Preliminary Performance Assessment of polyculture vertical flow constructed wetland for campus greywater treatment

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Abstract. Constructed wetlands (CW) are recognized as one of the best nature-based, sustainable solutions for wastewater treatment. This study evaluates the effectiveness of polyculture wetlands in treating campus greywater (GW). A pilot-scale CW, measuring 6 x 3 x 0.7 m (L x B x D), was set up on campus, containing three layers of filter media with plant species *Chlorophytum Comosum, Codiaeum Variegatum, and Cyperus Laxus*. CW was operated at a flow rate of 120 m³/d over 35 days. This study observed removal efficiencies of 97.8% for turbidity, 52.7% for chemical oxygen demand, 41.1% for biological oxygen demand, 41.7% for total coliforms, 38.2% for phosphorus, 36.7% for oil and grease, and 19.4% for total suspended solids The significant reduction in turbidity reflects the filter bed's efficiency, while organic matter removal demonstrates the biological activity facilitated by the plant- microbe interactions. These results prove that polyculture-based constructed wetlands offer a sustainable, efficient, and scalable wastewater treatment option applicable for campus decentralized applications. It presents a viable method to minimize environmental pollution and encourage water reuse with an eco-friendly, low-maintenance system, in line with institutional sustainability goals.

1 Introduction

Globally, most of the developing countries will face water shortages in the near future. Climate change exacerbates water scarcity through altered precipitation patterns, increased frequency of extreme weather events, and rising temperatures, which collectively strain existing water resources. Urban areas, with their high population densities and significant water demands, are particularly susceptible to these changes [1]. The existing water sources are contaminated because untreated sewage and industrial wastewater are discharged into surface waters, resulting in an impairment of water quality [2]. Increasing pressure on water resources worldwide has raised interest in recycling and reusing wastewater, driving the need for sustainable treatment solutions, especially in urban areas. Studies revealed that nearly 50–75% of potable water is used for non-potable applications [2]. Rainwater harvesting is a seasonal process, but greywater (GW) is available throughout the year. Reuse of untreated GW can cause health risks; therefore, GW should be properly treated and it should meet the specified standards before it is reused for certain applications [2]. On-site reuse of treated greywater for non-potable purposes such as toilet flushing, garden irrigation, and car washing is one of the alternatives to meet the increasing water demand and to reduce the load on sewage treatment plants [3]. In recent years, significant developments have been recorded worldwide in GW reuse practices and policies. GW treatment is one of the viable options for implementing the reclamation of wastewater. GW includes a significant portion of domestic wastewater originating from sinks, showers, and laundry [4]. GW is commonly referred to as "light" and "mixed", the former consisting of bath, shower, and bathroom sink water, and the latter including laundry and kitchen sink water [5]. The treatment of GW for reuse should be sustainable and affordable. The low capital and maintenance requirements of constructed wetlands (CW) make it a suitable small-scale treatment option for GW [4].

CWs are technologies based on natural processes for pollutant removal and have gained increasing acceptance in the treatment of domestic and industrial wastewater [6]. These are manmade wetlands designed to operate and mimic natural wetlands. The whole process is mediated by complex interactions between water, plants, media, microorganisms, and the atmosphere by using the power of nature and energy from the sun [7]. Key aspects of CW include the selection of vegetation, substrate, and a proper system of construction at suitable locations. However, previous studies showed that CW was used with monoculture plantations like any one particular plant species [4, 6], [8-15]. Emergent macrophytes like *Typha spp. Cattails, Scirpus spp. Bulrushes, Phragmites Australis Common Reed, and Lemna spp. Duckweed* are known for their high growth rate and tolerance to a wide range of environmental conditions and are the most widely used plant type in CWs [16]. They were effective in removing nutrients like nitrogen and phosphorus and in degrading organic pollutants. The use

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of multiple plant species in a single wetland system approach has gained a lot of interest recently due to its advantages over monoculture using a single plant species in improving the efficiency and resilience of wastewater treatment [17-18]. The polyculture in CW enhanced pollutant removal efficiency, increased biodiversity and system resilience, improved habitat for microbial communities, reduction of invasive species, risk-optimized oxygen transfer, water flow dynamics, aesthetic, and multifunctional benefits [19]. This study aims to evaluate the removal efficiency of a CW using polyculture with three different plant species in treating campus GW.

