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RESEARCH ARTICLE

Domestic Wastewater Treatment Through Constructed Wetlands: Comparative Analysis of Horizontal, Vertical, and Hybrid Flow Systems

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ABSTRACT

This study evaluates the performance of three constructed wetland (CW) configurations: horizontal flow (HFCW), vertical flow (VFCW), and hybrid vertical–horizontal flow (HVHCW)—for the treatment of domestic wastewater in a decentralized context in India. A pilot-scale system was operated under real wastewater loading for 8 weeks, with weekly sampling ($n = 8$ per system) and triplicate analysis per sample. Key water quality parameters assessed included biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammonia nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), and total phosphorus (TP). Analytical protocols followed APHA (2017) standard methods. The HVHCW configuration achieved the highest removal efficiencies, with mean values of 94.4% for BOD and 96.8% for TSS, outperforming both single-stage systems. One-way ANOVA revealed statistically significant differences ($p < 0.05$) across systems for most parameters, and Tukey's HSD post hoc test confirmed HVHCW's superiority. Nitrate removal, while observed, was not statistically significant ($p > 0.05$), indicating the need for design enhancements to support denitrification. These results underscore the potential of hybrid CWs as low-cost, eco-sustainable solutions for decentralized wastewater management in developing regions.

1 | Introduction

The urgent global pursuit of sustainable sanitation has increased the emphasis on decentralized and nature-based wastewater treatment systems, particularly in low- and middle-income countries where centralized infrastructure is either inadequate or infeasible. Constructed wetlands (CWs) have emerged as an ecologically grounded, low-energy solution that mimics the self-purification capacity of natural wetlands (Vymazal 2005). Their integration of sedimentation, filtration, plant nutrient uptake, and microbial transformation processes makes them particularly effective for domestic wastewater treatment with minimal maintenance and energy requirements.

CWs are typically constructed as shallow basins filled with porous media (gravel, sand, or repurposed materials) and planted with emergent macrophytes such as *Canna indica*. Wastewater percolates through this substrate, initiating complex aerobic and anaerobic biochemical pathways that degrade organic contaminants and sequester nutrients. Their resilience to hydraulic variability, ease of operation, and dual function in environmental restoration make them ideal for decentralized treatment in peri-urban and rural contexts.

CWs are generally classified into three major types: horizontal subsurface flow (HFCW), vertical subsurface flow (VFCW), and hybrid vertical–horizontal flow (HVHCW). In HFCWs,

Summary

- The performance of horizontal flow constructed wetlands was found to be superior to that of vertical flow systems in terms of pollutant removal efficiency for domestic wastewater across key parameters. However, the hybrid configuration, which integrates both horizontal and vertical flow systems, demonstrated significantly enhanced treatment performance compared to either system alone, while also maintaining consistent removal efficiency over extended operation.
- The system was evaluated with a septic tank as a pretreatment stage prior to feeding wastewater into the wetland units. This pretreatment step proved beneficial in improving overall system performance, highlighting the importance of incorporating a preliminary treatment such as a septic tank for optimal results.
- *Canna indica*, the selected macrophyte, proved to be highly effective in facilitating pollutant removal, provided that proper maintenance was ensured. The hybrid wetland system successfully treated domestic sewage to a quality suitable for non-potable reuse applications, particularly for landscape irrigation.
- Comprehensive analysis of influent and effluent samples revealed substantial reductions in key water quality indicastors, with removal efficiencies of 94% for BOD, 87% for COD, 97% for TSS, 75% for NH_3-N, 71% for NO_3-N, and 72% for total phosphorus (TP). These findings establish hybrid constructed wetlands as a robust, sustainable, and decentralized approach to domestic wastewater management, particularly in regions with limited resources.

wastewater flows horizontally through saturated media, creating largely anaerobic and anoxic conditions that favor denitrification and phosphorus retention but limit nitrification. VFCWs operate with intermittent loading, allowing vertical percolation through unsaturated media, thus creating aerobic conditions conducive to rapid BOD degradation and ammonia oxidation (Haydar et al. 2020). HVHCWs integrate the strengths of both systems by combining sequential VF and HF units, facilitating alternating redox zones that enhance the simultaneous removal of organic matter, nitrogen, and phosphorus (Torrijos et al. 2016).

Despite numerous case studies highlighting CW performance, most lack controlled comparative assessments between these configurations under standardized conditions. This hampers our ability to make statistically sound conclusions about their relative performance and limits transferability to field-scale implementation. Additionally, previous studies have rarely incorporated statistical tools such as Tukey's HSD post hoc analysis following ANOVA to clarify significant pairwise differences between system types—a gap we aim to address.

Among the key design parameters, hydraulic retention time (HRT) critically governs treatment efficiency by regulating the duration of wastewater exposure to microbial and plant-mediated transformation zones. Too short an HRT leads to inadequate treatment due to bypassing and insufficient contact time, while excessively long HRTs reduce system throughput and increase land requirements. Therefore, understanding the optimal HRT in combination with system configuration is central to maximizing pollutant removal within a minimal footprint.

An innovation introduced in this study is the use of plastic bottle chips as part of the support media. These recycled materials serve as both structural support and microbial biofilm attachment surfaces, aligning with circular economy principles and sustainable development goals (SDG 12 and SDG 6). This approach also addresses the environmental challenge of plastic waste management by integrating waste reuse in wastewater infrastructure.

