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Comparative analysis of greywater pollutant removal efficiency with horizontal free water surface flow wetland with other wetland technologies

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A R T I C L E I N F O

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A B S T R A C T

The reuse of treated wastewater for agriculture and other purposes is globally recognized as a reliable water source. Constructed wetlands are cost-effective and reliable green technologies for wastewater treatment, offering an environmentally friendly and affordable solution with minimal operational and maintenance requirements. This study assessed four wetland technologies (HFWSF, VFSF, VSSF, and HSSF) for treating greywater according to regulatory standards. The technologies effectively maintained pH levels, and both treated and untreated greywater samples met FEPA limits. They efficiently reduced dissolved and suspended particles, remaining below FEPA discharge limits for conductivity, TDS, turbidity, and TSS. However, elevated ammonia levels in both treated and untreated samples required additional treatment or mitigation. Sulphate levels were successfully mitigated, and phosphorus limits were met, with HFWSF already compliant even before treatment. Nitrate levels were reduced to meet FEPA limits, ensuring regulatory compliance. While BOD limits were met in both treated and untreated samples, untreated samples exceeded COD limits, necessitating more efficient treatment methods. HFWSF and HSSF complied with COD limits, whereas VFSF and VSSF did not. Both treated and untreated samples exceeded FEPA limits for oil and grease, indicating the need for additional treatment. Untreated samples exhibited high coliform contamination levels, underscoring the importance of effective treatment. However, all technologies successfully reduced coliform levels in treated samples, meeting FEPA limits and confirming treatment effectiveness. The combination of *Typha* (*Domingensis*) in the horizontal subsurface flow constructed wetland improved pollutant removal, nutrient removal, and contaminant elimination. Incorporating water *Hyacinth* (*Eichhornia crassipes*) with horizontal free water surface flow wetland technology demonstrated the highest efficacy in removing various pollutants. This combination outperformed other wetland technologies in effectively removing pollutants, including ammonia (60%), oil and grease (78.46%), COD (85%), TP (37.04%), FC (75%), and TC (79.59%), representing significant progress in greywater treatment.

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1. Introduction

The treatment and management of greywater, which encompasses wastewater generated from domestic sources such as showers, sinks, and laundry [1], play a vital role in addressing water scarcity and minimizing environmental pollution [2,3]. Constructed Wetlands technologies are designed to replicate the processes that occur in natural wetlands under controlled conditions. They are innovative technologies developed to mimic natural wetland systems for wastewater treatment [4–8]. ′These wetlands effectively reduce or eliminate pollutants from wastewater through engineered design and the presence of natural floating vegetation [9]. Various wetland technologies have been explored as promising alternatives for greywater treatment due to their potential for sustainable and cost-effective pollutant removal [10,11]. In this study, we aim to conduct a comparative analysis of the pollutant removal efficiency between a horizontal free-water surface flow wetland and other wetland technologies.

Greywater treatment through wetland systems offers several advantages, including natural processes, low energy requirements, and potential nutrient recovery. However, the performance of different wetland technologies in terms of pollutant removal efficiency can vary significantly [10]. Although previous studies have investigated the effectiveness of wetlands in treating greywater, a comprehensive comparative analysis to assess the specific benefits and limitations of various wetland technologies [12]. The current state of research in greywater treatment with wetland technologies has provided valuable insights into the potential of these systems. Studies have focused on aspects such as hydraulic design, vegetation selection, and system optimization [13,14]. Some research has examined the removal of specific pollutants, such as organic matter, nutrients, and pathogens [15]. However, a lack of comprehensive comparative studies exists that directly compare the pollutant removal efficiency of different wetland technologies, including the horizontal free water surface flow wetland. Controversies and diverging hypotheses in the field primarily revolve around the performance variations among different wetland technologies. Some researchers argue that certain wetland configurations can exhibit higher pollutant removal efficiencies, while others suggest that specific design characteristics or operational parameters can be more influential in achieving effective greywater treatment [16,17]. These different hypotheses underscore the need for a systematic comparative analysis to better understand the relative performance of wetland technologies in greywater treatment. The main objective of this study is to compare the greywater pollutant removal efficiency of a horizontal free-water surface flow wetland with other wetland technologies. By evaluating the effectiveness of different wetland configurations, the study aims to identify the strengths and limitations of each technology and provide valuable insights for the selection and design of efficient greywater treatment systems. In conclusion, this study addresses the critical need for a comparative analysis of the efficiency of greywater pollutant removal with a specific focus on the horizontal free-water surface flow of wetlands and other wetland technologies. By investigating the performance variations and potential controversies in the field, this research aims to contribute to the understanding of optimal wetland configurations for effective and sustainable greywater treatment. The findings of this study will provide valuable guidance for policymakers, engineers and researchers involved in the design and implementation of greywater treatment systems, ultimately promoting sustainable water management practices and environmental protection.

1.1. Rationale

The motivation behind this study arises from the need for affordable and sustainable solutions to wastewater treatment, particularly in small rural communities and developing countries. By evaluating the performance of different wetland technologies, our goal was to identify the most effective and efficient approach to the treatment of greywater. This knowledge can guide decision-making processes for implementing constructed wetlands and contribute to the overall objective of reducing pollutant loads in wastewater. Through this comparative analysis, we aimed to offer insights into the suitability and performance of HFWSF wetland technology for treating greywater. The findings of this study can advance wastewater treatment technologies, particularly in areas with limited resources and infrastructure.

2. Material and methods

2.1. Study area

The research for this study was carried out in Kaduna state, located in the northern region of Nigeria. Kaduna state is known for its diverse landscape, including hills, valleys, plains, and plateaus, within the ecological zone of the Sudan savannah. The capital city of Kaduna is surrounded by six neighboring states: Kano, Katsina, Niger, Zamfara, Kogi, and Plateau. The study focused on the National Water Resources Institute (NWRI), which was established in 1979 in Kaduna. The institute is situated in the northern part of the state at coordinates N10° 34′44.2 latitude and E07° 25′18.2 longitude, with an elevation of approximately 586 m [18]. The research area around the NWRI is characterized by the presence of the Kaduna River, an important water source, and typical Sudan savannah vegetation consisting of grasses, trees, and shrubs. Kaduna experiences a tropical climate with a wet season from April to October and a dry season from November to March. The dry season is accompanied by cold temperatures and dry harmattan winds originating from the northeastern part of Nigeria [19]. The NWRI site provides an ideal environment for research and education, offering various courses and programs related to water resource management, hydrology, irrigation, water quality, and sanitation. The institute is well equipped with facilities such as staff quarters, student lecture halls, laboratories, hostels, office buildings, and a library. Staff housing at NWRI is allocated based on rank, with senior members residing in bungalows and blocks of flats, while junior staff occupies one-bedroom flats. The bungalows have individual septic tanks and septic tanks to manage greywater and black water, while the flat

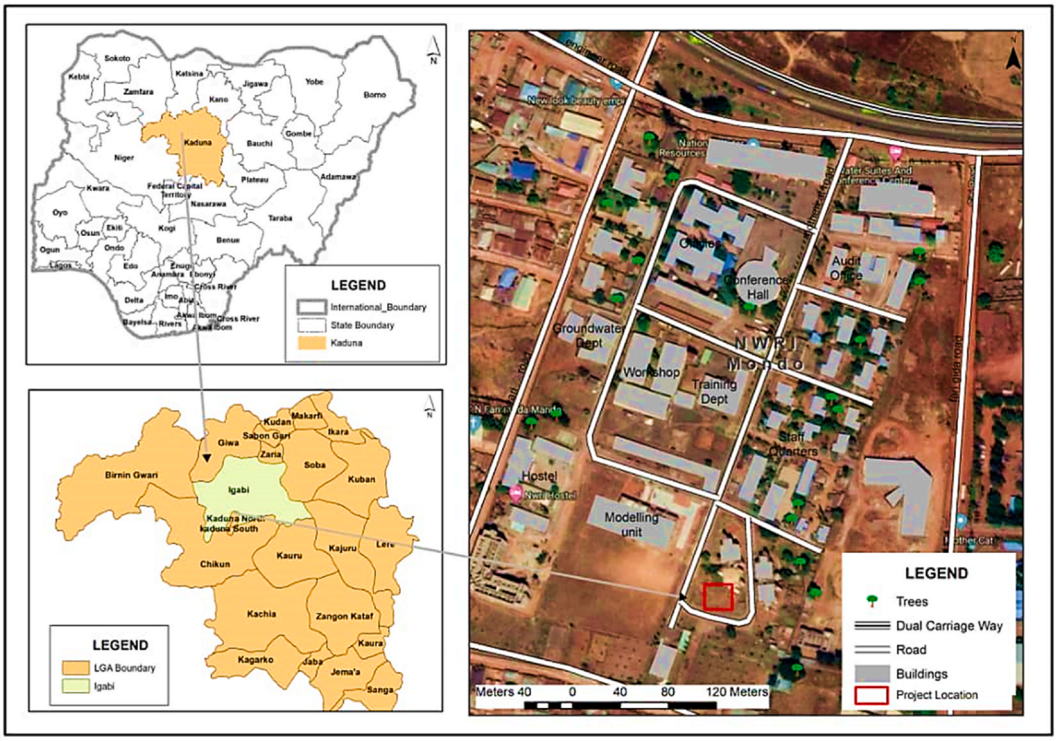

Fig. 1. Map showing the study area
Source: Field Survey, 2022.

