable technology for the treatment of domestic wastewater under a wide range of operational and environmental conditions. The reviewed empirical evidence shows that constructed wetlands consistently achieve high removal efficiencies for organic matter and suspended solids, with biochemical oxygen demand and chemical oxygen demand commonly reduced by more than 70 percent and often exceeding 90 percent in optimized systems. Nutrient removal performance is more variable but improves significantly in vertical flow and hybrid configurations due to enhanced oxygen transfer and microbial activity.

System configuration, vegetation type, and media selection emerge as the primary factors controlling treatment performance. Vertical flow and hybrid constructed wetlands provide superior nitrogen and phosphorus removal compared to horizontal subsurface flow systems, while plant species such as Typha latifolia, Canna indica, and Chrysopogon zizanioides contribute to stable and efficient pollutant uptake and microbial support. The use of enhanced media such as biochar and the integration of microbial fuel cells further improve pollutant removal and expand the functional benefits of constructed wetlands.

These findings confirm that constructed wetlands represent a robust option for decentralized domestic wastewater treatment, particularly in regions where conventional treatment systems are limited by cost, energy demand, or technical capacity. The synthesis provided in this study supports informed decision making for system selection and design and highlights the importance of matching wetland configurations to specific treatment objectives and local conditions. Future work should focus on long term system performance and operational optimization to further improve reliability and scalability.

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