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Evaluation of Rural Domestic Wastewater Treatment Using a Hybrid Constructed Wetland with Three Flow Configurations

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ABSTRACT: This study evaluated the performance of a hybrid constructed wetland (CW) system consisting of horizontal subsurface flow (HF), vertical subsurface flow (VF), and free water surface (FWS) units for domestic wastewater treatment under rural conditions. The system was operated at two hydraulic loading rates (HLR) of 5 and 10 cm/day to assess treatment efficiency under different operational scenarios. Results showed high removal efficiencies for organic matter and nitrogen, with average BOD_5 and NH_4^+-N removal reaching approximately 82.6–84.8% and 85.7–88.2%, respectively. Total suspended solids (TSS) removal ranged from 67.1% to 83.8%, while total coliform removal exceeded 98%. However, phosphorus removal remained low and unstable (14.2–17.2%), indicating the need for improved substrate materials. The performance of HF units varied depending on plant species, with *Caladium bicolor* demonstrating superior BOD_5 removal efficiency. The integration of HF and VF units, combined with intermittent feeding, enhanced nitrification–denitrification processes and improved nitrogen removal. Overall, the study demonstrated that the hybrid CW system was an effective, low-cost, and sustainable solution for domestic wastewater treatment in rural areas without requiring recirculation.

KEYWORDS: Hybrid constructed wetland; rural domestic wastewater; nutrient removal; treatment efficiency; China.

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1. Introduction

Currently, in many rural areas, domestic wastewater is still largely discharged directly into the environment without treatment, causing localized pollution in canals, ponds, and surface water sources [1]. The construction of centralized wastewater treatment plants has been considered; however, this approach has faced several limitations, such as high investment and operational costs, difficulties in synchronized implementation due to dispersed population density, and unstable operational efficiency. Therefore, the use of natural or semi-natural treatment systems with flexible scales, such as constructed wetlands (CW), has been considered a suitable and necessary approach for rural conditions [2].

CW technology has been regarded as one of the most appropriate wastewater treatment solutions for rural areas due to its many advantages. First, CW systems have relatively low construction and operational costs compared to conventional treatment technologies [3–5]. These systems mainly rely on natural processes such as sedimentation, filtration, adsorption, and biological degradation, and therefore do not require complex mechanical equipment. As a result, their energy consumption has remained very low, typically less than 0.1 kWh/m³, which is significantly lower than that of technologies such as activated sludge (0.76 kWh/m³), sequencing batch reactors (SBR) (1.13 kWh/m³), or stabilization ponds (1.16 kWh/m³) [6]. In addition, CW systems have been simple to operate and did not require highly skilled personnel, making them suitable for rural management conditions. According to Liu et al. (2009), the construction cost of CW systems was only about one-half to one-third that of conventional wastewater treatment plants [7].

However, the use of a single type of CW often did not achieve high treatment efficiency, especially for nutrients such as nitrogen and phosphorus [8,9]. This was because each type of CW (surface flow, horizontal subsurface flow, vertical subsurface flow, etc.) had different treatment mechanisms and environmental conditions, resulting in uneven pollutant removal performance. Therefore, the trend has shifted toward combining multiple CW types within one system to enhance overall treatment efficiency. These hybrid models improved nitrification–denitrification processes, thereby significantly enhancing nitrogen removal. At the same time, such combinations helped overcome the limitations of individual systems, maximize their advantages, and achieve a balance between treatment efficiency, stability, and adaptability to fluctuating pollutant loads [10].

This study aimed to evaluate and clarify the effectiveness of domestic wastewater treatment using a three-stage CW model with different plant species. Based on this, the study sought to determine optimal operating parameters such as hydraulic retention time, hydraulic loading rate, and flow distribution conditions within the system. Notably, the model operated without wastewater recirculation, thereby more closely reflecting real rural conditions and contributing to the proposal of appropriate, effective, and sustainable treatment solutions.