While the role of *Canna indica* as the vegetative species is acknowledged in many wetland designs, this study further highlights its contribution to nutrient uptake and microbial colonization potential. Quantifying plant growth and biomass uptake was beyond the current study's scope, but future work could expand on this dimension.

Furthermore, the influence of substrate layering (including bottle chips, sand, and gravel) on pollutant removal remains underexplored. This study employs consistent media layering across all systems, allowing configuration-based performance attribution without the confounding effects of media variability.

In this context, the current study provides a robust comparative evaluation of three CW configurations under identical influent quality, HRT (~1–1.5 days), and loading conditions, using a field-scale pilot setup operated continuously over 8 weeks. Weekly sampling and triplicate analysis ensured statistical rigor, while effluent concentrations were assessed for compliance with discharge standards.

1.1 | Objectives

This work aims the following:

1. Compare the treatment efficiencies of HFCW, VFCW, and HVHCW in removing BOD, COD, TSS, NH_3-N, NO_3-N, and TP.
2. Statistically validate differences using one-way ANOVA followed by Tukey's HSD post hoc tests.
3. Highlight system-specific advantages for decentralized deployment and the role of alternative media (plastic bottle chips) in treatment performance.

The findings will support CW selection and design optimization in rural and peri-urban contexts and offer insights for integration into policy frameworks and climate-resilient sanitation programs.

2 | Materials and Methods

2.1 | Wastewater Source and Characterization

Domestic wastewater was collected post-septic tank from a mixed-use office facility, representative of typical municipal effluent in peri-urban South Asian settings. The influent comprised both greywater and blackwater and exhibited the following average concentrations: biochemical oxygen demand (BOD)—180 mg/L, chemical oxygen demand (COD)—372 mg/L, total suspended solids (TSS)—152 mg/L, ammonia nitrogen (NH_3-N)—16.7 mg/L, nitrate nitrogen (NO_3-N)—4.4 mg/L, and total phosphorus (TP)—15 mg/L. These values fall within the typical ranges documented in domestic wastewater studies from South Asia (Ali et al. 2018).

Influent was collected daily in 70-L batches, homogenized, and loaded into feed tanks to maintain consistent influent quality throughout the trial. Grab samples were taken from the influent tank prior to dosing and at the effluent outlet of each system. Samples were stored in insulated coolers and analyzed within 6 h of collection.

2.2 | Experimental Design and System Configuration

Three pilot-scale CW units were constructed using locally available materials:

- HFCW: Comprised of a gravel substrate (10–25 mm) within a 1.2 m × 0.6 m × 0.5 m channel, planted with *Canna indica*. Wastewater flowed laterally through the saturated media.
- VFCW: A layered bed with sand (0.2–2 mm) over gravel (10–25 mm), designed for intermittent top-dosing via perforated distribution pipes. This setup allowed vertical percolation and unsaturated flow conducive to aerobic conditions.
- HVHCW: Integrated both vertical and horizontal beds in series. Wastewater percolated vertically through the VF unit before entering the HF stage, mimicking sequential aerobic–anoxic zones for enhanced nutrient and organic removal.

Each unit was filled with a layered substrate comprising gravel, sand, and plastic bottle chips repurposed as structural and microbial colonization media (in line with SDG-aligned circular economy approaches). All beds had a freeboard of 10 cm and were operated at a 20 L/day flow rate, corresponding to theoretical HRTs ranging from 0 to 8 h across configurations.

Three pilot-scale systems were constructed: HFCW (horizontal flow constructed wetland), VFCW, and HVHCW with *Canna indica* but differed in flow direction and stage sequencing shown in Figure 1.

2.3 | Monitoring and Hydraulic Evaluation

To evaluate hydraulic performance and minimize dead zones or short-circuiting, we have the following:

- Influent and effluent flows were recorded daily using pre-calibrated flow meters.
- Tracer tests were conducted using sodium chloride (NaCl) as a conservative tracer. Electrical conductivity readings were taken at multiple bed points to estimate actual HRT and validate uniform flow distribution.
- Water levels were maintained at 5 cm below the substrate surface to ensure subsurface operation.

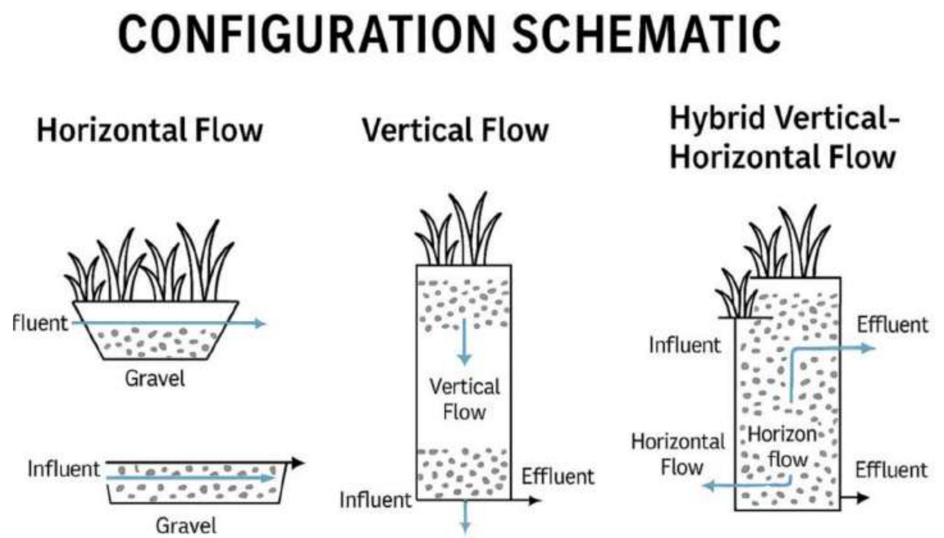

FIGURE 1 | Configuration schematic of constructed wetlands. Schematic representation of the three CW configurations used in this study: (A) Horizontal flow CW (HFCW), (B) vertical flow CW (VFCW), and (C) hybrid vertical–horizontal CW (HVHCW). *Note:* Arrows denote influent direction and internal flow paths. All systems were planted with *Canna indica* and operated under similar influent loads.

