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The Subsurface Flow Constructed Wetland System Uses *Phragmites australis* Plants - a Green Solution for On-Site Treatment of Domestic Wastewater in Urban Areas

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Abstract

The study evaluated a pilot horizontal subsurface-flow constructed wetland (SSF-CW) planted with Phragmites australis for decentralized domestic wastewater treatment. The system consisted of three identical modules connected in series; each module measured 1.5 m × 0.5 m, giving a total footprint of 2.25 m². Water depth of 0.55 m, the free pore volume was 433 L. Flow rates of 5.94, 7.13, and 8.91 L/h corresponded to hydraulic retention times (HRTs) of 3.0, 2.5, and 2.0 days. Influent wastewater contained 142–359 mg/L, 35–60 mg/L, and 216–420 mg/L for Chemical Oxygen Demand (COD), NH_4^+-N and Total Suspended Solids (TSS), respectively. At HRTs of 3.0, 2.5, and 2.0 days, mean effluent COD was 3.73 ± 5.31, 4.56 ± 8.96, and 8.51 ± 10.04 mg/L; NH_4^+-N was 2.88 ± 1.09, 3.86 ± 1.47, and 4.45 ± 1.09 mg/L, and TSS was 3.64 ± 2.58, 36.07 ± 15.16, and 52.98 ± 11.15 mg/L, respectively. The net water loss amounted to 42.1–45.0 % of the influent volume and was included in the mass-based removal efficiencies, which were 97.8–99.2 % for COD, 94.7–96.9 % for NH_4^+-N, and 91.2–99.3 % for TSS. COD and NH_4^+-N complied with column A limits of QCVN 14:2025/BTNMT at all three HRTs; TSS complied with column A at 3.0 and 2.5 days, and with column B at 2.0 days. At the shortest verified HRT the areal hydraulic loading was 95 (L/m².day); linear scale-up to 0.7 m³/day gives an indicative treatment area of 7.4 m². Since microbiological indicators were not measured, potential landscape-irrigation reuse requires further microbiological assessment.

Keywords: COD, domestic wastewater, NH_4^+, *Phragmites australis,* SSF-CW, TSS.

1. Introduction

Domestic wastewater typically contains high concentrations of organic matter Biochemical Oxygen Demand (BOD_5) in 5 days, *Chemical Oxygen Demand* (COD), total suspended solids (TSS), nitrogen compounds (NH_4^+-N and organic nitrogen), phosphorus compounds, and pathogenic microorganisms. According to QCVN 01:2026/BXD [1], the average domestic water consumption in major urban areas such as Hanoi exceeds 180 L/person/day, and domestic wastewater generation is assumed to be equivalent to 100 % of domestic water consumption. An average four-person household is therefore estimated to generate approximately 700 L of domestic wastewater per day. In densely populated urban areas such as Hanoi and Ho Chi Minh City, residential buildings are closely spaced and green space or household gardens are limited. Consequently, domestic wastewater is commonly discharged directly into urban drainage systems and ultimately into receiving rivers and lakes, leading to significant environmental degradation and deterioration of urban landscapes. Although centralized wastewater collection and treatment systems have been incorporated into the master plans of many urban areas, particularly newly developed districts, their implementation and coverage remain limited, which highlights the need for complementary decentralized wastewater treatment and reuse solutions.

In old urban areas, centralized collection and treatment of domestic wastewater may be difficult to implement comprehensively. Decentralized household-scale systems may therefore complement centralized infrastructure where suitable outdoor space and safe structural conditions are available. Constructed wetlands (CWs) are attractive because of their simple operation and low chemical demand, although their land requirement and site-specific performance must be considered [2–4].

CW systems have been applied for household-scale domestic wastewater treatment [5–7]. Horizontal and vertical flow constructed wetlands using willow trees have been applied in Denmark, meeting on-site treatment requirements with a compact scale and removing 90 % of the phosphorus in domestic wastewater [8]. Two- and three-stage constructed wetlands have been used to treat domestic wastewater from houses in agricultural areas; the optimal depth of the gravel filter material was 90 cm and the optimal volume ratio between the vertical flow (VF) and horizontal flow (HF) units was 1:2, giving

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removal efficiencies for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Suspended Solids SS, Total Nitrogen (TN), and Total Phosphorus (TP) of 99, 98, 99, 68, and 72 %, respectively. Combining VF and HF units can reduce the size of the CW system while maintaining treatment efficiency [9, 10]. In temperate climate regions such as Europe and northern Asia, household-scale applications treating a wastewater volume of about 0.7 m^3/ day require approximately 10 m^2 of CW area.