block of flats is connected to a centralized sewer system. (see Fig. 1)

2.2. Overview of the experimental set-up for the four alternative wetland technologies

The design of the alternative constructed wetland technologies involved the use of rectangular black plastic containers positioned beside the greywater facility. To provide support, the containers were elevated on metal rod stands and equipped with plastic taps at both the top and bottom ends. The experimental setup for the four alternative wetland technologies was developed to create an effective treatment process by facilitating interaction between vegetation and greywater flow. Based on existing literature and field procedures, four plastic containers were constructed to simulate the different constructed wetland technology systems, namely horizontal free water surface flow (HFWSF), Horizontal subsurface flow (HSSF), vertical free surface flow (VFSF) and vertical subsurface flow (VSSF).

2.3. Experimental procedure

Greywater was collected from households in the study area, channeled through a central pipe to the detention basin, and then stored in a storage tank. The greywater was pumped to each constructed wetland via their respective pipes. The greywater was then channeled to the roots of the plants, where it undergoes removal processes such as absorption, filtration, sedimentation, reduction, oxidation, and precipitation [20]. The inlet tap served as the entry point for the greywater, while the outlet tap facilitated the discharge of the effluent. The greywater was collected in a detention basin, piped to a storage tank, and then fed into plastic containers to ensure a continuous supply of greywater. The flow of greywater from the storage tank to the plastic containers was controlled using stop valves on the inlet pipes. Each of the four plastic containers utilized in the experiment for the wetland technologies (HSSF-CWT, VSSF-CWT, VFSF-CWT, and HFWSF-CWT) measured the same dimensions of 0.5 m in length, 0.32 m in width, and 0.24 m. Water *Hyacinth* (*Eichhornia crassipes*) and *Typha* (*Domingensis*) were planted in plastic containers, and each technology was designed based on flow pattern and direction style.

2.4. Sample collection/analysis

Greywater samples were collected from each cell, which is from the inlet and outlet cells of the plastic container wetland. The sample was collected in a sterilized plastic container and analyzed in a laboratory for physical, chemical, and microbial analysis. Each plastic container contained 2 L per volume of greywater, which was used to collect the sample from the study site in triplicate. This

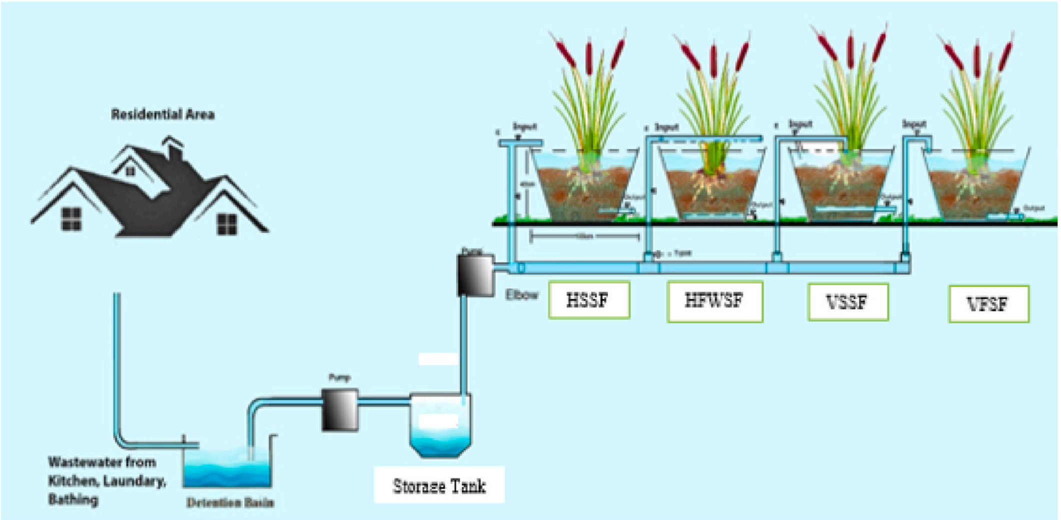

Fig. 2. Lab-scale constructed plastic wetland cells.

sample collection process was done for sixteen (16) weeks. The samples were prepared, measured, and analyzed by the American Public Health Association standard method for water and wastewater examination (APHA, 2012) [21]. Equation (1) shows the calculation of the removal efficiency in Fig. 6.

$$\textbf{Contaminat removal}\ (\%) = \frac{\textbf{Cin} - \textbf{Cout}}{\textbf{Cin}} \tag{1}$$

Where C_{in} is the influent concentration and C_{out} is the effluent concentration in mg/L.

2.5. Laboratory analysis/water quality monitoring

Greywater samples were collected from the outlet of each wetland technology (black plastic container) every 2 weeks for 4 months. The greywater quality in the wetland technologies was monitored for a continuous period of four months using a plastic container as a continuous flow system. Physical parameters such as pH, temperature, turbidity, electrical conductivity (EC), and total dissolved solids (TDS) were measured on-site, while analyses such as sulphate, total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus, nitrate, ammonia, oil and grease, total coliform, and feacal coliform were analyzed in the laboratory. All sample collection, preparation, and analysis were conducted according to the standard methods recommended by APHA in 2012. Table 1 outlines the analytical methods and instruments used to analyze each greywater parameter in this study.

Table 1
Analytical methods and instruments used in the analysis of the greywater in the study.

Parameters	Unit	Method	Equipment/Instrument
pH		pH meter	Wagtec pH meter/probe
Temperature	°C	Thermometer	Wagtec Thermometer
Electrical Conductivity	(μS/cm)	Conductivity meter	Wagtec Conductivity meter
Total Dissolve Solid	ppm/ mg/L	Conductivity meter/TDS	Wagtec TDS meter
Turbidity	NTU	Turbidimeter	Hach Turbidimeter
TSS	mg/L	Gravimetric method	Filtration setup (e.g. filter papers, filter funnel, vacuum pump), Analytical balance.
Biochemical oxygen demand (BOD)	mg/L	Empirical analysis using a 5-day incubator at 20 °C (BOD bottle method)	BOD bottles, incubator, water bath
Chemical oxygen demand (COD)	mg/L	Close reflux method (Dichromate method)	Spectrophotometer, Regents
Total phosphorus	mg/L	Spectrophotometer method	Spectrophotometer, regents
Nitrate	mg/L	Spectrophotometer method	Spectrophotometer, regents
Ammonia	mg/L	Spectrophotometer method	Spectrophotometer, regents
Sulphate	mg/L	Spectrophotometer method	Spectrophotometer, regents
Oil and grease	mg/L	Gravimetric method or Solvent extraction method	Analytical balance, Separatory funnel, Solvent
Total and feacal coliform	CFU/ 100 mL	Membrane filtration method	Membrane filtration setup (0.45 mm pore size membrane filter paper, filtration flask, *m*-Endo agar, TC and FC, incubator 37 °C and 44 °C).

2.6. Statistical/data analysis

To assists in evaluating if there are significant variations in the wetland technologies, the laboratory results were analyzed using two-way ANOVA in Excel Data Analysis tools. The analysis focused on comparing the means of the different wetland technologies and plotting against the discharge limits of the Federal Environmental Protection Agency (FEPA) for greywater. As presented in Tables 2 and 4 (see Fig. 2).