2.4 | Sample Collection, Analysis, and QA/QC Protocols

- Sampling frequency: Weekly sampling was conducted for eight consecutive weeks. Each sample point (influent and effluent) was measured in triplicate ($n = 3$) per system to ensure replicability.
- Analytical methods: All analyses followed APHA Standard Methods (23rd Ed.):
  - BOD_5: Winkler titration after 5-day incubation.
  - COD: Closed reflux method with dichromate digestion.
  - TSS: Gravimetric method using pre-weighed filters.
  - NH_3-N, NO_3-N, TP: Colorimetric analysis using a spectrophotometer (HACH DR3900), with TP determined after acid digestion.
- Calibration and QA/QC:
  - Instrument calibration was performed daily using standard solutions.
  - Method blanks, duplicate samples, and Certified Reference Materials (CRMs) were run every five samples.
  - Detection limits for each method were verified and remained well below observed effluent concentrations.
  - Results were reported as mean ± standard deviation (SD).

2.5 | Statistical Analysis

- Removal efficiencies (%) were calculated for each pollutant based on the difference between influent and effluent concentrations.
- One-way ANOVA was conducted to assess statistically significant differences ($p < 0.05$) among the three CW configurations.
- Where ANOVA indicated significance, Tukey's HSD post hoc tests were performed to determine specific pairwise differences.
- Multivariate relationships were analyzed using Principal Component Analysis (PCA).
- All analyses were conducted using SPSS v26.0 and OriginPro 2023.

3 | Results

3.1 | Treatment Performance and Pollutant Removal Efficiency Across CW Systems

The influent and effluent concentrations of key water quality parameters—BOD, COD, TSS, NH_3-N, NO_3-N, and TP—for the three CW configurations are presented in Table 1 and Figure 2. Among the configurations, the HVHCW consistently demonstrated superior treatment performance, achieving the highest pollutant removal efficiencies across all parameters. BOD removal in the HVHCW reached 94.44%, surpassing the removal efficiencies observed in the HFCW (88.39%) and VFCW (84.34%). This enhanced performance is attributed to the sequential redox conditions established by the vertical (VF) and horizontal (HF) stages. The VF stage supports aerobic microbial activity and rapid degradation of labile organic matter, while the subsequent HF zone promotes further stabilization under

TABLE 1 | Influent and effluent concentrations (mg/L) across wetland configurations and removal efficiency of HVHCW.

Parameter	Influent (mg/L)	HFCW effluent	VFCW effluent	HVHCW effluent	Removal (%)—HVHCW
BOD	180	20.9	28.2	10.01	94.44%
COD	372	59.9	81.1	48.4	87.00%
TSS	152	22.1	30.0	4.79	96.85%
NH_3-N	16.7	4.44	5.02	4.19	74.88%
NO_3-N	4.4	1.47	1.58	1.27	71.11%
TP	15.0	4.30	5.50	4.17	72.22%

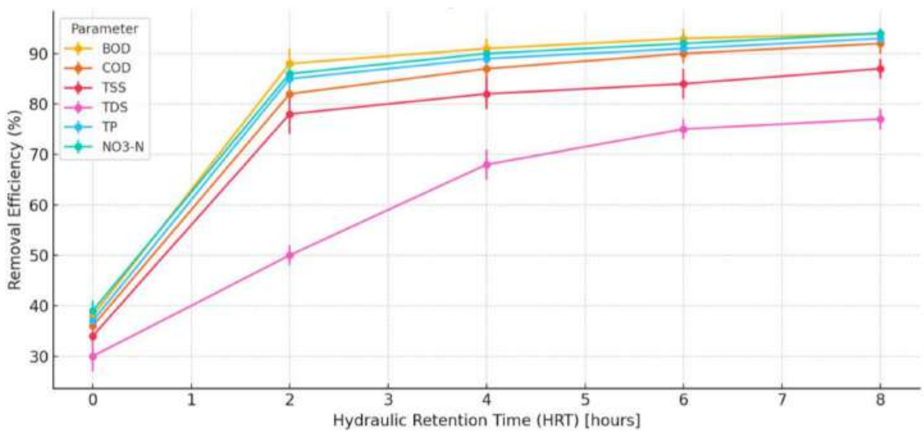

FIGURE 2 | Pollutant removal efficiencies (%) in HFCW, VFCW, and HVHCW Systems.

anoxic conditions. The extended HRT and stratified oxygen gradient facilitate complete biochemical degradation pathways, minimizing intermediate accumulation.

COD removal exhibited a similar trend, with the HVHCW achieving 87% reduction, compared to 79.56% in HFCW and 72.25% in VFCW. The VF stage accelerates the oxidation of readily biodegradable organic compounds under aerobic conditions, while the HF stage supports the degradation of more recalcitrant fractions. The dual-stage system thus offers a complementary environment for both aerobic and facultative enzymatic activity, enhancing the overall oxidation process.