2 Materials

2.1 Collection of material

Three different substrates of filter media were used: 20 mm gravel, 30 mm pebbles, and a sand layer. These materials are locally sourced. The three different plant species *Chlorophytum Comosum, Codiaeum Variegatum,* and *Cyperus Laxus* used to treat the GW were purchased from a local nursery.

2.2 Source of GW

The GW used in this study was pumped from the outlet drain of the college campus. The drain receives the GW from both the boys' and girls' hostel blocks, mess, and administrative buildings, having a population of 1600 members.

3 Methodology

3.1 Construction of wetland

The Schematic diagram illustrating the CW is displayed in Fig. 1. The detailed step-by-step construction of the wetland is shown in Fig. 2. Marking of basin excavation as pilot scale wetland measurements were assumed to hold and treat, based on the generated GW quantity. Basin excavation with inlet and outlet was made in the ground to a size of 6 meters in length, 3 meters in width, and with a depth of 0.70 meters. The excavated basin was lined with a polysheet to prevent GW from infiltrating into the groundwater, and a 60 cm difference was maintained between the inlet and outlet of the CW to accommodate the GW to maintain the effective treatment. The wetland was then filled with locally sourced materials as three substrate layers of pebbles, gravel, and sand, with each layer having a thickness of 200 mm. The bottom layer consisted of pebbles, the middle layer was gravel, and the top layer was sand, integrated with poly mesh to separate and reduce the internal clogging of substrate filling. The arrangements to divert the water through gravity into the reservoir for treatment and maintaining the constant discharge of the water level in the inlet reservoir, and the selected locally sourced plants of C*hlorophytum Comosum, Codiaeum Variegatum, and Cyperus Laxus* were then introduced into the wetland. C*hlorophytum Comosum (Spider plant)* is a native of tropical and southern Africa, belongs to the Asparagaceae family, and has long, aching green leaves that can grow up to 15 inches with yellow and white stripes and produces small white flowers and baby offshoots called spiderettes. This is a fast-growing plant that thrives in bright or indirect sunlight, and rhizobium zone enhances the microbial activity in pollutant removal. *Codiaeum Variegatum (Garden croton plant)* originates in Southeast Asia and belongs to the Euphorbiaceae family, having thick, glossy, vibrant colour leaves that thrive in warm and humid environments. *Cyperus Laxus (Loose Flatsedge)* originates from tropical regions of the Western Hemisphere and Africa, having narrow, grass-like leaves that form a dense clump thrives in wet environments and spreads through underground rhizomes, which may help in microbial growth and pollutant removal can tolerate seasonal flooding and enhances filtration.

3.2 Operation of CW

A tank was built to provide a consistent flow of GW to the wetland. The flow rate was approximately 120 cubic meters per day, and the entire experiment lasted for 35 days. This consistent flow helped to reduce the continuous