2. Materials and Methods

2.1. Characteristics of rural domestic wastewater.

The characteristics of the influent wastewater are presented in Table 1. Considerable variation was observed in wastewater quality, with BOD_5 ranging from 84.6 to 385.7 mg/l, TSS from 149.6 to 283.5 mg/l, NH_4^+-N from 10.1 to 56.2 mg/l, PO_4^{3-}-P from 1.2 to 3.5 mg/l, and total coliform from 7.0 × 10^3 to 3.48 × 10^5 CFU/100 ml. Such variability may adversely affect treatment performance if appropriate treatment technologies are not applied.

Table 1. Characteristics of rural domestic wastewater.

Parameter	Unit	Value
pH	-	6.5 – 7.2
BOD5	mg/l	84.6 – 385.7
TSS	mg/l	149.6 - 283.5
NH_4^+	mg/l	10.1 – 56.2
PO_4^{3-}	mg/l	1.2 – 3.5
Coliform	mg/l	7000 - 348000

2.2. Experimental setup.

The experimental system consisted of three horizontal subsurface flow (HF) tanks, followed by one vertical subsurface flow (VF) tank and one free water surface (FWS) tank (Figure 1). Influent wastewater first passed through a settling tank to remove sand and suspended solids, reducing the treatment load on subsequent units. The hybrid configuration was designed to combine the complementary treatment functions of different constructed wetland (CW) types. The HF units primarily promote sedimentation, filtration, and anaerobic/anoxic microbial processes for the removal of suspended solids and organic matter. The VF unit provides improved oxygen transfer through intermittent loading, enhancing aerobic degradation and nitrification. The final FWS unit serves as a polishing stage, supporting additional nutrient uptake, pathogen reduction, and stabilization of treated effluent. This sequential arrangement was intended to improve overall treatment efficiency by integrating physical, biological, and ecological treatment mechanisms within a single system. The HF and VF tanks were rectangular, while the FWS tank was cylindrical. The filter media consisted of layered gravel to support filtration and microbial growth.

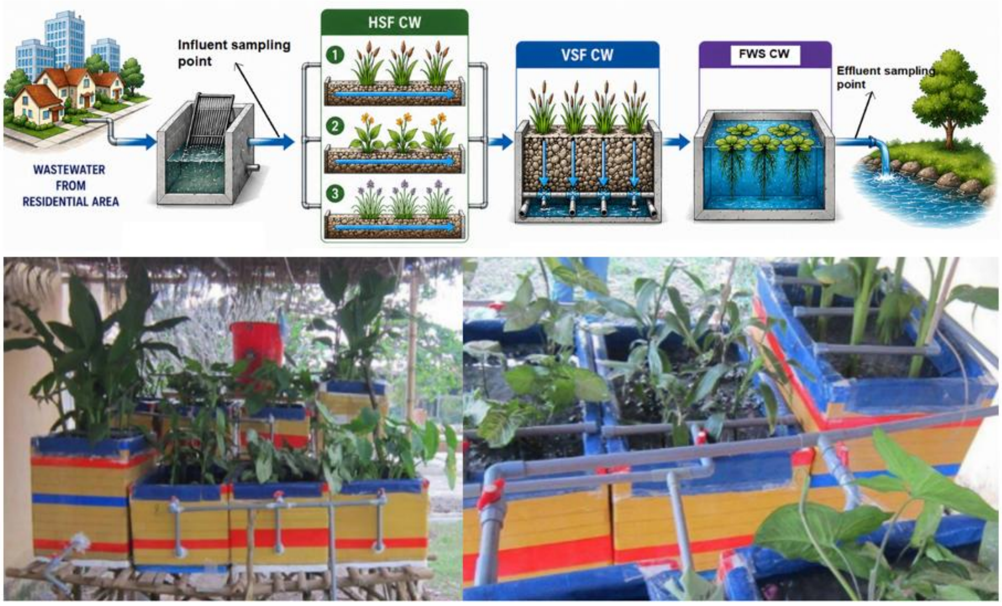

Figure 1. Experimental setup.