Recent studies at household or small-community scale differ from the configuration examined here in one or more essential respects. García-Ávila [11] operated vertical subsurface flow units planted with *Phragmites australis* and *Cyperus papyrus* at a Hydraulic Retention Time (HRT) of 1.12 days and a hydraulic loading of 200 L/m^2.day, obtaining a COD removal of about 81 % and a total solids removal of 63 %. Fu *et al.* [12] combined a surface-flow cell with three vertical subsurface flow cells filled with diatomite, vermiculite, zeolite, and hydrotalcite for rural households in subtropical China, at a HRT of 48 h and a hydraulic loading of 500 L/m^2.day. Shruthi and Shivashankara [13] examined HRTs between 2 and 10 days in a pilot horizontal subsurface flow unit planted with *Typha latifolia* and *Phragmites australis*, but fed with simulated rural wastewater. Temel *et al.* [14] reported a full-scale horizontal subsurface flow wetland planted with other species, in which the removals of NH_4^+-N (24–29 %) and of TSS (30-37 %) were much lower than those usually reported for pilot units. What is still unclear is therefore not whether constructed wetlands can treat domestic wastewater, but how far the footprint of a horizontal subsurface flow unit planted with *P. australis* can be reduced under tropical urban conditions before the effluent ceases to comply with the national discharge standard, and how the large water loss by evapotranspiration in such a climate affects the reported removal efficiencies.

Pollutant removal is achieved through the combined effects of the substrate, the microorganisms, and the plant roots, which provide oxygen, organic carbon, and surfaces for microbial growth [5, 15–19]. Various macrophytes, including *Phragmites australis*, *Typha* spp., *Carex* spp., *Schoenoplectus lacustris*, *Juncus effusus,* and *Iris pseudacorus*, have been widely used in CW systems [19]. In Vietnam, where the climate is hot and humid and *Phragmites australis* is readily available, this species is preferred because of its vigorous growth, extensive root system and high tolerance to local climatic and wastewater conditions. However, the recent household-scale studies are either vertical-flow or hybrid systems [7, 10, 12], use other plant species [14], or were operated with simulated wastewater [13]; horizontal subsurface flow units planted with this species, operated at household scale on real domestic wastewater under Vietnamese urban conditions and with the water balance quantified, remain scarce. In CWs, pollutants are removed through sedimentation, filtration, adsorption, microbial degradation, plant uptake, ion exchange, and antimicrobial substances secreted by the plants [20–25]. According to Domínguez-Solís *et al.* [5], Biswal and Balasubramanian [25], and Nguyen Hoang Nam [26], among the major pollutants present in domestic wastewater the removal efficiency of CW systems is lowest for ammonium, followed by organic compounds, whereas phosphorus compounds are removed mainly through adsorption by the substrate materials. In addition, harmful microorganisms such as *E. coli* and coliforms are removed very effectively in SSF-CW systems. Furthermore, the system design parameters are primarily based on the influent characteristics and the effluent standards for COD or NH_4^+-N [5, 26, 27].

Therefore, this study presents an evaluation of the treatment efficiency of an SSF-CW system planted with *Phragmites australis*, a species readily available in Vietnam, operated at household scale in an urban area of Hanoi. The specific objectives were (i) to quantify the removal of COD, NH_4^+-N, and TSS at three hydraulic HRTs (3.0, 2.5 and 2.0 days), (ii) to quantify the water loss from the bed, and to include it in the removal efficiencies, (iii) to relate the measured performance to the surface area obtained from the design (Kickuth) equation and to the areal hydraulic loading, so that the requirements of a four-person household can be estimated, and (iv) to compare the resulting system with recent household-scale constructed wetlands and to identify the physical quantities that govern its investment and operating requirements.

2. Materials and methods

2.1. Chemicals

The chemicals used in this study were: NH_4^+ standard solution, $HgCl_2$, KI, NaOH, $KNaC_4H_4O_6{\cdot}4H_2O$, H_2SO_4, NH_4Cl, KNO_3, $NaNO_2$, CH_3COOH, phenol, sulfanilic acid, α-naphthylamine, and ethylenediaminetetraacetic acid (EDTA). All chemicals were of analytical (PA) grade, manufactured by Merck (Germany). The COD reagent was supplied by Hach (USA).

Raw domestic wastewater was collected in the Pomelo residential area, Tay Ho district, Hanoi. The concentrations of NH_4^+-N, COD and TSS were in the ranges 35–60, 142–359, and 216–420 mg/L, respectively.

2.2. Experimental Set-up and Operation

The experimental train was reported as three identical stainless-steel modules connected in series. Each module measured 150 cm × 50 cm × 60 cm (L × W × H), giving a total plan area of 2.25 m² for the three modules. Each module was filled with 2–8 mm gravel. Perforated stainless-steel sieves separated 3-cm inflow and outflow zones from the gravel bed. The water level was maintained 5 cm below the gravel surface, corresponding to a water depth of 55 cm. Since no direct water-displacement measurement of the packed gravel was available, a porosity of 0.35 was adopted as a design assumption. This gives a nominal free pore volume of 144.4 L per module and 433 L for the three-module train. The resulting HRT values reported below are therefore nominal values and should be recalculated if a measured porosity becomes available.