3. Results

The study was to investigate treated and untreated greywater with different wetland technologies with the discharge limits established by the Federal Environmental Protection Agency (FEPA). Furthermore, the effectiveness of the wetland was examined and presented in Figs. 3.3–7. Four wetland technologies, namely, HSSF-CWT, HFWSF-CWT, VSSF-CWT, and VFSF-CWT, were evaluated using different macrophytes such as water hyacinth (*Eichhornia crassipes*) and *Typha* (*Domingensis)* each wetland.

4. Discussion

The study examined the properties of untreated and treated greywater flowing through inlet and outlet pipes in four distinct wetland plastic cells. It compared these findings to the discharge limits set by the Environmental Protection Agency and assessed additional factors. The research also evaluated the efficiency of contaminant removal through the treatment of water hyacinth (*Eichhornia crassipes*) and Typha (Domingensis) wetland plants within the constructed wetland technologies.

4.1. Characterization of the greywater with wetland technologies

Fig. 3, shows that the pH levels of both treated and untreated greywater samples collected from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies met the discharge limits specified by the Federal Environmental Protection Agency (FEPA). This indicates that the pH of the greywater, whether treated or untreated, from all four wetland technologies falls within the acceptable range specified by the FEPA discharge limits. The compliance of pH levels with FEPA discharge limits in the studied constructed wetland technologies demonstrates their effectiveness in maintaining the required pH standards for greywater treatment.

Fig. 3 shows that the findings of the study demonstrated that both the treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited electrical conductivity levels that were below the discharge limits specified by the Federal Environmental Protection Agency (FEPA). This indicates that the electrical conductivity of the greywater regardless of whether it was treated or untreated, from all four wetland technologies remained within the acceptable range outlined by the regulatory standards.

Fig. 3 shows that the results of the study revealed that both the treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited total dissolved solids (TDS) levels that were below the discharge limits set by the Federal Environmental Protection Agency (FEPA). This indicates that the concentration of dissolved solids in the greywater, regardless of the treatment status, complied with the regulatory standards outlined by FEPA. The attainment of TDS levels below the FEPA discharge limits in the investigated constructed wetland technologies highlights their effectiveness in reducing the concentration of dissolved solids in greywater. These findings suggest that the examined wetland technologies possess the capability to eliminate different dissolved substances and play a role in preserving water quality within the discharge limit. The ability of the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies to consistently achieve TDS concentrations below the FEPA discharge limits demonstrates their potential as viable options for treating greywater and reducing the content of dissolved solids effectively.

Fig. 3 shows that the findings of the study demonstrated that both the treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited turbidity levels that were below the discharge limits specified by

Table 2
Summary of the statistics analysis of untreated and treated greywater with constructed wetlands technologies.

Parameter/units		Untreated	Treated			
			HFWSF	VSSF	VFSF	HSSF
Ammonia (mg/L)	Min -Max	1.9–1.9	1.3–1.8	1.5–1.9	1.7–1.9	1.8–1.9
	Mean-STD	1.9 ± 0	1.6 ± 0.1773	1.7 ± 0.1553	1.8 ± 0.0916	1.9 ± 0.0354
COD (mg/L)	Min -Max	600–600	90–265	270–303	111–262	279–305
	Mean-STD	600 ± 0	170.875 ± 57.8827	286.625 ± 12.7160	178.625 ± 55.28094	291.5 ± 10.5289
Faecal coliform (CFU/100 mL)	Min -Max	130–130	20–84	70–130	28–87	43–98
	Mean-STD	130 ± 0	50.625 ± 21.1318	97.375 ± 9.4565	57.25 ± 20.4712	70.625 ± 19.7335
Oil and grease (mg/L)	Min -Max	780–780	168–458	178–426	200–460	220–462
	Mean-STD	780 ± 0	252.5 ± 99.9986	257.625 ± 90.0919	288.125 ± 91.4150	300.375 ± 84.8190
Total coliform (CFU/100 mL)	Min -Max	600–600	150–420	187–462	154–422	200–462
	Mean-STD	600 ± 0	308 .75 ± 119.4604	349.75 ± 101.6672	316.75 ± 118.1715	370.625 ± 07.0526
TP (mg/L)	Min -Max	2.7–2.7	1.7–1.9	2.6–2.94	2.1–2.46	2.5–2.87
	Mean-STD	2.7 ± 0	1.775 ± 0.0707	2.7388 ± 0.1344	2.3638 ± 0.1166	2.6538 ± 0.1456

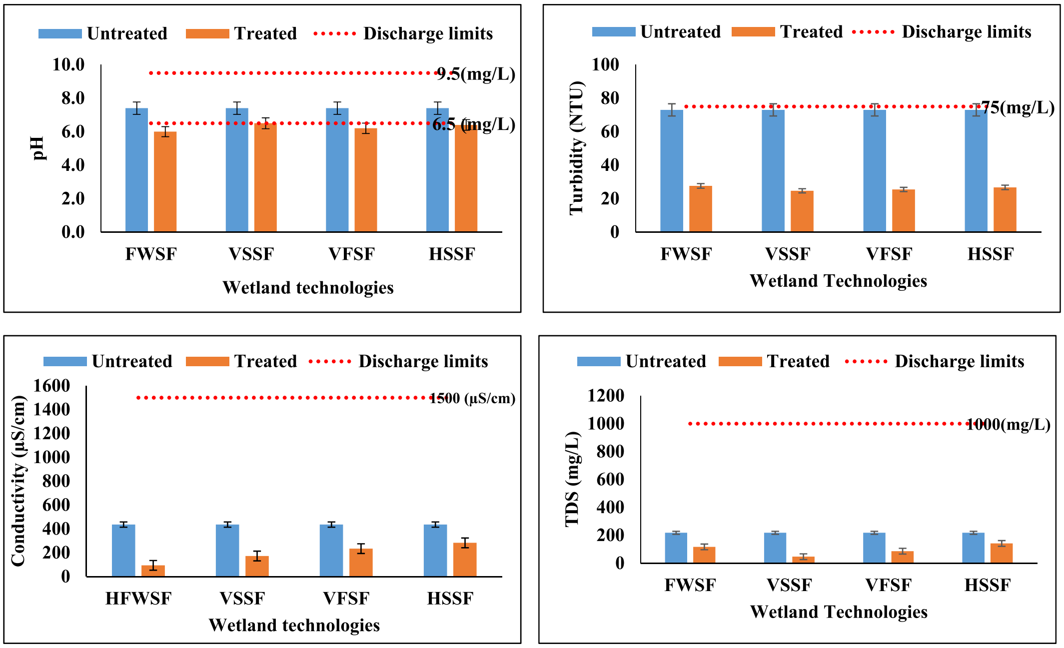

Fig. 3. Concentration of pH, EC, TDS, and turbidity in treated and untreated greywater using wetland technologies compared to the regulatory discharge limit.

the Federal Environmental Protection Agency (FEPA). This suggests that the clarity and transparency of the greywater, regardless of its treatment status, met the regulatory standards outlined by FEPA. Maintaining low turbidity levels in water is essential for ensuring its visual appeal, as well as its suitability for various applications. The ability of the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies to consistently achieve turbidity levels below the FEPA discharge limits indicates their efficacy in removing suspended particles and clarifying the greywater.

