



24 used as emergent plants and a retention tank was constructed to retain solid particles in the  
25 greywater as primary treatment. The experiments were carried out for two months using a  
26 Completely Randomized Design (CRD) for three replicates. The quality of the influent and  
27 effluent was tested fortnight for a number of water quality parameters. Results revealed that the  
28 removal efficiency of contaminants was increased. Cattail plants showed higher removal  
29 efficiency for dissolved oxygen (DO), chemical oxygen demand (COD), nitrates ( $\text{NO}_3^{1-}$ ), turbidity,  
30 and electrical conductivity. In addition, Canna plants had higher efficiencies for the removal of  
31 total dissolved solids (TDS) and phosphates ( $\text{PO}_4^{3-}$ ). Furthermore, Ferns plants presented higher  
32 efficiency only for removing sulphate ( $\text{SO}_4^{3-}$ ). Conclusively, Cattail plants presented the overall  
33 best performance in treating greywater. This can be attributed to the ability of the Cattail's dense  
34 fibrous root system to absorb more contaminants from greywater. This research also discussed the  
35 importance of microplastic analysis in greywater treatment which is a vital part of the current day  
36 research. The results of this study will be helpful to the further advanced research. Furthermore,  
37 this methodology can be implemented to other similar plants across the globe irrespective of  
38 geographical area.

39

40 **Keywords:** Canna plant; Cattail plant; constructed wetlands; Ferns plants; greywater treatment;

41 Vertical flow Construction Wetlands (VFCWs)

42

### 43 **1. Introduction**

44 Water is one of the most crucial resources for all living organisms. Even though 71% of the earth  
45 consists of water, the availability of fresh and potable water is very limited. According to the data  
46 available, 771 million people don't have any access to clean water in 2020 [1]. Furthermore,

47 according to statistics world population is expected to reach 8.45 billion by 2025, thus would result  
48 in risks of water shortages for 40% of the population [2]. This is a critical environmental concern;  
49 therefore, severe attention should be given to water supply systems. In addition, industrialization  
50 demands a high amount of water, and it is in an increasing phase [3]. On the other hand, the  
51 discharge of contaminated water from various industries into the environment has been identified  
52 as a major point source of pollution to receiving water bodies creating a considerable negative  
53 impact on all the sectors of the environment [4]. Furthermore, the degradation of water quality of  
54 receiving water bodies due to non-point sources of pollution which mainly includes urban  
55 stormwater runoff has also been identified as a major issue during the past few decades [5]. The  
56 degradation of the water quality directly impacts aquatic life, human life, and other species  
57 immensely. All these situations ultimately lead to the discussion of water scarcity and how to  
58 safeguard, reuse and save the water for future generations. In this context, wastewater treatment  
59 and reuse have been identified as one of the most practical and feasible methods to address the  
60 problems associated with water quantity and quality. Even though there are many methods that are  
61 being implemented to optimize the process of wastewater treatment in industries, the focus on the  
62 domestic level of wastewater treatment methods for different types of household discharges is not  
63 very progressive, particularly in developing countries like Sri Lanka.

64 Greywater is the effluent that discharges from households excluding toilet wastewater [6]. Usually,  
65 greywater is contaminated with different soluble and insoluble compounds such as dirt, grease,  
66 hair, food, and chemical substances, pathogens in general [7]. In addition, microplastics are readily  
67 available in grey water even though it is not yet given in- depth attention in most of the countries.  
68 In developing countries such as Sri Lanka, greywater production in urban and suburban areas is  
69 mostly discharged without any treatment to either a sewage line or stormwater drain, or the direct

70 environment. Discharges to the direct environment are very popular in many rural areas in  
71 developing countries as there are no policy regulations to prohibit that. As a result of these  
72 untreated greywater discharges, natural water bodies are in real danger with environmental impacts  
73 such as depletion of dissolved oxygen, high turbidity levels, eutrophication, etc. [6]. Most  
74 countries utilize greywater for home garden irrigation or agricultural purposes in regions where  
75 water scarcity is a major issue or when the cost of water supply is high. Even though greywater is  
76 considerably less polluted compared to other wastewater sources, it still contains various  
77 contaminants which need to be removed through a proper treatment process before attempting to  
78 reuse or release into the environment. This includes microplastics as well. If proper treatment is  
79 not carried out before reusing or discharging to the environment, it will lead to adverse impacts on  
80 human health, soil, groundwater quality, and the whole environment system ultimately [8].

81 Four different types of waste treatment methods are used in many countries. They are physical  
82 water treatment, biological water treatment, chemical water treatment, and sludge treatment. Some  
83 of the treatment techniques have combined methods. Constructed wetlands are under both physical  
84 and biological categories due to the involvement of both processes. There is an increasing demand  
85 for more environmentally friendly wastewater treatment technologies such as constructed  
86 wetlands. Constructed wetland is an engineered system that is designed to have a natural  
87 wastewater treatment process (which incorporates soil, vegetation, and microbial assemblages)  
88 [9]. They are mostly utilized for treating point source pollution such as municipal waste, and  
89 domestic waste [8]. But they can also be used to treat non-point source pollution (agricultural  
90 runoff, landfill leachate, etc.). However, by changing various design factors, constructed wetlands  
91 may treat a range of pollutants by utilizing low-energy and natural processes [10,11].