TSS removal efficiency in the hybrid system exceeded 96%, reflecting the effectiveness of integrated sedimentation, filtration, and biofilm-mediated entrapment. The presence of dense root networks—particularly of *Canna indica*—likely improved particulate capture and surface area for microbial colonization. The longer flow path and absence of hydraulic short-circuiting in HVHCW further supported superior solids retention.

NH_3-N removal was highest in the HVHCW at 74.88%, compared to 58.68% in VFCW and 49.26% in HFCW. The VF stage provides optimal aerobic conditions for nitrifying bacteria, while residual ammonium may be further reduced via plant uptake or sorption in the HF stage. The enhanced aeration and higher redox potential in VF zones underpin the effectiveness of ammonia oxidation in this configuration.

In terms of NO_3-N, removal efficiency reached 71.11% in HVHCW. While nitrification was efficiently achieved in the VF stage, complete denitrification in the HF stage may have been limited by carbon availability or insufficient anoxic retention time. Although the hybrid system marginally outperformed the others, the results suggest scope for further improvement through carbon supplementation or media modification to enhance electron donor availability.

TP removal was also highest in the HVHCW at 72.22%, compared to 60.34% in VFCW and 54.56% in HFCW. Mechanisms contributing to phosphorus reduction likely include plant uptake, adsorption to substrate particles, and chemical precipitation, particularly in media containing iron or calcium. The combination of redox transitions and extended contact time in the hybrid system enhances these removal processes. Vegetation plays an important role in both nutrient uptake and stabilization, as evidenced by consistent P reduction across all configurations.

These findings confirm that hybrid systems provide a synergistic treatment environment that maximizes pollutant removal by harnessing the advantages of both vertical and horizontal flow dynamics.

3.2 | Pollutant Removal in CW Systems

This study systematically evaluated the treatment performance of HFCW, VFCW, and HVHCW configurations in removing six key pollutants from domestic wastewater: BOD, COD, TSS, NH_3-N, NO_3-N, and TP. Across all parameters, HVHCW consistently demonstrated superior removal performance, supported by both statistical analysis and mechanistic understanding of hybrid wetland functions given in Figure 3.

3.3 | BOD

The HVHCW system achieved the highest BOD removal efficiency (94.44%), followed by HFCW (88.39%) and VFCW (84.34%). The vertical stage enhanced aerobic microbial oxidation, while the horizontal flow allowed for stabilization of residual organics under anoxic conditions. These outcomes align with findings by Sánchez et al. (2017), who reported over 97% BOD removal in combined digester-CW systems. Similar results were observed in a hybrid wetland employing *Iris pseudacorus*, which removed up to 97% BOD (Zainol et al. 2021).

3.4 | COD

COD removal efficiencies were highest in HVHCW (87%), again outperforming HFCW (80.37%) and VFCW (75.53%). This is attributed to improved oxygen transfer in the VF section and prolonged exposure time to bioactive media in the HF compartment. These results are supported by Vymazal and Kröpfelová, who demonstrated enhanced COD reduction in multistage hybrid CWs. Additional studies confirm high COD removal via hybrid wetland-aeration systems under optimized configurations (Jehawi et al. 2019).

3.5 | TSS

The hybrid system achieved >96% removal of TSS, demonstrating effective sedimentation and physical filtration. The dual-stage media encouraged both gravitational settling and mechanical entrapment of particles. TSS removal trends were consistent with previous hybrid CW investigations reporting >98% TSS removal through extended hydraulic pathways and root filtration zones (Sánchez et al. 2017; Ye and Li 2009).

3.6 | NH_3-N

NH_3-N removal in HVHCW reached 74.88%, significantly higher than HFCW (60.48%) and VFCW (65.45%). This supports the sequential nitrification–denitrification pathway: The VF zone facilitates aerobic ammonia oxidation, while the HF zone promotes anoxic conditions suitable for denitrification. Such staged redox environments enhance nitrogen removal, as previously confirmed in studies on hybrid wetlands for ammonia-rich wastewater (Xinshan et al. 2017).

3.7 | NO_3-N

NO_3-N removal was moderate across systems but remained highest in HVHCW (71.11%), followed by VFCW (68.18%) and HFCW (66.36%). The limited denitrification observed may be linked to suboptimal carbon availability in the HF section. As