Detailed specifications of the treatment units, media, and vegetation are summarized in Table 2. Different plant species were selected according to their functional characteristics in constructed wetland systems. *Canna hybrids* were used in the VF tank because of their extensive root systems, high oxygen transfer capacity, and documented effectiveness in enhancing pollutant removal in constructed wetlands. *Colocasia esculenta* and *Caladium bicolor* were selected for the HF tanks due to their vigorous growth, tolerance to flooded conditions, and dense root structures that provide attachment surfaces for microbial biofilms. *Dracaena sanderiana* was included because of its adaptability to wet environments and ornamental value, although its application in constructed wetlands has been less frequently reported. *Nymphaea* was planted in the FWS tank because floating-leaved aquatic plants can contribute to nutrient uptake, shading, and ecological stabilization of free water surface systems. Before installation, plants were propagated for 30 days and acclimatized in clean water for 15 days. At planting, they had an average height of 30–50 cm, with 3–6 leaves per plant, and were spaced to ensure appropriate growth density.

Table 2. Specifications of the experimental constructed wetland system.

Component	Specification
System configuration	3 HF tanks → 1 VF tank → 1 FWS tank
Tank material	Composite material
HF tank dimensions	70 × 50 × 60 cm (L × W × H)
VF tank dimensions	70 × 50 × 40 cm (L × W × H)
FWS tank dimensions	Cylindrical; 80 L; diameter 48.5 cm; height 54.5 cm
Filter media	Gravel in three layers
Media particle size	Bottom: 3–4 cm; Middle: 1–2 cm; Top: <1 cm
VF vegetation	*Canna hybrids*
HF1 vegetation	*Colocasia esculenta*
HF2 vegetation	*Caladium bicolor*
HF3 vegetation	*Dracaena sanderiana*
FWS vegetation	*Nymphaea*
Plant propagation	30 days
Plant acclimatization	15 days in clean water
Initial plant condition	Height 30–50 cm; 3–6 leaves per plant
Plant spacing	5–10 cm

2.3. Operation and sampling.

The system was operated under two hydraulic loading rates (HLR) to evaluate the effect of operating conditions on treatment performance. In Phase 1, HLR_1 = 5 cm/day (from May 12 to June 26), corresponding to a flow rate of Q = 60 L/day. In Phase 2, HLR_2 = 10 cm/day (from June 27 to August 11), with a flow rate of Q = 120 L/day. These HLR values fall within the range commonly reported for constructed wetland studies (1–29.5 cm/day). The hydraulic retention time (HRT) was calculated as: HRT = V/Q, where V is the effective tank volume (m^3) and Q is the influent flow rate (m^3/day). Therefore, increasing HLR increased the flow rate and proportionally reduced HRT. The tank volumes were 0.14 m^3 (HF), 0.21 m^3 (VF), and 0.08 m^3 (FWS). At HLR_1, the HRT values were 0.76 days (HF), 1.15 days (VF), and 1.0 day (FWS), giving a total system HRT of 2.91 days. At HLR_2, doubling the HLR reduced the HRT to 0.38 days (HF), 0.57 days (VF), and 0.5 days (FWS), with a total HRT of 1.46 days. During operation, wastewater was continuously supplied to the HF and FWS tanks to maintain stable flow conditions. In contrast, the VF tank was fed intermittently every 6 hours, creating alternating wet and dry phases that enhance oxygen transfer, oxidation processes, and microbial activity. Water samples were collected periodically at the influent and after each treatment stage (HF, VF, and FWS) to evaluate treatment performance at both unit and system levels.

2.4. Data analysis.

The treatment performance of the model was evaluated based on key water quality parameters, including pH, biochemical oxygen demand (BOD_5), total suspended solids (TSS), ammonium (NH_4^+-N), nitrate (NO_3^--N), phosphate (PO_4^{3-}-P), and total coliforms (TCol). These indicators represent the level of organic, nutrient, and microbiological pollution in domestic wastewater. Water samples were collected twice weekly at different locations within the system, with a total of 12 samples per sampling event, over the period from May 12, 2025 to August 11, 2025. After collection, the samples were preserved and analyzed according to standard methods, ensuring accuracy and reliability of the results. The collected data were processed and statistically analyzed to evaluate variations and treatment efficiency of the system across different operational stages. Statistical analyses and graphical representations were performed using R software (version 3.2.2), enabling comparison, trend evaluation, and assessment of differences under various experimental conditions. ANOVA was used to compare differences among experimental conditions, with $p < 0.05$ considered statistically significant.