92 Three main types of constructed wetlands can be identified based on the flow direction of effluent:  
93 horizontal flow (HFCWs), vertical flow (VFCWs), and hybrid flow (HFCW) [12]. In HFCW,  
94 wastewater flows through a porous medium under the emergent plants horizontally [13]. The  
95 treatment process involves aerobic, anaerobic, and anoxic zones to be passed through to treat the  
96 greywater. However, VFCWs operate in a different manner where wastewater is percolated  
97 through the soil with discontinuous loading periods and resting periods. These VFCWs are usually  
98 constructed either in shallow excavation or above ground with an impermeable linear covering  
99 around the wetland area. Also, emergent plants on the wetland assist in maintaining the hydraulic  
100 conductivity of the VFCW's bed. Typically VFCW requires a lesser area to treat wastewater when  
101 compared with HFCW [14]. VFCWs, unlike HFCWs, are a viable alternative when faced with  
102 restricted land availability and are usually suitable in domestic and industrial wastewater recycling.  
103 This treatment system is designed to effectively remove organic matter, nitrogen, phosphorus, and  
104 pathogens through microbial activity. Additionally, it is capable of managing solids due to the  
105 oxidation-reduction environment inside the system. Overall, this system offers ample and  
106 appropriate treatment for various types of contaminants [15-17]. Nevertheless, the hybrid flow  
107 constructed wetland influences both VFCW and HFCW to obtain higher treatment efficiency. This  
108 is also considered to be preferable for nitrogen as it provides less oxygen in the system.

109 On the other hand, wetland plants play a significant role in constructed wetlands. This primarily  
110 includes uptaking of the nutrients, absorbing, and accumulating heavy metal and poisonous  
111 substances from wastewater, and contributing significantly to simultaneous nitrification and de-  
112 nitrification, transferring oxygen to the rhizosphere for microorganism growth, reproduction, and  
113 decomposition [18]. The Root Zone theory by Seidel and Kickuth [19], highlighted the function

114 of macrophytes in wetlands' sewage treatment systems and significantly encouraged the study and  
115 use of constructed wetlands.

116 Even though literature showcases a number of studies to investigate the performance of these  
117 constructed wetlands [20-26], they are very limited in the context of Sri Lanka. The performance  
118 of VFCWs was never tested using the readily available plants in Sri Lanka. Therefore, such  
119 analysis is highly important as most of the generated greywater is not treated in Sri Lanka and is  
120 directly discharged to nearby environments. Thus, a high necessity is raised to investigate the  
121 performance of constructed wetlands using readily available Sri Lankan plants and then to promote  
122 such systems among the community. Therefore, this study for the first time in the context of Sri  
123 Lanka, is focused on the investigation of VFCW performance using three different plant species  
124 readily available.

125 ..

126 Most of the studies have shown that Canna plants and Cattail plants exhibit good performance  
127 overall [27] [28]. Canna lily is a plant that consists of soft tissues and is used as an emergent plant.  
128 Even though many studies have been conducted related to macrophyte use in greywater treatment,  
129 studies on Canna plant utilization are rarely done. . This plant has higher efficiencies in removing  
130 nitrogen and phosphate[29]. This is due to the ability of the Canna plant to carry out  
131 evapotranspiration at higher rates compared to the other plants. Also, it has higher rates of dry  
132 weight and nutrient accumulation within the Canna plant tissue. As per Polomski et al. [29], the  
133 study has found the maximum storage capacity lies within the shoots and roots of the plant.  
134 Moreover, the Canna plant has a higher growth rate with a higher biomass production [30] and has  
135 a direct relationship with nutrient uptake. The Canna plant's tolerance towards wastewater stress  
136 and the presence of chemicals gives this plant the potential for phytoremediation.

137 Fern is a nonflowering vascular plant, which contains true roots, complex leaves, and stems. Fern  
138 plants are utilized for wastewater treatment at the domestic level expecting to lower the  
139 concentration of BOD levels, COD levels, and Ammonia levels [31]. Fern has a good growth rate  
140 that contributes towards lowering the above parameters in wastewater. Several researchers have  
141 highlighted the ability to use Ferns in phytoremediation which is an important aspect of wastewater  
142 treatment [32-34]. With more focus on constructed wetlands, it is a viable choice to use Ferns as a  
143 free-floating emergent plant. In addition, Ferns consist of a high tolerance ability to pollutants  
144 while having a high potential for phytoremediation ability [32]. Cattail plants can rapidly colonize  
145 any type of wetland covering a great range as it produces wind-dispersed seeds [32]. The rapid  
146 growth rate of Cattail plants combined with their large size and aggressive expansion nature create  
147 a dense stand in wetlands [35]. State that Cattail has great potential to be used as a wetland  
148 emergent plant for wastewater treatment.

