

Performance Evaluation of a System of Horizontal Subsurface Flow Constructed Wetlands Planted with *Typha angustifolia* for Household Greywater Treatment

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Abstract— The challenge of decentralized wastewater management in rural areas necessitates robust, low-cost technologies for greywater treatment. A study was conducted with the objective of analyzing the efficiency of four Horizontal Subsurface Flow Constructed Wetlands (HSFCW) in series for household greywater treatment using the macrophyte *Typha angustifolia* and a pumice substrate. The methodology involved five monitoring events over a 120-day period, with sampling at the inlet and outlet of each HSFCW. Field parameters, including pH (8.12) and water temperature (24°C), as well as the final turbidity (8.2 NTU), were within permissible ranges. An increase in electrical conductivity was observed, reaching 1.982 mS/cm. Contaminant removal percentages were 97.52% for oils and greases, 96.66% for BOD₅, 93.21% for COD, 98.11% for nitrates, 97.63% for total phosphorus, and 46.21% for TSS. The implementation of the HSFCW with *Typha angustifolia* and pumice substrate proved to be an efficient alternative for treating greywater, exhibiting a high potential for sustainable and decentralized solutions. This validated performance makes it suitable for future integration with real-time monitoring and smart management systems.

Keywords- Constructed wetland, greywater, water treatment, removal efficiency, *Typha angustifolia*.

I. INTRODUCTION

Wastewater treatment constitutes one of the greatest environmental challenges of the 21st century, particularly in rural areas of low- and middle-income countries where sanitation infrastructure is not widespread. The so-called greywater, which comes from showers, sinks, washing machines, and dishwashers, represents between 50% and 70% of the total volume of domestic wastewater [1]. This water contains organic compounds, nutrients, microorganisms, and chemicals that can generate negative impacts on ecosystems if discharged without treatment [2].

In response to this problem, constructed wetlands have emerged as a solution [3]. In particular, Horizontal Subsurface Flow Constructed Wetlands (HSFCW) offer a technology based on natural principles. In this system, water

flows through a permeable bed planted with macrophytes and replicates processes such as sedimentation, filtration, adsorption, aerobic and anaerobic biodegradation, as well as nutrient uptake by the plants. However, its performance depends on a series of variables, such as Hydraulic Retention Time (HRT), temperature, substrate type, bed surface area, depth, slope, the plant species used, and the hydraulic and organic load.

Despite this, the reviewed literature does not document experiences of this system in real-world settings. It is in this context that the present study is proposed, with the objective of designing, constructing, and evaluating the performance over 120 days of an HSFCW system in series with *Typha angustifolia* and a pumice substrate for the treatment of greywater generated in rural homes. The reliability of this natural system is essential for the subsequent integration of IoT sensors and optimization models.

The rest of the document is organized into five sections. Section 2 presents a review of the background and related studies. Section 3 describes the parameters considered and the methodology used for the design, construction, and evaluation of the system. Section 4 presents and analyzes the results obtained. Section 5 discusses these findings in relation to similar research. Finally, Section 6 summarizes the main conclusions of the study and proposes future lines of research.

II. RELATED WORK

This section presents a review of the academic literature on the use of constructed wetlands for greywater treatment, with a focus on horizontal subsurface flow systems. The studies analyzed demonstrate the effectiveness of this technology for removing various contaminants, as well as its applicability in single-family and rural contexts.

The performance of subsurface flow constructed wetlands has been compared in several studies. In 2018, Ramprasad et al. [4] evaluated the performance of three pilot-scale HFCW, vertical flow (VFCW), and hybrid (HYCW). These systems were fed with greywater and

planted with *Phragmites australis*. The results showed that the HFCW was the most efficient, with average removal efficiencies of 95% for BOD₅, 96% for COD, 98% for TSS, 92% for Total Phosphorus and 92% for Total Nitrogen.

In 2024, Suleman et al. [5] studied the performance of a domestic-scale HFCW for greywater treatment. The system used *Eichornia crassipes* and was evaluated with HRT of two and three days. Removal efficiencies varied, reaching values between 74% and 93% for BOD₅ and between 47% and 80% for COD with a two-day HRT. With a three-day HRT, removals improved, achieving between 67% and 96% for BOD₅ and between 57% and 91% for COD. The results concluded that the effluent met government standards for both retention times, establishing HFCW as an effective solution on a single-family scale.

