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Initial Stage in Designing Household Constructed Wetlands: Selection of a Suitable Aquatic Plant

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Abstract—**Constructing centralized wastewater treatment plant systems to serve and control city sanitation requirements is vastly expensive in developing countries. Consequently, employing decentralized wastewater treatment systems through utilizing constructed wetlands (CWs) for individual households should be promoted. In this study, the most appropriate aquatic species planted in constructed wetlands were examined for treating greywater at the household level in humid tropical regions. Three different decorative aquatic plants (i.e., *Echinodorus palaefolius, Typha latifolia*, and *Cyperus alternifolius*) were compared based on their performances. Also, three similar wetlands having a total working volume of 158.42 liters with a gravel sand filter were used in this study. One day, a period was allocated for the hydraulic retention time (HRT), which corresponds to the applied hydraulic loading rate of 115.5- and 150.5-mm d^{-1} for the first and second experiments, respectively. The high percentage removal of 5-day biological oxygen demand (BOD_5), along with an aesthetic green view and minimum maintenance of decorative plants, was employed as the selection criteria. *In-situ* measurements were also undertaken for pH, temperature, and total dissolved solids. The findings indicate that the most significant BOD_5 removal was with the *Cyperus alternifolius* plants, which showed a very high BOD_5 removal rate (91.18%). The *Cyperus alternifolus* species were more resistant in full direct sunlight conditions and adaptable to grow in temporarily or fully submerged conditions. These results, therefore, suggest that *Cyperus alternifolius* is the most suitable plant species for the treatment of greywater in household CWs in the tropics.**

Keywords— ***Cyperus alternifolius*; constructed wetland; greywater; household treatment.**

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I. INTRODUCTION

Urban activities have negatively affected both the quantity and quality of water sources (e.g., rivers, groundwater, and lakes) [1]. In terms of water quantity, it refers mainly to the rate of population growth and the demand for water [2]. Meanwhile, water quality is predicted to become worse globally in the coming decades [3]. It has been estimated that over 80% of the world's wastewater is released into the environment without treatment [4]. In Indonesia, household wastewater contributes to contaminate the river water in urban areas [5]. Most of the household wastewater comes from greywater (i.e., wastewater without any input from latrines). The greywater is commonly discharged into the drainage system without any treatment. As households regularly dispose of greywater, it has become a significant contributor to water pollution.

Centralized wastewater treatment plants, known as conventional plants, consume high amounts of energy, including significant costs for construction and maintenance, have large mechanical parts made of non-renewable materials (e.g., concrete and steel), and require continuous monitoring [6], [7]. In countries where cost is one of the major factors, low-cost alternative technology is more suitable to be applied. For this purpose, constructed wetlands (CWs) are seen as a viable option for application in developing countries, particularly by small communities, because the CWs are characterized by relatively low costs in capital, operation, and maintenance cost [8], [9]. These CWs involve interconnection of wetland plants, soils, and microorganisms supporting the wastewater treatment [10]. They offer several benefits including natural process utilization, low production cost, simple construction design, uncomplicated operation, and aesthetically pleasant green views [11], [12].

The CWs are artificially engineered ecosystems designed and constructed to mirror or replicate natural wetland system processes under controlled conditions for treating wastewater [6], [13]. The first experiment on the possibility of wastewater treatment with wetland plants was conducted by Seidel in the 1960s and by Kickuth in the 1970s [14]. The use of CWs for wastewater treatment has been becoming more popular in many developed countries. The CWs are also suitable for developing countries [8]. However, they still have to become better known. In the last few decades, the development of CWs has received great attention from both scientists and engineers to treat several types of wastewater (e.g., domestic sewage [15], industrial effluent [16], reverse osmosis concentration [17], pharmaceutical contaminants [18], agricultural wastes [19]).

The CWs can be categorized according to the water flow path through the system and the wetland plant type. Based on the flow path, two different CWs are available (i.e., free water surface and subsurface flow CWs), in which for the subsurface flow CWs, they can be created using either vertical or horizontal flow. Meanwhile, considering the wetland plant type, the CWs include free-floating, emergent, and submerged wetland types. A combined system consisting of more than one system is normally called a hybrid wetland [6], [12].

Plants are considered to be an essential part of CWs [20], [21]. The larger aquatic plants growing in wetlands are usually named macrophytes, while the most common CW systems are those with rooted emergent macrophytes [7]. There are numerous aquatic plant species, but only a limited number are frequently planted in CWs [14], [22]. Many studies have demonstrated that these plants, directly and indirectly, contribute to the process of wastewater treatment. Of late, ornamental flowering plants (e.g., *Lavandula sp., Spathiphyllum wallisii, Zantedeschia aethiopica, Canna spp., Heliconia psittacorum,* and *Irish pseudacorus*) have been utilized for the removal of various wastewater pollutants in CWs [22], [23].

However, no study has been conducted at this stage comparing flowering and non-flowering plants from the available species found in humid tropical regions. Indeed, it was recommended that locally available aquatic plant species need to be chosen [12]. As an initial task in designing CWs is to select suitable plant species, three locally available plant species (i.e., *Echinodorus palaefolius* (flowering plant), *Typha latifolia* and *Cyperus alternifolius* (non-flowering plants)) were then selected to be examined in this study for investigating their characteristics.

