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Vertically constructed wetlands for greywater reuse: Performance analysis of plants

Kushan D. Siriwardhana [a], Nandika Miguntanna [b,*], Dimantha I. Jayaneththi [a], Komali Kantamaneni [c], Upaka Rathnayake [d,*]

[a] Water Resources Management and Soft Computing Research Laboratory, Millennium City, Athurugiriya 10150, Sri Lanka
[b] Department of Civil Engineering, Faculty of Engineering, Sri Lanka Institute of Information Technology, Malabe 10150, Sri Lanka
[c] School of Engineering, University of Central Lancashire, Preston PR1 2HE, United Kingdom
[d] Department of Civil Engineering and Construction, Faculty of Engineering and Design, Atlantic Technological University, Sligo F91 YW50, Ireland

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ABSTRACT

Vertical Flow constructed wetlands (VFCWs) are environmentally feasible engineered systems that mimic the functions of natural wetlands. They are alternative engineering systems that are economical, and simple in structure with reduced land area compared to Horizontal Flow Constructed Wetlands (HFCW). Thus provides a sustainable solution for greywater treatment to a considerable extent. However, VFCWs feasibility and plant performance were not tested in the context of Sri Lanka for the greywater treatment. Therefore, the purpose of this study is to evaluate the potential of household greywater treatment using a pilot-scale VFCW and examine the performance characteristics of different types of plants. Three types of plants, the Canna plant (*Canna indica*), Ferns plant (*Matteuccia struthiopteris*), and Cattail plant (*Typha latifolia*) were used as emergent plants and a retention tank was constructed to retain solid particles in the greywater as primary treatment. The experiments were carried out for two months using a Completely Randomized Design (CRD) for three replicates. The quality of the influent and effluent was tested fortnight for a number of water quality parameters. Results revealed that the removal efficiency of contaminants was increased. Cattail plants showed higher removal efficiency for dissolved oxygen (DO), chemical oxygen demand (COD), nitrates (NO_3^{1-}), turbidity, and electrical conductivity. In addition, Canna plants had higher efficiencies for the removal of total dissolved solids (TDS) and phosphates (PO_4^{3-}). Furthermore, Ferns plants presented higher efficiency only for removing sulphate (SO_4^{3-}). Conclusively, Cattail plants presented the overall best performance in treating greywater. This can be attributed to the ability of the Cattail's dense fibrous root system to absorb more contaminants from greywater. This research also discussed the importance of microplastic analysis in greywater treatment which is a vital part of the current day research. The results of this study will be helpful to the further advanced research. Furthermore, this methodology can be implemented to other similar plants across the globe irrespective of geographical area.

1. Introduction

Water is one of the most crucial resources for all living organisms. Even though 71% of the earth consists of water, the availability of fresh and potable water is very limited. According to the data available, 771 million people don't have any access to clean water in 2020 (Caruso, 2023). Furthermore, according to statistics world population is expected to reach 8.45 billion by 2025, thus would result in risks of water shortages for 40% of the population (Kulshreshtha, 1998). This is a critical environmental concern; therefore, severe attention should be given to water supply systems. In addition, industrialization demands a high amount of water, and it is in an increasing phase (Messay and Mekibib, 2019). On the other hand, the discharge of contaminated water from various industries into the environment has been identified as a major point source of pollution to receiving water bodies creating a considerable negative impact on all the sectors of the environment (Sultana et al., 2019). Furthermore, the degradation of water quality of receiving water bodies due to non-point sources of pollution which mainly includes urban stormwater runoff has also been identified as a major issue during the past few decades (Xue et al., 2022). The

* Corresponding authors.
E-mail addresses: nandika.m@sliit.lk (N. Miguntanna), Upaka.Rathnayake@atu.ie (U. Rathnayake).

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degradation of the water quality directly impacts aquatic life, human life, and other species immensely. All these situations ultimately lead to the discussion of water scarcity and how to safeguard, reuse and save the water for future generations. In this context, wastewater treatment and reuse have been identified as one of the most practical and feasible methods to address the problems associated with water quantity and quality. Even though there are many methods that are being implemented to optimize the process of wastewater treatment in industries, the focus on the domestic level of wastewater treatment methods for different types of household discharges is not very progressive, particularly in developing countries like Sri Lanka.

Greywater is the effluent that discharges from households excluding toilet wastewater (Morel and Diener, 2006). Usually, greywater is contaminated with different soluble and insoluble compounds such as dirt, grease, hair, food, and chemical substances, pathogens in general (Asgharnejad, 2021). In addition, microplastics are readily available in grey water even though it is not yet given in- depth attention in most of the countries. In developing countries such as Sri Lanka, greywater production in urban and suburban areas is mostly discharged without any treatment to either a sewage line or stormwater drain, or the direct environment. Discharges to the direct environment are very popular in many rural areas in developing countries as there are no policy regulations to prohibit that. As a result of these untreated greywater discharges, natural water bodies are in real danger with environmental impacts such as depletion of dissolved oxygen, high turbidity levels, eutrophication, etc. (Morel and Diener, 2006). Most countries utilize greywater for home garden irrigation or agricultural purposes in regions where water scarcity is a major issue or when the cost of water supply is high. Even though greywater is considerably less polluted compared to other wastewater sources, it still contains various contaminants which need to be removed through a proper treatment process before attempting to reuse or release into the environment. This includes microplastics as well. If proper treatment is not carried out before reusing or discharging to the environment, it will lead to adverse impacts on human health, soil, groundwater quality, and the whole environment system ultimately (Kumar and Dutta, 2019).

