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Chapter 7
“Constructed Wetlands”— An Environmentally Friendly Approach to Treating Wastewater: A Review

Shiromi DISSANAYAKA

1. Introduction

In this chapter, my goal is to introduce the utilization of constructed wetlands (CWs) as an environmentally friendly method for treating wastewater, and I will also share some of the recent research conducted at the Faculty of Agriculture, Rajarata University of Sri Lanka (RUSL). Firstly, I would like to provide a brief overview of CWs, natural wetlands are often considered as *nature's kidneys* because they perform similar functions to the kidneys in the human body. Just as the kidneys filter and purify blood, wetlands filter and purify water naturally. They act as a natural water filtration system, trapping sediments, nutrients, and pollutants, while also providing habitat for diverse plant and animal species. Wetlands help improve water quality, regulate water flow, and provide numerous ecological benefits, making them vital ecosystems for both wildlife and humans. Wetlands are increasingly being recognized and utilized for their effectiveness in wastewater treatment, often referred to as “the newest old thing” in this context. While wetland ecosystems have been naturally purifying water for millions of years, their potential for wastewater treatment has gained more attention in recent years as a sustainable and cost-effective alternative to traditional treatment methods. CWs, specifically designed for wastewater treatment, mimic the processes that occur in natural wetlands but are engineered to optimize treatment efficiency. They can be used to treat various types of wastewaters, including municipal sewage, agricultural runoff, and industrial effluents (Vymazal 2010). The use of CWs for wastewater treatment has been growing worldwide due to their ability to remove contaminants, improve water quality, and provide additional environmental benefits such as habitat creation and carbon sequestration.

Figure 1: Photos of CWs. Source: Author

Three main components can be identified in a CW system: (1) Impermeable layer, which prevents the filtration of pollutants downward into the lower aquifers; (2) Substrate layer, providing nutrients and support for the root zone where water flows, facilitating bioremediation and denitrification processes; and (3) Ground vegetation zone, either planted intentionally or allowed to establish naturally. Figure 2 depicts the primary components of CWs.

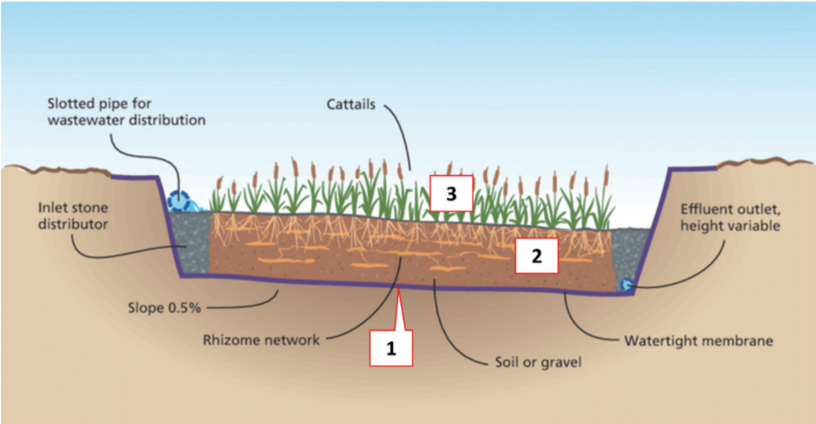

Figure 2: Three main components of CWs. Source: Author

Utilizing constructed wetlands for wastewater treatment enables us to embody the concept of "WASTEWATER is no more WASTE" by reclaiming valuable resources, fostering a circular economy, enhancing environmental sustainability, and achieving cost-effective solutions for wastewater management.

2. Wetland Research at RUSL

CW research conducted at our university, RUSL, includes research on: (1) Greywater treatment, (2) CW units for urban environments, (3) Improvement of the CW media/substrate for better pollutant adsorption, and (4) Constructed Floating Wetlands.

(1) Greywater Treatment (Field Method)

We conducted two experiments using CWs for greywater. The first experiment involved comparing the effectiveness of CWs planted with invasive plant species, namely narrow leaf cattail (*Typha angustifolia*) and bulrush (*Scirpus grossus*), for greywater decontamination treatment (Jinarajadasa et al. 2017). The second experiment utilized CWs planted with native plant species, specifically thunhiriya pan (*Actinoscirpus grossus*), combined with fungal inoculum (Navanjana et al. 2020) to treat greywater.