Fig. 4 shows that the study results revealed that both the treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited total suspended solids (TSS) levels that were below the discharge limits set by

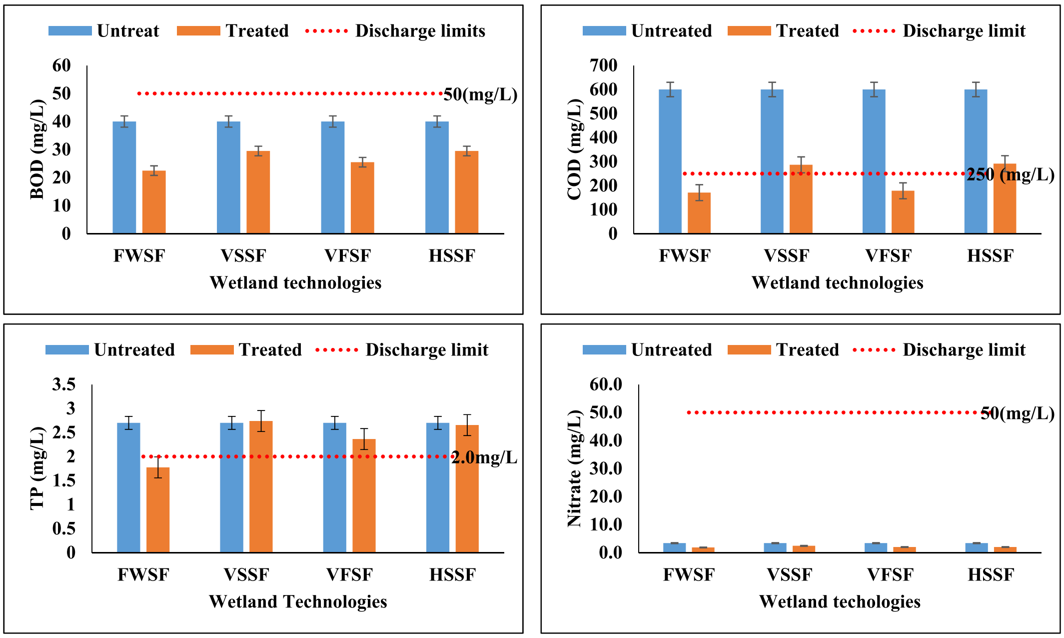

Fig. 4. Concentration of Nitrate, BOD, COD, and Oil and Grease in treated and untreated greywater using wetland technologies compared to the regulatory discharge limit.

the Federal Environmental Protection Agency (FEPA). This implies that the concentrations of solid particles suspended in the water, regardless of treatment, met the regulatory standards established by FEPA. Managing TSS levels in water is crucial as high concentrations of suspended solids can negatively impact water quality and various environmental processes. The ability of the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies to consistently achieve TSS levels below the FEPA discharge limits demonstrates their effectiveness in removing solid particles and maintaining water clarity.

The results presented in Fig. 4 indicate that both treated and untreated greywater samples obtained from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies displayed elevated levels of ammonia that surpassed the discharge limits established by the Federal Environmental Protection Agency (FEPA). Ammonia is a commonly found pollutant in wastewater, and its presence exceeding the discharge limits can have adverse impacts on aquatic ecosystems. It can result in heightened toxicity, imbalances in nutrients, and potential harm to aquatic organisms [22].

Fig. 4 shows that the results of the study revealed that both the treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited sulphate concentrations that were below the discharge limits set by the Federal Environmental Protection Agency (FEPA). This indicates that these wetland technologies effectively reduced sulphate levels in the greywater, ensuring compliance with the regulatory standards for discharge. Sulphate is a water quality indicator that, when present in excessive amounts, can have detrimental effects on both human health and the environment. By achieving sulphate levels below the FEPA discharge limits, the constructed wetland technologies demonstrated their ability to mitigate potential environmental risks associated with elevated sulphate concentrations in greywater.

Fig. 4 shows that the findings of the study revealed varying levels of Total phosphorus in both the treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies. The results showed that the untreated greywater from all four wetland technologies exceeded the discharge limits set by the Federal Environmental Protection Agency (FEPA) for total phosphorus. This indicates that the untreated greywater contained higher concentrations of total phosphorus than what is considered acceptable for discharge. However, after treatment, the VFSF, VSSF, and HSSF-constructed wetland technologies were able to bring the total phosphorus levels below the FEPA discharge limits. On the other hand, the HFWSF technology managed to achieve total phosphorus levels that were already below the discharge limits even before treatment. Total phosphorus is an important water quality indicator, and its excessive presence in water bodies can contribute to eutrophication and harm aquatic ecosystems. The treated greywater from the VFSF, VSSF, and HSSF technologies demonstrated their effectiveness in reducing TP concentrations, thereby ensuring compliance with the regulatory standards for total phosphorus discharge.

Fig. 5 demonstrates that both the treated and untreated greywater samples obtained from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies displayed nitrate levels that remained within the discharge limits established by the Federal Environmental Protection Agency (FEPA). This indicates that the concentrations of nitrate in the greywater, after treatment and in its untreated state, were within the acceptable range for discharge. The fact that the greywater samples from all four wetland technologies met the FEPA discharge limits for nitrate suggests that these technologies were effective in reducing nitrate concentrations to a safe and compliant level. The results of this study align with the regulatory standards established by the FEPA, which aim to protect water resources and ensure the safety of discharged wastewater. By demonstrating successful nitrate removal, the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies can be considered suitable options for treating greywater and maintaining compliance with regulatory requirements.

Fig. 5 shows that the results of the study demonstrated that both treated and untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited BOD levels that were within the discharge limits set by the Federal Environmental Protection Agency (FEPA). BOD is an important indicator of organic pollution in water bodies, as it measures the amount of oxygen required by microorganisms to decompose organic matter. Compliance with FEPA discharge limits ensures that the greywater treated by these wetland technologies has a reduced impact on water quality.

Fig. 5 shows that the study results revealed that the untreated greywater samples from the HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exhibited chemical oxygen demand (COD) concentrations that exceeded the discharge limits specified by the Federal Environmental Protection Agency (FEPA). This indicates that the levels of COD in the untreated greywater were higher than what is considered acceptable for discharge. COD is an important parameter used to assess the organic pollution level in water. Elevated COD levels can indicate the presence of organic pollutants that may have negative impacts on aquatic ecosystems and the environment. The fact that the untreated greywater samples exceeded the FEPA discharge limits for COD highlights the need

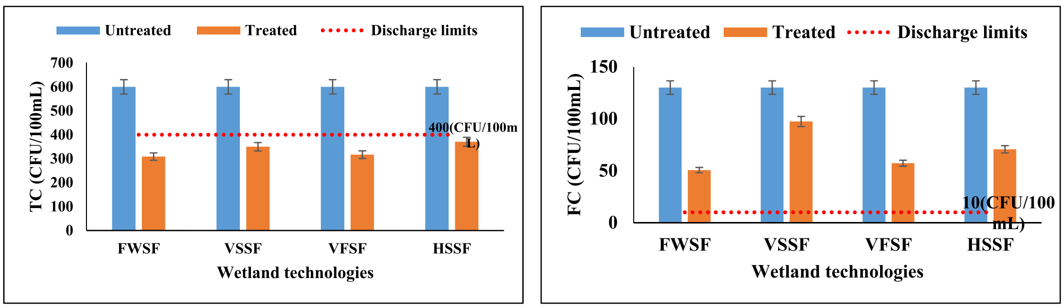

Fig. 5. Concentration of Total coliform and Feacal coliform in treated and untreated.

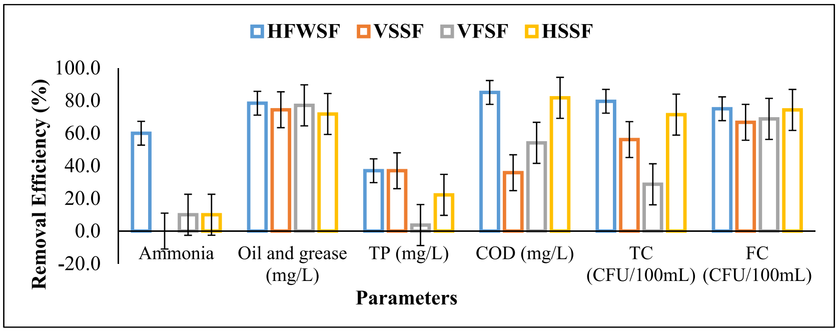

Fig. 6. Removal efficiency rate for the respective constructed wetland technologies.

for effective treatment to reduce organic pollutant concentrations before discharge. However, the treated greywater samples from the VFSF and VSSF-constructed wetland technologies also exceeded the FEPA discharge limit for COD, indicating that these technologies were not able to sufficiently reduce organic pollutant concentrations to meet the discharge limit requirement. On the other hand, the treated greywater samples from the HFWSF and HSSF-constructed wetland technologies were below the FEPA discharge limits for COD, suggesting that these technologies effectively removed organic pollutants and achieved compliance with regulatory standards. The findings underscore the significance of employing suitable treatment methods, such as the HFWSF and HSSF-constructed wetland technologies, to mitigate COD levels in greywater and ensure adherence to environmental regulations. By efficiently reducing organic pollutant concentrations, these technologies can contribute to maintaining water quality and safeguarding the health of aquatic ecosystems.