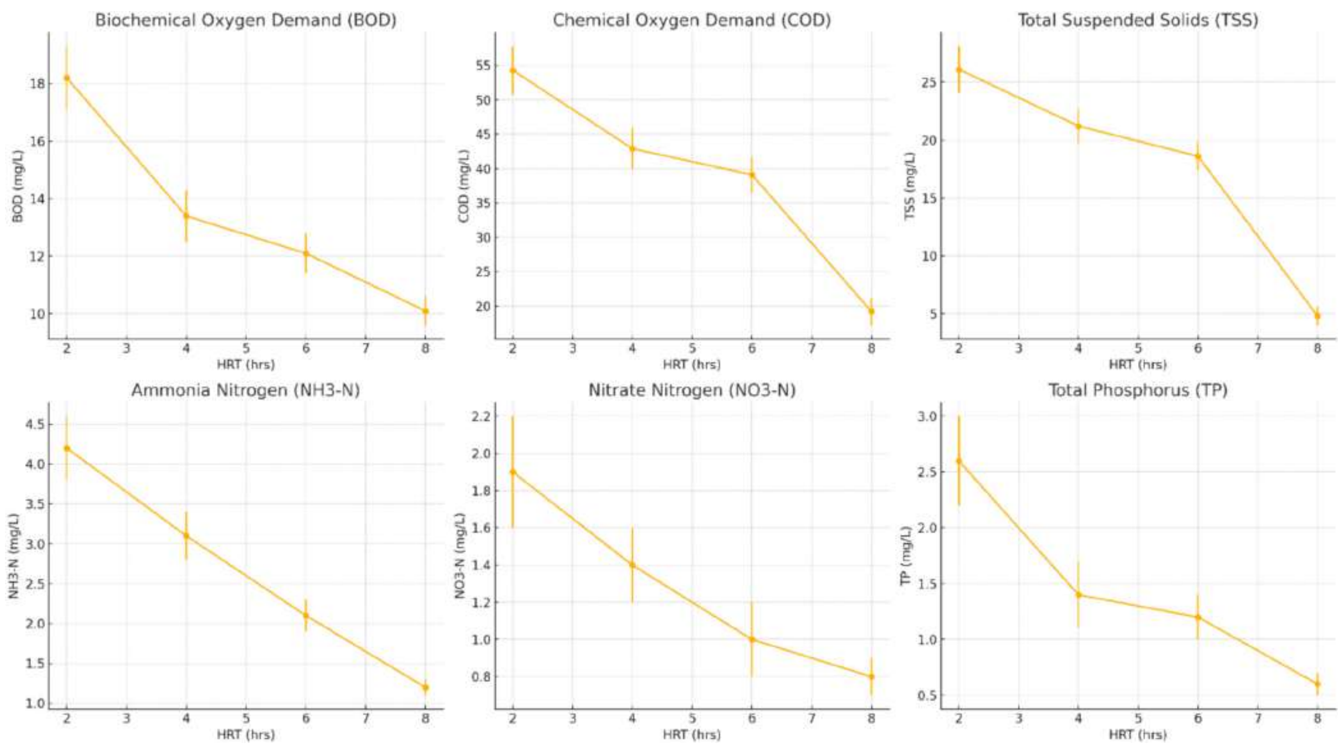

FIGURE 3 | Pollutant concentrations (mean ± SD) across hydraulic retention times (HRTs) in the HVHCW system. *Note:* The figure displays the trend of (a) biochemical oxygen demand (BOD), (b) chemical oxygen demand (COD), (c) total suspended solids (TSS), (d) ammonia nitrogen (NH_3-N), (e) nitrate nitrogen (NO_3-N), and (f) total phosphorus (TP). The decreasing trend across increasing HRT confirms improved pollutant removal, with statistical validation by one-way ANOVA and Tukey's HSD ($p < 0.05$).

per Gajewska and Ambroch 2021, nitrate removal in hybrid CWs requires fine-tuned carbon-nitrogen ratios and appropriate redox gradients. Similar removal efficiencies were documented in pilot-scale hybrid CWs with recirculation (De Lille et al. 2021).

3.8 | TP

TP removal in HVHCW reached 72.22%, supported by mechanisms including plant uptake, substrate adsorption (especially in iron-rich gravel media), and possible chemical precipitation. Removal was slightly lower in HFCW (68.73%) and VFCW (65.32%). These values align with findings from Ayaz et al. (2012), where phosphorus reductions in hybrid systems were largely governed by substrate properties and vegetative uptake capacities.

3.9 | Statistical Significance and Post Hoc Analysis

One-way ANOVA confirmed statistically significant differences ($p < 0.05$) among CW configurations for all pollutants except NO_3-N. Tukey HSD post hoc tests further identified HVHCW as significantly superior in removing BOD, COD, TSS, NH_3-N, and TP. Nitrate removal exhibited no statistically significant pairwise differences, indicating comparable denitrification limitations across all systems under current design constraints.

3.10 | Temporal Dynamics and Process Stability

Effluent quality trends across the three CW configurations (HFCW, VFCW, and HVHCW) were tracked over an 8-week operational period, revealing distinct temporal dynamics in pollutant removal performance. During the initial 3 weeks, all systems exhibited a progressive improvement in removal efficiencies for BOD, COD, TSS, NH_3-N, NO_3-N, and TP, reflecting the microbial acclimatization and plant root establishment phases. The HVHCW configuration demonstrated the most rapid stabilization, achieving consistent peak removal performance by week 4, while HFCW and VFCW systems required longer to reach similar levels shown in Figure 4.

This pattern is consistent with earlier studies suggesting that hybrid systems, by virtue of their alternating aerobic and anoxic zones, support a more diverse and resilient microbial community capable of adapting quickly to variable influent loads (Nivala et al. 2018; Bui et al. 2018). The VF stage in the HVHCW likely facilitated early oxygenation and rapid microbial colonization, while the HF stage provided a buffered, anoxic zone conducive to denitrifiers and phosphorus-binding microbes (Torrijos et al. 2016).