Four different types of waste treatment methods are used in many countries. They are physical water treatment, biological water treatment, chemical water treatment, and sludge treatment. Some of the treatment techniques have combined methods. Constructed wetlands are under both physical and biological categories due to the involvement of both processes. There is an increasing demand for more environmentally friendly wastewater treatment technologies such as constructed wetlands. Constructed wetland is an engineered system that is designed to have a natural wastewater treatment process (which incorporates soil, vegetation, and microbial assemblages) (Hammer and Bastian, 1989). They are mostly utilized for treating point source pollution such as municipal waste, and domestic waste (Kumar and Dutta, 2019). But they can also be used to treat non-point source pollution (agricultural runoff, landfill leachate, etc.). However, by changing various design factors, constructed wetlands may treat a range of pollutants by utilizing low-energy and natural processes (Vymazal, 2010; Waly, 2022).

Three main types of constructed wetlands can be identified based on the flow direction of effluent: horizontal flow (HFCWs), vertical flow (VFCWs), and hybrid flow (HFCW) (Vymazal, 2022). In HFCW, wastewater flows through a porous medium under the emergent plants horizontally (Delgado, 2020). The treatment process involves aerobic, anaerobic, and anoxic zones to be passed through to treat the greywater. However, VFCWs operate in a different manner where wastewater is percolated through the soil with discontinuous loading periods and resting periods. These VFCWs are usually constructed either in shallow excavation or above ground with an impermeable linear covering around the wetland area. Also, emergent plants on the wetland assist in maintaining the hydraulic conductivity of the VFCW's bed. Typically VFCW requires a lesser area to treat wastewater when compared with HFCW (Ilyas and Masih, 2017). VFCWs, unlike HFCWs, are a viable alternative when faced with restricted land availability and are usually suitable in domestic and industrial wastewater recycling. This treatment system is designed to effectively remove organic matter, nitrogen, phosphorus, and pathogens through microbial activity. Additionally, it is capable of managing solids due to the oxidation–reduction environment inside the system. Overall, this system offers ample and appropriate treatment for various types of contaminants (Kouki, 2009; Wang, 2009; Otter et al., 2020). Nevertheless, the hybrid flow constructed wetland influences both VFCW and HFCW to obtain higher treatment efficiency. This is also considered to be preferable for nitrogen as it provides less oxygen in the system.

On the other hand, wetland plants play a significant role in constructed wetlands. This primarily includes uptaking of the nutrients, absorbing, and accumulating heavy metal and poisonous substances from wastewater, and contributing significantly to simultaneous nitrification and de-nitrification, transferring oxygen to the rhizosphere for microorganism growth, reproduction, and decomposition (Zhang and Hong, 2006). The Root Zone theory by Seidel and Kickuth (Vymazal, 2005), highlighted the function of macrophytes in wetlands' sewage treatment systems and significantly encouraged the study and use of constructed wetlands.

Even though literature showcases a number of studies to investigate the performance of these constructed wetlands (Khan, 2023; Liu et al., 2023; Liu et al., 2023; Yan et al., 2023; Yan et al., 2023; Zhang et al., 2023; Zhao et al., 2023), they are very limited in the context of Sri Lanka. The performance of VFCWs was never tested using the readily available plants in Sri Lanka. Therefore, such analysis is highly important as most of the generated greywater is not treated in Sri Lanka and is directly discharged to nearby environments. Thus, a high necessity is raised to investigate the performance of constructed wetlands using readily available Sri Lankan plants and then to promote such systems among the community. Therefore, this study for the first time in the context of Sri Lanka, is focused on the investigation of VFCW performance using three different plant species readily available.

Most of the studies have shown that Canna plants and Cattail plants exhibit good performance overall (Karungamye, 2022) (Marín-Muñiz, 2020). Canna lily is a plant that consists of soft tissues and is used as an emergent plant. Even though many studies have been conducted related to macrophyte use in greywater treatment, studies on Canna plant utilization are rarely done.. This plant has higher efficiencies in removing nitrogen and phosphate(Polomski, 2008). This is due to the ability of the Canna plant to carry out evapotranspiration at higher rates compared to the other plants. Also, it has higher rates of dry weight and nutrient accumulation within the Canna plant tissue. As per Polomski et al. (Polomski, 2008), the study has found the maximum storage capacity lies within the shoots and roots of the plant. Moreover, the Canna plant has a higher growth rate with a higher biomass production (Chen, 2009) and has a direct relationship with nutrient uptake. The Canna plant's tolerance towards wastewater stress and the presence of chemicals gives this plant the potential for phytoremediation.

Fern is a nonflowering vascular plant, which contains true roots, complex leaves, and stems. Fern plants are utilized for wastewater treatment at the domestic level expecting to lower the concentration of BOD levels, COD levels, and Ammonia levels (Zimmels et al., 2009). Fern has a good growth rate that contributes towards lowering the above parameters in wastewater. Several researchers have highlighted the ability to use Ferns in phytoremediation which is an important aspect of wastewater treatment (Forni, 2001; Rai, 2007; Vermaat and Khalid Hanif, 1998). With more focus on constructed wetlands, it is a viable choice to use Ferns as a free-floating emergent plant. In addition, Ferns consist of a high tolerance ability to pollutants while having a high potential for phytoremediation ability (Forni, 2001). Cattail plants can rapidly colonize any type of wetland covering a great range as it produces wind-dispersed seeds (Forni, 2001). The rapid growth rate of Cattail plants combined with their large size and aggressive expansion nature create a dense stand in wetlands (Bansal, 2019). State that Cattail has great potential to be used as a wetland emergent plant for wastewater treatment.