Fig. 5 shows that the study results indicated that both the treated and untreated greywater samples from HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exceeded the Federal Environmental Protection Agency (FEPA) discharge limits for oil and grease. This finding is significant considering that oil and grease are common contaminants in household wastewater and can have adverse effects on aquatic ecosystems. Household activities such as cooking, cleaning, and personal care products contribute to the presence of oil and grease in wastewater.

Fig. 6 shows that the study findings revealed that the untreated greywater samples from HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exceeded the Federal Environmental Protection Agency (FEPA) discharge limits for total coliform contamination. Total coliforms are commonly used as indicators of microbial contamination and can include bacteria originating from feacal matter, soil, and other sources. The presence of high levels of total coliforms in untreated greywater suggests inadequate treatment and the potential for health risks. On the other hand, the treated greywater samples from all four constructed wetland technologies met the FEPA discharge limits for total coliforms. The treatment processes employed in these systems effectively reduced the total coliform levels to an acceptable range, ensuring the safety and quality of the treated greywater. Fig. 6 shows that the study findings revealed that both the treated and untreated greywater samples from HFWSF, VFSF, VSSF, and HSSF-constructed wetland technologies exceeded the Federal Environmental Protection Agency (FEPA) discharge limits for feacal coliform contamination. Feacal coliforms are indicator organisms used to assess the presence of feacal contamination in water, and their elevated levels suggest potential health risks and inadequate treatment efficiency.

4.2. *Removal efficiency of greywater treatment with vegetation and constructed wetland technologies*

Fig. 6 shows the effectiveness of different wetland technologies in removing pollutants, specifically ammonia and oil, and grease. Regarding ammonia removal, HFWSF-CWT demonstrated the highest efficiency, exhibiting a substantial increase from 10% to 60%. In contrast, VFSF-CWT, HSSF-CWT, and VSSF-CWT exhibited lower removal efficiencies of 10%, 0%, and 6%, respectively. For the removal of oil and grease, all wetland technologies exhibited satisfactory performance. HFWSF-CWT, VFSF-CWT, HSSF-CWT, and VSSF-CWT achieved removal efficiencies of 78.46%, 71.79%, 74.36%, and 77.18%, respectively. These results indicate the successful

Table 3
Contaminant removal performance.

Wetland Technology	Vegetation	Wastewater	Removal Efficiency Rate (%)
HFWSF	*Hyacinth* (*Eichhornia crassipes*)	Greywater	Ammonia 60% Oil and grease 78.46%, COD 85%, total phosphorus 37.04%, FC 75%, TC 79.59%
HSSF	*Typha* (*Domingensis*)	Greywater	Ammonia 10%, Oil and grease 71.79%, COD 81.67%, total phosphorus 22.22%, FC 74.33%, TC 71.43%
VSSF	*Typha* (*Domingensis*) *crassipes*)	Greywater	Ammonia 0%, Oil and grease 74.35%, COD 53.83%, total phosphorus 37.04%, FC 66.67%, TC 56.12%
VFSF	*Hyacinth* (*Eichhornia crassipes*)	Greywater	Ammonia 6%, Oil and grease 77.18%, COD 54.1%, total phosphorus 3.70%, FC68.83%, TC 28.57%

reduction of oil and grease content in the treated greywater across all wetland technologies. The findings align with the results reported by Ref. [23], who also assessed treatment efficiency in terms of pollutant removal percentages. The agreement between the current study and previous research reinforces the reliability and consistency of the results. Overall, the effectiveness of the HFWSF-CWT configuration was confirmed and aligned with the predictions made in section 3.2. Additionally, it is interesting to compare the outcomes of this study with those reported in the existing literature. Table 3 provides a summary of the removal efficiencies observed in this study.

4.3. *Typha (Domingensis) treatment performance with horizontal subsurface flow constructed wetland technology. (HSSF-CWT)*

The study findings indicated that the inclusion of *Typha* (*Domingensis*) in the horizontal subsurface flow constructed wetland had a positive influence on the treatment performance of greywater leading to high removal efficiency of various pollutants, such as COD, ammonia, TP, and TN. This can be attributed to the increased oxygen supply to the rhizosphere via the plant roots [24]. The wetland technology using *Typha* (*Domingensis*) was effective in reducing the concentrations of most of the parameters studied, including total and feacal coliform. The performance and removal efficiencies of the horizontal subsurface flow (HSSF) showed a reduction of 10%, 71.79%,81.67%, 22.22%, 74.33%, and 71.43% for Ammonia, Oil and grease, COD, P, FC, and TC, respectively. These findings are consistent with the results of previous studies [25,26]. The satisfactory performance of the wetland technology demonstrates its potential as an effective and sustainable solution for greywater treatment because it was able to treat 4 out of 6 pollutants [27].

4.4. *Water hyacinth (Eichhornia crassipes) treatment performance with horizontal free water surface flow constructed wetland technology (HFWSF-CWT)*

As shown in Fig. 6, the use of wetland technology horizontal free water surface flow with water *Water Hyacinth (Eichhornia crassipes)* is effective in reducing the concentrations of various pollutants in greywater. Water *Hyacinth* has been increasingly used as a functional unit in greywater treatment with wetlands technology due to its high potential for reducing a wide range of pollutants from greywater [28,29,29,30]. The plant has been reported to effectively reduce BOD, COD, total phosphorus, Nitrate, Ammonia, and Total and Faecal coliform in greywater [31]. The findings suggest that the integration of water *Hyacinth* with HFWSF wetland technology enhances the treatment of greywater. This is evident through improved nutrient removal, where water *Hyacinth* demonstrates a remarkable capacity to absorb nutrients like nitrate and total phosphorus from greywater, leading to enhanced removal efficiency. Furthermore, the combination of water hyacinth and HFWSF wetland technology shows promise in augmenting the elimination of various contaminants, such as organic matter, suspended solids, and specific pollutants commonly present in greywater. The effectiveness of the system is increased as a result, contributing to better treatment outcomes and improved water quality. These findings are consistent with previous research, providing further support for the efficacy of this combined approach in greywater treatment [32–35] The findings of this study show that the Horizontal free water surface flow (HFWSF-CWT) with water *Hyacinth* effectively reduces the concentration of pollutants such as ammonia, oil and grease, COD, TP, FC, and TC. The removal efficiency rate shows a reduction of 60%, 78.4%, 85%, 37.04%, 75%, and 79.58% respectively.The higher removal efficiency rate of COD (85%) is attributed to the presence of surfactants and personal care products used during laundry service to improve the efficiency of COD removal by assisting in the breakdown of organic compounds and providing additional sites for adsorption in the treatment media. As supported by previous studies [12]. The study also found a high removal rate of 75% for feacal coliforms which is consistent with the results of a previous study [12]. The use of water *Hyacinth* in wetland technology is an effective approach for treating greywater and reducing its

Table 4
Two-way ANOVA statistical analysis.

Parameters	Source	df	MS	F	*P*-value
Ammonia	CWT	6	0.000476	1	0.468221
	Plant	2	0.080476	169	1.62E-09
	Error	12	0.000476		
Oil and grease	CWT	6	11379.43	98.93107	1.64E-09
	Plant	2	3498.857	30.41855	2E-05
	Error	12	115.0238		
COD	CWT	6	1510.302	2.710489	0.06682
	Plant	2	36132.76	64.84629	3.69E-07
	Error	12	557.2063		
T. phosphorus	CWT	6	0.035475	9.077579	0.000693
	Plant	2	0.246919	63.184	4.25E-07
	Error	12	0.003908		
T. Coliform	CWT	6	35783.65	59.71208	3.07E-08
	Plant	2	5708.048	9.525004	0.003332
	Error	12	599.2698		
F. Coliform	CWT	6	1160.159	169.3859	6.93E-11
	Plant	2	3384.571	494.1553	2.98E-12
	Error	12	6.849206		

Note: In parentheses is the *P*-value, df = Degree of freedom, MS = Mean Squares, F=F-Statistics, with the significance level set at $P < 0.05$. The *P-value* of greywater was estimated using the data Excel analysis tool.

pollutant concentrations [32].