1) Greywater Treatment with Cattail and Bulrush

Two plant species, cattail and bulrush, are frequently employed in CW systems due to their ability to thrive in wetland environments and their effectiveness in wastewater treatment. In this experiment, they were also used as wetland plants for greywater treatment. For the filter media, we used gravel and soil. The photos of plants and filter media used in this study are shown in Figure 3.

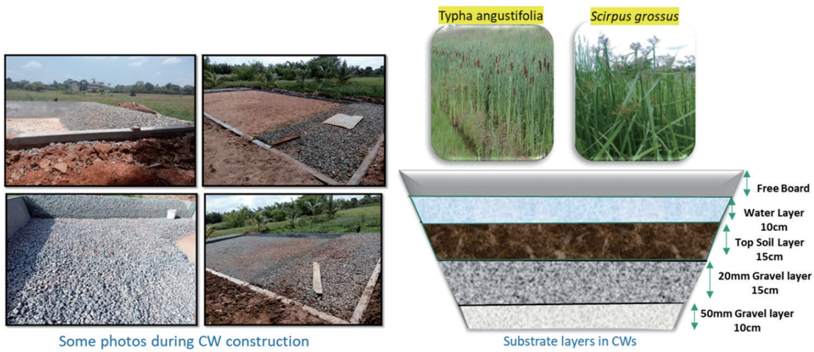

Figure 3: Substrates and plants used in CWs. Source: Author

Two free water surface CWs were designed to purify greywater at RUSL. After 1.5 months of operation, we found that both CW systems planted with cattail and bulrush showed high effectiveness in organic and nutrient removal. The removal efficiencies of the system planted with cattail for biological oxygen demand, phosphate-phosphorus, nitrate-nitrogen, ammonium-nitrogen, and total suspended solids were 68%, 43%, 67%, 78%, and 82%, respectively, while those for the system planted with bulrush were 90%, 53%, 85%, 86%, and 79%, respectively. The bulrush-planted wetland system showed more effectiveness in greywater decontamination compared to the cattail-planted wetland system. Hence, free water surface CWs with bulrush are recommended for scaling up to treat greywater before releasing it into the natural environment (Jinarajadasa et al. 2017).

2) Greywater Treatment with Thunhiriya Pan

Despite the high treatment performance demonstrated by CWs planted with cattail and bulrush in greywater treatment, these plants belong to invasive species, posing potential threats to local natural vegetation in Sri Lanka. Therefore, we explored the use of thunhiriya, a native plant within the same plant group, for greywater treatment. Furthermore, phosphorus removal in the cattail- and bulrush-planted wetland systems remains limited. Therefore, we applied fungal inoculum to the soil surface of the CW with the aim of enhancing pollutant removal efficiency through synergistic interactions between plants and fungal communities. The fungal inoculum was prepared using fungi isolated from the roots of a thunhiriya plant, with a concentration of 1 x 107 spores per 1 ml. Figure 4 presents the steps for isolating and cultivating fungi for incorporation into CWs.

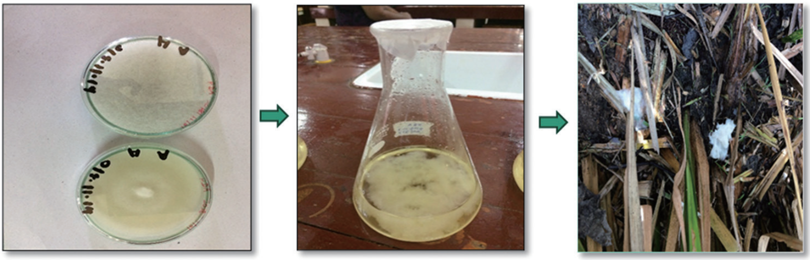

Figure 4: Procedure for fungal inoculum into CWs. Source: Author

The combination of thunhiriya pan reeds and fungal inoculum in CWs capitalizes on the complementary roles of wetland plants and fungi in nutrient uptake, organic matter decomposition, rhizodegradation, promotion of microbial diversity, and enhancement of ecosystem resilience. The results indicated that the microbially enhanced CWs, planted with thunhiriya, demonstrated effective removal of biological oxygen demand, nitrogen, and phosphorus. Specifically, the phosphorus removal reached 72.6%, surpassing that of the cattail- and bulrush-planted wetland systems (43–53%) (Navanjana et al. 2020).