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

153

## 154 **2. Materials and methods**

### 155 **2.1. Wetland construction**

156 Three experimental setups were designed and constructed with the same density of Canna, Ferns,  
157 and Cattail plants. Wetland sizes were calculated based on the formula proposed by Kicked [36]  
158 and a septic tank was established for the primary retention purposes. The surface area of each  
159 wetland was kept at 1 m<sup>2</sup>. Literature recommended a depth of 500 – 800 mm for the wetland [37]

160 and it was kept at 700 mm for this study. Therefore, three rectangular VFCWs were constructed  
 161 using cement blocks (refer to Figure 1a). Each VFCW has an effective surface area of 1500 mm x  
 162 660 mm, and a depth of 700 mm. Walls and beds were completely sealed using cement mortar and  
 163 tested twice for leakages using water before the experiments. This setup was developed for filtering  
 164 a continuous greywater flow of 1.2 m<sup>3</sup>/day. Two separate outlets (One extra outlet for emergencies)  
 165 for each wetland were arranged at the lowest levels of the bed.  
 166



Figure 1a VFCW Replicates

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

Figure 1(b). VFCW Layers Structure

167 The wetland was designed with seven layers and the cross section of VFCW is shown in Figure  
 168 1b. The purpose of cabals (layer 1), coarse gravel (layer 2), and medium gravel layer (layer 4) was  
 169 to provide more flow and retention time and surface area for microbiological activities for  
 170 wastewater and then to have efficient oxygen transport into the root zone to encourage the  
 171 oxidation of hazardous metals that have been reduced to support a large rhizosphere [10,38]. The  
 172 purpose of the plastic mesh in between layers 2 and 4 was to prevent aggregates block below the  
 173 coarse gravel and cabal layers. Otherwise, all the fine and gravel particles would block the layers,

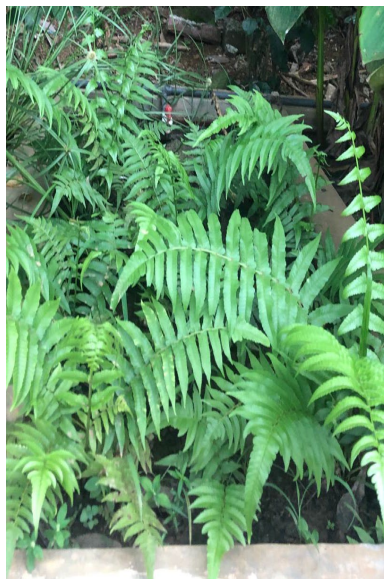
174 and it may cause low performance. In addition, the purpose of the charcoal layer was to remove  
175 toxins from the water without stripping important minerals and applying locally dominating  
176 macrophyte species [39]. The top sand and vegetation layers (6th and 7th) were intended to provide  
177 proper conditions for the plants to grow. At the same time, it creates an environment that is suitable  
178 for microbial populations, and it helps to transport oxygen to roots efficiently. This setup allows  
179 to absorption nutrients of in greywater while facilitating oxidization to reduce toxic metal.

180

## 181 **2.2. Introduction of wetland plants**

182 After laying subsurface material, three selected plants namely *Canna* (*Canna indica*), Ferns (*Typha*  
183 *angustifolia*), and Cattail (*Fiddlehead Fern*) were planted in the constructed wetland at the same  
184 density (refer to Figure 2). The selection of the plants was entirely based on the literature as  
185 discussed in the introduction section. The main functionality of the roots of wetland plants is to  
186 enable the environment to remove pollutants from wastewater [11] and to offer an ample surface  
187 area for the development of microbial biofilms [40].

188



(a) Canna Palnts

(b) Fern plants

(c) Cattail plants

189

Figure 2. Wetland plants

190

### 191 2.3. Retention tank construction

192 It is crucial to remove all debris and particles from untreated greywater before entering the

193 constructed wetland. If not removed, the substrate of the wetland might quickly fill up with these

194 materials. Wetlands' low flow velocities promote the sedimentation of suspended solids [41].

195 Therefore, a minimal pre-treatment should be offered to remove these solid materials. This is very

196 common in most of the constructed wetlands. As shown in Figure 3, a setup was placed above the

197 inlet of the wetland. The outlet of the retention tank was connected to VFCW, and gravity flows

198 were maintained. Furthermore, a sludge removal outlet at the bottom and an overflow outlet at the

199 top of the retention tank were arranged. These tanks need to be de-slugged and cleaned regularly.

200 If not the water quality of the effluent might be very poor due to higher suspended solids. Thus,

201 the wetlands can be clogged. Therefore, regular attention should be paid.

202



203

204

Figure 3. Retention tank Setup

205 **2.4. Sample collection**

206 The retention tank outflow was connected to the VFCW system at 0.83 L/min (1.2 m<sup>3</sup>/day) rate  
207 and controllers were used to control the flow. This setup was designed for 24 hours of hydraulic  
208 retention time. Higher hydraulic retention time ensures a higher removal performance of  
209 contaminants [42]. The arranged final set was showcased in Figure 4.