3. Results and Discussion

3.1. TSS removal.

The TSS removal efficiency of the system was also relatively high; however, a clear decline was observed with increasing HLR (Figure 2). Specifically, at HLR_1 = 5 cm/day, the removal efficiency reached 83.8%, with an effluent concentration of 32.7 mg/L. When the HLR increased to HLR_2 = 10 cm/day, the efficiency decreased to 67.1%, and the effluent concentration rose to 60.2 mg/L. This indicates that TSS is more sensitive to changes in HLR compared to BOD_5, as TSS removal relies heavily on physical mechanisms such as sedimentation and filtration. At the same time, an increase in HLR led to a decrease in HRT, meaning that the settling time was reduced. The HF and VF units played a primary role in TSS removal through the retention of solid particles within the filter media (gravel) and plant root systems. The FWS unit further supported sedimentation and the removal of remaining fine particles. The TSS removal efficiency among the three HF units was relatively similar, suggesting that plant species did not significantly influence the removal of suspended solids. However, toward the end of the monitoring period, the effluent TSS concentration showed an increasing trend. This may be related to plant growth and decay processes within the system, where aging biomass decomposes and is carried along with the flow, increasing suspended solids content [11, 12]. To better evaluate this trend, longer-term studies are needed.

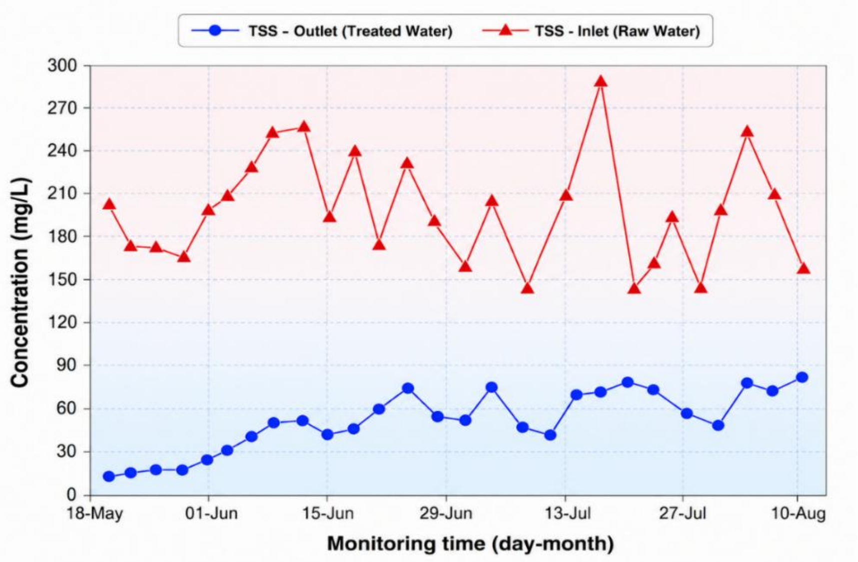

Figure 2. Variation of TSS concentrations in the experimental CW systems.