(2) CW Units for Urban Environments

Next, I would like to discuss the use of CW units for treating kitchen wastewater and reverse osmosis (RO) concentrate. Additionally, I will explore the effectiveness of various wetland plants for wastewater treatment.

1) CW Units for Kitchen Wastewater Treatment

In this experiment, we used eight CW treatment units planted with three plant species, namely vetiver grass (*Vetiveria zizanioides*), lasia (*Lasia spinosa*, locally known as Kohila), and water spinach (*Ipomoea* *aquatica*, locally known as Kangkong) (Dissanayaka et al. 2019; Dissanayaka et al. 2022). The CW treatment units, plants, and diagrams of each CW are depicted in Figure 5.

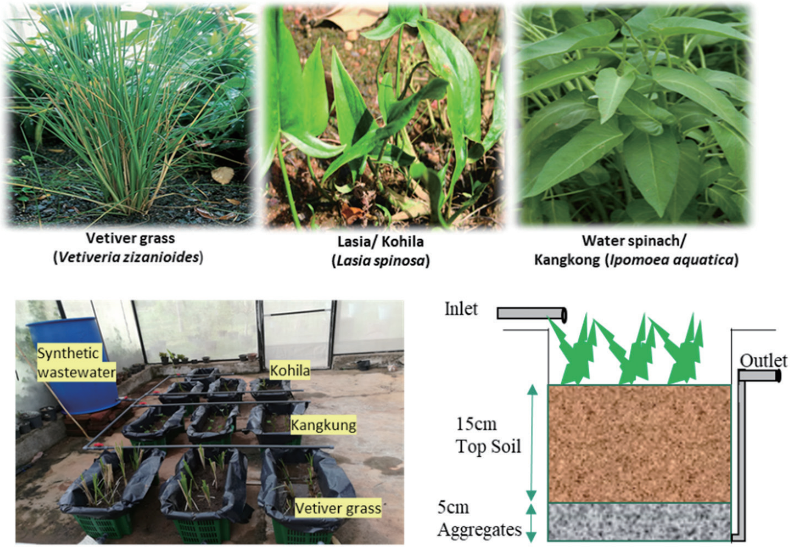

Figure 5: Plants and diagrams of CW treatment units. Source: Author

During a two-month period, the vetiver grass exhibited superior performance in removing ammonium-nitrogen, nitrate-nitrogen, and phosphorus, achieving removal efficiencies of 89%, 83%, and 71% respectively, surpassing the performance of lasia and water spinach. Moreover, the vetiver grass led to a notable increase (46%) in biological oxygen demand removal efficiency during the treatment process.

Overall, it can be affirmed that small-scale CW units, particularly those incorporating vetiver grass, represent practical and effective technology for greywater treatment at the domestic level. Vetiver grass has been recognized for its ability to uptake nutrients and pollutants from water, making it particularly suitable for use in CWs for greywater treatment. Vetiver's dense root systems help in filtration and purification processes, effectively removing contaminants such as suspended solids, organic matter, and certain nutrients from the greywater. Moreover, small-scale CW units are relatively low-cost, low-maintenance, and environmentally friendly compared to conventional treatment systems. They can be easily integrated into residential settings, providing an efficient and sustainable solution for greywater treatment. However, it is important to ensure proper design, construction, and maintenance of these systems to optimize their performance and longevity. Additionally, local regulations and guidelines should be followed to ensure compliance with standards for greywater treatment and reuse.

2) CW Units for RO Concentrate

Sri Lanka, like many other countries, faces challenges with water scarcity and disease prevalence, particularly in dry areas. The high prevalence of diseases and the need for clean drinking water often led to the implementation of water treatment solutions such as reverse osmosis (RO) plants. RO is a water purification technology that uses a semi-permeable membrane to remove ions, molecules, and larger particles from drinking water. However, it may not eliminate all types of pathogens and impurities. Additionally, the use of antibiotics and other pharmaceuticals can contribute to water contamination, posing challenges for water treatment processes. Since RO concentrate typically contains a high concentration of salts and other dissolved solids, disposing of it can be expensive. CWs can help reduce the volume of concentrate by promoting evaporation and transpiration, ultimately decreasing disposal costs. Furthermore, wetland plants can uptake nutrients such as nitrogen and phosphorus, which are often present in RO concentrate, and effectively remove various pollutants from water, including organic matter, suspended solids, and heavy metals. This can lead to improved water quality, rendering the treated water suitable for reuse or discharge into the environment.