210



211

212 Figure 4. Final arrangement of VFCW

213

214 Samples of both treated and untreated greywater were collected in two stages. Samples from  
215 retention tank outflow were collected in Phase 1. Then three samples from each tank were collected  
216 in phase 2 from the outlets of constructed wetland for quality examination. The sample collection  
217 procedure was followed as per the guidelines of the National Engineering Handbook [43]. After  
218 completing the in-situ measurements, all the samples were then carefully transported to the Central  
219 Environmental Authority laboratory (CEA Laboratory Ratnapura, Sri Lanka which is 30 km away  
220 from the site) for testing of physio-chemical parameters.

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

228

## 229 **2.5. Water quality analysis**

230 Water samples were evaluated for key physio-chemical parameters namely pH, electrical  
 231 conductivity (EC), total dissolved solids (TDS), salinity, temperature, turbidity, dissolved oxygen  
 232 (DO), chemical oxygen demand (COD), phosphates ( $\text{PO}_4^{3-}$ ), nitrates ( $\text{NO}_3^-$ ) and sulphate ( $\text{SO}_4^{2-}$ ).  
 233 Due to the limitations of the water quality testing facility, only these were considered in this study.  
 234 However, it is well noted the importance of measuring heavy metals and microplastics in  
 235 greywater. The sample testing was done at the site and the CEA Laboratory, Rathnapura, Sri Lanka  
 236 as per the guidelines of the standard methods for the examination of water and wastewater [44]  
 237 Table 1 presents the details of these water quality tests.

238

239 Table 1. Water quality testing

Parameter	Unit	Test method	Testing facility Location
pH		Water Quality Tester	VFCW site
Temperature	$^{\circ}\text{C}$		premises

Electrical conductivity (EC)	$\mu\text{s}/\text{cm}$	(Make -ALTIFUNCTION, Model-EZ-9909SP)
Total dissolved solids (TDS)	Part per million (ppm)	
Salinity	Part per thousand (ppt-%)	
Turbidity	NTU	Water Quality Monitor (Make - HORIBA, Model-U500)
Dissolved oxygen (DO)	mg/l	Water Quality Monitor (Make - HORIBA, Model-U500)
Chemical oxygen demand (COD)	mg/l	CEA Laboratory APHA 5220D
Nitrite ( $\text{NO}_3^{1-}$ )	mg/l	APHA 418D
Phosphate ( $\text{PO}_4^{3-}$ )	mg/l	APHA 4500P-E
Sulphate ( $\text{SO}_4^{2-}$ )	mg/l	APHA 4500 SO42-

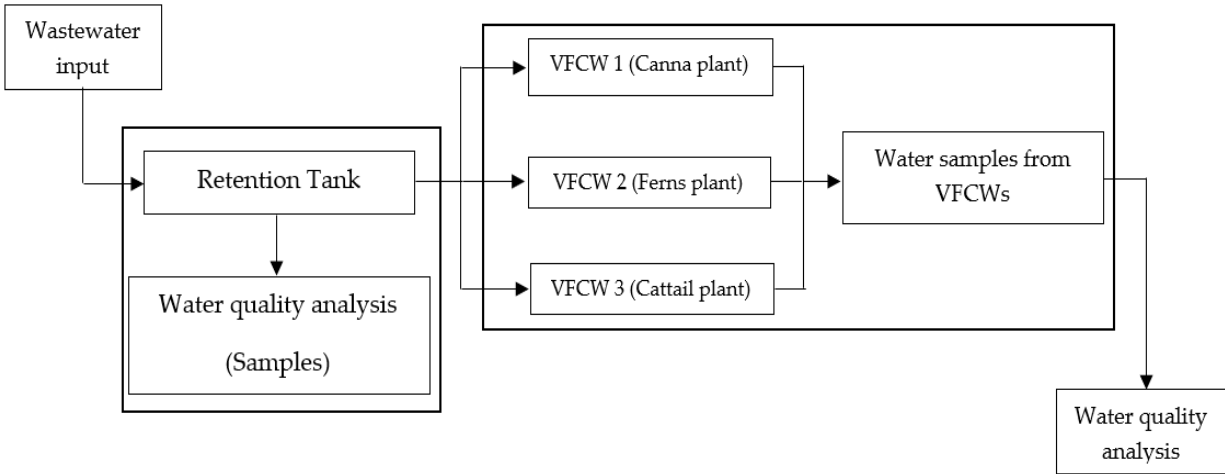
240

241 **2.6. Overall methodology**

242 The flowchart for the overall methodology carried out in the experiments was shown in Figure 5.

243 This is for easy understanding of the experimental work which was carried out.

244



245

246

Figure 5. The overall methodology flowchart

247

## 248 4. Results

### 249 4.1 Water quality analyses

250 The outcomes of the water quality analyses for various water quality parameters are presented in

251 Figure 6. The variation of water quality for six weeks is given for the retention tank, and VFCWs

252 with three plants. Figure 6a shows the variation of pH values of the effluents of all three VFCW

253 units. The pH values of all three VFCW outlets have shown slight changes in the variation. The

254 outlet's mean pH values of Canna, Fern, and Cattail plants were 6.69, 6.71, and 6.79 respectively.