Hydraulic retention time (HRT) is the time given to wastewater residing CWs. HRT is an important factor that affects the treatment process's efficiency in CWs and is usually decided by designers [7], [12]. The longer the HRT, the more efficient the pollutant removal as the microbial community has sufficient contact time to remove contaminants. However, the effect of HRT may also differ between CWs depending on the dominant plant species and temperature [14]. Besides, prolonged retention time may affect biological oxygen demand (BOD) removal performance in the wetland system, which could be observed from various HRTs applied in CWs by different designers [7]. Even though there has been much research undertaken using different HRTs, limited information is available on using an HRT one day. Also, the limitation of acquiring such information represents a significant knowledge gap in one-day treatment. As households regularly discharge greywater each day, this study applied the HRT for one day.

All design equations for pollutant removal and treatment performance in constructed wetlands are generally based on the parameters of BOD [24]. Therefore, this study as an initial stage of designing household CW emphasized the BOD removal to be examined to select the most appropriate aquatic plant for the household wetland. Whereas other parameters (e.g., pH, temperature, and total dissolved solids) were also tested. Accordingly, the purpose of this study was to select the most suitable aquatic decorative species planted in CWs for greywater treatment at the household level, applying a one-day HRT. The most efficient plant for removing BOD, which had an aesthetic appearance and required low maintenance, was subsequently employed as the selection criteria.

II. Materials and Methods

A. Experimental Setup

The study was conducted in a house yard located in the City of Surakarta, Central Java Province, Indonesia. The city is located at 110° 45’ 15” to 110° 45’ 35” East longitude and between 7° 36’ and 7° 56’ South latitude. The climate in the area is categorized as a humid tropical climate with temperature ranging from 15.1 to 33.5°C, and humidity varied between 69 and 87% on average.

The experimental setup consisted of three identical plastic tanks (i.e., beds) having a length of 71 cm, a width of 42.5 cm, and a depth of 52.5 cm. The total working volume and the area of each bed were 158.42 liters and 3017.5 $cm^{2,}$ respectively. All the beds had 1% slope bottom. Aeration pipes 20 mm in diameter were also installed at the bottom of each bed. It aimed at achieving higher removal efficiency of organic pollutants (*biological oxygen demand* or *chemical oxygen demand)* as confirmed by Stefanakis *et al*. [6], who observed high efficiency of organic removal in their wetland systems due to improving system bed aeration. The schematic layout and longitudinal section of each bed are presented in Fig 1.

In the initial experiment, the beds were filled with coarse sand, as the first layer, with a ranged diameter between 5-10 mm to a depth of 20 cm at the bottom of the beds. On the top of this layer, fine sand with a ranged diameter of 1-5 mm was filled to a depth of 15 cm. In the second experiment, the height of the second layer was then added to be 25 cm. Hence, the media filter's total depths in the first and second experiments were 35 and 45 cm, respectively. The sands were cleaned first before placing them into the beds.

Each of the three beds (i.e., bed A, B, and C) was planted with the aquatic plant species: *Echinodorus palaefolius*, *Typha latifolia*, and *Cyperus alternifolius*, respectively, at approximately 13 cm intervals apart. These plants can be found easily in local markets in the study area. Before planting them in the beds, their roots needed to be carefully washed to remove any remaining soils. At the beginning of the experiment, the three species' plants were set to have a maximum root length of 15 cm, a plant height of ± 50 cm, and a biomass weight of ± 50 gram.