In this experiment, we designed CW treatment units for the treatment of RO concentrate, with the same dimensions as those used in the previous experiment for kitchen wastewater treatment. The plants utilized in this experiment were vetiver grass, cattail, canna, and bulrush (Yapa et al. 2019).

Over the 4-month operation period, we observed increasing removal efficiencies for biological oxygen demand, nitrogen, phosphorus, and total dissolved solids, demonstrating that the four plant species utilized in this study effectively remove pollutants from RO concentrate. The effluent pH values experienced a slight decrease, maintaining a more neutral range of 6.7–7.6 in all CWs, compared to the inlet values of 8.3. The cattail plants exhibited the highest removal efficiencies for phosphorus, nitrate, and ammonium at 45%, 30%, and 39%, respectively. Additionally, cattail plants demonstrated the most substantial reduction in electrical conductivity (EC) at 15% after 12 weeks. Both cattail and bulrush plants achieved the highest reduction in total dissolved solids at 13%. It was noteworthy that the sodium adsorption ratio values for all treatment plants remained within the low sodium (0-10) water quality class. The pH and EC values, as well as the concentrations of phosphate and nitrate in the soil, are shown in Table 1.

Table 1: Soil chemical characteristics

CW treatment unit	pH		EC (μS/cm)		Nitrate-nitrogen (mg/L)		Nitrate-nitrogen (mg/L)	
	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment
Vetiver-CWs	8.02	8.06	62.60	132.90	20.25	26.66	39.96	3.72
Cattail-CWs	8.02	8.11	62.60	121.87	20.25	22.74	39.96	7.66
Cannas-CWs	8.02	8.23	62.60	141.13	20.25	33.65	39.96	4.51
Bulrush-CWs	8.02	8.16	62.60	135.67	20.25	23.85	39.96	6.97
Control-CWs	8.02	8.21	62.60	126.40	20.25	25.87	39.96	30.98

Source: Author

The pH and EC values increased, along with concentrations of phosphate-phosphorus in the soil after the treatment, while the nitrate-nitrogen concentration decreased. In addition, the plants exhibited higher concentrations of trace elements and metals post-treatment.

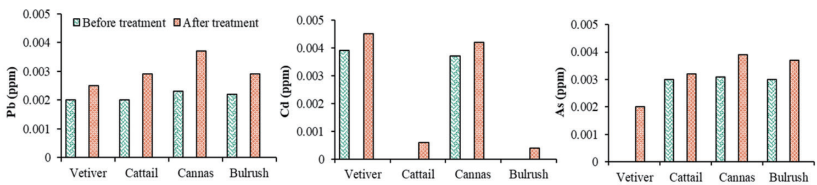

Figure 6: The concentration of trace elements in four plants.
Source: Author

Overall, the quality of RO concentrate can be enhanced using CW treatment units. However, further studies adjusting different hydraulic retention times to achieve maximum performance in wetland units are vital to identify the most effective plant species for treating RO concentrate. Additionally, this study could be further extended by incorporating the mixing of RO concentrate with kitchen wastewater to improve the microbial processes within the wetland systems.

(3) Improvement of the CW Media/Substrate for Better Pollutant Adsorption

The substrate in CWs plays a vital role in removing pollutants from wastewater by providing a supportive environment for diverse microbial communities and biogeochemical processes that contribute to pollutant removal and water treatment. Proper selection and management of the substrate are essential for maximizing treatment efficiency and ensuring the long-term performance of CW systems.

In this study, we investigated the utilization of Grumusol for phosphorus removal, as well as evaluating the effectiveness and environmental suitability of clay brick and laterite brick as adsorbents for treating heavy metals in wastewater.