255 All three plant types have performed efficiently, and Cattail has shown relatively higher efficiency

256 in pH reduction than Canna and Ferns plants. pH variations of plants were closer to 7 and showed

257 consistency in the results throughout the study period. This phenomenon can be explained by the

258 fact that plants absorb CO<sub>2</sub> and produce O<sub>2</sub> when they expose to adequate sunlight. While O<sub>2</sub> has

259 no impact on the pH of water, carbon dioxide induces a decrease in pH and makes water more

260 acidic. As a result of that, the pH of the water gradually rises as plants absorb CO<sub>2</sub>. However,

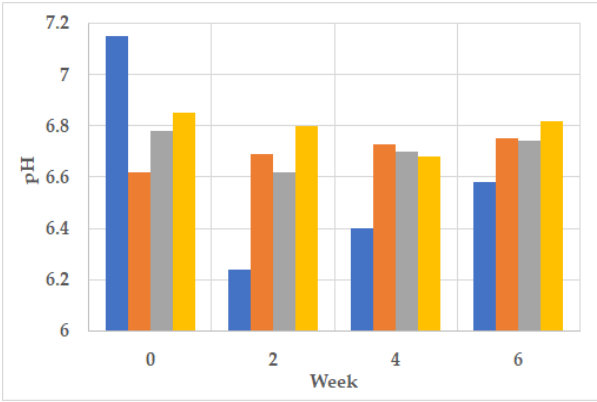
261 plants can also metabolize a number of other compounds and alter pH. For instance, NH<sub>3</sub> and other

262 nitrogen molecules in the water can be absorbed by plants. Additionally, free hydrogen ions ( $H^+$ )  
263 are produced by biological reactions often causing the pH of the water to be close to 7 [45]. The  
264 pH of values showcases a sudden decrease in the retention tank in week 2 and back to normal after  
265 that.

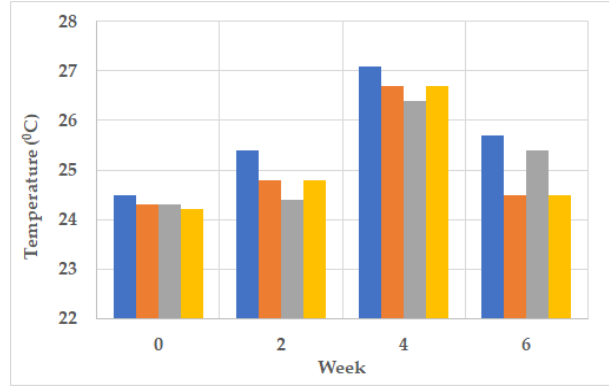
266 Figure 6b shows the variation of the temperature in the effluent of each VFCW unit. Wastewater  
267 temperatures of the effluent of VFCWs were comparatively lower than the temperatures of the  
268 wastewater in the retention tank. The atmospheric temperature might have an impact on these  
269 readings. Similar trends of temperature can be seen in Cattail and Canna plants. However, these  
270 temperatures were less than the outflow of the retention tank (inflows to the VFCWs). It could be  
271 due to the absorbance of  $CO_2$  of greywater from the roots of plants. In addition, the surface area  
272 of the wetlands might have influenced the temperature levels. That could be another reason to have  
273 lower temperatures in the wetlands. In addition, the filtration process has significantly increased  
274 the quality of the greywater (refer to Figure 6c). Reduced total dissolved solids can be seen in all  
275 samples. The VFCW with Canna plants performed the best. On average 49%, 38.6%, and 32.3%  
276 of removal efficiencies have been observed in the experiments for Canna, Ferns, and Cattail plants  
277 respectively. Similar results have been found by researchers [46].

278

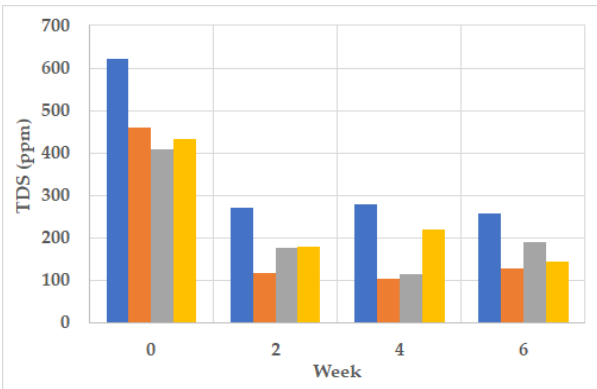
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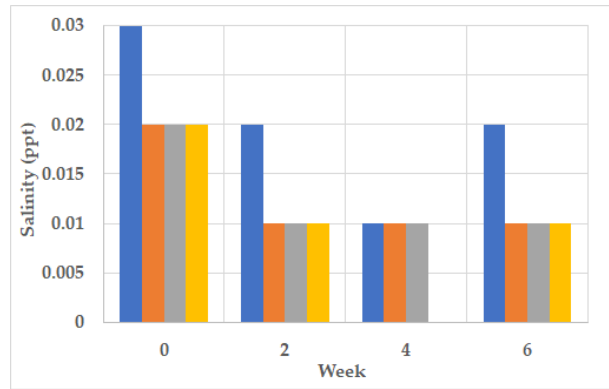
(a) pH