The versatility of constructed wetlands for treating wastewater under various conditions has also been documented. For example, Abunaser S. G. and Abdelhay A. [6] in 2020 implemented a pilot project in Jordan to treat greywater for reuse in irrigation. The authors designed four VFCW systems and demonstrated their effectiveness with removal efficiencies of 90% for BOD₅, 90% for COD and 92% for TSS. Meanwhile, Hdidou et al. [7] in 2022 conducted a review of 29 studies to evaluate the potential of wetlands in Morocco. They concluded that they are a simple, sustainable, and economical technology for wastewater treatment in rural areas.

In 2018, Meso et al. [8] considered the use of the dynamic and mechanistic compartmental model "Constructed Wetlands 2D" (CW2D) to simulate the hydraulic and treatment performance of a horizontal subsurface flow wetland (HSFCW). The model was tested on a pilot-scale HSFCW system in Nakuru, Kenya, and the results showed a good match with the measured data, validating CW2D as an effective tool for the evaluation and optimization of these systems.

Other studies have explored modifications to improve wetland performance. In 2017, Martinez et al. [9] evaluated an HSFCW in that used blast furnace slag as a substrate. The system achieved an average removal of 96.9% for total phosphorus, demonstrating that the improvements introduced can achieve similar or superior performance to some hybrid systems. On the other hand, Jehawi et al. [10] in 2020 used a hybrid wetland with a three-stage aeration system (surface, vertical, and horizontal flow) for domestic wastewater treatment. Planted with the native species *Scirpus grossus*, the system achieved an average removal of 84.7% of NH₄-N and 71.0% of PO₄-P, confirming the technical and economic viability of this configuration for small communities.

Based on the literature analyzed, the effectiveness of constructed wetlands, particularly horizontal subsurface flow systems, for greywater treatment is evident. However, there is a need for more studies that focus on the specific evaluation of macrophytes such as *Typha angustifolia* and pumice as part of the substrate in these systems, as well as the implementation of substrates like pumice. This work contributes to filling this gap by providing a comprehensive evaluation of the performance of a system of HSFCW.

III. MATERIALS AND METHODS

This section describes in detail the experimental design, the components of the HSFCW system, the procedures for data collection and analysis, and the variables evaluated. Calculations, dimensioning, and figure generation were executed using programmed scripts in MatLab 2025a.

A. Design and Construction of the HSFCW

The construction of the HSFCW system involved the excavation of trenches, the installation of a low-density polyethylene (LDP) geomembrane, and a layered substrate as shown in Figure 1, consisting of 33% pumice, 45% gravel, and 22% large stones. The macrophyte *Typha angustifolia* was used.

The porosity of the three materials was calculated volumetrically with a 0.125 m³ cube and is shown in Table I.

TABLE I. SUBSTRATE MATERIAL POROSITY AND VOLUME PERCENTAGE

Material	Porosity (ϕ)	Volume Percentage
Gravel	0.37	45%
Stone	0.44	22%
Pumice	0.49	33%

The average porosity of the system was 0.425. The total working volume of the HSFCW is 19.35 m³. It was estimated to operate at 70% due to sludge generation. The design flow rate will be 5.76 m³/day.

The HSFCW's surface area was calculated using (1) the first-order biological filter design equation utilized to model BOD₅ reduction.

$$S = \frac{Q \cdot \ln\left(\frac{C_i}{C_e}\right)}{K_T \cdot h \cdot \eta} \quad (1)$$

Where Q is the design flow rate, C_i is the influent BOD₅ concentration (419 mg/L), C_e is the desired effluent concentration (30 mg/L), K_T is the first-order reaction rate constant, h is the depth (1.2 m), and η is the average porosity of the system.

K_T was calculated using (2):

$$K_T = 1.104 \times 1.06^{T-20} \quad (2)$$

Where T is the average water temperature. According to historical data, the average annual temperature is 24°C. The calculations resulted in a K_T of 1.39 and a surface area (S) of 21.35 m². The HSFCW has a volume similar to a frustum of a pyramid. The dimensions of the HSFCW at the bottom base are 3.75 m by 2.5 m, at the top they are 6.0 m by 4.0 m, with a depth of 1.20 m and a slope of 1%. The Hydraulic Retention Time (HRT) was calculated using (3).

$$TRH = \frac{V}{Q} \quad (3)$$

Where V is the effective volume of the system (19.35 m³). The calculation resulted in a HRT of 3.36 days.