With all these positive points, these three plants were selected to understand their performance of them in VFCWs with the aid of an experimental study. As it was stated earlier, this is essential to develop and implement policy decisions to reduce the pollution levels in greywater discharges in an economical way in Sri Lanka.

2. Materials and methods

2.1. Wetland construction

Three experimental setups were designed and constructed with the same density of Canna, Ferns, and Cattail plants. Wetland sizes were calculated based on the formula proposed by Kicked (Un-habitat, 2008) and a septic tank was established for the primary retention purposes. The surface area of each wetland was kept at 1 m^2. Literature recommended a depth of 500 – 800 mm for the wetland (Hua, 2017) and it was kept at 700 mm for this study. Therefore, three rectangular VFCWs were constructed using cement blocks (refer to Fig. 1a). Each VFCW has an effective surface area of 1500 mm × 660 mm, and a depth of 700 mm. Walls and beds were completely sealed using cement mortar and tested twice for leakages using water before the experiments. This setup was developed for filtering a continuous greywater flow of 1.2 m^3/day. Two separate outlets (One extra outlet for emergencies) for each wetland were arranged at the lowest levels of the bed.

The wetland was designed with seven layers and the cross section of VFCW is shown in Fig. 1b. The purpose of cabals (layer 1), coarse gravel (layer 2), and medium gravel layer (layer 4) was to provide more flow and retention time and surface area for microbiological activities for wastewater and then to have efficient oxygen transport into the root zone to encourage the oxidation of hazardous metals that have been reduced to support a large rhizosphere (Vymazal, 2010; Tran et al., 2019). The purpose of the plastic mesh in between layers 2 and 4 was to prevent aggregates block below the coarse gravel and cabal layers. Otherwise, all the fine and gravel particles would block the layers, and it may cause low performance. In addition, the purpose of the charcoal layer was to remove toxins from the water without stripping important minerals and applying locally dominating macrophyte species (Johnson, 2014). The top sand and vegetation layers (6th and 7th) were intended to provide proper conditions for the plants to grow. At the same time, it creates an environment that is suitable for microbial populations, and it helps to transport oxygen to roots efficiently. This setup allows to absorption nutrients of in greywater while facilitating oxidization to reduce toxic metal.

Fig. 1a. VFCW Replicates.

	Layer description	Layer height
Layer 7 Vegetation layer	Using topsoil seventh layer was filled.	200 mm
Layer 6 Sand layer	2 mm - 4 mm size fine aggregates	100 mm
Layer 5 Charcoal layer	Using active charcoal fifth layer was filled.	100 mm
Layer 4 Medium Gravel layer	8 mm - 16 mm size aggregates	100 mm
Layer 3 Plastic Mesh	High-quality plastic mesh (5mm holes)	-
Layer 2 Coarse Gravel layer	16 mm - 64 mm size aggregates	100 mm
Layer 1 Cabals layer	64 mm- 100 mm size aggregates	100 mm

Fig. 1b. VFCW Layers Structure.

2.2. Introduction of wetland plants

After laying subsurface material, three selected plants namely Canna (*Canna indica*), Ferns (*Typha angustifolia*), and Cattail (*Fiddlehead Fern*) were planted in the constructed wetland at the same density (refer to Fig. 2). The selection of the plants was entirely based on the literature as discussed in the introduction section. The main functionality of the roots of wetland plants is to enable the environment to remove pollutants from wastewater (Waly, 2022) and to offer an ample surface area for the development of microbial biofilms (Lee et al., 2009).

2.3. Retention tank construction

It is crucial to remove all debris and particles from untreated greywater before entering the constructed wetland. If not removed, the substrate of the wetland might quickly fill up with these materials. Wetlands' low flow velocities promote the sedimentation of suspended solids (Budd et al., 2009). Therefore, a minimal pre-treatment should be offered to remove these solid materials. This is very common in most of the constructed wetlands. As shown in Fig. 3, a setup was placed above the inlet of the wetland. The outlet of the retention tank was connected to VFCW, and gravity flows were maintained. Furthermore, a sludge removal outlet at the bottom and an overflow outlet at the top of the retention tank were arranged. These tanks need to be de-slugged and cleaned regularly. If not the water quality of the effluent might be very poor due to higher suspended solids. Thus, the wetlands can be clogged. Therefore, regular attention should be paid.

2.4. Sample collection

The retention tank outflow was connected to the VFCW system at 0.83 L/min (1.2 m^3/day) rate and controllers were used to control the flow. This setup was designed for 24 h of hydraulic retention time. Higher hydraulic retention time ensures a higher removal performance of contaminants (Merino-Solís, 2015). The arranged final set was showcased in Fig. 4.