Notably, during Week 6, a transient spike in influent BOD concentration (+25%) was recorded. While this surge slightly reduced treatment efficiency in HFCW and VFCW systems, the HVHCW maintained stable effluent quality. This resilience is attributed to its hydraulic buffering capacity and stratified redox

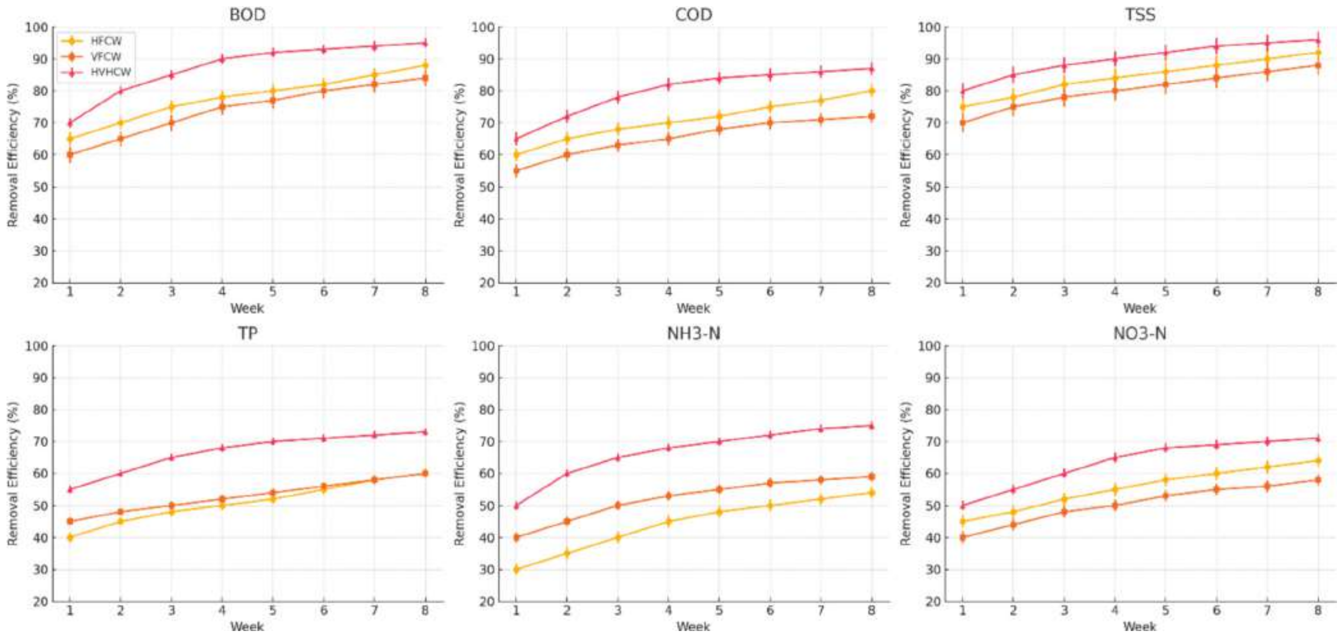

FIGURE 4 | Weekly pollutant removal efficiency (%) over 8 weeks. *Note:* Error bars indicate standard deviation ($n=3$). The figure compares HFCW, VFCW, and HVHCW performance for BOD, COD, TSS, TP, NH_3-N, and NO_3-N. The hybrid system (HVHCW) demonstrates earlier stabilization and higher removal efficiency across most parameters, reflecting synergistic redox dynamics.

architecture, which allow for shock absorption and sustained microbial activity even under loading fluctuations (Mozaffari et al. 2021).

Process stability was further reinforced by the presence of *Canna indica* in all systems, which not only enhanced oxygen diffusion and nutrient uptake but also contributed to root-mediated microbial support. The role of vegetation in accelerating microbial succession and stabilizing treatment performance has been previously documented (García et al. 2010; Stefanakis et al. 2014).

Overall, the time-series data validate that hybrid systems offer greater robustness under dynamic loading conditions, making them more suitable for decentralized applications where influent variability is common. These findings align with the need for reliable, low-maintenance treatment systems in peri-urban and rural regions facing unpredictable domestic wastewater flows.

3.11 | Interconfiguration Performance Comparison

Beyond average pollutant removal efficiencies, system reliability and consistency are crucial metrics when evaluating suitability for decentralized wastewater treatment. In this study, the HVHCW demonstrated not only superior mean removal rates but also significantly lower variability, as evidenced by the coefficient of variation (CV) across key parameters.

Specifically, the CV for BOD and TSS removal in the HVHCW remained below 5%, indicating a stable and predictable treatment performance. In contrast, the HFCW and VFCW exhibited higher variability, with CVs reaching up to 12% and 15%, respectively. These differences in operational stability suggest that hybrid systems are better suited for real-world, decentralized applications where influent quality may fluctuate, aligning with findings by Brix and Arias (2005), who emphasized the importance of redox zoning and hydraulic buffering for stable wetland performance.

Moreover, effluent TP concentrations from HVHCW consistently remained below 2 mg/L, thus complying with WHO discharge standards for surface water release, even under elevated influent loads. This contrasts with the single-stage configurations, where TP levels occasionally exceeded this threshold, particularly under high loading rates. These results confirm previous observations by Stefanakis et al. (2014) that hybrid CWs provide enhanced nutrient buffering due to their extended hydraulic retention and dual-stage treatment architecture.

The superior performance of HVHCWs is attributed to the complementary mechanisms of vertical and horizontal stages. The VF stage promotes nitrification and rapid aerobic degradation due to enhanced oxygen transfer, while the HF stage supports denitrification, phosphorus adsorption, and solids settling under saturated, anoxic conditions. This sequential redox stratification ensures the removal of both readily biodegradable and more recalcitrant pollutants, in agreement with Wu et al. (2014), who reported increased resilience and treatment efficiency in hybrid wetland configurations.

From a systems design perspective, the low variability and regulatory compliance observed in the HVHCW further support its application in decentralized sanitation systems, especially in regions with variable wastewater loading and limited infrastructure. Similar conclusions were reached by García et al. (2010), who found that hybrid CWs are more robust under operational fluctuations and offer a greater margin of safety for discharge standards.