4.5. Typha (Domingensis) treatment performance with vertical subsurface flow constructed wetland technology (VSSF-CWT)

Based on the study, Fig. 6 shows that combining *Typha* (*Domingensis*) with vertical subsurface flow (VSSF-CWT) wetland technology was effective in reducing pollutant loads of greywater. The technology achieved removal efficiencies ranging from 0% for ammonia to 74.35% for oil and grease, 53.83% for chemical oxygen demand (COD), 37.04% for total phosphorus, 66.67% for feacal coliform (FC), and 56.12% for total coliform (TC). However, there was no removal rate for ammonia and this may be due to; insufficient duration of contact: Adequate contact time between wastewater and the treatment media or plant roots is crucial for effective ammonia removal in wetlands. When the contact time is inadequate, there may be limited opportunities for ammonia removal to take place also s availability of nitrogen: Ammonia can be transformed into nitrate through nitrification, a process that necessitates the presence of sufficient oxygen and nitrogen-oxidizing bacteria. If the wetland system lacks these conditions or if there is limited nitrogen availability, the removal of ammonia may be more constrained than the values obtained in previous studies such as [36,37]. On the other hand, the removal efficiency of oil and grease, ammonia, and total and feacal coliform was higher in this study than that reported by Ref. [37]. It should be noted that the lower removal efficiency of ammonia in this study may be due to the hydraulic retention time (HRT) which plays a crucial role in the efficiency of ammonia removal. A shorter HRT means less contact time between the wastewater and the treatment media and plant roots, limiting the opportunity for ammonia removal. Similarly, temperature influences ammonia removal as it is a temperature-dependent process. Higher temperatures generally promote greater ammonia removal rates, while lower temperatures can reduce the activity of ammonia-oxidizing bacteria and result in lower ammonia removal efficiency. The influent concentration of ammonia also directly affects its removal efficiency, with higher concentrations posing a greater challenge for removal. If the treatment system is not optimized for high ammonia levels, a lower removal efficiency under such conditions can lead to increased ammonia concentrations in the treated water. Considering the experimental conditions of HRT, temperature, and influent concentration, the lower removal efficiency of ammonia can have a detrimental impact on the overall performance of the *Typha* (*Domingensis*) treatment combined with VSSF-CWT, potentially compromising water quality and treatment effectiveness [16]. Therefore, further studies are needed to optimize the performance of VSSF-CWT technology in treating greywater.

4.6. Water hyacinth (Eichhornia crassipes) treatment performance with vertical free surface flow (VFSF-CWT)

The study found that Fig. 6 shows that using vertical free surface flow constructed wetland technology with water *Hyacinth* (*Eichhornia crassipes*) vegetation effectively reduced the concentration of pollutant loads in greywater, with removal efficiencies of 77.18% for oil and grease, 54.1% for COD, 68.83% for FC, 6% for ammonia, 68.83% for TP, and 28.57% for TC (Figs. 3.3–16). The COD removal efficiency of 54.1% is consistent with the findings of [38] who reported less than 51.61 ± 13.56% for greywater treatment using water *Hyacinth* (*Eichhornia crassipes*). However, the ammonia removal efficiency rate in this study is lower than that of [38], who reported a high ammonia removal rate of 61.96 ± 12.11%. Table 2 provides the minimum, maximum, average, and standard deviation values for the different wetland technologies for untreated and treated greywater characteristics. During the sampling time, the wetland technology measured several parameters such as ammonia, COD (Chemical Oxygen Demand), oil and grease, feacal coliform, total coliform, and phosphorus. Variations in these characteristics were found and described in the following sections.

4.7. Statistics analysis of the constructed wetland technologies

The results showed that the ammonia concentration in the untreated greywater and treated greywater using HSFS-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT ranged from 1.9 to 1.9 (mg/L) and 1.3–1.9 (mg/L), 1.5–1.9 (mg/L), 1.7–1.9 (mg/L), 1.8–1.9 (mg/L), respectively. Table 2 shows the average range of the ammonia parameters for the untreated and treated greywater samples using different wetland technologies as observed, they range from 1.9 ± 0 (mg/L), 1.6 ± 0.1773 (mg/L), 1.7 ± 0.1553 (mg/L), 1.8 ± 0.0916 (mg/L), and 1.9 ± 0.034 (mg/L) for HSFS-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT, respectively. Greywater ammonia is produced from the decomposition of organic kitchen waste [22]. The ammonia concentration in greywater samples is low, although the ammonia removal efficiency varied among different wetland technologies. The results of the study showed a slight increase in ammonia levels during the greywater treatment process in HFWSF-CWT, VSSF-CWT, and VFSF-CWT wetlands. Among these wetlands, HFWSF-CWT showed the highest removal efficiency, with a minimum and maximum ammonia level of 1.3–1.8 (mg/L) in treated greywater. The dense fibrous root of the water *Hyacinth* used in this wetland may have contributed to its high removal efficiency. Other studies have also used adsorption techniques to remove ammonia [22], However, the degradation of plants in the system reduces the amount of dissolved oxygen, which affects the treatment efficacy. The removal efficiency observed in this study can be attributed to nitrification and plant uptake through a well-developed rhizosphere, as reported by Ref. [38].

The results show that the COD concentration in untreated greywater ranged between 600 and 600 (mg/L) and was reduced by the treated wetland technologies. The range of COD concentration in HFWSF-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT treated greywater were 90–265 (mg/L), 270–303 (mg/L), 111–262 (mg/L), and 279–305 (mg/L) respectively. The average removal of COD from the treated greywater using wetland technologies was found to be effective, ranging from 170.875 ± 57.8827 to 291.5 ± 10.5289 (mg/L). The high concentration of COD in greywater could be attributed to the presence of detergents used in laundry and dishwashing [39]. The Water *Hyacinth* (*Eichhornia crassipes*) showed good COD removal performance, and HFWSF-CWT was found to be the most effective among the wetland technologies. The study's results are consistent with [40], which showed the HSSF-CWT and VSSF-CWT constructed wetland technology's performance in treating COD. The COD concentrations value of (90–265) (mg/L) decreased significantly after treatment with the Water *Hyacinth* (*Eichhornia crassipes*) and HFWSF-CWT [41].

The study found that the oil and grease concentration in untreated greywater has a high, concentration value of 780-780 (mg/L), and exceeded the permissible limit for discharge into water bodies. However, after treatment with the four wetland technologies, there was a significant reduction in the concentration of oil and grease. HFWSF-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT reduced the concentration of oil and grease to 168–458 (mg/L), 178–426 (mg/L), 200–460 (mg/L), and 220–462 (mg/L), respectively. The study also reported that the untreated greywater had an average concentration of 780 ± 0 (mg/L) oil and grease, which was reduced to an average of 252.5 ± 99.9986 (mg/L), 257.625 ± 90.0919 (mg/L), 288.125 ± 90.4150 (mg/L), and 300.375 ± 84.8190 (mg/L) after treatment with HFWSF-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT, respectively.

The high level of oil and grease in household greywater may be attributed to various factors. Firstly, during cooking and food preparation, oil and grease are commonly used and can be present in different food items. When dishes are washed or rinsed in the sink, some of the oil and grease can enter the greywater. Secondly, dishwashing involves the use of dish soap or detergent, which may not eliminate all the oil and grease from plates, utensils, and cookware. As a result, residual oil and grease can find their way into the greywater. Additionally, personal care products like soaps, shampoos, conditioners, and lotions often contain oils and greases. When we shower or wash our hands, these substances can be washed off and enter the greywater [42]. Discharging untreated greywater into water bodies may lead to a range of adverse consequences such as; water contamination: Greywater contains a mixture of contaminants, including bacteria, pathogens, nutrients, and chemicals. When untreated greywater is released into water bodies, it introduces these pollutants, leading to water pollution. This is particularly concerning when the water body serves as a source of drinking water or when people engage in recreational activities in the polluted water. Therefore, it is essential to treat greywater before discharging it. The study's results demonstrate that wetland technologies, particularly HFWSF-CWT, can effectively reduce the concentration of oil and grease in greywater, making it safe for discharge into the environment.