Samples of both treated and untreated greywater were collected in two stages. Samples from retention tank outflow were collected in Phase 1. Then three samples from each tank were collected in phase 2 from the outlets of constructed wetland for quality examination. The sample collection procedure was followed as per the guidelines of the National Engineering Handbook (National Engineering Handbook, 1992). After completing the in-situ measurements, all the samples were then carefully transported to the Central Environmental Authority laboratory

(a) Canna Palnts (b) Fern plants (c) Cattail plants

Fig. 2. Wetland plants.

Fig. 3. Retention tank Setup.

(CEA Laboratory Ratnapura, Sri Lanka which is 30 km away from the site) for testing of physio-chemical parameters.

These samples were routinely collected fortnightly. Before collecting samples, all the wetland beds were cleaned using high-quality mineralized water 24 h before the process and poured greywater into the retention tank up to its maximum level. Afterward, a sample from the retention tank was collected and the flow was directed to the VFCW. Subsequently, three treated water samples from each tank were collected after the following of next 24 h. Throughout the testing process, the retention tank inlets were blocked during the sample collecting period to get highly accurate and precise data for quantitative analysis.

2.5. Water quality analysis

Water samples were evaluated for key physio-chemical parameters namely pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, temperature, turbidity, dissolved oxygen (DO), chemical oxygen demand (COD), phosphates (PO_4^{3-}), nitrates (NO_3^-) and sulphate (SO_4^{2-}). Due to the limitations of the water quality testing facility, only these were considered in this study. However, it is well noted the importance of measuring heavy metals and microplastics in greywater. The sample testing was done at the site and the CEA Laboratory, Rathnapura, Sri Lanka as per the guidelines of the standard methods for the examination of water and wastewater (SLS 614, 2013) Table 1 presents the details of these water quality tests.

2.6. Overall methodology

The flowchart for the overall methodology carried out in the experiments was shown in Fig. 5. This is for easy understanding of the experimental work which was carried out.

3. Results

3.1. Water quality analyses

The outcomes of the water quality analyses for various water quality parameters are presented in Fig. 6. The variation of water quality for six

Fig. 4. Final arrangement of VFCW.

Table 1
Water quality testing.

Parameter	Unit	Test method	Testing facility Location
pH		Water Quality Tester (Make -ALTIFUNCTION, Model-EZ-9909SP)	VFCW site premises
Temperature	^{0}C		
Electrical conductivity (EC)	µs/cm		
Total dissolved solids (TDS)	Part per million (ppm)		
Salinity	Part per thousand (ppt-%)		
Turbidity	NTU	Water Quality Monitor (Make - HORIBA, Model-U500)	CEA Laboratory
Dissolved oxygen (DO)	mg/l	Water Quality Monitor (Make - HORIBA, Model-U500)	
Chemical oxygen demand (COD)	mg/l	APHA 5220D	
Nitrite (NO_3^{1-})	mg/l	APHA 418D	
Phosphate (PO_4^{3-})	mg/l	APHA 4500P-E	
Sulphate (SO_4^{2-})	mg/l	APHA 4500 SO42-	

weeks is given for the retention tank, and VFCWs with three plants. Fig. 6a shows the variation of pH values of the effluents of all three VFCW units. The pH values of all three VFCW outlets have shown slight changes in the variation. The outlet's mean pH values of Canna, Fern, and Cattail plants were 6.69, 6.71, and 6.79 respectively. All three plant types have performed efficiently, and Cattail has shown relatively higher efficiency in pH reduction than Canna and Ferns plants. pH variations of plants were closer to 7 and showed consistency in the results throughout the study period. This phenomenon can be explained by the fact that plants absorb CO_2 and produce O_2 when they expose to adequate sunlight. While O_2 has no impact on the pH of water, carbon dioxide induces a decrease in pH and makes water more acidic. As a result of that, the pH of the water gradually rises as plants absorb CO_2. However, plants can also metabolize a number of other compounds and alter pH. For instance, NH_3 and other nitrogen molecules in the water can be absorbed by plants. Additionally, free hydrogen ions (H^+) are produced by biological reactions often causing the pH of the water to be close to 7 (Bezbaruah and Zhang, 2004). The pH of values showcases a sudden decrease in the retention tank in week 2 and back to normal after that.

Fig. 6b shows the variation of the temperature in the effluent of each VFCW unit. Wastewater temperatures of the effluent of VFCWs were comparatively lower than the temperatures of the wastewater in the retention tank. The atmospheric temperature might have an impact on these readings. Similar trends of temperature can be seen in Cattail and Canna plants. However, these temperatures were less than the outflow of the retention tank (inflows to the VFCWs). It could be due to the absorbance of CO_2 of greywater from the roots of plants. In addition, the surface area of the wetlands might have influenced the temperature levels. That could be another reason to have lower temperatures in the wetlands. In addition, the filtration process has significantly increased the quality of the greywater (refer to Fig. 6c). Reduced total dissolved solids can be seen in all samples. The VFCW with Canna plants performed the best. On average 49%, 38.6%, and 32.3% of removal efficiencies have been observed in the experiments for Canna, Ferns, and Cattail plants respectively. Similar results have been found by researchers (Kurniawati Wulandari, 2019).