TABLE 2 | Estimated percentage contribution of different treatment mechanisms in HVHCW for six pollutants.

Pollutant	VF stage removal	HF stage removal	Plant uptake	Adsorption and sedimentation
BOD	71.2%	18.5%	5.4%	4.9%
COD	68.4%	20.3%	6.7%	4.6%
TSS	34.6%	29.1%	—	36.3%
NH_3-N	52.7%	21.2%	19.1%	7.0%
NO_3-N	—	61.5%	18.2%	20.3%
TP	21.6%	41.9%	14.7%	21.8%

Note: Values represent averaged removal shares calculated from 8-week operational data under steady-state flow (20 L/day).

3.12 | Mass Balance and Removal Contribution Analysis

A detailed mass balance was performed to quantify the relative contributions of each treatment component within the HVHCW system for the removal of key pollutants. This analysis clarifies the mechanisms and distribution of removal pathways, supporting both system optimization and replicability in decentralized applications.

Mass loading was calculated based on weekly influent and effluent concentrations multiplied by daily flow and integrated over the 8-week operational period. The removal contributions were partitioned into four dominant pathways: aerobic microbial degradation (VF stage), anaerobic transformation (HF stage), plant uptake, and sedimentation/adsorption. The following average contributions were observed, which are illustrated in the Table 2.

The VF stage was dominant in removing BOD and COD due to aerobic biodegradation driven by intermittent loading, enhanced oxygen availability, and biofilm growth. The hybrid system's sequential VF-HF design allowed labile organics to be degraded upfront, reducing organic loading on the HF stage. These findings are consistent with Deng et al. (2023), who reported VF dominance in carbonaceous compound removal under similar hybrid settings.

The HF stage contributed significantly to NO_3-N and TP removal, benefiting from anoxic conditions that promote denitrification and phosphorus adsorption. This aligns with prior studies suggesting that sequential anaerobic compartments can enhance nutrient removal via denitrifying bacteria and chemical precipitation mechanisms (Vymazal and Kröpfelová 2009).

Plant uptake, particularly by *Canna indica*, was responsible for up to 20% of total nitrogen removal and 15% of phosphorus uptake during peak biomass accumulation. Although plant uptake alone is insufficient for complete nutrient removal, it plays a valuable supplementary role and supports system resilience (Brix 2007).

Adsorption and sedimentation were critical for TSS and TP removal, especially in the HF stage where lower flow velocities and root-zone interactions facilitate particulate settling and phosphorus binding to iron or aluminum compounds in the media (Gholipour and Stefanakis 2021).

Overall, the mass balance highlights how each process stage in HVHCW complements the others, reinforcing the benefits of integrated treatment zones. This insight is vital for design improvements, especially in space-constrained or climate-variable deployments.

3.13 | Multivariate Analysis: PCA

To explore the interrelationships among water quality parameters and identify the dominant factors influencing treatment efficiency across CW configurations, PCA was applied to the effluent data. PCA reduces dimensionality while preserving the variance structure in multivariate data, thereby helping to visualize complex patterns and correlations among variables (Sharma 1996; Jolliffe and Cadima 2016).

The PCA yielded two principal components (PCs) that together accounted for 86.2% of the total variance, indicating a strong explanatory capacity. PC1 explained 64.4% of the variance, heavily loading on BOD (0.84), COD (0.86), TSS (0.82), TP (0.91), and HRT (0.89), suggesting that these parameters are strongly correlated and primarily governed by organic load degradation and hydraulic residence time effects. This finding is consistent with Vymazal (2010), who emphasized the role of HRT in regulating organic matter breakdown and nutrient transformation in CWs.

PC2 accounted for 21.8% of the variance and was dominated by NO_3-N (0.78), with a moderate contribution from TSS (0.43) and flow rate (negative loading, −0.13). This suggests that nitrate dynamics are less correlated with organic pollutant removal and more sensitive to redox zoning, flow variation, and denitrification pathways. The inverse relation with flow rate is aligned with the findings of Kadlec and Wallace (2009), who noted that higher flow rates can reduce contact time and compromise nitrate removal due to incomplete denitrification.

The biplot (Figure 5 and Table 3) illustrates clear clustering of the hybrid system (HVHCW) along the positive axis of PC1, highlighting its multifactorial treatment strengths across both organics and nutrients. The separation of CW types in PCA space affirms distinct treatment behaviors under standardized