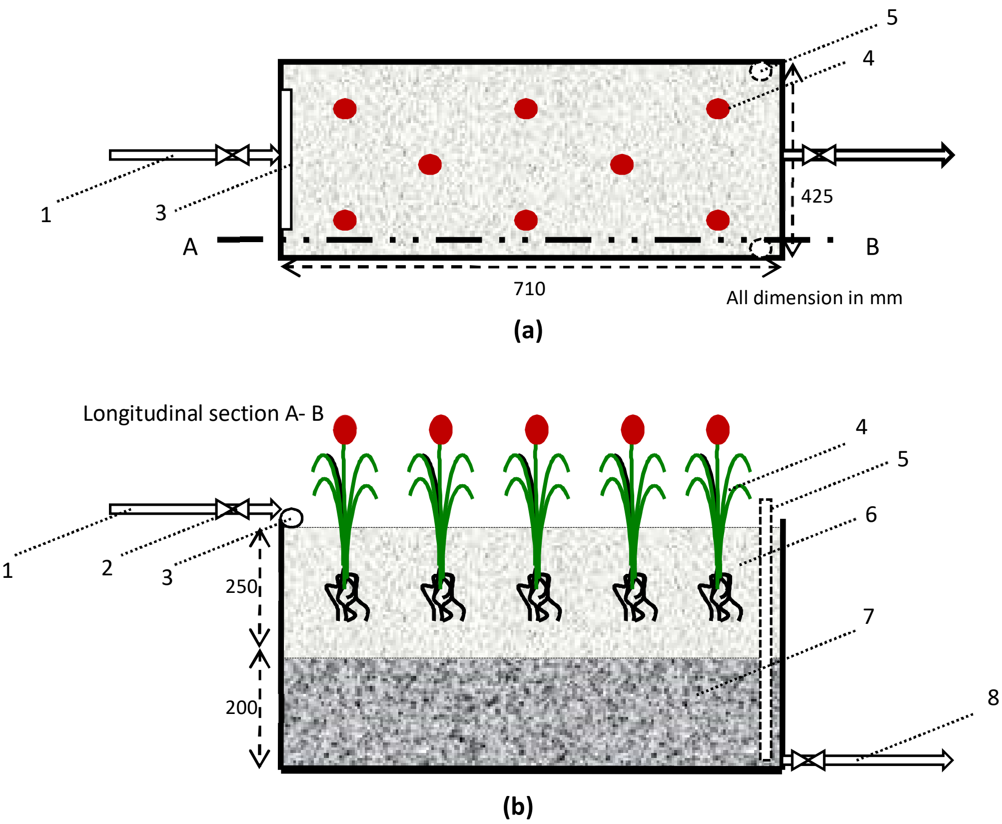


Fig. 1 Schematic layout (a) and longitudinal section (b) of a CW: (1) inlet pipe; (2) valve; (3) horizontal drainage pipe; (4) plants; (5) aeration pipe; (6) 1-5 mm fine sand; (7) 5-10 mm coarse sand; (8) outlet pipe

B. Feeding of Greywater

Wetland can be fed in continuous, batch, and intermittent modes. These modes affect the oxygen to be transferred and diffused in the wetland system resulting in treatment efficiency. The batch feeding mode generally shows better treatment performance compared to the continuous one as the former can provide more oxygen in the wetland system [7], [14]. Therefore, the batch feeding mode was applied in this study.

Before collecting the data, acclimatization of the plants to the greywater was conducted for 2 months. This was required to allow the plants and their bio-films to develop [11], [20]. During acclimatization, the concentration of the greywater gradually increased from 25 to 100%. To characterize the influent and a steady-state system, the following parameters were calculated [25].

$$HLR = \frac{Q}{A} \quad (1)$$

$$HRT = \frac{\rho V}{Q} \quad (2)$$

where
HLR is the hydraulic loading rate (m d^{-1})
HRT is the hydraulic retention time (d)
V is the volume of the water in the system (m^3)
Q is the water flow rate through the system (m^3 d^{-1})
A is the surface area of the bed (m^2)
ρ is the porosity of the filter media

In the batch feeding mode, the greywater was filled rapidly in each bed through the inlet pipe. The valve at the outlet pipe was kept close. The water level in each bed was maintained at 2 cm below the surface of the media filter. After having *HRT* of 1 day, the greywater was then drained entirely by opening the outlet valve. *HRT* of 1 day and the porosity value of 0.35 corresponding to the Q and *HLR* of 34.85 liter/day and 115.5 mm d^{-1} respectively, for the first experiment; and 45.41 liters/day and 150.5 mm d^{-1} respectively, for the second experiment.

C. Sampling and Water Analysis

Sampling for the first and second experiments was conducted between October and November 2018 and between December 2018 and January 2019, respectively. The first experiment used beds A, B, and C, which were planted with *Echinodorus palaefolius, Typha latifolia, and Cyperus alternifolus*, respectively. The aquatic plants, which resulted in the lowest BOD removal, were not examined any further as part of the second experiment.

In the batch operation, the household greywater was fed into the beds rapidly, and the influent samples were collected and transported to the Laboratory of Sanitary, Engineering Faculty, Sebelas Maret University. After remaining in the beds for one day HRT, the treated effluent greywater was then collected from the outlet zone, where it was discharged on the same day and at the same time in the early morning. Then, the effluents were transported to the same laboratory. The influent and effluent were analyzed for five-day biological oxygen demand (BOD_5) based on the Indonesian National Standard no. 6989.72-2009. In addition to it, *in-situ* measurements were carried out for pH, temperature, and total dissolved solids (TDS). The pH was measured using a standard digital pH meter. The total dissolved solids were characterized with a standard digital TDS meter having automatic temperature measurement capability. BOD removal efficiency was calculated by comparing the concentration level of the parameter at both inlet and outlet of the beds as percent removal (%R).

$$\%R = \frac{(Ci-Ce)}{Ci} x100\% \quad (3)$$

where *Ci* and *Ce* represent the influent and effluent BOD concentrations (mg/l), respectively.

The sampling of influent and effluent of each experiment was conducted five times (trials). The wetland beds were allowed to acclimatize to the higher concentration rate for about one week between each trial.

A two-sample *t*-test analyzed the tests for significant differences between the aquatic plants in the second experiment. The results were considered significant when $p<0.05$. Graphical plots were used to analyze all calculations with the aid of Microsoft correlation and *t*-test statistic equations.

Fig. 2 presents the bed's A, B, and C, which were planted with *Echinodorus palaefolius, Typha latifolia, and Cyperus alternifolus,* respectively. Fig. 3 shows a sample of greywater influent before treatment and 3 samples of the three beds effluent after treatment.

(a) (b) (c)

Fig. 2 The plants of *Echinodorus palaefolius* (a), *Typha latifolia* (b) and *Cyperus alternifolus* (c) used in the first experiment of this study

(a) (b)

Fig. 3 A sample of influent (a) and three samples of effluent (b)

III. Results and Discussion

A. BOD_5 Removal

In the CWs, the elimination of BOD_5 concentration is caused by some processes (e.g., microbial metabolism, sedimentation, and absorption) [22]. Besides, in a wetland system, the release of oxygen through the roots supports the elimination of the BOD_5 [20]. In this study, the influent and effluent BOD_5 concentrations and the treatment efficiency (%) of BOD5 on the first and second experiments are presented in Tables I and II, respectively.