The results of the salinity levels in the water filtered through VFCW with Canna, Ferns, and Cattail plants have shown significant decreases (refer to Fig. 6d). Similar decreasing trends can be seen in the electrical conductivity variation plots as well (refer to Fig. 6e). The relationship between the total dissolved solids and electrical conductivity is clearly visualized. Turbidity levels also showcased a significant reduction for all three VFCWs compared to the Turbity levels in the effluent of the retention tank (refer to Fig. 6f). The best results were found in the VFCW with the Cattail plants (refer to Fig. 6h). Notably, the turbidity-removing efficiency of the Cattail plant was 90% making it the highest whereas Ferns plants and Canna plants with efficiencies of 82% and 74% respectively. However, turbidity levels of all the VFCW outlets progressively reached 0 NTU during the 6th week which was an indication of its maximum performance. The growth of the cattail plant might have improved the removal efficiency as the results showcase 100% removal efficiency during the 4th week. The removal mechanisms of water turbidity in the constructed wetland are attributed to sedimentation and filtration facilitated by macrophyte roots that reduce interspaces between gravel by forming dense filter media that is capable of removing

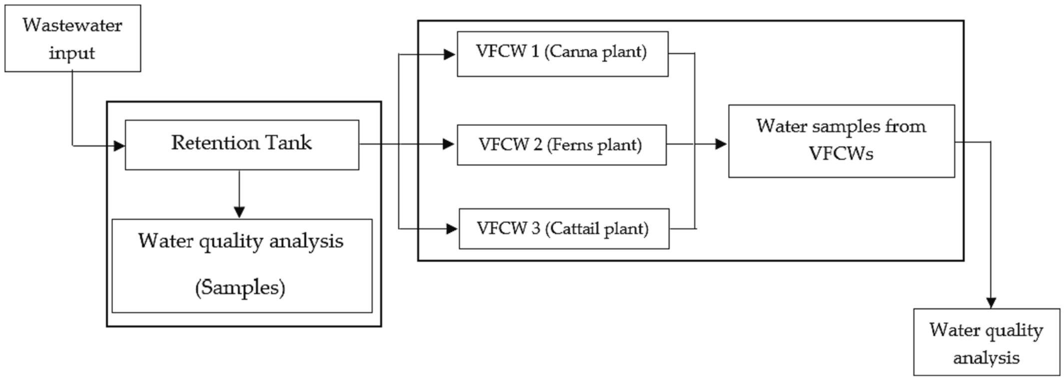

Fig. 5. The overall methodology flowchart.

suspended particles (Mtavangu, 2017). Turbidity removal in sand filters (sand layers in VFCW) is attributed to sedimentation, microbial biodegradation of suspended organic matter, and filtration through the sand layer in the VFCWs.

DO level of the water is an important parameter that ascertains the Physicochemical and biological activities taking place in water. In constructed wetlands and sand filters, DO facilitate in degradation of organic matter by aerobic microorganisms (Kurniawati Wulandari, 2019). DO levels of the greywater of all the VFCW units have shown a significant increment compared to the DO levels in the retention tank as shown in Fig. 6g. This is a clear indication of improvement in the quality of greywater after passing through the VFCW system. Furthermore, this strengthens the fact that the aquatic plants and microorganisms in constructed wetlands together play an integral role in the process of treating greywater. Moreover, plants add oxygen during the process of photosynthesis or by direct transport from the atmosphere through their stems and roots to the rhizosphere of constructed wetlands (Rehman, 2016). Therefore, DO levels eventually get increased after going through the remediation process of the wetland. However, the best result was obtained from the Cattail plant with an average DO value of 6.7 mg/l compared to the 4.9 mg/l with the Fern plant and 3.5 mg/l with the Canna plant as shown in the graph.

In contrast and as expected COD levels have shown a significant reduction in all VFCWs compared to the COD levels of retention tank effluent (refer to Fig. 6h). This is very good evidence to showcase the increased water quality due to the wetland process. The best results were found in the wetland with Cattail plants. The final COD levels but in the range of acceptable levels for wastewater treatment.

Similar to other water quality constituents NO_3^-, PO_4^{3-}, and SO_4^{2-} showcased significant reductions for the effluents from wetlands compared to the effluents of the retention tank (refer to Fig. 6i, j, and k). Therefore, the water quality of the greywater was significantly increased because of the filtration process through the wetlands. Wetland plants have done a significant improvement in absorbing nitrates. The Cattail plant (94% of overall efficiency) and the Fern plant (92% overall efficiency) provided a better arrangement for nitrate absorption. However, the Canna plant (78% overall efficiency) has also contributed. The roots of the wetland plants take up some of the nitrates and incorporate them into their biomass. Microorganisms in the gravel layer further break down any remaining nitrates into nitrogen gas through a process called denitrification. This process requires a low-oxygen environment, which is created by the plant roots that grow into the gravel (Chang, 2013).

The VFCWs with Canna plants and Ferns plants showcased a better performance PO_4^{3-} removals. Fern and Cattail plants showcased a similar performance for SO_4^{2-} removals. Sulphates can be reduced in constructed wetlands through both biological and chemical processes. Microorganisms in the wetland's soil and plants can convert sulphates into sulphides, which are less soluble and can precipitate out of the water. This process is called sulphate reduction and it occurs under anaerobic conditions (Wiessner, 2005). Overall, mixed results can be observed from these wetlands with three types of plants.

3.2. Statistical analysis

Statistical analysis of the results for water quality analysis are given in Table 2 for the three plants which were used in this analysis. The table revealed the overall treatment capacity of the three plants.