Phragmites australis was planted at a reported density of 1500–2000 shoots/m². Fig. 1 schematically represents one module and the associated feed and collection tanks; the two inter-module connections of the full three-module train are not shown.

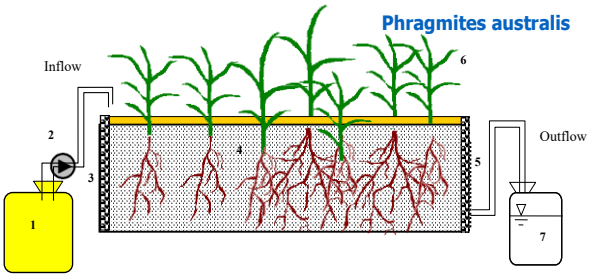


Fig. 1. Schematic plan view of one representative module of the three-module horizontal subsurface flow SSF-CW train (inter-module connections not shown): 1 – feeding storage tank; 2 – pump; 3 – inlet distribution chamber; 4 – gravel bed; 5 – outlet collection chamber; 6 – plants; 7 – outflow storage tank

Wastewater was continuously pumped through the three-module train at flow rates of 5.94, 7.13, and 8.91 L/h (142.6, 171.1 and 213.8 L/day), corresponding to nominal HRTs were 3.0, 2.5, and 2.0 days, respectively. The system was operated in three consecutive phases:

Phase A: 28/02/2025 – 28/04/2025, influent flow rate F equal 5.94 L/h (HRT equal 3.0 days);

Phase B: 29/04/2025 – 30/06/2025, influent flow rate F equal 7.13 L/h (HRT equal 2.5 days);

Phase C: 02/07/2025 – 29/08/2025, influent flow rate F equal 8.91 L/h (HRT equal 2.0 days).

Sixteen samples (n equal 16) were collected during each phase. As all phases were conducted consecutively using the same treatment unit, the plants and the biofilm were already established when the HRT was shortened.

2.3. Design Basis and Surface Area of the System

The required surface area of a CW system can be calculated from the design criteria for COD, TSS or NH_4^+-N. In practice, the largest area is normally obtained from the COD criterion, using Kickuth's formula [28]:

$$A_h = Q_d\,(lnC_i - lnC_e) / K_{COD} \quad (1)$$

where: A_h is the surface area (m²); Q_d is the domestic wastewater flow rate (m³/day); C_i is the influent COD (mg/L), taken as the maximum value; C_e is the target effluent COD (mg/L); and K_{COD} is the areal rate constant (m/day):

$$K_{COD} = K_T \cdot d \cdot n \quad (2)$$

$$K_T = K_{20} \cdot 1.06^{(T-20)} \quad (3)$$

where K_{20} is the reaction rate constant at 20 °C, taken as 2.2/day [28]; T is the mean temperature of the system (T_{avg} = 23.6 °C); d is the water depth (0.55 m, within the range commonly used for horizontal subsurface flow wetlands [29]); and n is the porosity of the 2–8 mm gravel (35 %). The length-to-width ratio of each module was 3:1.

With these values, K_T = 2.71/day and K_{COD} = 0.52 m/day. For a typical four-person household (Q_d = 0.7 m³/day), a maximum influent COD of C_i = 359 mg/L and a target effluent equal to the column A limit of QCVN 14:2025/BTNMT (C_e = 80 mg/L) [30], (1) gives a required surface area (A_h) of 2.0 m². The pilot unit had a footprint of 2.25 m² (three modules of 1.5 m × 0.5 m), providing an approximately 10% design margin.

Equation (1) describes removal kinetics and does not independently ensure the required HRT. At 0.7 m³/day, a 2.25 m² bed with the assumed porosity would have a nominal HRT of approximately 0.6 days, which is below the experimentally tested range. The pilot was operated at 0.14–0.21 m³/day. Accordingly, Section 3 reports performance only at these experimental flow rates. The 7.4 m² value presented in Section 3.5 is an indicative linear scale-up based on the shortest experimentally tested areal hydraulic loading; rather than a validated full-household design.

2.4. Analytical Methods

Samples were taken twice a week at the inlet and outlet, collected in PE bottles and stored according to TCVN 6663-3:2016. Before sampling, the bottles were purged with N_2 gas, and the samples were stored at −20 °C (TCVN 6663-3:2016). Prior to COD and NH_4^+-N analysis, samples were filtered through a 0.45 µm membrane in accordance with DIN 38404-6 (1984); whereas TSS was determined gravimetrically using unfiltered samples.

NH_4^+-N and COD were analysed by molecular absorption spectrophotometry using an Optizen 2120UV UV-VIS spectrophotometer. The manufacturer and country of origin are not stated because these details could not be verified from the available equipment record.