The results of organic removal, in terms of BOD_5, performed significantly high in all types of decorative plants. In the first experiment (Table I), on days 1 to 36 of the study, the influent levels of BOD_5 reduced from an average of 136.31 mg/l to 23.96; 22.39; and 21.85 mg/l at the effluent, representing an average removal rate of about 82.32%, 83.46%, and 83.71% for *Echinodorus palaefolius, Typha* *latifolia*, and *Cyperus alternifolius,* respectively. The lowest BOD_5 removal was recorded for the *Echinodorus palaefolius* plant, which was not investigated in the second experiment.

TABLE I
THE CONCENTRATION AND TREATMENT EFFICIENCY OF BOD5 ON THE FIRST EXPERIMENT USING A 35 CM SAND FILTER

Trial	Influent	Effluent					
		A[1]		B[2]		C[3]	
	(mg/L)	(mg/L)	(%)	(mg/L)	(%)	(mg/L)	(%)
1	122.22	12.96	89.40	5.93	95.15	9.63	92.12
2	126.67	39.58	68.75	44.58	64.80	42.22	66.67
3	138.67	21.25	84.68	19.58	85.88	24.58	82.27
4	142.00	20.50	85.56	22.17	84.39	19.50	86.27
5	152.00	25.50	83.22	19.67	87.06	13.33	91.23
Av	136.31	23.96	82.32	22.39	83.46	21.85	83.71

A[1]: bed A planted with *Echinodorus palaefolius*
B[2]: bed B planted with *Typa latifolia*
C[3] :bed C planted with *Cyperus alternifolius*

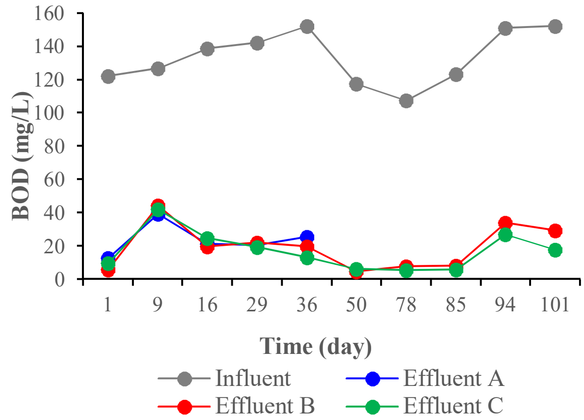
The second experiment (Table II) was carried out from day 50 to day 101, which resulted in the influent levels of BOD_5 decreasing from an average of 130.22 mg/l to 16.86 and 12.42 mg/l at the effluent, representing an average cumulative removal rate of 87.75% and 91.18% for *Typha latifolia* and *Cyperus alternifolius,* respectively. The findings indicate that the greatest BOD_5 removal from both experiments was with the *Cyperus alternifolius* plant's presence. The results showed very high BOD_5 removal (91.18%). This value is higher compared to that of a previously reported study [13] which used ornamental plants and resulted in 75-83% BOD_5 removal. The BOD_5 removal of this study is also much better than the study [26], which used *Cyperus alternifolius* plant, applied HRT for four days, and resulted in 73% BOD_5 removal. However, the value is slightly lower than the previous finding [27] using the same plant of *Cyperus alternifolius*, applying the same HRT for one day, and resulting in 98.55% BOD_5 removal.

TABLE II
THE CONCENTRATION AND TREATMENT EFFICIENCY OF BOD5 ON THE SECOND EXPERIMENT USING A 45 CM SAND FILTER)

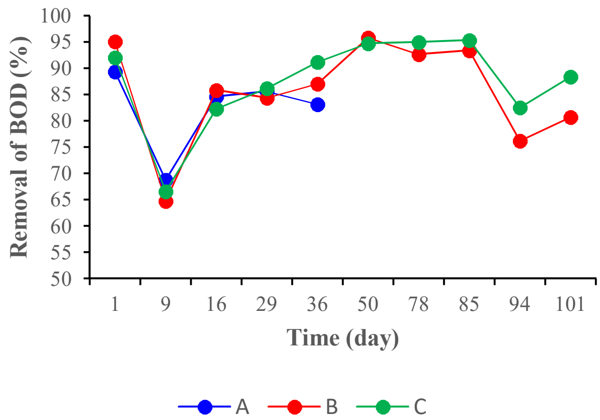
Trial	Influent	Effluent			
		B[2]		C[3]	
	(mg/L)	(mg/L)	(%)	(mg/L)	(%)
6	117.33	4.89	95.84	6.22	94.70
7	107.41	7.92	92.63	5.42	94.96
8	123.33	8.15	93.39	5.78	95.32
9	150.91	34.00	76.17	27.00	82.52
10	152.12	29.33	80.72	17.67	88.39
Av	130.22	16.86	87.75	12.42	91.18

B[2]: bed B planted with *Typa latifolia*
C[3] :bed C planted with *Cyperus alternifolius*

Fig. 4 displays the concentrations of the influent/effluent and the percentage removal of BOD_5, respectively. Fig. 4a shows that all BOD effluent concentrations, except the 2nd sample, were lower than 30 mg/L. Fig. 4b confirms that the 2nd sample shows the lowest percentage BOD removal. Based on the Regulation of the Minister of the Environment and Forestry of the Republic of Indonesia number 68-year 2016, the permitted maximum BOD concentration limit is 30 mg/L. It suggests that the BOD effluent concentrations meet the water quality standard and thereby is safely released to water bodies environment.