1) Enhancement of Phosphorus Removal from Wastewater Using Grumusol

In wastewater treatment, phosphorus can be challenging to remove efficiently from CWs compared to certain other nutrients. In order to enhance phosphorus removal from wastewater, we used Grumusol in Murunkan, Sri Lanka, as substrate in CWs. Grumusol, also known as Chernozem, is a soil type recognized for its high fertility and abundant organic matter (Subasinghe et al. 2022). Murunkan soil falls under the Grumusol classification and showcases specific attributes: high cation exchange capacity (CEC), abundance of 2:1 clay minerals, and enhanced retention ability for various elements. A previous study by Jayawardhana et al. (2015) has revealed Murunkan clay's outstanding adsorption capabilities, notably in the removal of phosphorus. In this batch experiment, we set up a series of batch column experiments to assess the effectiveness of clay mixed with sands at various ratios for the removal of phosphorus from wastewater. The physicochemical properties of Murunkan clay, the properties of the experimental columns, and the experimental setup are presented in Tables 2 and 3, and Figure 7, respectively.

Table 2: Physicochemical properties of Murunkan clay.

Physicochemical properties of Murunkan clay at 27°C	Measured values
pH	8.4 ± 0.4
EC	114.5 ± 3 µS/cm
TDS	49.8 ± 1.4 mg/L
CEC	41.2 ± 2.1 cmol/kg
Available P	7.9 ± 0.3 mg/kg
Organic matter	0.40%

Table 3: Basic properties of the experimental columns.

Parameters	Values			
Ratio clay/sand	0:100	20:80	30:70	40:60
Height of the column (cm)	30	30	30	30
Cross-sectional area of the column (cm^2)	30.2	30.2	30.2	30.2
Bulk density of the mixed media (g/cm^3)	1.48	1.45	1.42	1.4
Particle density of the mixed media (g/cm^3)	2.61	2.52	2.46	2.45
Pore volume (cm^3)	385	387	399	402

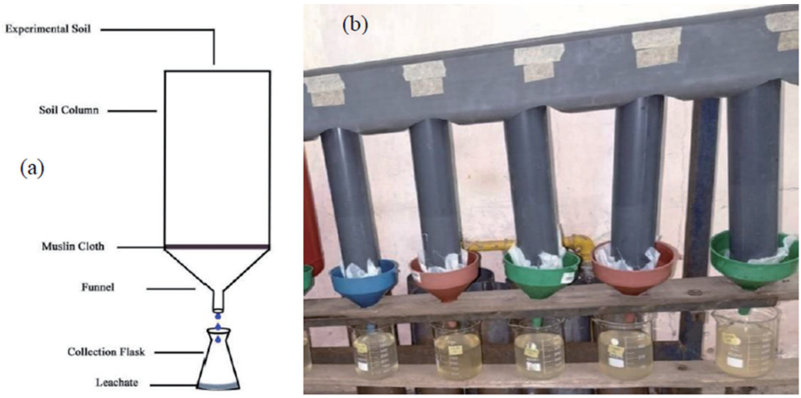

Figure 7: (a) Diagram of a typical column, and (b) laboratory arrangement of the columns. Source: Author

The experimental results demonstrated that Murunkan clay efficiently adsorbed phosphorus in aqueous solutions (see Figure 8). Over 99.75% of the applied phosphorus was adsorbed from the mixed media. These findings indicated that a significant amount of phosphorus can be adsorbed using a small quantity of Murunkan clay. Therefore, further research should investigate the optimal clay percentage required to adsorb a specific amount of phosphorus. Subsequently, varying proportions of clay (below 20%) should be combined with sand and exposed to different phosphorus concentrations to assess clay efficiency.

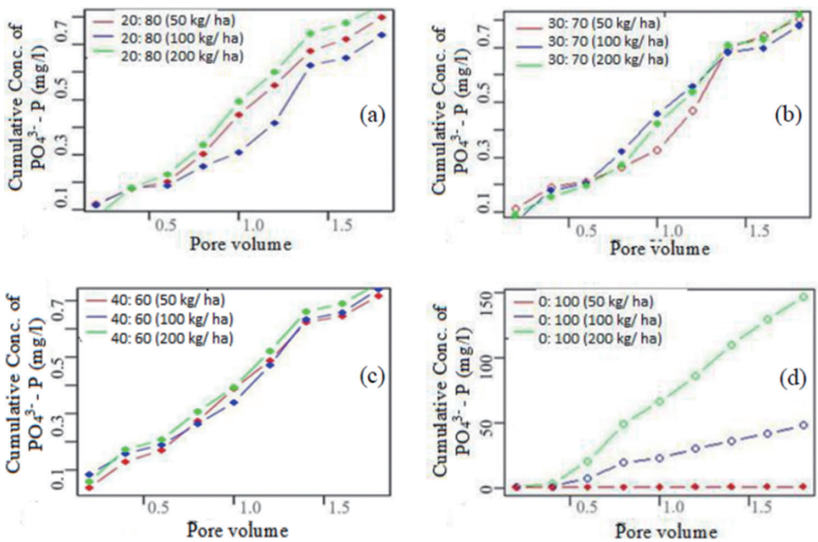

Figure 8: Cumulative concentration of phosphate in leachate from various clay and sand mixture media: (a) 20:80 clay–sand mixture media, (b) 30:70 clay–sand mixture media, (c) 40:60 clay–sand mixture media, and (d) 0:100 clay–sand mixture media. Source: Author