2.5. Data Processing

Since a substantial part of the influent volume is lost from the bed (Section 3.1), the removal of COD, NH_4^+-N and TSS was calculated on a mass basis:

$$R\,[\%] = [(V_{in}C_{in} - V_{out}C_{out}) / (V_{in}C_{in})] \times 100 \quad (4)$$

where R is the removal efficiency (%); C_{in} and C_{out} are the influent and effluent values of COD, NH_4^+-N or TSS (mg/L); and V_{in} and V_{out} are the influent and effluent water volumes (L) over the same sampling interval. V_{in} was calculated from the applied pump flow rate and the length of the interval, and V_{out} from V_{in} and the water loss reported in Section 3.1. Equation (4) is dimensionless because both terms of the ratio represent pollutant masses. When the water loss is neglected (V_{out} = V_{in}), (4) reduces to the concentration-based efficiency $R_c = [(C_{in} - C_{out})/C_{in}] \times 100$.

For each phase, mean values and standard deviations were calculated in Microsoft Excel based on the 16 samples (n = 16).

2.6. Discharge Standard Used for Comparison

The effluent quality was compared with QCVN 14:2025/BTNMT [30], which applies to domestic wastewater discharged from individual facilities.

3. Results and Discussion

3.1. Evapotranspiration

In CW systems, water is lost through the vegetation and through the contact surface between water and air (evapotranspiration, ET). The ET rate in a CW system is typically much higher than in other treatment systems, and it also affects the quality of the effluent (Fig. 2).

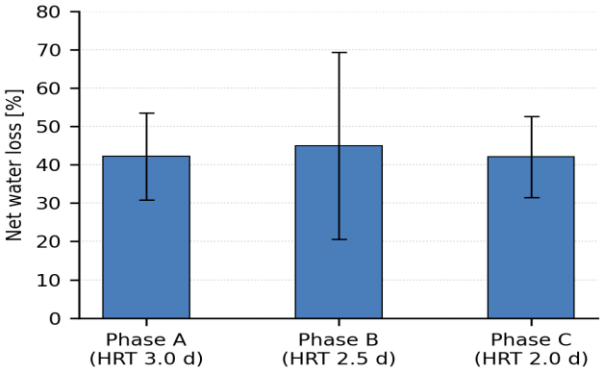


Fig. 2. Net water loss (evapotranspiration minus direct precipitation) in the SSF-CW system in the three operating phases (Phase A: 28/02/2025 – 28/04/2025; Phase B: 29/04/2025 – 30/06/2025; Phase C: 02/07/2025 – 29/08/2025); n = 16 samples per phase

The results showed similar mean water losses across the three phases, but with different variability due to weather conditions. The mean water losses were 42.23 ± 11.34 % in phase A (HRT of 3.0 days), 44.95 ± 24.37 % in phase B (HRT of 2.5 days) and 42.11 ± 10.58 % in phase C (HRT of 2.0 days). In phase A, relatively low temperature (10–20 °C), high humidity, light winds, and occasional drizzle resulted in limited evapotranspiration. Phase B experiences higher temperature (20–35 °C), lower humidity occasional showers, and strong winds leading to greater variability in water loss. In phase C, despite higher temperature (25–35 °C), sunny conditions, light winds, and higher humidity than in phase B resulted in a mean water loss comparable to that in phase A.

Overal, water losses amounted to 42–45 % of the influent volume, increasing outlet pollutant concentrations, and therefore affecting the calculated removal efficiencies (4). As the bed was open to the atmosphere and direct rainfall was not measured separately, these values represent net water losses (evapotranspiration minus precipitation). Thus, the losses measured during phases A and B, when drizzle and occasional showers occurred, should be considered lower-bound estimates of actual evapotranspiration. This result is consistent with Nguyen Hoang Nam and Do Khac Uan (2014) [31], who reported water deficit rates of 30–70 %, whereas Bois *et al.* (2021) [32] reported that the hourly evapotranspiration rate peaks at 26 % of the incoming flow during the warmest days of summer.

Table 1. Daily water balance and pollutant loads of the SSF-CW system in the three operating phases

Parameter	Phase A	Phase B	Phase C
Influent flow (L/day)	142.6	171.1	213.8
Net water loss (%)	42.2	45.0	42.1
Water loss (L/day)	60.2	76.9	90.0
Effluent flow (L/day)	82.4	94.2	123.8
Hydraulic loading (L/m^2. day)	63.4	76.1	95.0
COD load in/out (g/day)	38.1/0.31	38.0/0.43	48.3/1.05
NH_4^+-N load in/out (g/day)	7.63/0.24	8.21/0.36	10.36/0.55
TSS load in/out (g/day)	43.2/0.30	49.8/3.40	74.2/6.56

The water balance of the three phases is summarised in Table 1. Influent flow rates were 142.6, 171.1 and 213.8 L/day while the corresponding effluent flow rates, calculated from the water loss, were 82.4, 94.2, and 123.8 L/day. Since evapotranspiration removes water but not pollutants, it concentrates the effluent and increases outlet concentration, thereby causing concentration-based removal efficiency to underestimate actual mass removal. Thus, the treatment performance reported in Sections 3.2 to Section 3.4 can not be attributed to the water loss, which instead acts conservatively against the observed removal efficiencies. Pollutant loads at the inlet and outlet are presented in Table 1, and the two removal-efficiency approaches are compared in Table 2.