The construction of 4 wetlands with the same characteristics in series has been considered, as shown in the diagram in Figure 1.

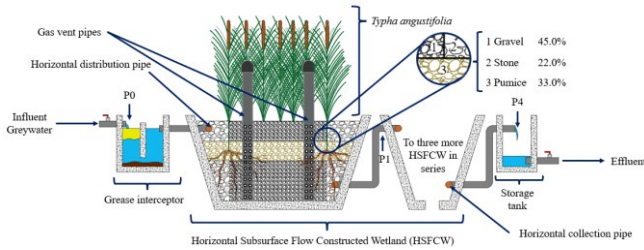


Figure 1. Cross-Section of HSFCW System

B. Sampling of Post-Treatment Parameters

Measurements of the physicochemical parameters of the greywater were taken before treatment on day 0 at point P0 (see Figure 1). Subsequently, four monitoring events were carried out after the HSFCW implementation: at 30, 60, 90, and 120 days. Sampling points P1, P2, P3, and P4 were located at the outlet of each HSFCW. The analyses were performed according to [11]. All field instruments were verified using certified standards. The analytical quality assurance was guaranteed by using trip blanks, field blanks, field duplicates, and the appropriate preservatives.

C. Evaluation of Contaminant Removal

The evaluated parameters included pH, temperature, electrical conductivity, turbidity, BOD₅, COD, TSS, oils and greases, total phosphorus, and nitrate. The percentage of contaminant removal was calculated using (4).

$$R = \frac{C_i - C_e}{C_i} \times 100 \quad (4)$$

D. Evaluation and Comparison Criteria

In order to evaluate the efficiency of the HSFCW in treating greywater, the values of the physicochemical parameters measured in the effluent were compared with the Maximum Permissible Limits (MPL) established in the guidelines of the International Finance Corporation (IFC)

E. Biodegradability Index (BI)

Wastewater biodegradability was assessed via the index calculated using the relationship provided in (5):

$$BI = \frac{BOD_5}{COD} \quad (5)$$

This index is a key indicator of the nature of the organic matter. A value greater than 0.5 suggests that the organic matter is readily biodegradable, making it suitable for biological treatment. The evolution of this ratio over the treatment period was used to measure the efficiency of the wetland in removing the easily degradable fraction.

IV. RESULTS

This section presents the results of the HSFCW's application for greywater treatment. First, the initial characterization of the wastewater before treatment is detailed. Subsequently, the physicochemical parameters of the effluent are compared with the MPL throughout the monitoring period, and the removal percentage is analyzed.

A. Wastewater Characterization and Biodegradability Analysis on Day 0

The initial monitoring revealed the composition of the greywater before it was treated. The results showed that the pH (8.17) and temperature (24 °C) were within an acceptable range for biological processes. However, the BOD₅ at 419 mg/L and the COD at 751 mg/L significantly exceeded the World Bank's discharge limits (30 mg/L and 125 mg/L, respectively). Other parameters, such as nitrates (23.3 mg/L) and total phosphorus (9.3 mg/L), also indicated a high pollutant load.

To evaluate the nature of the organic matter, the BOD₅/COD ratio was analyzed. The biodegradability index of the influent was 0.56. This value, being greater than 0.5, indicates that the organic matter in the greywater was predominantly biodegradable and, therefore, highly susceptible to being treated by a biological system like an HSFCW.

B. In-Situ Parameter Analysis

The evaluation of the parameters over five monitoring events (Day 0, 30, 60, 90, and 120) showed the following:

1) *pH*: It was maintained in a stable range of 8.17 to 8.12, which is within the permissible limit (6.0-9.0), indicating that the system maintains adequate conditions for the development of microorganisms without significant alterations in acidity or alkalinity.

2) *Temperature*: The average was 24.0°C, but peaks of 29.0°C were observed. This increase can be attributed to solar radiation and the metabolic activity of microorganisms, which can positively influence degradation rates.