(a)



(b)

Fig. 4 The removal of BOD_5 (a) and its percentage removal (b) in the first (from day 1 to 36) and second experiments (from day 50 to 101).

The comparison of the average BOD_5 removal, which was significantly affected by the media filter's depth, is shown in Fig. 5. The first experiment used a 35 cm filter resulting in the lowest BOD_5 removal for the *Echinodorues palaefolius* plant, which was then not investigated in the second experiment. In the second experiment, the results were enhanced significantly compared to the first one. Using a 45 cm filter, it yielded the highest BOD_5 removal value for the *Cyperus alternifolius* plant species. Media filter provides the primary support for the wetland plant and microorganism growth, enhancing biodegradation of wastewater pollution [22]. The media also removes pollutants from the wastewater by ion exchange, adsorption, precipitation [7], improving the effluent quality to meet the reuse standard in agriculture. Therefore, it is reasonable that the higher media filter in the second experiment resulted in the higher percentage removal of the BOD_5 pollutants compared to the first one. It also agrees well with the previously reported study by Meng et al. [28]. The higher sand filter may increase the available surface area supporting the microorganism community for better wastewater treatment biologically resulting in effluent quality improvement.

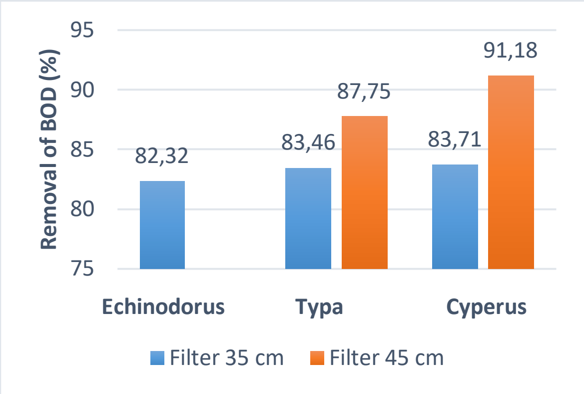


Fig. 5 Removal percentage of BOD_5 for the three plants in two different filter depths (i.e., 35 and 45 cm).

The effects of *Typha latifolia* (Plant B) and *Cyperus alternifolus* (Plant C) on the BOD_5 removals in the second experiment were statistically analyzed. The correlation between the influent and effluent and the significant differences are summarized in Table III.

TABLE III
COMPARISON OF THE EFFLUENT AND INFLUENT CONCENTRATIONS OF BOD5 BETWEEN *TYPHA LATIFOLIA* (B) AND *CYPERUS ALTERNIFOLIUS* (C)

	Mean	St.Dev	Coef. Correlation		t-test	
Effluent B	16.86	13.68	0.94		Significant different	
Influent	130.22	20.26		0.90		Significant different
Effluent C	12.42	9.64				

The same sources of greywater were discharged to beds B and C with *Typha latifolia* (B) and *Cyperus alternifolus* (C), respectively, as influents through their inlets. These resulted in the effluents for beds B and C at their outlets. High positive correlations expressed a strong correlation between the influent and effluent loading of BOD for both beds. The coefficient correlation values between the influent and effluent were 0.94 and 0.90 for plants B and C, respectively. The *t*-tests resulted in significantly different performances both before and after treatment for both plants. The 45 cm filter displayed in Fig. 5 resulted in the average BOD removal rates of 87.75% and 91.18% for *Typha latifolia* and *Cyperus alternifolius,* respectively. However, statistically, there was no significant difference in the removal of BOD that was found between both plants.

B. Plant Observation

The plant observation indicated that all plant species grew well, in terms of their leave numbers, new shoot growths, and produced vegetation views, yielding the bed aesthetic green appearances. However, for the *Echinodorus palaefolius*, significant growth occurred if the plant was in a shady area. Daily observation on the plants' growth highlighted that the leaves and stems of the *Echinodorus palaefolius* species initially experienced withering and dying. In contrast, the *Typha latifolia* and *Cyperus alternifolus* species were more resistant in full direct sunlight conditions.

Notably, for tropical regions, the more resistant plants to direct sunlight instead of the high removal of BOD pollutant is key in selecting a suitable plant. Therefore, only *Typha latifolia* and *Cyperus alternifolus* were further examined in the second step of the study, applying a 45 cm media filter. The observation showed that the *Echinodorus palaefolius* has a horizontal root growth shape, while both *Typha latifolia* and *Cyperus alternifolus* have a vertical root growth pattern. The plants are responsible for transferring oxygen from their roots to the rhizosphere, providing aerobic conditions to enhance the pollutant degradation in the system [20]. It was hypothesized that the different root growths could cause differences in their treatment performances. During 36 days of the first experiment, the maximum heights of *Echinodorus palaefolius*, *Typha latifolia,* and *Cyperus alternifolus* were approximately 68, 78, and 65 cm, respectively.