Table 2. Removal efficiency of the SSF-CW system: concentration-based value / mass-based value calculated with (4)

Phase (HRT)	COD [%]	NH_4^+-N [%]	TSS [%]
A (3.0 d)	98.6 / 99.2	94.6 / 96.9	98.8 / 99.3
B (2.5 d)	98.0 / 98.9	92.0 / 95.6	87.6 / 93.2
C (2.0 d)	96.2 / 97.8	90.8 / 94.7	84.7 / 91.2

3.2. Efficiency of Organic Pollutant Removal

Mean influent COD were 267 ± 40 mg/L in phase A, 222 ± 70 mg/L in phase B and 226 ± 59 mg/L in phase C. Effluent COD remained consistently low throughout all three phases: at 3.73 ± 5.31, 4.56 ± 8.96, and 8.51 ± 10.04 mg/L, respectively (Fig. 3). Despite shortening the HRT from 3.0 to 2.5 and 2.0 days , the effluent COD values remained very low, even with 42–45 % water loss from the bed and the resulting concentration of the remaining flow.

Wu *et al.* (2025) [9] reported a maximum COD removal efficiency of 70 % among the experimental configurations used to investigate the effect of the COD/N ratio, which was considerably lower than the 91.22 ± 2.80 % reported by Fernández-Fernández *et al.* (2020) [33]. In comparison, the concentration-based COD removal efficiency in the present study was 96.2–98.6 % (Table 2) exceeding both reported values.

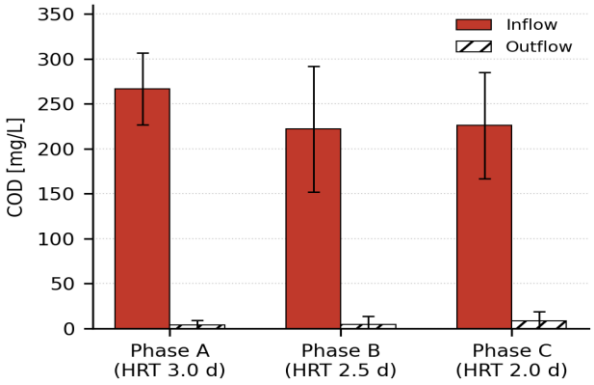


Fig. 3. COD removal in the SSF-CW system in the three operating phases; n = 16 samples per phase

Despite variations in influent COD values, the weather conditions and HRTs, the system maintained consistently low effluent COD. Even at an HRT of 2.0 days, the effluent COD remained well below the limit of column A of QCVN 14:2025/BTNMT (80 mg/L). This findings suggests that shortening the HRT may be feasible for increasing treatment capacity, although further validation under higher loading conditions is required. The results are consistent with those of Seo *et al.* [10], who evaluated two- and three-stage constructed wetland systems to treat domestic wastewater from households surrounding agricultural villages. They reported an optimal crushed-stone filter depth of 90 cm, the optimal volume ratio between the VF and HF units was 1:2, and the removal efficiencies for BOD, COD, SS, TN and TP were 99, 98, 99, 68, and 72 %, respectively.

In SSF-CWs, organic compounds are removed through microbial degradation via fermentation, aerobic, and anaerobic respiration and mineralization processes [34, 35]. In addition, a major portion of the COD may be associated with particulate matter and can therefore be removed through particle deposition and filtration [36, 37].

These pathways were not experimentally distinguished in the present study, and their relative contributions can therefore only be assessed indirectly. Two observations are particularly relevant. First, the influent COD/TSS ratio was 0.65–0.88, indicating that a large part of the organic matter was associated with suspended solids. In a horizontal subsurface-flow bed, these solids are expected to be retained physically within the upstream section of the gravel bed, suggesting that filtration and sedimentation contributed substantially to COD removal. Second, reducing the HRT from 3.0 to 2.0 days increased effluent COD by only 4.8 mg/L, compared with a 49.3 mg/L increase in effluent TSS. If COD removal were primarily limited by biological reaction kinetics, a stronger response to the reduced HRT would be expected. Taken together, these observations suggest that particulate COD retention by filtration and deposition was an important removal pathway, followed by anaerobic and anoxic degradation of the retained organic matter within the bed and aerobic degradation in the oxygenated rhizosphere microzones. The residual soluble COD fraction may therefore have been an important determinant of effluent quality. Definitive identification of the dominant removal pathway would require separate measurement of soluble and particulate COD fractions and redox potential profiling along the bed, which will be planned for the next stage of this work.

3.3. Efficiency of NH_4^+-N Removal

As shown in Fig. 4, the NH_4^+-N concentration at the inlet was highest in phase A, with a mean value of 53.54 ± 5.42 mg/L, and decreased to 2.88 ± 1.09 mg/L at the outlet.