3.2. BOD_5 removal.

The results presented in Figure 3 show that the overall BOD_5 removal efficiency of the system was high, averaging approximately 83.7–83.8%. Specifically, at a hydraulic loading rate of HLR_1 = 5 cm/day, the removal efficiency reached 84.8%, with an average effluent BOD_5 concentration of 32.1 mg/L. When the loading rate increased to HLR_2 = 10 cm/day, the efficiency slightly decreased to 82.6%, corresponding to an effluent concentration of 35.9 mg/L. This reduction can be explained by the decrease in HRT as HLR increases, which limits the contact time between wastewater and microbial communities [8]. Compared with previous studies, the model in this study demonstrates relatively high BOD_5 removal efficiency. Abidi et al. (2009) [13] reported an efficiency of only about 53% for an HF–VF system at HLR = 8.6 cm/day. In the present study, the organic loading rate reached 15.7 g/m^2/day, which is significantly higher; however, the system still maintained stable treatment efficiency, indicating good load tolerance. Considering individual treatment stages, the initial settling tank significantly reduced influent BOD_5. Among the three HF units, treatment performance varied depending on plant species: HF2 (planted with *Caladium bicolor*) showed the highest efficiency, while HF1 (planted with *Colocasia esculenta*) performed lower. This difference may be attributed to the more vigorous root system and biomass development in HF2, which enhances microbial activity and organic matter degradation [14].

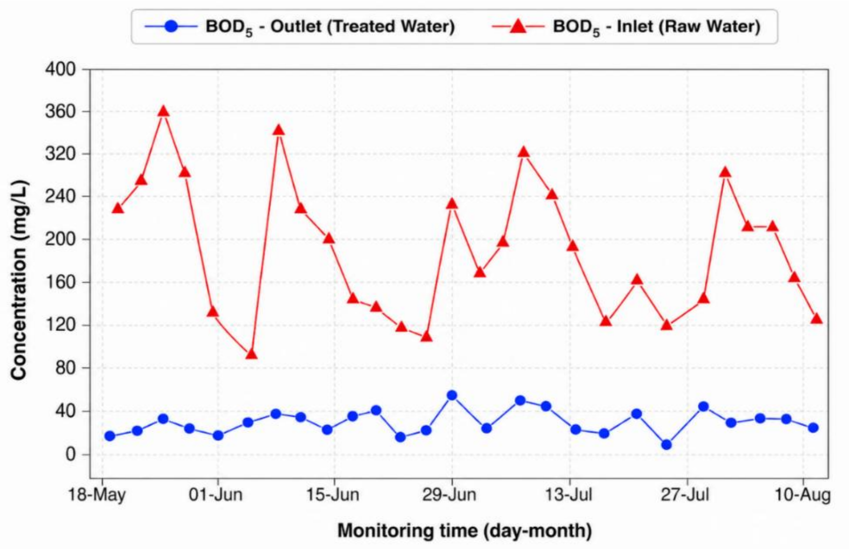

Figure 3. Variation of BOD_5 concentrations in the experimental CW systems.

3.3. NH_4^+–N removal.

NH_4^+-N removal efficiency of the system was high, averaging approximately 87.0–88.2%. Specifically, at a hydraulic loading rate of HLR_1 = 5 cm/day, the removal efficiency reached 85.7%, with the effluent concentration decreasing from 31.2 mg/L to 4.5 mg/l (Figure 4). When the HLR increased to HLR_2 = 10 cm/day, the efficiency slightly improved to 88.2%, with an effluent concentration of 4.6 mg/l. These results are lower than some other studies such as Vyzamal (2005) [10] and Brix (2003) [15], where efficiencies ranged from 90–96%. The high NH_4^+-N removal efficiency can be attributed to improved aerobic conditions within the system, particularly in the intermittently operated VF unit, which favors nitrification. In terms of treatment mechanisms, ammonium removal in constructed wetlands primarily occurs through a combination of biological and physicochemical processes. The dominant pathway is nitrification, in which ammonium is oxidized to nitrite (NO_2^-) and then to nitrate (NO_3^-) by autotrophic nitrifying bacteria (e.g., Nitrosomonas and Nitrobacter) under aerobic conditions [16]. The intermittent feeding regime in the VF unit enhances oxygen transfer into the media, thereby promoting this process. Additionally, plant uptake contributes to ammonium removal, as macrophytes absorb nitrogen for growth and biomass production. The extensive root systems also release oxygen into the rhizosphere, further supporting microbial activity [17]. Adsorption and ion exchange onto the surface of gravel media can temporarily retain ammonium, especially in the early stages of operation. Furthermore, part of the produced nitrate may subsequently be removed via denitrification in anoxic zones within the HF units, where heterotrophic bacteria convert nitrate into nitrogen gas (N_2), thus completing the nitrogen removal pathway [18, 19]. The integration of HF and VF units therefore creates alternating aerobic–anoxic conditions, enhancing overall nitrogen removal efficiency.