The presence of *Escherichia coli* in greywater is an important indication of feacal pollution and its study can provide significant information on potential health hazards. The untreated greywater was found to have feacal coliform loads within the range of 130-130 (mg/L), while the ranges of HFWSF-CWT, VSS-CWT, VFSF-CWT, and HSSF-CWT for treated greywater were 20–84 (mg/L), 70–130 (mg/L), 28–87 (mg/L), and 43–98 (mg/L), respectively. The value of the untreated greywater was reduced to 50.625 ± 21.1318 (mg/L), 97.375 ± 9.4565 (mg/L), 57.25 ± 20.4712 (mg/L), and 70.625 ± 19.7335 (mg/L), respectively, after treatment as shown in Table 2. The higher levels of fecal coliforms found in greywater, particularly in the water from the kitchen sink, indicate that the kitchen sink water has the potential to be a source of microbial contamination. This is particularly relevant during activities such as washing fecal-stained clothes or handling raw meats as reported by Ref. [43]. According to the study, the HFWSF-CWT (High-Flow Constructed Wetland with Continuous Water Treatment) has demonstrated the most effective removal performance in terms of fecal coliform load. It achieved a slight reduction with an average removal of 50.625 ± 21.1318 (mg/L), ranging from 20 to 84 (mg/L), surpassing the performance of other wetlands examined in the study. The study found that the total coliform concentrations in untreated greywater ranged from 600 to 600 (CFU/100 mL). After treatment with HFWSF-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT wetland technologies, the total coliform concentrations were reduced to 150–420 (CFU/100 mL), 187–462 (CFU/100 mL), 154–422 (CFU/100 mL), and 200–462 (CFU/100 mL), respectively. The HFWSF-CWT technology had the best removal performance, with a reduction to 308.75 ± 119.4604 (CFU/100 mL). These findings indicate that wetland technologies are effective in reducing the total coliform loads in greywater.

The reduction in total coliform loads is a crucial indicator of the effectiveness of the treatment process. The World Health Organization (WHO) recommends a maximum of 1000 CFU/100 mL for irrigation of crops and a maximum of 100 CFU/100 mL for recreational water. The study concludes that the HFWSF-CWT technology showed the best removal performance for total coliform loads. This finding is consistent with the results of previous studies that have reported the effectiveness of constructed wetlands in removing feacal coliform bacteria from greywater [44,45].

Total phosphorus concentrations in greywater are typically within the range of 2.7–2.7 (mg/L) for untreated and vary depending on the type of wetland technology used for treatment. The treated greywater samples of HFWSF-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT show total phosphorus ranges of 1.7–1.9 (mg/L), 2.6–2.94 (mg/L), 2.1–2.46 (mg/L), and 2.5–2.87 (mg/L), respectively. The untreated greywater had a value of 2.7 ± 0 (mg/L) total phosphorus concentration, which was reduced to 1.775 ± 0.0707 (mg/L), 2.7388 ± 0.1344 (mg/L), 2.3638 ± 0.1166 (mg/L), and 2.6538 ± 0.1456 (mg/L) for HFWSF-CWT, VSSF-CWT, VFSF-CWT, and HSSF-CWT, respectively, as indicated in Table 2. The observed reduction in total phosphorus concentration from 2.7 to 2.7 to 1.7–1.9 (mg/L) after treatment with wetland technology indicates that the wetland technology effectively removes total phosphorus s from the greywater.HFWSF-CWT wetland technology was found to be a better option for the removal of total phosphorus from greywater [11].

5. Conclusion

This study systematically evaluated different constructed wetland technologies for greywater treatment and their compliance with regulatory standards. The tested technologies effectively maintained pH levels within the acceptable range set by FEPA and reduced concentrations of dissolved and suspended particles, meeting FEPA discharge limits for electrical conductivity, TDS, turbidity, and TSS in both treated and untreated samples. However, elevated ammonia levels in both treated and untreated samples necessitate additional treatment or mitigation strategies to meet FEPA limits. The technologies successfully mitigated elevated sulphate levels and complied with phosphorus limits, with HFWSF already below limits before treatment. They also reduced nitrate levels to meet FEPA limits, ensuring compliance. While both treated and untreated samples met BOD limits, untreated samples exceeded COD limits, requiring more efficient treatment methods. HFWSF and HSSF complied with COD limits, while VFSF and VSSF did not. Additional treatment is needed for oil and grease removal. Untreated samples had high coliform contamination, emphasizing the importance of effective treatment. All technologies reduced coliform levels in treated samples, meeting FEPA limits. The combination of water hyacinth with horizontal free water surface flow wetland technology demonstrated the highest effectiveness in pollutant removal. Incorporating *Typha* in the horizontal subsurface flow wetland improved pollutant and nutrient removal. This combined approach outperformed other technologies in removing pollutants, offering significant advancements in greywater treatment.

Author contribution statement

Vivien Chikogu Ameso: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; wrote the paper and reagents, materials, analysis tools or data.

Helen Michelle Korkor Essandoh; Emmanuel Amponsah Donkor; Michael Obiekwe Nwude: They supervised, revised the manuscript to enhance its critical intellectual content, and granted approval for the final version to be submitted.

Data availability statement

No data was used for the research described in the article.

Additional information

No additional information is available for this paper.

Ethical approval

No ethical approval was required to conduct this study.

Declaration of competing interest

The authors declare no conflicting financial interests.

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References

[1] H. Filali, N. Barsan, D. Souguir, V. Nedeff, C. Tomozei, M. Hachicha, Greywater as an alternative solution for a sustainable management of water resources—a review, Sustain. Times 14 (2022) 1–13, https://doi.org/10.3390/su14020665.

[2] A. Mustafa, Constructed wetland for wastewater treatment and reuse: a case study of developing country, Int. J. Environ. Sustain Dev. 4 (2013) 20–24, https://doi.org/10.7763/ijesd.2013.v4.296.

[3] S.A.A.A.N. Almuktar, S.N. Abed, M. Scholz, Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review, Environ. Sci. Pollut. Res. 25 (2018) 23595–23623, https://doi.org/10.1007/s11356-018-2629-3.

[4] S. Wu, S. Wallace, H. Brix, P. Kuschk, W. Kipkemoi, F. Masi, R. Dong, Treatment of industrial effluents in constructed wetlands : challenges, operational strategies, and overall performance, Environ. Pollut. 201 (2015) 107–120, https://doi.org/10.1016/j.envpol.2015.03.006.

[5] Luise Davis, A Handbook of Constructed Wetlands: A Guide to Creating Wetlands for Agricultural Wastewater, Domestic Wastewater, Coal Mine Drainage, and Stormwater, vol. 1, 2016, pp. 1–53. https://www.epa.gov/sites/production/files/2015-10/documents/constructed-wetlands-handbook.pdf.

[6] F. Hussain, G. Mustufa, R. Zia, A. Faiq, M. Matloob, H. ur Rehman Shah, W. Rafique Ali, J.A. Irfan, Constructed wetlands and their role in remediation of industrial effluents via plant-microbe interaction – a mini review, J. Biorem. Biodegrad. 9 (2018), https://doi.org/10.4172/2155-6199.1000447.

[7] F. García-Ávila, J. Patiño-Chávez, F. Zhinín-Chimbo, S. Donoso-Moscoso, L. Flores del Pino, A. Avilés-Añazco, Performance of phragmites australis and Cyperus papyrus in the treatment of municipal wastewater by vertical flow subsurface constructed wetlands, Int. Soil Water Conserv. Res. (2019), https://doi.org/10.1016/j.iswcr.2019.04.001.

[8] O. Sanicola, T. Lucke, M. Stewart, K. Tondera, C. Walker, Root and shoot biomass growth of constructed floating wetlands plants in saline environments, Int. J. Environ. Res. Publ. Health 16 (2019) 275, https://doi.org/10.3390/ijerph16020275.

[9] P.F. Schwammberger, T. Lucke, C. Walker, S.J. Trueman, Nutrient uptake by constructed floating wetland plants during the construction phase of an urban residential development, Sci. Total Environ. 677 (2019) 390–403, https://doi.org/10.1016/j.scitotenv.2019.04.341.

[10] D.Q. Zhang, K.B.S.N. Jinadasa, R.M. Gersberg, Y. Liu, W.J. Ng, S.K. Tan, Application of constructed wetlands for wastewater treatment in developing countries - a review of recent developments (2000-2013), J. Environ. Manag. 141 (2014) 116–131, https://doi.org/10.1016/j.jenvman.2014.03.015.

[11] A. Albalawneh, T.-K. Chang, Review of the greywater and proposed greywater recycling scheme for agricultural irrigation reuses, Int. J. Res. -GRANTHAALAYAH. 3 (2015) 16–35, https://doi.org/10.29121/granthaalayah.v3.i12.2015.2882.