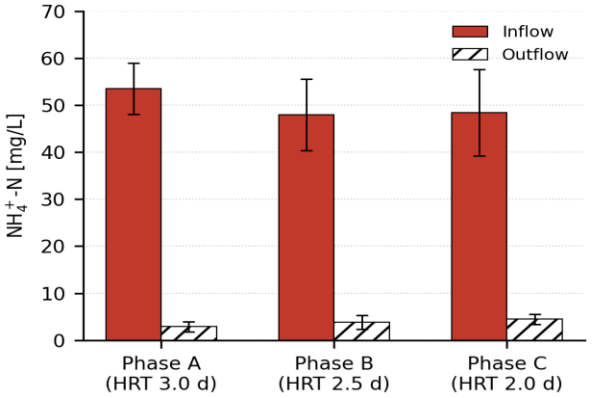


Fig. 4. Ammonium removal in the SSF-CW system in the three operating phases; n = 16 samples per phase

When the HRT was reduced to 2.5 days (phase B), the mean influent concentration was lower than that in phase A (47.96 ± 7.61 mg/L) and the effluent concentration was 3.86 ± 1.47 mg/L. When the HRT was further reduced to 2.0 days (phase C), the influent concentration was similar to that in phase A (48.43 ± 9.17 mg/L), whereas the effluent concentration increased slightly to 4.45 ± 1.09 mg/L compared with phase B.

The results show that, similar to COD, NH_4^+-N concentrations fluctuated noticeably in the influent, whereas effluent concentration remained relatively stable and below the discharge limits. In phase C the HRT was shortened to 2.0 days and the weather was warmer than in phases A and B, however, the effluent concentration increased only slightly, from 3.86 to 4.45 mg/L.

The effluent NH_4^+-N concentrations of the three phases (2.88, 3.86 and 4.45 mg/L) were all below 6.0 mg/L, and therefore complied with column A of QCVN 14:2025/BTNMT [30], even at the shortest HRT. The relatively stable NH_4^+-N removal suggests that processes such as rhizosphere nitrification, plant uptake and substrate adsorption were not substantially affected by the reduction in HRT within the investigated range. Since nitrite and nitrate were not measured, the fate of the removed nitrogen could not be determined and this mechanistic interpretation remains provisional.

3.4. Efficiency of *Total Suspended Solids* Removal

The efficiency of TSS removal by the SSF-CW system is shown in Fig. 5. During the three phases A, B, and C, the influent TSS concentration varied, with mean values of 303.16 ± 54.82, 291.00 ± 43.49, and 347.27 ± 55.66 mg/L, respectively. In all three phases the effluent TSS decreased markedly, to 3.64 ± 2.58, 36.07 ± 15.16, and 52.98 ± 11.15 mg/L, respectively.

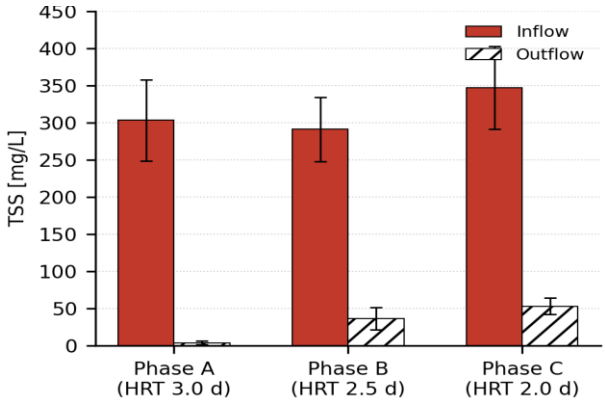


Fig. 5. TSS removal in the SSF-CW system in the three operating phases; n = 16 samples per phase

Although the influent TSS fluctuated significantly throughout the testing period, the effluent remained stable and below the column B limit of QCVN 14:2025/BTNMT in all three phases. In phase A, at an HRT of 3.0 days, the effluent TSS was well below the column A of QCVN 14:2025/BTNMT, reaching approximately 3.64 ± 2.58 mg/L. Reducing the HRT from 3.0 to 2.5 days and then to 2.0 days resulted in progressively higher effluent TSS. In phase C (HRT of 2.0 days) the higher hydraulic loading was accompanied by higher effluent TSS (52.98 ± 11.15 mg/L) exceeding the limit of column A (50 mg/L) but remained below that of column B (60 mg/L).

The TSS removal in the SSF-CW system can be attributed primarily to filtration, coagulation, and deposition of colloidal and suspended particles. Additional removal may occurs through gravity sedimentation, and adsorption onto biofilms attached to the gravel and to plant roots [38-41].