The second experiment showed that the *Cyperus alternifolus* plant, having no branches, was more efficient in removing the BOD pollutant compared to Typha latifolia, as explained previously. Besides, the *Cyperus alternifolius* plant was very adaptable to grow in temporarily or fully submerged conditions. By the end of the second experiment, the maximum heights of *Typha latifolia* and *Cyperus alternifolus* were 89 and 76 cm, respectively. Besides, there was no existing litter on the surface of the bed unit that was planted with *Cyperus alternifolius.* In contrast, many stems of Typha latifolia had withered, eventually died during the period of study. Consequently, CW's application using this plant would require more effort to control and more time to remove them regularly. Moreover, it appeared that litter existing on the surface of the constructed wetland beds would need to be regularly cleaned to look aesthetically nice.

C. pH

The pH of wastewater is a critical factor that may affect the organic (BOD) removal [7] as it controls several biotic processes and the degree of ionizable compounds [22]. Considering the possible reuse of the greywater effluent for home gardening or irrigation, the treated greywater pH values are very important. This study showed that the pH of greywater at the influent and effluent for all beds in the experiment varied between 6.8 and 7.5, as shown in Fig. 6. This suggests that all treatment beds could maintain a stable pH level. These pH values meet the existing Indonesian Government Regulation No 82 the year 2001 for irrigation water ($6.0 < pH < 9.0$). Besides, the values observed in this study are within the range of values ($4.0 < pH < 9.5$) recommended by Wu et al.[30], in which the pH values allow a good activity of bacteria. Hence, the pH stability along this study provides supports to microorganisms in the BOD degradation.

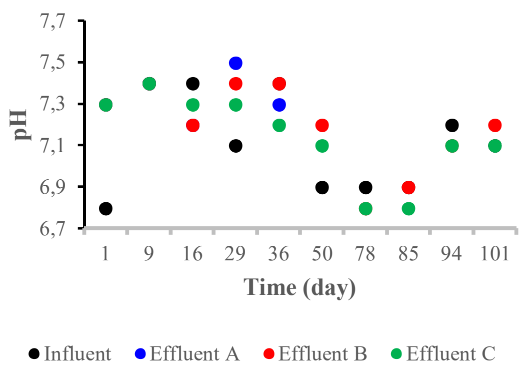
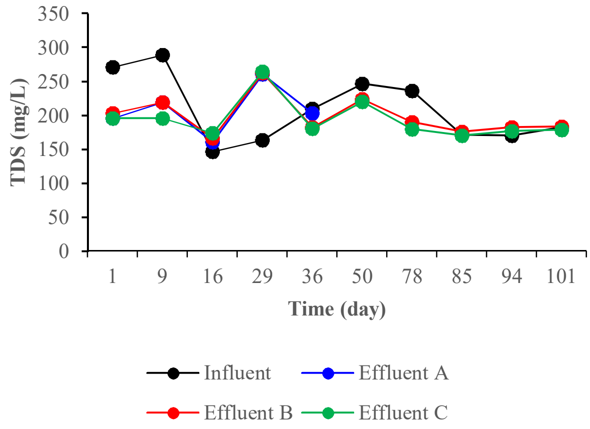


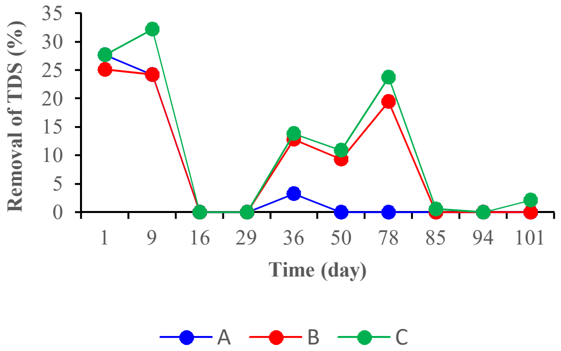
Fig. 6 The measured pH values during the study

D. Total Dissolved Solid (TDS)

Fig. 7 displays the TDS removal in the three beds for all-day experiments. Some of the outlet's TDS values were recorded to increase, i.e., 3rd, 4th, 9th samples (Fig 7a). Some biofilms attached to the developed roots might likely be broken and dissolved. These findings lend to the assumption that there are no TDS removals (Fig 7b). However, no significant different TDS removals were found amongst the beds at each testing.



(a)



(b)

Fig. 7 The removal of TDS (a) and its percentage removal (b) in the first (from day 1 to 36) and second experiments (from day 50 to 101).

E. Temperature

The water temperature directly affects the treatment efficiency in wetlands. It is because of a direct link between microbial activity and temperature in the wetlands and the subsequent impact on the pollutant removal efficiency [29]. The wetland treatment efficiency by microbial degradation is enhanced in tropical conditions [30]. This study was carried out in a tropical climate with temperature ranging from 15.1 to 33.5°C and resulted in the average accompanying temperature readings varied from 26.7°C for the influent and 26.6, 26.8, and 26.7°C for the effluents at beds A, B, and C, respectively. This is consistent with earlier findings where the temperature of greywater varied between the range of 18-38 °C, as explained by Oteng-Peprah et al. [31].