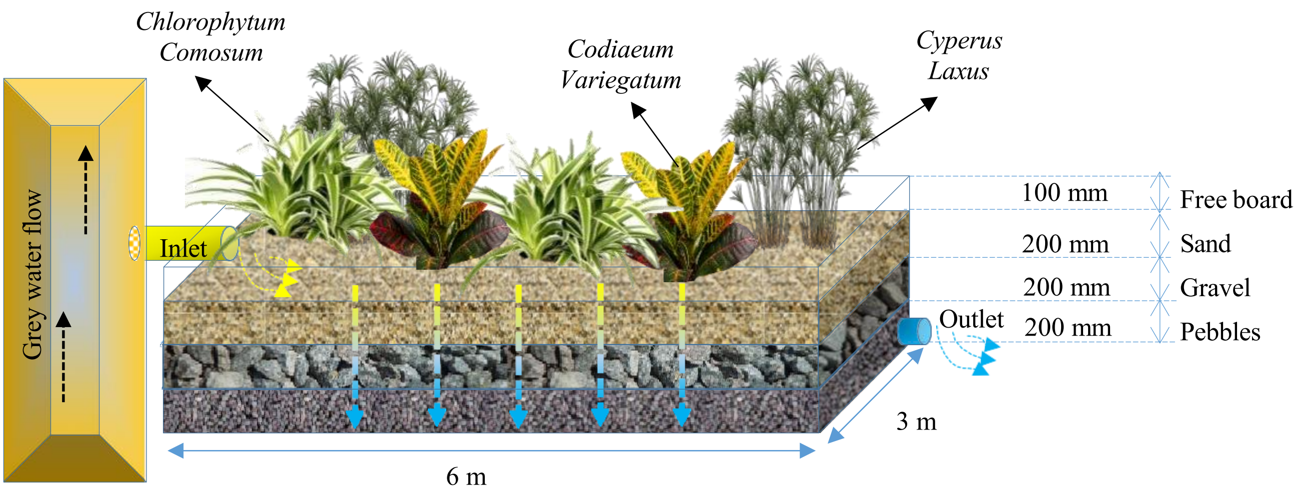

Fig. 1. Schematic illustration of the CW

overloading that led to a loss of treatment capacity due to excessive suspended solids, sludge, or other pollutants. The inlet and outlet flow were regularly monitored to prevent clogging in the substrate.

Fig. 2. Construction stages of the constructed wetland (CW): (1) Basin marking; (2) Excavation with inlet and outlet; (3) Laying the pipelines; (4) Polysheet lining with layering of pebbles (each 200 mm); (5) Sand layer; (6 & 7) Gravity-fed water inlet tank; (8) *Chlorophytum comosum*, *Codiaeum variegatum*, and *Cyperus laxus* plants.

3.3 Water quality analysis

The influent GW that enters the CW and the effluent treated water that flows out of the bottom of the CW samples were characterized for total suspended solids (TSS), turbidity, biological oxygen demand (BOD), chemical oxygen demand (COD), oil & grease, total coliforms (TC), and phosphorus (P). Samples were collected before and after 35 days of treatment in the constructed wetland, with each sample collected in triplicate and subsequently analysed. The turbidity was measured using a Nephelometer (Make: Elico). The dissolved oxygen (DO) was measured using a DO meter (Make: Elico). COD and P were measured following the protocols given in the Standard Methods for the Examination of Water and Wastewater [20]. The removal efficiency of the CW was calculated by subtracting the effluent concentration from the influent concentration and dividing the obtained value by the influent concentration. The obtained decimal value was multiplied by 100 to convert it to a percentage.

4 Results and discussion

The data from different previous studies were compared with the water quality parameters abounding in this study, and the results are shown in Table 1. The parameters include TSS, turbidity, phosphorus, BOD, COD, oil and grease, and total coliforms. Each parameter provides important information about ecosystem health and water pollution. The TSS level in the current study was 72 mg/L, which is within the range of 204 ± 41 mg/L that has been reported by Aygun 2014 [21] and 29–505 mg/L in Domestic and campus GW reported by Arden 2020 [5]. In this study, turbidity was measured at 58 NTU. This figure is greater than the majority of the values found across other studies, including 19.2–119 NTU reported by Liu 2016 [22] and 8.4 NTU reported by Kuo 2018 [25]. However, a slightly higher turbidity of 65 NTU was observed by Laaffat 2019 [24].

The phosphorus concentration of 11 mg/L, compared with other reported results, such as 2.4 ± 0.9 mg/L reported by Tuttolomondo 2020 [17] and 0.8 mg/L reported by Laaffat 2019 [24], is significantly higher. In aquatic systems, too much phosphorus can cause eutrophication, which results in algal blooms and oxygen depletion. Here, the BOD level was 190 mg/L, which is a clear symptom of serious organic pollution. It is in line with the range of 111–290 mg/L observed by Liu 2016 [22], although it is significantly higher than values found in other studies by Tuttolomondo 2020 [17] and Laaffat 2019 [24]. Increased organic matter decomposition is indicated by elevated BOD, which can damage aquatic life and reduce dissolved oxygen. COD values of 440 mg/L was found in this study, indicating significant amounts of chemical and organic pollutants. This is comparable to the 383 ± 57 mg/L reported by Aygun 2014 [21], but higher than the values of 189.4 ± 38.6 mg/L reported by Tuttolomondo 2020 [17] and 77.2 mg/L reported by Laaffat 2019 [24]. The high amounts of BOD and COD indicate a large amount of untreated wastewater. In this study, oil and grease levels were measured at 3 mg/L; however, no comparable results from other studies were presented. Despite the seemingly tiny concentration of 3 mg/L, even minute amounts can produce surface coatings that restrict oxygen exchange and damage aquatic life. In this study, the total coliform counts were 3.6×10^5 MPN/100 ml, falling between the $1–7.4 \times 10^5$ MPN/100 ml range observed by Arden 2020 [5]. Fecal contamination is strongly indicated by elevated coliform levels. These results underscore potential public health risks and the need for improved sanitation practices.