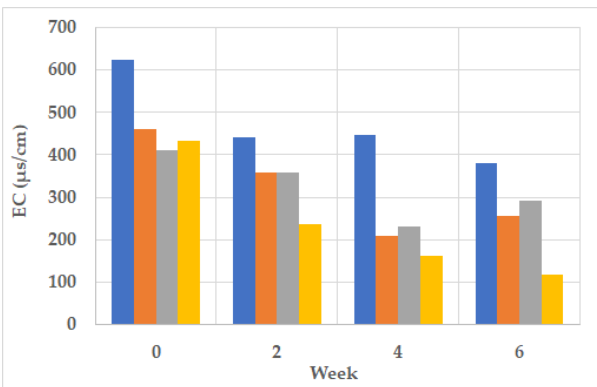
(b) Temperature



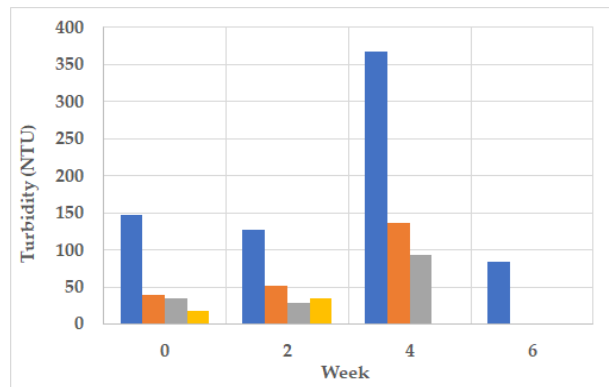
(c) TDS



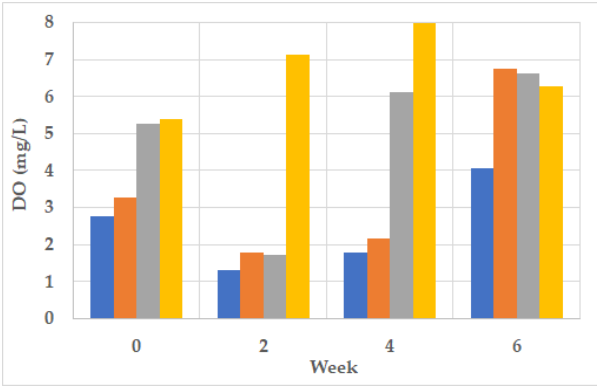
(d) Salinity



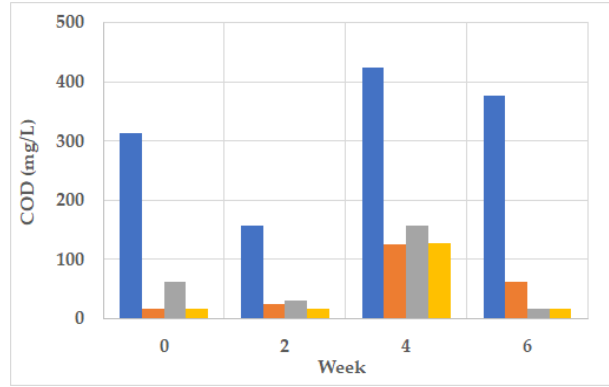
(e) EC



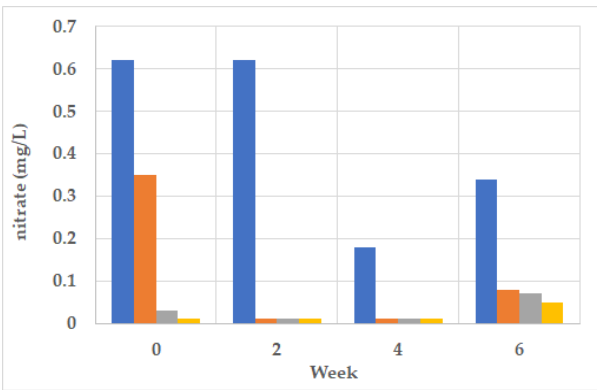
(f) Turbidity



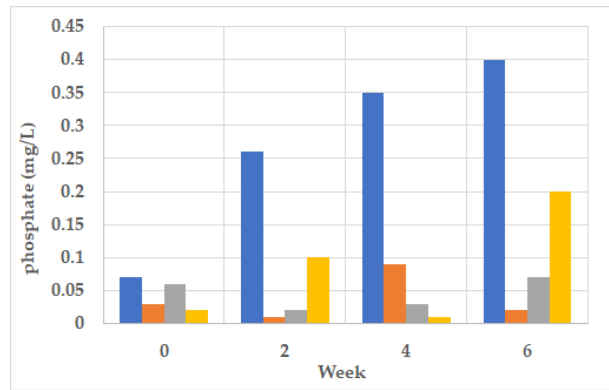
(g) DO



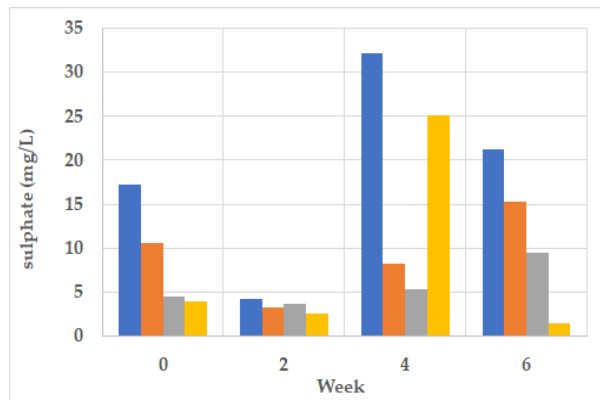
(h) COD



(i) nitrate



(j) phosphate



(k) sulphate

■ Retention tank ■ Canna plant ■ Ferns plant ■ Cattail plant

280 Figure 6. Temporal variation of water quality constituents

281 The results of the salinity levels in the water filtered through VFCW with Canna, Ferns, and Cattail  
282 plants have shown significant decreases (refer to Figure 6d). Similar decreasing trends can be seen  
283 in the electrical conductivity variation plots as well (refer to Figure 6e). The relationship between  
284 the total dissolved solids and electrical conductivity is clearly visualized. Turbidity levels also  
285 showcased a significant reduction for all three VFCWs compared to the Turbidity levels in the  
286 effluent of the retention tank (refer to Figure 6f). The best results were found in the VFCW with  
287 the Cattail plants (refer to Figure 6h). Notably, the turbidity-removing efficiency of the Cattail  
288 plant was 90% making it the highest whereas Ferns plants and Canna plants with efficiencies of  
289 82% and 74% respectively. However, turbidity levels of all the VFCW outlets progressively  
290 reached 0 NTU during the 6th week which was an indication of its maximum performance. The  
291 growth of the cattail plant might have improved the removal efficiency as the results showcase  
292 100% removal efficiency during the 4<sup>th</sup> week. The removal mechanisms of water turbidity in the  
293 constructed wetland are attributed to sedimentation and filtration facilitated by macrophyte roots  
294 that reduce interspaces between gravel by forming dense filter media that is capable of removing  
295 suspended particles [47]. Turbidity removal in sand filters (sand layers in VFCW) is attributed to  
296 sedimentation, microbial biodegradation of suspended organic matter, and filtration through the  
297 sand layer in the VFCWs.

298 DO level of the water is an important parameter that ascertains the Physicochemical and biological  