The TSS removal efficiency is primarily influenced by particle settling characteristic, hydraulic loading, and wetland length. In CW systems the plants and their root systems, as well as the substrate (e.g. rocks and gravel), reduce the flow velocity and thereby promote particle retention through sedimentation and filtration [42]. Accordingly, longer HRT in phase A resulted in lower effluent TSS than in phases B and C. In addition to plant selection, the choice of substrate material plays a crucial role in improving CW performance. Novel substrates such as corn cob, palm shell, and coconut peat, combined with ornamental plants such as *Phragmites australis*, *Typha latifolia*, *Duranta repens*, *Pennisetum pedicellatum,* and *Pistia stratiotes*, have shown promising performance for household-scale domestic wastewater treatment. However, developing compact, user-friendly and energy-efficient CW systems remains a major challenge for reducing operational costs [5, 9].

Reduced hydraulic conductivity increases the retention of non-degradable solids. Previous studies have reported that approximately 98.4 % of suspended solids may be non-degradable, with accounting for approximately 75 % of removal compared with 15 % through biodegradation [37, 42]. These proportions were not determined experimentally in the present study because suspended solids were not fractionated, therefore, they are cited only as indicative values rather than as evidence for the mechanisms operating in the present system. The SSF-CW system planted with *P. australis* achieved concentration-based TSS removal efficiencies of 84.7–98.8 % (Table 2).

3.5. Overall Removal Efficiency and Compliance

Table 3 summarises the removal efficiencies calculated with (4). Since 42–45 % of the influent volume was lost from the bed (Section 3.1), the mass-based efficiencies are consistently higher than the concentration-based values. The difference is small for COD (0.6–1.6 percentage points) but was greatest for TSS at the shortest HRT (6.4 percentage points). Neglecting the water loss therefore underestimates the actual pollutant removal, particularly at short HRT and in the warmer season.

At the shortest nominal HRT tested (2.0 days), the pilot treated 0.214 m^3/day over 2.25 m^2, corresponding to an areal hydraulic loading of 95 L/m^2.day. Linear scale-up to 0.7 m^3/day gives an indicative surface area of approximately 7.4 m^2, which was selected because it remains within the tested loading range. However, this extrapolation assumes geometric and hydraulic similarity and requires validation at full household flow. Comparison with temperate-climate systems is qualitative; as continuous water-temperature data were unavailable.

At HRTs of 3.0 and 2.5 days, all three parameters complied with column A of QCVN 14:2025/BTNMT. At 2.0 days, COD (8.51 mg/L), and NH_4^+-N (4.45 mg/L) renained below column A, whereas TSS (52.98 mg/L) exceeded column A but complied with column B. Thus, an HRT of 2.5 days or more is required for compliance with column A for all three parameters, while 2.0 days may be acceptable under Column B conditions.

3.6. Comparison with Recent Household-Scale Constructed Wetlands

Table 3 compares the present system with recent studies on household- and small-community-scale constructed wetlands. Two features distinguish the present unit. First, it is a horizontal subsurface-flow bed using a single, locally available plant species and an inexpensive substrate, whereas the compared systems are mostly vertical-flow or hybrid configurations, often using multiple engineered substrates [12]. Second, the system treated real domestic wastewater from an urban residential area, with a COD/TSS ratio typical of Vietnamese households, rather than simulated wastewater [13]. At a comparable or shorter HRT, the present system achieved lower effluent concentrations than the full-scale unit of Temel *et al.* [14] and comparable performance to the hybrid systems. However, its hydraulic loading (63–95 L/m^2.day) was lower than that of the vertical-flow units [11, 12], and the horizontal-flow unit of Shukla *et al.* [40], consistent with its horizontal-flow configuration and longer HRTs. Overall, the comparison suggests that the compact footprint of the present system is primarily associated with the warm climate and short HRTs, rather than from a higher hydraulic loading rate.

3.7. Space, Energy and Maintenance Requirements

For a hypothetical four-person household, linear scale-up from the tested areal hydraulic loading gives an indicative area of 7.4 m² and approximately 4.1 m³ of 2–8 mm gravel at a water depth of 0.55 m. These values are preliminary estimates rather than a validated design. The pilot used a dosing pump, but its model and rated power were not documented; therefore, energy consumption could not be quantified. A gravity-fed arrangement could eliminate pumping where site levels permit. Routine maintenance would include inlet inspection, solids removal, pump checks where applicable, and periodic reeds harvesting. Site-specific structural, waterproofing and access checks are required before rooftop or balcony installation.

The service life and clogging interval were not determined experimentally. Because clogging typically develops first near the inlet, inspection and local gravel cleaning or replacement should be based on observed surface ponding or hydraulic short-circuiting rather than fixed service-life estimate.