The overall performance of the Canna, Cattail, and Fern plants can be considered acceptable based on the mean and standard deviation values of the parameters. Furthermore, standard deviation elaborates volatility of results for 4 samples. These plants are specifically used as emergent plants as they have naturally adapted structures to contain these constituents within the plants themselves. However, the mean values highlight some parameters such as pH, Temperature, EC, TDS and DO are relatively lower which means plants are capable of handling them very well. Finally, these emergent plants can be recommended for wetlands and further studies can be done to narrow down their performances with different parameters to properly utilize them.

3.3. Effluent water quality against the WHO standards

Table 3 presents the average water quality levels of the effluent of wetlands against the World Health Organization water quality standards. These water quality levels are based on the Sri Lankan standards; SLS614. In addition, the table presents the average water qualities of the effluents of the retention tank. High performance of treatment levels can be found in all three VFCWs with three different plants. However, DO levels have not reached the standard of 6–8 mg/L for potable water use. Nevertheless, the DO levels are acceptable for aquatic living species. Furthermore, Turbidity exceeded the level of acceptable levels (<5 NTU), and when compared to the septic tank VFCW shows good performance in the removal of solid particles, also it's acceptable for aquatic life. Therefore, the VFCW performed well with the used plants.

3.4. Discussion

In this study, plant performance in VFCWs for greywater treatment was tested using an experimental study. Interesting findings were observed for three commonly found plants in Sri Lanka to use in VFCWs. Canna and Cattail plants have performed well in maintaining hydraulic balance as their tall and sturdy stems facilitated uniform flow distribution across the wetland bed. On the other hand, Ferns have exhibited slightly lower hydraulic efficiency due to their smaller size and less dense foliage. Plant growth and biomass production of the three plants were also observed throughout the study. It was observed that Canna plants have exhibited vigorous growth and high biomass production. They have formed a dense root system and abundant above-ground biomass. Cattail plants have also shown good growth and biomass

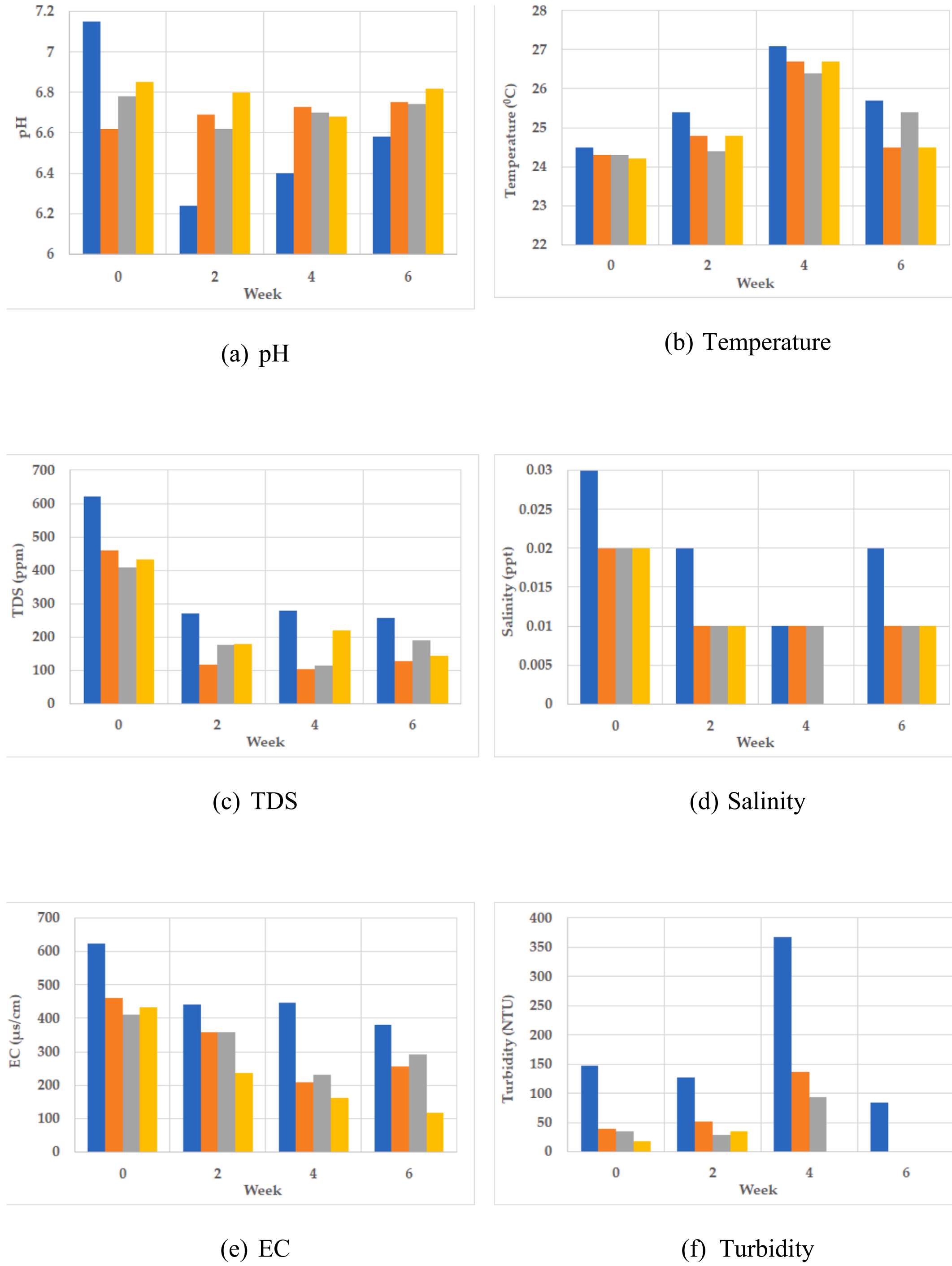

Fig. 6. Temporal variation of water quality constituents.

production, with tall stalks and dense foliage. Fern plants have a rather modest growth rate and lower biomass production compared to Canna and Cattail.