299 activities taking place in water. In constructed wetlands and sand filters, DO facilitate in  
300 degradation of organic matter by aerobic microorganisms [46]. DO levels of the greywater of all  
301 the VFCW units have shown a significant increment compared to the DO levels in the retention

302 tank as shown in Figure 6g. This is a clear indication of improvement in the quality of greywater  
303 after passing through the VFCW system. Furthermore, this strengthens the fact that the aquatic  
304 plants and microorganisms in constructed wetlands together play an integral role in the process of  
305 treating greywater. Moreover, plants add oxygen during the process of photosynthesis or by direct  
306 transport from the atmosphere through their stems and roots to the rhizosphere of constructed  
307 wetlands [48]. Therefore, DO levels eventually get increased after going through the remediation  
308 process of the wetland. However, the best result was obtained from the Cattail plant with an  
309 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  
310 Canna plant as shown in the graph.

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

316 Similar to other water quality constituents  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ , and  $\text{SO}_4^{2-}$  showcased significant reductions  
317 for the effluents from wetlands compared to the effluents of the retention tank (refer to Figure 6i,  
318 j, and k). Therefore, the water quality of the greywater was significantly increased because of the  
319 filtration process through the wetlands. Wetland plants have done a significant improvement in  
320 absorbing nitrates. The Cattail plant (94% of overall efficiency) and the Fern plant (92% overall  
321 efficiency) provided a better arrangement for nitrate absorption. However, the Canna plant (78%  
322 overall efficiency) has also contributed. The roots of the wetland plants take up some of the nitrates  
323 and incorporate them into their biomass. Microorganisms in the gravel layer further break down  
324 any remaining nitrates into nitrogen gas through a process called denitrification. This process

325 requires a low-oxygen environment, which is created by the plant roots that grow into the gravel  
326 [49].