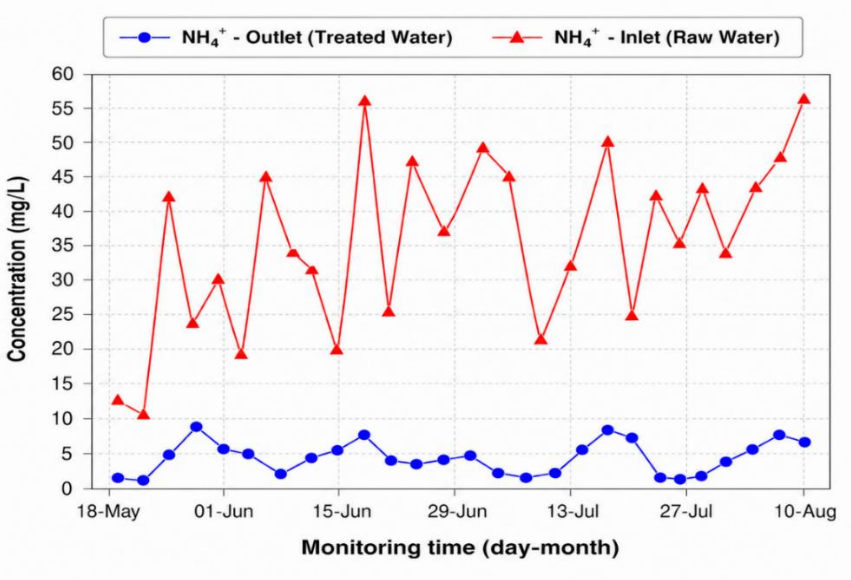

Figure 4. Variation of NH_4^+ concentrations in the experimental CW systems.

3.4. PO_4^{3-}-P removal.

The PO_4^{3-}-P removal efficiency of the system was relatively low and unstable (Figure 5). At HLR_1, the removal efficiency was 17.2%, with the concentration decreasing from 2.2 mg/l to 1.8 mg/l. At HLR_2, the efficiency slightly decreased to 14.2%, with an effluent concentration of 1.9 mg/l.

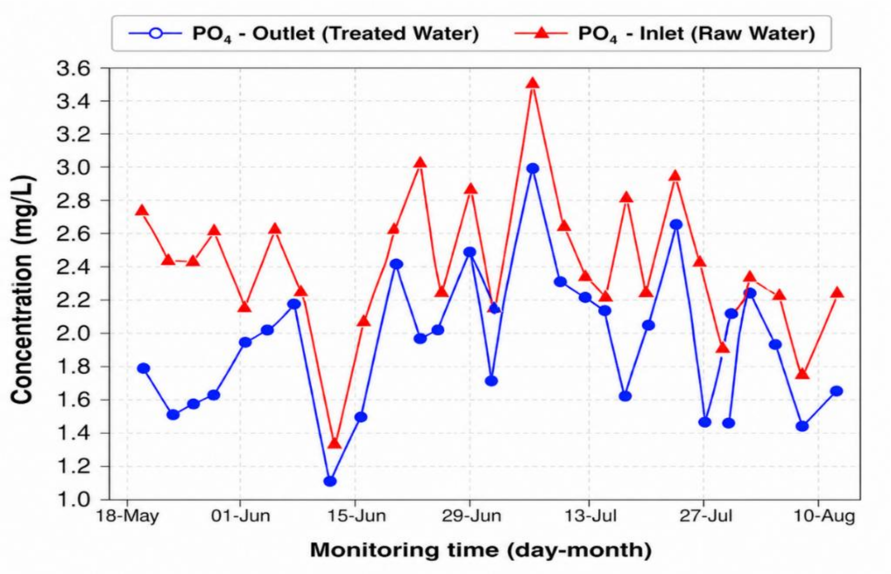

Figure 5. Variation of PO_4^{3-}-P concentrations in the experimental CW systems.