F. All Measured Parameters

The design of constructed wetlands is generally based on the parameters of BOD [24]. As shown in Fig. 4a, almost all BOD effluent concentrations, by 90%, were lower than 30 mg/L. Therefore, the treated water is safely released to water bodies environment, based on the Regulation of the Minister of the Environment and Forestry of the Republic of Indonesia number 68 the year 2016. Among the three aquatic plants, *Cyperus alternifolius* had the highest performance in minimizing BOD concentration. The pH stability along this study provides supports to microorganisms in the BOD degradation. It can be seen from the pH values that are within the range (4.0 < pH < 9.5), in which the pH values allow a good activity of microorganisms [30]. Related to temperature, there is a direct link between microbial activity and temperature in the wetland and the subsequent impact on pollutant removal efficiency [7]. So, the higher temperature during this study (around 26.7°C) significantly impacted the treatment process associated with the rate of BOD degradation. Related to TDS, as shown in Fig. 7a, in some points (3rd, 4th, 9th), the amount of outlet TDS is more than the inlet TDS (negative elimination efficiency). Hence, there are no TDS removal in those points. The mobility of dissolved solid within wetlands is a complex process. It involves several different chemical species, many of which are simply recycled and thereby remain within in the wetland system. Only the portion adsorbed to soil particles, or inserted into plant tissue, is permanently removed. Comparing the BOD and TDS removal, as seen in Fig. 4 and Fig. 7, there is no similar pattern in reducing BOD and TDS concentration observed during the study period. This could be because the removal of BOD was mainly supposed to be due to the microbial activity through biofilm formation on the media filter material, whereas the removal of TDS was mainly due to physical processes (sedimentation and filtration) rather than biological processes. Based on the Indonesian Government Regulation number 82 the year 2001, water with TDS load less than 2000 mg/L can be used to irrigate crops. Thus, the household greywater used in this study could be used for plant needs.

IV. Conclusion

Fine growths have been demonstrated by the decorative plant species of *Echinodorus palaefolius, Typha latifolia*, and *Cyperus alternifolius* in the constructed wetlands (CWs), which are fed with greywater from a single household. The highest efficiency of *biological oxygen demand* (BOD) removal was found in the *Cyperus alternifolius* plant species, achieving at 91.18% removal rate. This plant has adapted well to grow in temporarily or fully submerged conditions and been resistant in full direct sunlight conditions. By the end of the study, no dead plant material (litter) has been found on the bed unit's surface planted with *Cyperus alternifolius*. Significant efforts are not required in maintaining and cleaning the bed vegetated with this plant. It can be concluded that the *Cyperus alternifolius* is the most suitable to be used in a CW for greywater treatment of single households in tropical areas. A further benefit of the wetlands planted with the *Cyperus alternifolius* is that it provides an aesthetically green and clean appearance to built-up household yards. Accordingly, this study can be further extended by considering other significant water quality parameters and applying various hydraulic loading rates as another parameter design of a CW system.

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REFERENCES

[1] A. A. Hermawan, A. Talei, J. Y. C. Leong, M. Jayatharan, H. W. Goh, and S. Alaghmand, "Performance assessment of a laboratory scale prototype biofiltration system in tropical region," *Sustain.*, 2019, doi: 10.3390/su11071947.

[2] C. Rodríguez *et al.*, "Water balance assessment in schools and households of rural areas of coquimbo region, north-central chile: Potential for greywater reuse," *Water (Switzerland)*, 2020, doi: 10.3390/w12102915.

[3] S. Lou, W. Huang, S. Liu, and G. Zhong, "Scarcity of drinking water in Taihu Lake Basin, China: A case study of Yixing City," *Water (Switzerland)*, 2019, doi: 10.3390/w11020362.

[4] United Nations, "Executive Summary - Wastewater The Untapped Resource," 2017.

[5] Sisnayati, M. Said, S. Nasir, and D. P. Priadi, "The utilization of ceramic membrane for treating of water from Sekanak River Palembang to produce clean water," *Int. J. Adv. Sci. Eng. Inf. Technol.*, 2018, doi: 10.18517/ijaseit.8.5.4724.

[6] A. I. Stefanakis, "The Role of Constructed Wetlands as Green Infrastructure for Sustainable Urban Water Management," *Sustainability*, 2019, doi: 10.3390/su11246981.

[7] S. A. A. A. N. Almuktar, S. N. Abed, and M. Scholz, "Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review," *Environmental Science and Pollution Research*. 2018, doi: 10.1007/s11356-018-2629-3.

[8] M. A. Rodriguez-Dominguez, D. Konnerup, H. Brix, and C. A. Arias, "Constructed wetlands in Latin America and the Caribbean: A review of experiences during the last decade," *Water (Switzerland)*. 2020, doi: 10.3390/w12061744.

[9] J. A. Herrera-Melián, A. Borreguero-Fabelo, J. Araña, N. Peñate-Castellano, and J. A. Ortega-Méndez, "Effect of substrate, feeding mode and number of stages on the performance of hybrid constructed wetland systems," *Water (Switzerland)*, 2018, doi: 10.3390/w10010039.

[10] X. Fu, X. Wu, S. Zhou, Y. Chen, M. Chen, and R. Chen, "A constructed wetland system for rural household sewage treatment in subtropical regions," *Water (Switzerland)*, vol. 10, no. 6, 2018, doi: 10.3390/w10060716.

[11] L. C. Sandoval-Herazo, A. Alvarado-Lassman, J. L. Marín-Muñiz, J. M. Méndez-Contreras, and S. A. Zamora-Castro, "Effects of the use of ornamental plants and different substrates in the removal of wastewater pollutants through microcosms of constructed wetlands," *Sustain.*, 2018, doi: 10.3390/su10051594.