[12] C. Ramprasad, C.S. Smith, F.A. Memon, L. Philip, Removal of chemical and microbial contaminants from greywater using a novel constructed wetland: GROW, Ecol. Eng. 106 (2017) 55–65, https://doi.org/10.1016/j.ecoleng.2017.05.022.

[13] L.S. Vienna, G. Dotro, J. Nivala, Wetland Technology, Practical Information on the Design and Application of Treatment Wetlands, 2019, https://doi.org/10.2166/9781789060171.

[14] S. Wu, P.N. Carvalho, J.A. Müller, V.R. Manoj, R. Dong, Sanitation in constructed wetlands: a review on the removal of human pathogens and fecal indicators, Sci. Total Environ. 541 (2016) 8–22, https://doi.org/10.1016/J.SCITOTENV.2015.09.047.
[15] H. Wu, J. Fan, J. Zhang, H. Hao, W. Guo, S. Liang, J. Lv, S. Lu, W. Wu, S. Wu, Bioresource Technology Intensified organics and nitrogen removal in the intermittent-aerated constructed wetland using a novel sludge-ceramsite as substrate, Bioresour. Technol. 210 (2016) 101–107, https://doi.org/10.1016/j.biortech.2016.01.051.
[16] J. Vymazal, Constructed wetlands for wastewater treatment, Water (Switzerland) 2 (2010) 530–549, https://doi.org/10.3390/w2030530.
[17] H. Wu, Y. Qian, R. Lu, W. Tan, A theoretical study on the electronic property of a new two-dimensional material molybdenum dinitride, Phys. Lett. A. 380 (2016) 768–772, https://doi.org/10.1016/j.physleta.2015.12.017.
[18] H.C. Yayock, I.S. Ndams, E. Kogi, A.B. Ahmed, J.B. George, Distribution of mosquito species in Kaduna metropolis, Kaduna state northern Nigeria, Am. J. Trop. Med. Hyg. 101 (2019) 50-. https://www.cochranelibrary.com/central/doi/10.1002/central/CN-02073048/full.
[19] Yayock, et al., Level Of Awareness, Access, And Use Of Long-Lasting Insecticidal Nets (LLINs) in five public health centres within kaduna metropolis, Fudma J. Sci. 4 (2020) 343–350.
[20] P. Andreo-Martínez, N. García-Martínez, J. Quesada-Medina, L. Almela, Domestic wastewater reuse reclaimed by an improved horizontal subsurface-flow constructed wetland: a case study in the southeast of Spain, Bioresour. Technol. 233 (2017) 236–246, https://doi.org/10.1016/j.biortech.2017.02.123.
[21] APHA, AWWA, WEF, Standard Methods for the Examination of Water and Wastewater, twenty-second ed., American Public Health Association, Washington, 2012, p. 1360. ISBN 978-087553-013-0, http://www.standardmethods.org/. Am. Public Heal. Assoc. 5 (2012) 335.
[22] T.A.K. Wardani, Sudarno, N. Hardyanti, Syafrudin, M. Hadiwidodo, I.W. Wardhana, Removal of ammonia in domestic wastewater by using multi-soil layering, IOP Conf. Ser. Earth Environ. Sci. 802 (2021), https://doi.org/10.1088/1755-1315/802/1/012005.
[23] N.A. Oladoja, Appropriate technology for domestic wastewater management in under-resourced regions of the World, Appl. Water Sci. 7 (2017) 3391–3406, https://doi.org/10.1007/s13201-016-0495-z.
[24] S. Kataki, et al., Constructed wetland, an eco-technology for wastewater treatment: a review on types of wastewater treated, and components of the technology (macrophyte, biolfilm, and substrate), J. Environ. Manag. 283 (2021), 111986, https://doi.org/10.1016/j.jenvman.2021.111986.
[25] M. Khazaleh, B. Gopalan, Constructed Wetland for Wastewater Treatment Constructed Wetland for Wastewater Treatment, 2019.
[26] A. Mustafa, Constructed wetland for wastewater treatment and reuse: a case study of developing country, Int. J. Environ. Sustain Dev. 4 (2013) 20–24, https://doi.org/10.7763/ijesd.2013.v4.296.
[27] J. Vymazal, Constructed wetlands for wastewater treatment: five decades of experience, Environ. Sci. Technol. 45 (2011) 61–69, https://doi.org/10.1021/es101403q.
[28] H. Chua, Bio-accumulation of environmental residues of rare earth elements in aquatic flora Eichhornia crassipes (Mart.) Solms in Guangdong Province of China, Sci. Total Environ. 214 (1998) 79–85, https://doi.org/10.1016/S0048-9697(98)00055-2.
[29] Piyush Gupta, et al., Treatment of water using water hyacinth, Water Lettuce and Vetiver Grass - A Review 2 (2012) 202–215, https://doi.org/10.5923/j.re.20120205.04.
[30] B.C. Wolverton, R.C. McDonald, The water hyacinth: from prolific pest to potential provider, Ambio 8 (1979) 2–9.
[31] M, et al., Delgado, Organic and inorganic nutrients removal from pig slurry by water hyacinth, J. Environ. Sci. Heal. (2008) 347–367.
[32] D.O. Olukanni, K.O. Kokumo, Efficiency assessment of a constructed wetland using Eichhornia crassipes for wastewater treatment, Am. J. Eng. Res. (2013) 450–454.
[33] D. Sukumaran, Phytoremediation of heavy metals from industrial effluent using constructed wetland technology, Appl. Ecol. Environ. Sci. (2013), https://doi.org/10.12691/aees-1-5-4.
[34] A. Valipour, V.K. Raman, Y.H. Ahn, Effectiveness of domestic wastewater treatment using a Bio-hedge water hyacinth wetland system, Water (Switzerland) 7 (2015) 329–347, https://doi.org/10.3390/w7010329.
[35] S.E. Agarry, K.M. Oghenejoboh, G.K. Latinwo, C.N. Owabor, Biotreatment of petroleum refinery wastewater in vertical surface-flow constructed wetland vegetated with Eichhornia crassipes: lab-scale experimental and kinetic modelling biotreatment of petroleum refinery wastewater in vertical surface-flow constructed, Environ. Technol. 0 (2018) 1–21, https://doi.org/10.1080/09593330.2018.1549106.
[36] S.O.O. Muvea, M. F, G.M. Ogendi, Nutrient removal efficiency by floating macrophytes, Glob. J. Environ. Sci. Manag. 5 (2020) 415–430, https://doi.org/10.22034/gjesm.2019.04.02.
[37] E. Rahmadyanti, O. Audina, The performance of hybrid constructed wetland system for treating the batik wastewater, J. Ecol. Eng. 21 (2020) 94–103, https://doi.org/10.12911/22998993/118292.
[38] R. Prasad, D. Sharma, K.D. Yadav, Preliminary study on effect of detention time on nutrient removal from greywater using water hyacinth, water conserv, Manag 5 (2021) 20–25, https://doi.org/10.26480/wcm.01.2021.20.25.
[39] Y. Boyjoo, V.K. Pareek, M. Ang, A review of greywater characteristics and treatment processes, Water Sci. Technol. 67 (2013) 1403–1424, https://doi.org/10.2166/wst.2013.675.
[40] H. Cordesius, S.H. Minor, F. Study, A Feasibility Study on Sustainable Wastewater Treatment Using a Constructed Wetlands-An Example from Cochabamba, 2009. Bolivia.
[41] R. Prasad, D. Sharma, K.D. Yadav, H. Ibrahim, Study on greywater treatment using water hyacinth, Appl. Water Sci. 11 (2021) 1–8, https://doi.org/10.1007/s13201-021-01422-4.
[42] A. Morel, S. Diener, Greywater Management in Low and Middle-Income Countries, 2006.
[43] L.M. Casanova, C.P. Gerba, M. Karpiscak, Chemical and microbial characterization of household graywater, J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 36 (2001) 395–401, https://doi.org/10.1081/ESE-100103471.
[44] A. Albalawneh, T.-K. Chang, Review of the greywater and proposed greywater recycling scheme for agricultural irrigation reuses, Int. J. Res. -GRANTHAALAYAH. 3 (2015) 16–35, https://doi.org/10.29121/granthaalayah.v3.i12.2015.2882.
[45] WHO.UNEP, Safe Use Wastewater, Excreta and Greywater., 2006.