The variability and heterogeneity in the wastewater characteristic concentrations across the studies are influenced by multiple factors, like college population density, water usage patterns, cafeteria waste discharge,

Table 1. Initial characterization of GW

TSS mg/L	Turbidity NTU	Phosphorous mg/L	BOD mg/L	COD mg/L	Oil and grease mg/L	Total Coliforms MPN/100 ml	Wastewater Type	References
72	58	11	190	440	3	3.6×10^5	Campus greywater	[This Study]
29-505	12.5-240	0.1-48.8	20-240	100-633	n.d.	$1\text{-}7.4 \times 10^5$	Domestic wastewater	[5]
17.6 ± 4.6	n.d.	2.4 ± 0.9	86.9 ± 29.3	189.4 ± 38.6	n.d.	n.d.	Campus greywater	[17]
n.d.	n.d.	n.d.	n.d.	374	n.d.	n.d.	Domestic wastewater	[18]
204 ± 41	n.d.	8.85 ± 2.7	280 ± 32	383 ± 57	n.d.	n.d.	Campus greywater	[21]
n.d.	19.2 -119	n.d.	111 -290	n.d.	n.d.	n.d.	Campus greywater	[22]
n.d.	n.d.	24.7-39.3	n.d.	164 -256	n.d.	n.d.	Campus greywater	[23]
0.8	65	0.8	44.2	77.2	n.d.	n.d.	Campus greywater	[24]
10.1	8.4	3.7	n.d.	35.1	n.d.	n.d.	Campus greywater	[25]

Table 2. Performance (removal efficiency %) of polyculture in CW in treating greywater

Plant species	Bed Substrate	Root zone microbial activity	TSS mg/L	Turbidity NTU	Phosphorous mg/L	Nitrogen mg/L	BOD mg/L	COD mg/L	Oil and Grease mg/L	Total Coliforms MPN/ 100 ml	References
Chlorophytum Comosum, Codiaeum Variegatum, Cyperus Laxus	Sand, gravel, and pebbles	High [a], n.d., High [b]	9.4	93.3	38.2	n.d.	41	52.7	36.7	41.7	[This Study]
Phragmites Australis	Clay and gravel	High [c]	88.9	98.2	n.d.	n.d.	84	58.6	n.d.	2.1	[4]
Phragmites Australis	Coarse gravel	High [c]	63	n.d.	n.d.	2	51	36	n.d.	n.d.	[9]
Eichhornia Crassipes	n.d.	High [d]	96.6	100	n.d.	n.d.	93.7	88.5	n.d.	n.d.	[10]
Phragmites Australis, Arundo Donax L	Silica quartz river gravel	High [c], High [e]	50.8	n.d.	21	59	75.2	62.5	n.d.	n.d.	[17]
Cannax Generalis, Equisetum Giganteum	Gravel, blast furnace slag, soil with geotextile blanket	Moderate [f], Moderate [g]	n.d.	n.d.	n.d.	n.d.	n.d.	66	n.d.	n.d.	[18]
Typha Latifolia	Coarse gravel	High [h]	90	88	50	42	87	89	n.d.	n.d.	[24]
Pittosporum Tobir	Coarse gravel, fine gravel, sand	n.d.	95.3	n.d.	21.7	n.d.	92.7	97.2	n.d.	41	[34]

[a] [26], [b] [27] , [c] [28] , [d] [29] , [e] [30], [f] [31], [g] [32] , [h] [33]. n.d.- no data

sanitation infrastructure, and mostly seasonal fluctuations and existing wastewater management practices. These collective practices contribute to the pollutant profiles of the campus wastewater. The findings of this study highlight significant variations across key water quality parameters compared to other studies. Elevated levels of BOD, COD, phosphorus, and coliforms suggest notable pollution stress. The comparison highlights that campus GW has considerable contamination, making it unsuitable for direct use without treatment.