2) Applicability of Clay Brick and Laterite Brick as Effective and Environmentally Friendly Substrates in CWs for Treating Heavy Metals in Wastewater

This was the second experiment in a series aimed at enhancing the substrate to improve the treatment efficiency of CWs, which involved utilizing clay brick and laterite brick as adsorbent materials for the removal of heavy metals, specifically cadmium (Cd^{2+}) and lead (Pb^{2+}), from wastewater (Hettiarachchi et al. 2022).

As you may know, the release of industrial wastewater containing heavy metals into the environment is a significant environmental concern. Among the heavy metals commonly present in such wastewater are Cd^{2+} and Pb^{2+}. It is essential to remove these heavy metals before discharging the wastewater into the environment to safeguard both environmental quality and human health.

In this experiment, we examined clay brick and laterite brick, with physicochemical properties detailed in Table 4, as adsorbents for the removal of Cd and Pb.

Table 4: Physical and chemical properties of clay brick and laterite brick

Adsorbents	Particle size (mm)	Moisture content (%)	Specific gravity	pH	EC (mS/cm)	CEC (Cmol/Kg)
	0.5	0.036±0.00		6.04±0.23	0.31±0.01	20.87±0.35
Clay brick	1.0	0.032±0.00	2.45	5.95±0.16	0.28±0.02	19.30±0.75
	2.0	0.016±0.00		6.03±0.11	0.18±0.02	16.80±0.36
	0.5	0.004±0.01		5.08±0.10	3.24±0.10	18.30±0.50
Laterite brick	1.0	0.005±0.00	3.07	6.09±0.09	1.85±0.75	14.70±0.44
	2.0	0.005±0.00		6.18±0.05	0.75±0.05	18.23±0.76

We observed that the maximum adsorption capacity of clay brick and laterite brick reached 210.85 mg/g and 210.72 mg/g for Pb^{2+}, respectively. Additionally, the maximum adsorption capacity of Cd^{2+} by clay brick and laterite brick was 4.52 mg/g and 4.51 mg/g, respectively. The Langmuir and Freundlich models provided good fits for Cd^{2+} adsorption on both clay brick and laterite brick within the range of 0–1000 mg/L. Moreover, the adsorption of Pb^{2+} onto clay brick and laterite brick was well represented by all tested isotherm models. We noted a consistent adsorption pattern across all particle sizes of clay brick and laterite brick. The findings of this study confirmed the significant capability of clay brick and laterite brick in removing Cd and Pb, rendering them promising materials for heavy metal removal in CWs. Additionally, utilizing clay brick and laterite brick as substrate materials in CWs offers an efficient and environmentally friendly approach for eliminating heavy metals from wastewater. Both materials possess porous structures and high surface areas, providing ample sites for heavy metal adsorption. Furthermore, they contain minerals or compounds capable of chemically interacting with heavy metals, facilitating their precipitation or binding. These mechanisms, including co-precipitation and ion exchange, enhance heavy metal removal efficiency. Moreover, clay brick and laterite brick are widely available construction materials, making them cost-effective alternatives to specialized adsorbents. Their abundance in certain areas further supports their use in CWs for heavy metal removal. Additionally, their durability and resistance to degradation ensure their suitability for long-term use in CWs, even under harsh environmental conditions. Consequently, they maintain consistent heavy metal removal efficiency over time, contributing to the overall effectiveness of wastewater treatment in CW systems.