Table 3. Comparison of the present system with recent household- and small-community-scale constructed wetlands

System / reference	Substrate; plant	Influent COD / NH_4^+-N / TSS (mg/L)	HRT (d)	HLR (L m^{-2} d^{-1})	Area (m^2)	Removal COD / NH_4^+-N / TSS (%)	Effluent COD / NH_4^+-N / TSS (mg/L)
Horizontal SSF, household (this study)	Gravel 2–8 mm; *P. australis*	222–267 / 48–54 / 291–347	2.0–3.0	63–95	2.25	96–99 / 91–95 / 85–99	3.7–8.5 / 2.9–4.5 / 3.6–53
Hybrid VF + HF, individual houses [10]	Crushed stone, 90 cm; n.r.	n.r.	n.r.	n.r.	n.r.	98 / n.r. / 99 (SS)	n.r.
Vertical SSF, pilot [11]	n.r.; *P. australis*, *C. papyrus*	n.r.	1.12	200	n.r.	81 / 70 / 63 (TS)	n.r.
Surface flow + 3 vertical SSF, rural household [12]	Diatomite, vermiculite, zeolite, hydrotalcite; mixed community	n.r.	2.0	500	4.0	n.r.	n.r.
Horizontal SSF, pilot, simulated wastewater [13]	Gravel; *T. latifolia*, *P. australis*	n.r.	2–10	n.r.	1.0	n.r.	n.r.
Horizontal SSF, secondary treatment of sewage [40]	Coarse and fine gravel 1:2, 70 cm; *T. latifolia*	n.r.	0.5–2.0	171	35	n.r.	n.r.
Horizontal SSF, full scale, village [14]	n.r.; *J. acutus*, *C. selloana*	n.r.	n.r.	n.r.	n.r.	n.r. / 24–29 / 30–37	n.r.

Note: n.r. = not reported in the source consulted; values for the present study are ranges over the three phases

Study limitations. The available records lack direct porosity measurements, continuous water-temperature data, pH and microbiological results, pump specifications, electricity consumption, current unit prices, and complete data for all studies in Table 3. The water-loss measurement procedure and potential contribution of rainfall were also not documented. The three phases covered February-August 2025, representing a single warming period rather than a full seasonal cycle. Conclusions are therefore limited to COD, NH_4^+-N, and TSS under the tested flow conditions.

Three main limitations should be noted. First, the three HRTs were tested consecutively rather than in parallel, therefore, HRTs effects were confounded by the seasonal temperature, system age, and solids accumulation: phase A was operated at air temperatures of 10–20 °C in February–April and phase C at 25–35 °C in July–August. Thus, the increase of the effluent TSS from 3.64 to 52.98 mg/L cannot be attributed to the shortening of the HRT alone. Second, no unplanted control bed was included, so the contribution of *Phragmites australis* - root oxygen release, plant uptake, and the additional attachment surface - was inferred from the literature rather than demonstrated experimentally. Third, only one treatment train was operated, so the 16 samples per phase represent temporal measurements of one system rather than independent replicates.

Future studies should operate parallel planted and unplanted trains at different HRTs over at least one seasonal cycle, with direct measurement of the packed-bed porosity, water-temperature, logging, nitrogen species, and microbiological indicators. This would help separate the effects of hydraulic loading, temperature, and plant, better assess effluent reuse potential.

A detailed economic assessment was beyond the scope of this study because local unit prices, pump energy consumption, and labour costs were unavailable. The reported material quantities can nevertheless support a site-specific cost estimate once these parameters and system specifications are established.

4. Conclusions

This study evaluated a three-module subsurface flow constructed wetland planted with *Phragmites australis* at nominal HRTs of 3.0, 2.5, and 2.0 days. The nominal HRTs were calculated using an assumed gravel porosity of 0.35; direct porosity measurement should be reported in future work. At HRTs of 3.0 and 2.5 days, mean effluent COD, NH_4^+-N, and TSS complied with column A of QCVN 14:2025/BTNMT. At 2.0 days, COD and NH_4^+-N complied with column A, whereas mean TSS complied with column B. These conclusions apply only to the measured parameters.

At the shortest tested HRT, the pilot treated 0.214 m^3/day at an areal hydraulic loading of 95 L/m^2.day. Linear scale-up to 0.7 m^3/day gives an indicative area of 7.4 m^2, but full-scale hydraulic validation is required. The estimated 2.0 m^2 from the Kickuth equation should be regarded as an illustrative kinetic because its temperature and porosity inputs were not independently verified.

Overall, the system shows potential as a decentralized physicochemical treatment step under the tested conditions. However, microbiological indicators, including coliforms, were not measured. Therefore, the results do not establish suitability for landscape irrigation or other reuse applications, which require microbiological testing and compliance with applicable public-health and reuse requirements.

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Contributions of Authors

Nguyen Hoang Dung: Funding acquisition, Conceptua-lization, Methodology, Validation, Writing - review & editing. Nguyen Hoang Nam: Supervision, Conceptualization, Methodology, Investigation, Resources, Writing -original draft, Writing - review & editing. Nguyen Thi Ha: Project administration, Methodology, Visualization, Data curation, Investigation, Validation, Formal analysis. Pham Viet Duc: Software, Methodology, Data curation, Investigation, Validation. Dang Thi Ngoc Thuy: Investigation, Data curation, Formal analysis, Writing -review & editing.

Conflict of Interest

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

Data Availability

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

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