The CW displayed varying levels of efficiency in removing different pollutants from GW, as indicated by the results given in Table 2. Various plant species used in GW treatment systems, along with their associated bed substrates. The study's findings suggest that different plants excel in different aspects of wastewater treatment, making species selection crucial depending on the target pollutant and the root zone microbial activity, which were evaluated based on the root zone structure, density, and surface area, as high, medium, and low, which helps the microbial mechanism in pollutant degradation. The choice of bed substrate significantly influences pollutant removal efficiency. Clay and gravel systems with *Phragmites australis* demonstrate strong TSS and phosphorus removal, while coarse gravel systems with *Typha latifolia and Phragmites australis* also perform well in these aspects, which was observed by. Lava rock- based membrane filters excel in reducing BOD with 97% and COD with 84% [35], indicating that high surface area media enhance microbial activity. Conversely, with silica quartz river gravel, *Phragmites Australis* and *Arundo donax L* achieved only 21% phosphorus reduction [17], showing that substrate alone is insufficient for effective phosphorus removal. The presence of gravel, blast furnace slag, and geotextile blankets, with *Carex generalis* and *Equisetum giganteum,* contributes to COD reduction of 66% [18], demonstrating the importance of integrated systems for optimal treatment. Among the listed species, *Phragmites Australis* with clay and gravel achieved 98.2% in turbidity reduction, along with *Pittosporum Tobira* with gravel and clay also showed strong turbidity and TSS removal efficiencies of 88.9% and 94.8% respectively [34]. In terms of BOD reduction, *Phragmites Australis* with clay and gravel achieved an 84% reduction, followed by *Eichhornia Crassipes* 93.7% has been reported by Tandekar 2022 [10]. The significant BOD reduction by *Eichhornia Crassipes* suggests its suitability for nutrient-heavy wastewater, indicating its strong biological treatment capacity. For COD removal, *Pittosporum tobira*, *Eichhornia crassipes*, and membrane filters achieved reductions of 97.2%, 88.5%, and 84%, respectively, demonstrating significant treatment efficiency. COD measures the organic matter in water, and high reduction rates indicate the system's ability to break down pollutants effectively. Regarding oil and grease and total coliform (TC) removal, *Chlorophytum comosum*, *Codiaeum variegatum*, and *Cyperus laxus* achieved moderate performance, with removal efficiencies of 36.7% and 41.7%, respectively. Oil and grease removal is crucial for wastewater treatment in industrial and urban areas. All these highlight variabilities in treatment efficiencies due to different experimental conditions. The current study's system, *Chlorophytum Comosum, Codiaeum Variegatum, and Cyperus Laxus* with sand, gravel, and pebbles as substrate media, shows moderate removal across all parameters, performing best in removing turbidity (97.8%) and COD (52.7%). On the other hand, the efficiency of *Chlorophytum Comosum and Codiaeum Variegatum* in removing pollutants like TSS, BOD, total coliforms, and nutrients was found to be moderate in comparison to more commonly used species like *Phragmites Australis*, indicating the potential for improvement through system optimization. These species with dynamic growth are adapted to the local climate, and their removal efficiency for total coliforms, COD, and oil and grease are optimal compared to other studies. Notably, terrestrial species like *Codiaeum Variegatum* have been less explored in the literature for GW treatment, which adds a novel aspect to this study compared with traditional aquatic macrophytes, potentially expanding the range of effective plant species used in CW. Integrating these plant species, particularly *Cyperus Laxus*, could enhance treatment efficiency for specific pollutants, especially in systems requiring significant microbial load reduction. The primary limitations of this study is its relatively short operational period of 35 days. While the observed removal efficiencies are encouraging, this duration may be insufficient to fully evaluate the long-term performance and stability of the constructed wetland system, particularly with regard to issues such as substrate clogging. Moreover, the study does not encompass the effects of varying climatic conditions or seasonal fluctuations, which are critical for assessing the robustness and optimizing the performance of the system under real-world conditions.

5 Conclusion

This study demonstrates the effectiveness of CWs employing polyculture plant species in removing pollutants from GW produced in educational institutions. It was observed that major pollutants such as COD, Phosphorus, and microbial indicators are removed in considerable quantities. The removal efficiencies obtained in the present study reveal that the CW technique may be applied to mitigate the environmental impacts of GW. The use of polyculture, plant species was particularly positive in CWs, where it seems to enhance general treatment performance through the uptake of more nutrients and an increase in microbial activity. More importantly, the adaptability of CWs to different kinds of environmental conditions makes their utility suitable even for areas with problems of water shortage. From the findings of this study, it can be concluded that CWs integrated with polyculture plant species are practical for GW treatment. Future studies should, therefore, focus on the long-term performance and maintenance requirements addressing potential clogging and seasonal variance of such systems, as well as their applicability in other urban areas, in further establishing their role in environmental sustainability and resource conservation.

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