3) *Conductivity*: An increase from 1.617 mS/cm to 1.982 mS/cm was observed at the end of the period. This rise is explained by the concentration of dissolved salts and ions due to evaporation and the degradation of organic matter, which releases ions into the medium.

4) *Turbidity*: The initial value of 4 NTU increased to 8.2 NTU. This increase is attributed to bioaccumulation in the gravel bed, which includes the formation of a biofilm on the roots and suspended particles resulting from the decomposition of organic matter and the proliferation of microorganisms.

C. Laboratory Parameter Analysis

The concentrations of the parameters and their evolution are analyzed below. Figure 2 shows the evolution of the concentrations during the monitoring period on a logarithmic scale, and Figure 3 shows the removal efficiency.

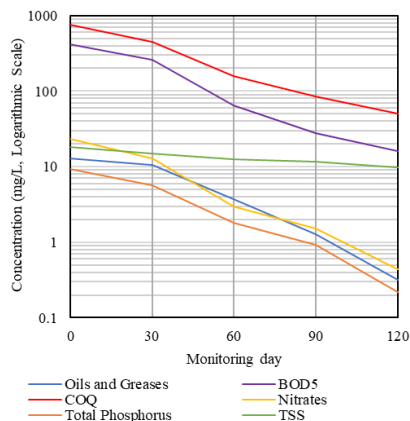


Figure 2. Evolution of Physicochemical Parameter Concentrations in the Artificial Wetland During the Monitoring Period in P4.

1) *Oil and Grease*: A removal of 97.52% was observed. This result demonstrates the efficiency of the grease trap; however, since this parameter is difficult to biodegrade, this high removal may be due to its accumulation in the HSFCW. The values remained well below the World Bank's MPL of 10 mg/L.

2) *BOD₅*: A removal efficiency of 96.66% was achieved. This result shows the great capacity of the system to degrade biodegradable organic matter through the activity of aerobic and anaerobic microorganisms that form the biofilm on the roots of the cattail and in the gravel. The final value is 14 mg/L, which is below the MPL.

3) *COD*: A removal efficiency of 93.21% was achieved. This demonstrates the high efficiency of the system in degrading a large portion of organic matter. The final concentration was 51 mg/L, which is below the MPL.

4) *Nitrates*: A significant decrease was experienced with a performance of 98.11%. The high removal is explained by the assimilation of nitrates by the macrophytes as an essential nutrient for their metabolism, and by the microbiological processes of nitrification (oxidation of ammonium to nitrate) and denitrification (conversion of nitrate to gaseous nitrogen) in the HSFCW anoxic zones.

5) *Total Phosphorus*: A drastic reduction was recorded, representing an efficiency of 97.63%. This removal is explained by two main mechanisms: absorption by the macrophytes in their metabolism and chemical precipitation and adsorption in the gravel substrate, where phosphorus forms insoluble complexes with metals, such as calcium, iron, and aluminum. This final value complies with the World Bank's MPL of 2 mg/L.

6) *Total Suspended Solids (TSS)*: experienced a 46.21% removal, decreasing from 18.22 mg/L to 9.80 mg/L. This low removal percentage is due to the bioaccumulation of decomposing organic matter in the gravel bed and the generation of algal and microorganism biomass, which

counteracts physical filtration. The initial concentrations were already below the World Bank's MPL of 50 mg/L.

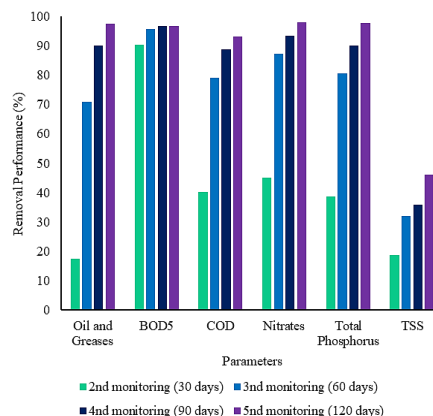


Figure 3. Evolution of Removal Performance.

D. Biodegradability Index:

The final monitoring showed that the BOD₅/COD ratio in the effluent was 0.27. The decrease in the ratio from 0.56 to 0.27 is clear evidence that the HSFCW was highly efficient in the removal of the biodegradable fraction of the organic matter, leaving a greater proportion of recalcitrant or non-biodegradable compounds.