Furthermore, in terms of aesthetic aspects and adaptability to the VFCW environment, Canna and Cattail plants were found to be visually appealing with their tall and vibrant appearance. They added aesthetic value to the system. Ferns, on the other hand, have a more subtle appearance and may be less visually appealing to some individuals. Nevertheless, it is highly subjective. When considering maintenance and operation, Canna and Cattail plants required regular maintenance including trimming of leaves and stalks, maintaining their efficiency, and preventing overgrowth. Ferns have lower maintenance requirements due to their slower growth rate. However, its lower biomass production may result in reduced removal capacity of pollutants compared to the other two species.

Overall, all three species of plants have demonstrated a good performance in treating greywater in VFCWs. However, the specific choice of plant species should be based on the desired removal efficiencies for different pollutants, the feasibility of maintenance, and aesthetic preferences. Cattail plants are recommended for systems that require high organic matter with considerable efficiency in the removal of nitrogen. At the same time, Cattail plants perform well in the removal of salinity,

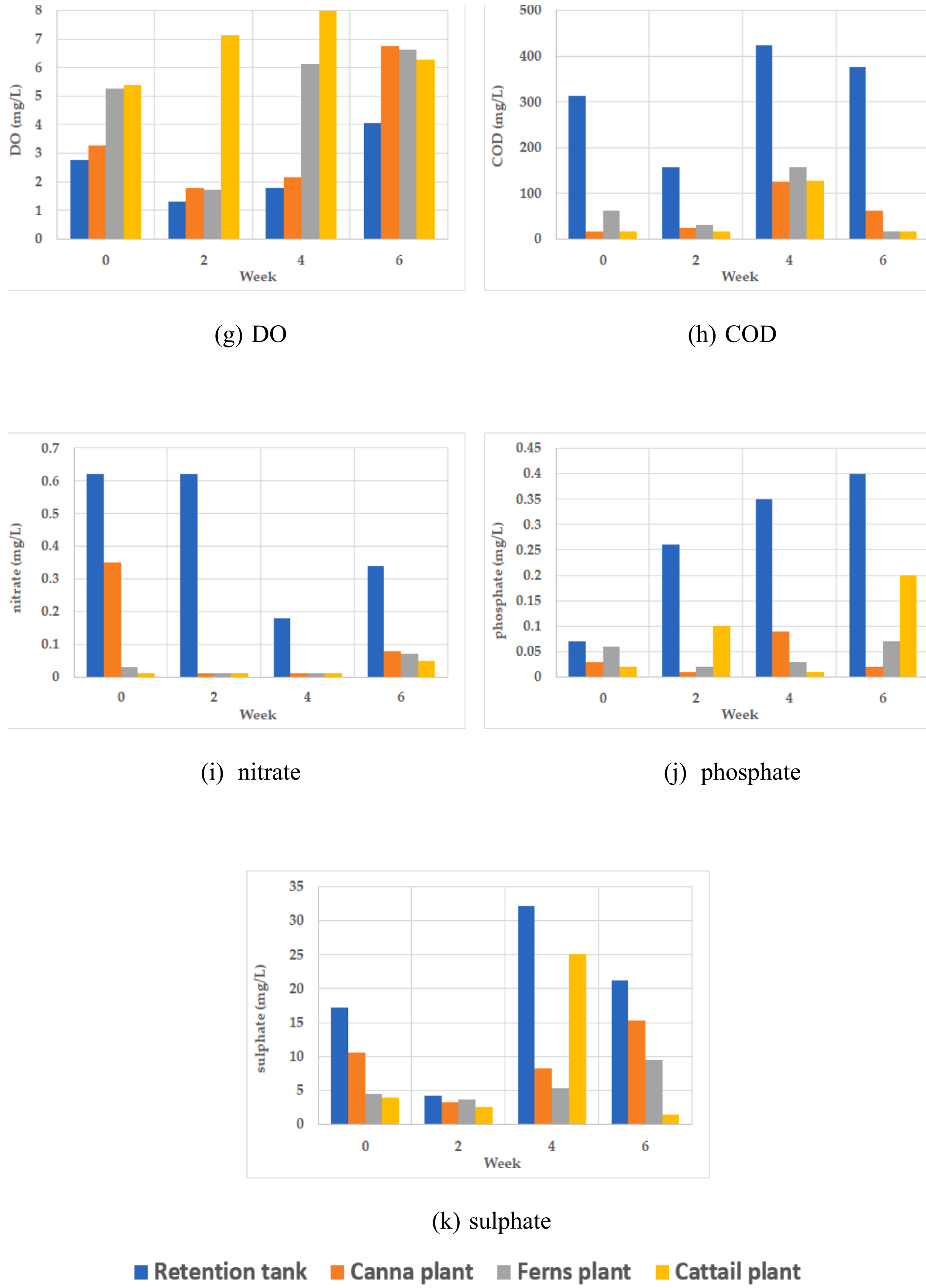

Fig. 6. (*continued*).

turbidity, COD, NO_3^-, and SO_4^{2-} when compared to the other two plants. In addition, Cattail performed well in DO enhancement and PH stabilization. Additionally, Canna plants are suitable for systems that focus on the removal of PO_4^{3-} and TDS while Ferns showed better performance in the reduction of PO_4^{3-} and SO_4^{2-}. When considering all the factors, it can be stated that Cattail Plants are the most suitable emergent plants for wetlands with the better overall performance.