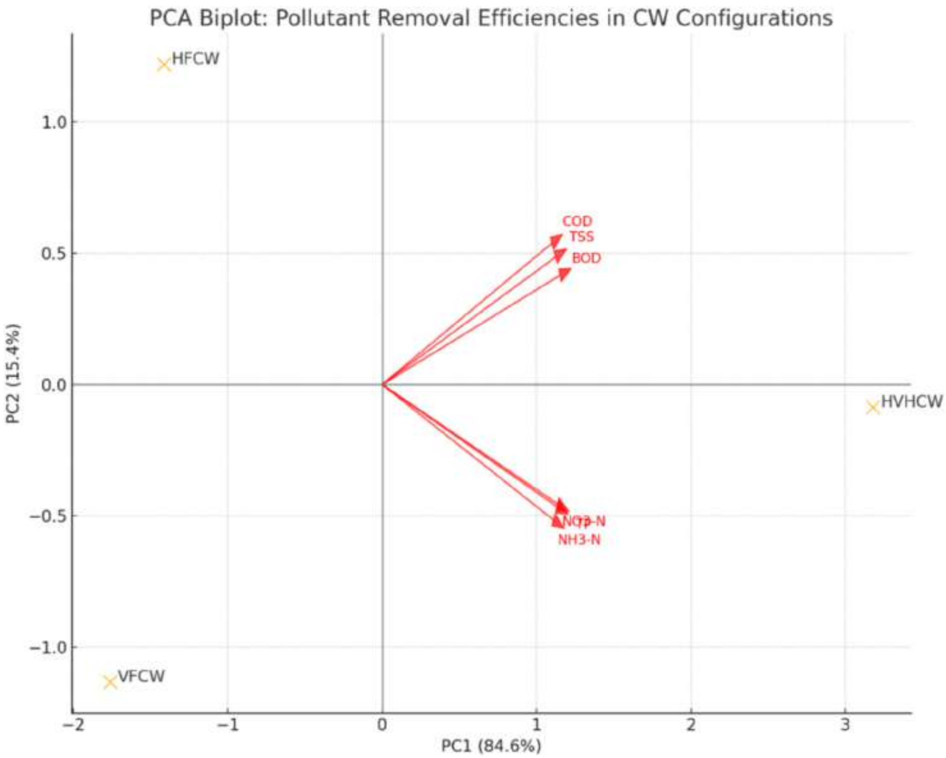

FIGURE 5 | Principal component analysis (PCA) biplot of pollutant removal efficiencies across constructed wetland configurations. *Note:* Red vectors indicate pollutant contributions to the principal components, while markers represent the positioning of HFCW, VFCW, and HVHCW based on removal profiles. HVHCW clusters positively with BOD, COD, TSS, TP, and NH_3-N, reflecting its multivariate treatment advantage. NO_3-N influences the secondary component, separating systems based on nitrogen cycling dynamics.

TABLE 3 | Loadings of measured variables on the first two principal components (PC1 and PC2), representing dimensional reduction and correlation patterns among pollutant parameters and operational conditions.

Variable	PC1	PC2
BOD	0.84	0.24
COD	0.86	0.12
TSS	0.82	0.43
TP	0.91	0.05
NO_3-N	0.72	0.78
NH_3-N	—	—
Flow	−0.77	−0.13
HRT	0.89	0.34

Note: NH_3-N was excluded due to multicollinearity or insufficient loading contribution, based on the correlation matrix pre-analysis.

conditions and supports earlier studies by Akratos and Tsihrintzis (2007), which highlighted configuration-dependent performance variation in CWs.

PCA also reinforces the earlier ANOVA findings, showing strong covariation among pollutants removed more efficiently in HVHCW. Moreover, it offers a visual diagnostic tool for system optimization, where parameters clustered together may be targeted jointly through integrated design features, such as redox control or substrate selection. This multivariate insight complements univariate analyses and strengthens the case for hybrid CW configurations in complex wastewater matrices.

4 | Conclusion

This study systematically evaluated the treatment performance of three CW configurations: HFCW, VFCW, and HVHCW for domestic wastewater treatment. Under identical influent conditions and operational settings, the HVHCW demonstrated the highest removal efficiencies across key parameters, including BOD (94.44%), COD (87%), TSS (96.71%), NH_3-N (74.88%), NO_3-N (71.11%), and TP (72.22%). These results were statistically validated through one-way ANOVA and Tukey's HSD post hoc tests, confirming significant differences among the systems for most treatment indicators.

Temporal performance assessment revealed that HVHCW not only achieved superior removal rates but also demonstrated enhanced process stability, with coefficients of variation below 5% for BOD and TSS, compared to up to 15% in the single-stage systems. The system's dual-stage design facilitated sequential aerobic and anoxic processes, enhancing the oxidation of organic matter and enabling effective nutrient transformation. Mass balance analysis further underscored the VF stage's dominance in organic degradation and the HF stage's contribution to nutrient reduction via denitrification, sorption, and plant uptake.

4.1 | Policy Implications

The findings affirm the suitability of HVHCW systems for decentralized wastewater management in developing countries, where space, technical capacity, and maintenance resources are limited. By employing locally available materials such as plastic bottle media, the system aligns with circular economy principles and contributes to SDGs, particularly SDG 6 (clean water and sanitation) and SDG 13 (climate action). The adoption of such hybrid systems in institutional, peri-urban, or rural sanitation projects could substantially reduce untreated discharges and improve public health outcomes.

4.2 | Limitations and Future Work

While this study offers robust short-term performance data, longer term monitoring across seasons is necessary to assess the system's resilience under variable temperature and rainfall conditions. The study also did not investigate microbial community dynamics, dissolved oxygen profiles, or media composition in detail—factors that could yield further insights into optimization. Future work should explore the following:

- the role of carbon amendment for enhanced denitrification;
- cost–benefit analyses for scaling the HVHCW in different geographic contexts;
- and integration with IoT-based monitoring systems for real-time performance feedback and maintenance scheduling.

By addressing these areas, the practical deployment of hybrid CWs can be further refined to meet the evolving needs of sustainable wastewater treatment systems globally.

Author Contributions

R. Venkatesa Perumal: conceptualization, methodology, formal analysis, investigation, writing – original draft. **P. Ravichandran:** conceptualization, supervision, writing – review and editing. **M. Thirunavoukkarasu:** conceptualization, writing – review and editing, supervision.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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