327 The VFCWs with Canna plants and Ferns plants showcased a better performance  $\text{PO}_4^{3-}$  removals.  
328 Fern and Cattail plants showcased a similar performance for  $\text{SO}_4^{2-}$  removals. Sulphates can be  
329 reduced in constructed wetlands through both biological and chemical processes. Microorganisms  
330 in the wetland's soil and plants can convert sulphates into sulphides, which are less soluble and  
331 can precipitate out of the water. This process is called sulphate reduction and it occurs under  
332 anaerobic conditions [50]. Overall, mixed results can be observed from these wetlands with three  
333 types of plants.

334

#### 335 4.2 Statistical analysis

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

339

340 Table 2. Statistical analysis of results obtained

Parameter	Canna plant		Ferns plant		Cattail plant	
	Mean	Standard Deviation	Mean	Standard Deviation	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 <sub>3</sub> <sup>2-</sup>	0.11	0.162	0.19	0.35	0.16	0.25
PO <sub>4</sub> <sup>3-</sup>	0.04	0.036	0.05	0.02	0.02	0.01
SO <sub>4</sub> <sup>2-</sup>	9.37	5.015	6.58	2.21	8.24	9.77

341

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

350

### 351 **4.3 Effluent water quality against the WHO standards**

352 Table 5 presents the average water quality levels of the effluent of wetlands against the World  
353 Health Organization water quality standards. These water quality levels are based on the Sri  
354 Lankan standards; SLS614. In addition, the table presents the average water qualities of the  
355 effluents of the retention tank. High performance of treatment levels can be found in all three  
356 VFCWs with three different plants. However, DO levels have not reached the standard of 6-8 mg/L

357 for potable water use. Nevertheless, the DO levels are acceptable for aquatic living species.  
 358 Furthermore, Turbidity exceeded the level of acceptable levels (<5 NTU), and when compared to  
 359 the septic tank VFCW shows good performance in the removal of solid particles, also it's  
 360 acceptable for aquatic life. Therefore, the VFCW performed well with the used plants.

361

362 Table 5. Comparative water qualities with WHO standards

Parameter	Unit	WHO acceptable	Retention	VFCW	VFCW	VFCW
		limits for portable	tank	with	VFCW	with
		use (SLS614)	effluent	Canna	with Ferns	Cattail
				plants	plants	plants
pH		6.0-8.5	6.6	6.7	6.7	6.8
Temperature	°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 <sub>3</sub> <sup>2-</sup>	mg/L	< 1	0.44	0.11	0.03	0.02
PO <sub>4</sub> <sup>3-</sup>	mg/L	< 1	0.27	0.04	0.05	0.08
SO <sub>4</sub> <sup>2-</sup>	mg/L	< 25	18.7	9.4	5.7	8.2

363

364

#### 365 4.4 Discussion

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

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

386 Overall, all three species of plants have demonstrated a good performance in treating greywater in  
387 VFCWs. However, the specific choice of plant species should be based on the desired removal

388 efficiencies for different pollutants, the feasibility of maintenance, and aesthetic preferences.  
389 Cattail plants are recommended for systems that require high organic matter with considerable  
390 efficiency in the removal of nitrogen. At the same time, Cattail plants perform well in the removal  
391 of salinity, turbidity, COD,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$  when compared to the other two plants. In addition,  
392 Cattail performed well in DO enhancement and PH stabilization. Additionally, Canna plants are  
393 suitable for systems that focus on the removal of  $\text{PO}_4^{3-}$  and TDS while Ferns showed better  
394 performance in the reduction of  $\text{PO}_4^{3-}$  and  $\text{SO}_4^{2-}$ . When considering all the factors, it can be stated  
395 that Cattail Plants are the most suitable emergent plants for wetlands with the better overall  
396 performance.

397 Recently, microplastics and water treatments particularly from greywaters have become a hot topic  
398 in the academic press in the field of ecology and environmental management because of its eco-  
399 toxicological effects on aquatic environments. This study only looked at some of the water quality  
400 constituents due to limited testing facilities. Microplastics in greywater have been a very  
401 interesting topic in today's world [51-53]. Amrutha et al. [54] presented the present state of  
402 microplastic research in SAARC countries and showcased its importance. Microplastics in the  
403 marine environment including coastal sand, coastal waters, and lagoons were tested in Sri Lanka  
404 by several researchers [55-57]. In addition, microplastics were tested for personal care and  
405 cosmetic products in Sri Lanka by Nawalage and Bellanthudawa [58]. They stated that 21.4 trillion  
406 microplastics were annually released into the environment. Furthermore, Kapukotuwa et al. [59]  
407 have found more microplastic levels in raw salt than commercial salts. Therefore, there is a high  
408 chance of having microplastics in the greywater. However, it has never been tested in greywater  
409 in the context of Sri Lanka and for this study. Currently, microplastics in greywater were not  
410 considered in this study due to the study limitations. However, this will be the next priority research

411 target to investigate the performance of wetland plants to reduce microplastics in greywater. The  
412 vertical flow constructed wetland (VFCW) method will be used to investigate the removal  
413 potential of the microplastics/fiber microplastics from greywater in Sri Lanka in our next study.

414

## 415 **Conclusions**

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

434

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439

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