(4) Floating Constructed Wetlands

Finally, I would like to discuss research involving the use of floating constructed wetlands (FCWs) for wastewater treatment. FCWs are engineered systems designed to replicate the functions of natural wetlands while floating on the surface of water bodies (Kekulawala et al. 2022). Typically, these systems comprise a buoyant platform or raft that accommodates wetland vegetation, substrate materials, and sometimes additional treatment components. FCWs employ similar processes to traditional CWs for wastewater treatment, involving physical filtration, biological degradation, and nutrient uptake by plants. Figure 9 depicts the main components in the FCW, and an actual scale FCW image from our research.

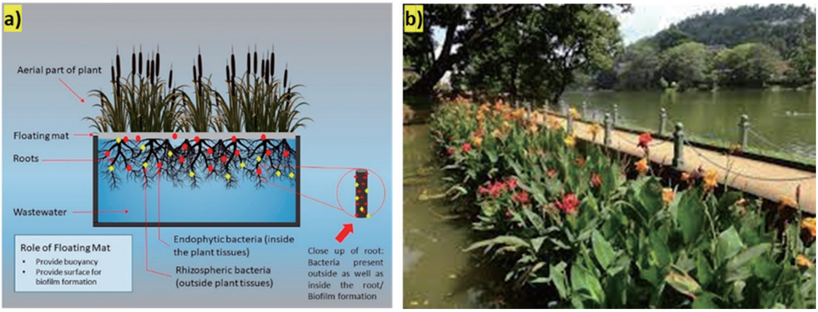

Figure 9: (a) The main components in the FCW, and (b) an actual scale FCW image. Source: Author

Vegetation is one of the most important components of FCWs, as it contributes significantly to the treatment efficiency and ecological functions of these systems. In this experiment, we assessed biomass production and pollutant uptake by various plant species in FCWs. The FCW was installed at one of the inlets of Kandy Lake, located in Sri Lanka. Kandy Lake spans an area of 6,544 square meters with a capacity of 704 acre-feet. The perimeter of the lake measures 3.4 kilometers, and its maximum depth reaches 18 meters (59 feet). The catchment area of the lake is approximately 1.045 square kilometers. We utilized umbrella palm (*Cyperus alternifolius*) and canna (*Canna iridiflora*) as plants for FCW. These young plants were initially cultivated in a greenhouse for adaptation before being transferred to the floating treatment platforms. Figure 10 depicts the plants transferred to FCWs, as well as diagrams of each FCW. The floating treatment wetland was constructed using PVC pipes, with dimensions of 1.75 meters in length and 1.2 meters in width. Coconut coir was utilized as the growing medium. To compare the treatment effectiveness of umbrella palm and canna in FCWs with their performance in terrestrial conditions, we installed two CWs in terrestrial conditions. These CWs employed the same plant species and dimensions as the FCWs to treat the same wastewater.

Figure 10: (a) Transferring plants to FCWs, and (b) A diagram of each FCW. Source: Author

After two months of operation, FCWs exhibited greater shoot growth, while terrestrial conditions promoted greater root growth in both umbrella palm and canna. This was probably because FCWs provided a consistently moist environment due to the presence of water. In such conditions, plants may prioritize shoot growth as they do not need to allocate resources extensively to develop root systems for water uptake, whereas, in terrestrial conditions, especially in environments with intermittent or limited water availability, plants tend to invest more in root growth to explore soil volumes for water uptake, ensuring their survival during periods of drought or water stress.

In both FCWs and terrestrial environments, the shoot and root biomass of canna (28.79g/plant and 6.61g/plant, respectively) were significantly higher ($p<0.05$) than those of the umbrella palm. The nitrogen and phosphorus contents in the shoots of both plants surpassed those in the roots. Furthermore, in both FCWs and terrestrial conditions, canna demonstrated higher total nitrogen and phosphorus uptake compared to the umbrella palm. Specifically, canna absorbed 23.28 mg/plant of nitrogen and 31.09 mg/plant of phosphorus, whereas the umbrella palm absorbed 14.91 mg/plant of nitrogen and 7.89mg/plant of phosphorus. Overall, canna emerges as the preferred choice among the two selected plants for use in FCWs to mitigate urban lake pollution. Its tolerance to a wide range of pollutants and adverse environmental conditions makes it particularly resilient in polluted water bodies commonly found in urban areas. Additionally, its attractive foliage and vibrant flowers add aesthetic value to floating constructed wetlands, enhancing the visual appeal of water treatment systems in urban or recreational areas.

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Chapter 7. "Constructed Wetlands" — An Environmentally Friendly Approach to Treating Wastewater: A Review

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