These results indicate that phosphorus removal in CW systems largely depends on the characteristics of the filter media and processes such as adsorption and precipitation. As HLR increased, turbulence within the water also increased, which reduced the efficiency of phosphorus precipitation or retention. In some cases, negative removal efficiency may occur due to the release of phosphorus from sediments or decomposing plant biomass [11, 20, 21].

3.5. TCol removal.

The TCol removal efficiency of the system was very high, averaging approximately 98.7–99.14%. Specifically, at HLR_1, the concentration decreased from 17,857 to 2,355 MPN/100 ml (E = 98.7%), and at HLR_2, it decreased from 114,338 to 984 MPN/100 ml (E = 99.14%) (Figure 6). This high treatment efficiency is attributed to the multi-stage system, in which bacteria are removed through mechanisms such as sedimentation, filtration, adsorption onto media, as well as the effects of microorganisms and environmental conditions (light, temperature) in each unit, including the initial settling tank [6, 10].

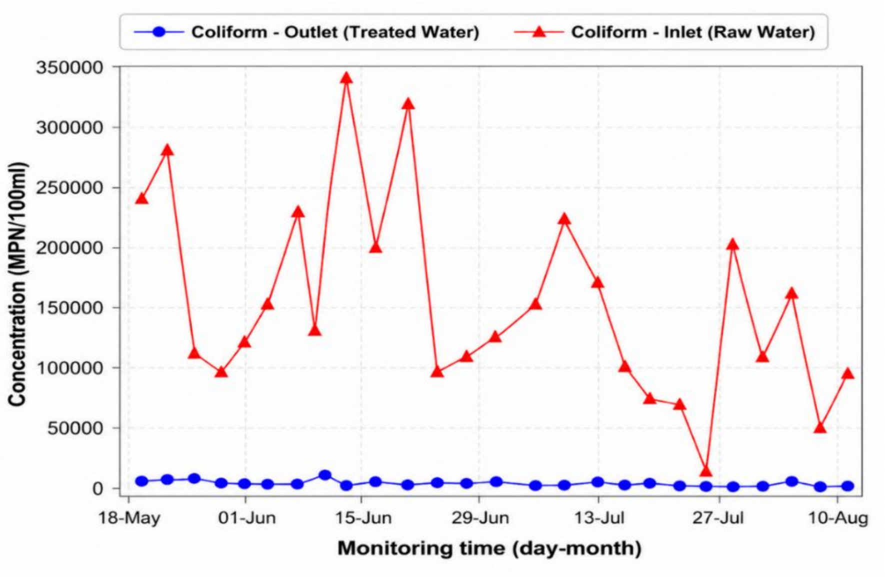

Figure 6. Variation of TCol concentrations in the experimental CW systems.

4. Conclusions

The study shows that the combined HF–VF–FWS model operated at hydraulic loading rates of 5–10 cm/day can effectively treat domestic wastewater with high efficiency. The plant species in the system grew well under experimental conditions, in which the HF unit planted with *Caladium bicolor* achieved higher BOD_5 removal efficiency compared to other species. Therefore, for wastewater with high BOD_5 concentrations, *Caladium bicolor* should be prioritized in practical CW systems. Arranging the HF unit before the VF unit, combined with intermittent feeding, contributed to improving NH_4^+-N removal efficiency. In addition, the PO_4^{3-}-P removal efficiency was unstable and could even be negative in some cases. Therefore, if the influent has a high phosphorus concentration, it is necessary to incorporate filter media with strong phosphorus adsorption capacity to improve treatment performance..

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Author Contribution

Xiaojuan Feng: Conceptualization, Methodology, Data Analysis, Writing; Xingjie Wang: Methodology, Data Collection; Bui Thi Van Nga: Data Analysis, Writing. Nguyen Thi Xuyen: Methodology, Data Analysis, Data Collection, Writing.

Competing Interest

The authors declare no competing interests.

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