Recently, microplastics and water treatments particularly from greywaters have become a hot topic in the academic press in the field of ecology and environmental management because of its eco-toxicological effects on aquatic environments. This study looked at some of the water quality constituents due to limited testing facilities. Microplastics in greywater have been a very interesting topic in today's world (Wang et al., 2020; Wei et al., 2020; Long et al., 2021). Amrutha et al. (Amrutha et al., 2021) presented the present state of microplastic research in SAARC countries and showcased its importance. Microplastics in the marine environment including coastal sand, coastal waters, and lagoons were tested in Sri Lanka by several researchers (Sevwandi Dharmadasa et al., 2021; Athapaththu et al., 2020; Sewwandi et al., 2022). In addition, microplastics were tested for personal care and cosmetic products

Table 2
Statistical analysis of results obtained.

Parameter	Canna plant Mean	Standard Deviation	Ferns plant Mean	Standard Deviation	Cattail plant Mean	Standard Deviation
pH	6.7	0.057	6.71	0.07	6.79	0.06
Temperature	25.08	1.103	25.13	0.98	25.20	1.02
EC	290.25	114.875	344.25	79.20	382.50	62.56
TDS	144.75	57.755	171.50	39.25	189.00	29.77
Salinity	0.01	0.005	0.01	0.01	0.01	0.01
Turbidity	57.03	57.719	39.13	38.98	53.60	73.83
DO	3.49	2.259	4.93	2.22	6.70	0.97
COD	57.25	49.547	66.75	63.28	43.75	48.06
NO_3^{2-}	0.11	0.162	0.19	0.35	0.16	0.25
PO_4^{3-}	0.04	0.036	0.05	0.02	0.02	0.01
SO_4^{2-}	9.37	5.015	6.58	2.21	8.24	9.77

Table 3
Comparative water qualities with WHO standards.

Parameter	Unit	WHO acceptable limits for portable use (SLS614)	Retention tank effluent	VFCW with Canna plants	VFCW with Ferns plants	VFCW with Cattail plants
pH		6.0–8.5	6.6	6.7	6.7	6.8
Temperature	^{0}C	12 to 25	25.7	25.0	25.1	25.0
EC	µs/cm	< 400	473	320	322	237
TDS	ppm	500–1000	358	202	223	245
Salinity	%	< 0.5	0.02	0.01	0.01	0.01
Turbidity	NTU	< 5	181	57	39	13
DO	mg/L	6.0–8.0	2.5	3.5	4.9	6.7
COD	mg/L	< 250	317	57.2	66.8	43.8
NO_3^{2-}	mg/L	< 1	0.44	0.11	0.03	0.02
PO_4^{3-}	mg/L	< 1	0.27	0.04	0.05	0.08
SO_4^{2-}	mg/L	< 25	18.7	9.4	5.7	8.2

in Sri Lanka by Nawalage and Bellanthudawa (Nawalage and Bellanthudawa, 2022). They stated that 21.4 trillion microplastics were annually released into the environment. Furthermore, Kapukotuwa et al. (Kapukotuwa et al., 2022) have found more microplastic levels in raw salt than commercial salts. Therefore, there is a high chance of having microplastics in the greywater. However, it has never been tested in greywater in the context of Sri Lanka and for this study. Currently, microplastics in greywater were not considered in this study due to the study limitations. However, this will be the next priority research target to investigate the performance of wetland plants to reduce microplastics in greywater. The vertical flow constructed wetland (VFCW) method will be used to investigate the removal potential of the microplastics/ fiber microplastics from greywater in Sri Lanka in our next study.

4. Conclusions

This study assessed the effectiveness of a pilot-scale vertical flow constructed wetland (VFCW) system in treating household greywater with three emergent plants (Canna, Ferns, and Cattail plants). The greywater qualities were tested for several water-quality constituents and found encouraging results. VFCW with Cattail plants performed the best while the other two plants also had higher performances. The VFCW systems are more cost-effective and require less space than horizontal flow-constructed wetlands (HFCWs). Therefore, VFCWs are preferred. Overall, it can be recommended that the small-scale VFCW units are a promising technology for greywater treatment at the household level with the Cattail plant (Typha latifolia) because of its dense fibrous root structure which leads to the removal of more contaminants in domestic greywater. This would be highly important for developing countries like Sri Lanka to encourage the treatment of domestic greywater sustainably. These VFCWs should be further studied to investigate the possibilities of introducing them to rural domestics to protect the environment. This can be an economical and sustainable solution to rural areas due to the financial capacities of communities. However, this study does not look at the microplastic levels in greywater due to experimental limitations. Therefore, it is highly recommended to investigate the microplastic levels of greywater and the treatment efficiencies using VFCWs using commonly available wetland plants. Our future research will be on the removal of fiber microplastics by using vertical flow constructed wetland (VFCW) method.

Declaration of Competing 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

Data will be made available on request.

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