[12] A. Gorgoglione and V. Torretta, "Sustainable management and successful application of constructed wetlands: A critical review," *Sustainability (Switzerland)*. 2018, doi: 10.3390/su10113910.

[13] T. Tuttolomondo, G. Virga, M. Licata, C. Leto, and S. La Bella, "Constructed wetlands as sustainable technology for the treatment and reuse of the first-flush stormwater in agriculture-A case study in Sicily (Italy)," *Water (Switzerland)*, 2020, doi: 10.3390/w12092542.

[14] H. Wu *et al.*, "A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation," *Bioresource Technology*. 2015, doi: 10.1016/j.biortech.2014.10.068.

[15] T. Benvenuti, F. Hamerski, A. Giacobbo, A. M. Bernardes, J. Zoppas-Ferreira, and M. A. S. Rodrigues, "Constructed floating wetland for the treatment of domestic sewage: A real-scale study," *J. Environ. Chem. Eng.*, 2018, doi: 10.1016/j.jece.2018.08.067.

[16] T. Saeed, S. Muntaha, M. Rashid, G. Sun, and A. Hasnat, "Industrial wastewater treatment in constructed wetlands packed with construction materials and agricultural by-products," *J. Clean. Prod.*, 2018, doi: 10.1016/j.jclepro.2018.04.115.

[17] R. K. Chakraborti and J. S. Bays, "Natural Treatment of High-Strength Reverse Osmosis Concentrate by Constructed Wetlands for Reclaimed Water Use," *water*, 2020, doi: 10.3390/w12010158.

[18] H. Ilyas and E. D. van Hullebusch, "Role of design and operational factors in the removal of pharmaceuticals by constructed wetlands," *Water (Switzerland)*. 2019, doi: 10.3390/w11112356.

[19] M. Seres, T. Hnátková, J. Vymazal, and T. Vaněk, "Removal efficiency of constructed wetland for treatment of agricultural wastewaters," *Chem. J. Mold.*, 2017, doi: 10.19261/cjm.2017.403.

[20] L. Sandoval, S. A. Zamora-Castro, M. Vidal-Álvarez, and J. L. Marín-Muñiz, "Role of wetland plants and use of ornamental flowering plants in constructed wetlands for wastewater treatment: A review," *Applied Sciences (Switzerland)*. 2019, doi: 10.3390/app9040685.

[21] M. Carrasco-Acosta, P. Garcia-Jimenez, J. A. Herrera-Melián, N. Peñate-Castellano, and A. Rivero-Rosales, "The effects of plants on pollutant removal, clogging, and bacterial community structure in palm mulch-based vertical flow constructedwetlands," *Sustain.*, 2019, doi: 10.3390/su11030632.

[22] M. E. Rahman *et al.*, "Design, operation and optimization of constructed wetland for removal of pollutant," *International Journal of Environmental Research and Public Health*. 2020, doi: 10.3390/ijerph17228339.

[23] D. Kotsia, A. Deligianni, N. M. Fyllas, A. S. Stasinakis, and M. S. Fountoulakis, "Converting treatment wetlands into 'treatment gardens': Use of ornamental plants for greywater treatment," *Sci. Total Environ.*, 2020, doi: 10.1016/j.scitotenv.2020.140889.

[24] M. Gajewska *et al.*, "Kinetics of pollutants removal in vertical and horizontal flow constructed wetlands in temperate climate," *Sci. Total Environ.*, 2020, doi: 10.1016/j.scitotenv.2020.137371.

[25] F. Licciardello, A. Sacco, S. Barbagallo, D. Ventura, and G. L. Cirelli, "Evaluation of different methods to assess the hydraulic behavior in horizontal treatment wetlands," *Water (Switzerland)*, 2020, doi: 10.3390/w12082286.

[26] D. H. Shahi *et al.*, "Comparing the efficiency of Cyperus alternifolius and Phragmites australis in municipal wastewater treatment by subsurface constructed wetland," *Pakistan J. Biol. Sci.*, 2013, doi: 10.3923/pjbs.2013.379.384.

[27] S. Qomariyah, A. H. Ramelan, Sobriyah, and P. Setyono, "Use of macrophyte plants, sand & gravel materials in constructed wetlands for greywater treatment," 2017, doi: 10.1088/1757-899X/176/1/012018.

[28] P. Meng, H. Pei, W. Hu, Y. Shao, and Z. Li, "How to increase microbial degradation in constructed wetlands: Influencing factors and improvement measures," *Bioresource Technology*. 2014, doi: 10.1016/j.biortech.2014.01.095.

[29] S. Wu, P. N. Carvalho, J. A. Müller, V. R. Manoj, and R. Dong, "Sanitation in constructed wetlands: A review on the removal of human pathogens and fecal indicators," *Science of the Total Environment*. 2016, doi: 10.1016/j.scitotenv.2015.09.047.

[30] M. Varma, A. K. Gupta, P. S. Ghosal, and A. Majumder, "A review on performance of constructed wetlands in tropical and cold climate: Insights of mechanism, role of influencing factors, and system modification in low temperature," *Science of the Total Environment*. 2021, doi: 10.1016/j.scitotenv.2020.142540.

[31] M. Oteng-Peprah, M. A. Acheampong, and N. K. deVries, "Greywater Characteristics, Treatment Systems, Reuse Strategies and User Perception—a Review," *Water. Air. Soil Pollut.*, 2018, doi: 10.1007/s11270-018-3909-8.