E. Performance de remocion de los HSFCW

The BOD₅ removal efficiency in the four HSFCWs in series improved over time. The system demonstrated a high purification capacity, as a removal of 91.75% was reached at the outlet of the last HSFCW (P4) at 30 days. At 120 days, the performance was even more notable, achieving 94.27% removal with just the first HSFCW (P1). There is a high purification capacity, reaching a final removal in P4 of 96.79% at 120 days. It confirms the effectiveness of this series configuration for the degradation of organic matter. Figure 4 shows the evolution of the removal performance of BOD₅ concentrations during the monitoring period.

V. DISCUSSION

The system's performance for organic matter removal was notable, achieving an efficiency of 96.66% for BOD₅ and 93.21% for COD. These results are within the performance range documented in similar studies. Suleman et al. [5] reported BOD₅ removal efficiencies between 74% and 93%, and COD between 47% and 91% in a domestic-scale HFCW. Similarly, the results are comparable to the findings of Abunaser S. G. et al. [6] in a vertical flow system, which achieved 90% for BOD₅ and COD, demonstrating competitiveness with HFCWs.

The removal of nutrients, Total Phosphorus and Nitrates, was particularly successful and compares favorably with reference studies. The 97.63% efficiency for Total Phosphorus is remarkable and aligns almost identically with the 92% efficiency reported by Ramprasad et al. [4] in their hybrid system, as well as the 96.9% from Martinez et al. [9] in their optimized system with blast furnace slag. This

consistency in results underscores the effectiveness of HFCWs for chemical precipitation and the absorption of phosphorus by plants and microorganisms. For nitrates, the removal efficiency of 98.11% surpassed the 84.7% efficiency for $\text{NH}_4\text{-N}$ obtained by Jehawi et al. [10] in a hybrid wetland.

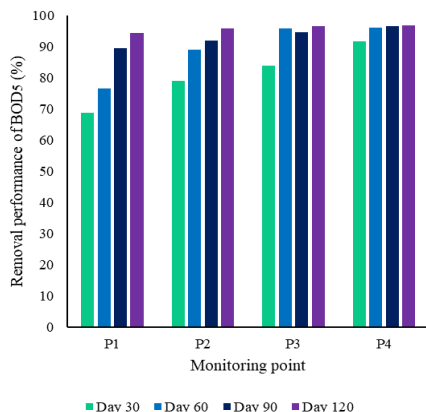


Figure 4. Evolution of Removal Performance of BOD₅

The high BOD₅ removal efficiency at 120 days (96.66%) confirms the effectiveness of the HSFCW system. However, a single pond might be sufficient, since 94.27% removal was achieved at P1 in the same period. This time is explained by the need for adaptation and development of microorganisms in the substrate and the *Typha angustifolia*.

Although a high TSS removal was not recorded, it does not represent a disadvantage. This is attributed to the generation of biofilms and algae. The concentrations of oils and greases showed a high removal of 97.52%, mainly thanks to the grease trap. All evaluated parameters complied with the MPL. In summary, the system is shown to meet discharge standards, despite challenges in the removal of certain contaminants, as discussed in the literature [7].

VI. CONCLUSION

This work is an initial evaluative study establishing base performance and feasibility. This study contributes directly and significantly to Sustainable Development Goal (SDG) 6: Clean Water and Sanitation, by demonstrating the viability of an effective technology for wastewater treatment and its potential for safe reuse. In this context, the performance of a HSFCW has been evaluated as a solution for greywater treatment. The system proved to be highly effective in the removal of the main pollutants, with efficiencies of up to 97.52% for oils and greases, 96.66% for BOD₅, 93.21% for COD, 98.11% for nitrates, 97.63% for Total Phosphorus, and 46.21% for TSS. This demonstrates that the HSFCW is capable of operating effectively and complying with discharge standards, confirming the viability of using constructed wetlands as a greywater treatment technology.

Future work will focus on the optimization of the system by exploring the Hydraulic Retention Time (HRT), studying other native macrophyte species, and testing different types of substrate. Furthermore, its connection with the principles of digitalization will be addressed. This involves the

incorporation of sensors that capture data in real time [12] to enable remote monitoring of key parameters and the development of predictive models for system optimization, thus establishing a direct bridge between environmental biotechnology and smart infrastructure solutions.

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