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New Challenges in Constructed Wetlands for Sustainable Wastewater Treatment: Intensification Strategies Based on Asian Experiences

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AJI BOOKS

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ISBN 978-4-910550-06-0 (Online)
ISBN 978-4-910550-07-7 (Print)

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Editor's Preface

It is my pleasure to launch this volume of the AJI books series. The content of this volume is a record from the international workshop named "New Challenges in Constructed Wetlands for Sustainable Wastewater Treatment: Intensification Strategies Based on Asian Experiences" that was held in July 2023, hosted by the Asia-Japan Research Institute (AJI), Ritsumeikan University.

As urbanization, pollution, and the negative impacts of climate change increase, demand for more sustainable wastewater treatment technologies intensifies. Constructed wetlands (CWs) have been used as an alternative to conventional technologies with many advantages, such as low cost, low energy, and simple operation. However, the efficiency of CWs exhibits a large variability, depending on their properties and design. To achieve a high treatment performance, it is necessary to employ effective strategies in the improvement of pollutant decontamination. In this workshop, eight speakers from Asian countries provided an overview of using CWs in wastewater management and the current development of CW strategies and techniques for enhanced sustainable wastewater treatment. Some case studies were presented, and the overall treatment performance of those innovative systems and their shortcomings were discussed. After the workshop, all the researchers promised to promote international academic research-sharing platforms and strengthen collaboration in the future.

The workshop served as an exceptional platform for young researchers to exchange ideas and cultivate lasting academic connections. Notably, it attracted undergraduate and graduate students from esteemed institutions such as Ritsumeikan University, Osaka University, Vietnam Japan University, and Vietnam National University, alongside several researchers from international companies. This broad participation underscores a profound interest in leveraging green technology for sustainable water treatment. Following the workshop, we received much positive feedback from attendees. Their support, encouragement, and recognition are powerful sources of motivation for researchers, fueling their passion and commitment to advancing knowledge and making meaningful contributions to their research fields.

The workshop surpassed my expectations, a feat made possible by the dedication, hard work, and collaboration of many individuals. I extend my deep appreciation to the Asia-Japan Research Institute for providing us with this invaluable opportunity through its policy of fostering a new generation of young researchers. Particularly, I am indebted to Professor Yasushi Kosugi, Director of the Asia-Japan Research Institute, whose unwavering support has been instrumental in propelling my scientific endeavors forward. I am also grateful to Professor Satoshi Soda, my supervisor, for his invaluable guidance in planning and selecting the topic of this workshop. I am immensely appreciative of Professor Anthony Brewer's unwavering assistance and guidance as my special advisor. His dedication to organizing the concept paper workshop, communicating with participants, and ensuring the excellence of our materials has been invaluable.

Gratitude is also extended to the eight outstanding speakers, whose expertise and insights enriched the workshop program and inspired all attendees. Their valuable contributions played a crucial role in creating a stimulating and intellectually rewarding experience for everyone involved.

Furthermore, I would like to express my sincere appreciation to AJI's members for their enthusiastic support in organizing and executing the workshop, and to all participants whose active engagement and support fostered a vibrant atmosphere conducive to fruitful discussions.

Finally, I am hopeful that this pulbication will foster an academic network among researchers and make a substantial contribution to the wastewater treatment sector, particularly in developing countries reliant on simple, effective, and affordable technologies.

Thi Thuong NGUYEN

Contributors

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Chapter 1. Removal Optimization and Material Balance of Antibiotics from Freshwater and Seawater Aquaculture Tailwater in Constructed Wetlands

Dr. Dan A is an Associate Professor at Zhongkai University of Agriculture and Engineering, China. She received her Ph.D. in Environmental Engineering, from Osaka University, Japan. She has been focusing on the study of the rhizosphere micro-interface process of emergent pollutants and related molecular response mechanisms and the application of ecological remediation technology of agricultural non-point source pollution.

2. Dr. Thi Dieu Hien VO

Chapter 2. Shallow-Bed Constructed Wetland System: A Promising Innovative Nature-Based Solution Towards Circular and Resilient Cities

Dr. Vo Thi Dieu Hien currently serves as Head of Program of the Institute of Applied Technology and Sustainable Development - Nguyen Tat Thanh University, Vietnam. She has a Ph.D. in Environmental Technology from the National Kaohsiung University of Science and Technology, Taiwan. Her research focuses on environmental engineering and technology including constructed wetlands, wetland roofs, biochar, food waste composting, membrane bioreactors, algae-based wastewater treatment, and air pollution monitoring.

3. Saurabh SINGH

Chapter 3. Design and Performance Assessment of Subsurface Constructed Wetlands for Pollutant Removal

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4. Dr. Nehreen MAJED

Chapter 4. Towards Multifaceted Mitigation of Climate Change Impacts: Ensuring Sustainable Treatment Solutions with Constructed Wetlands

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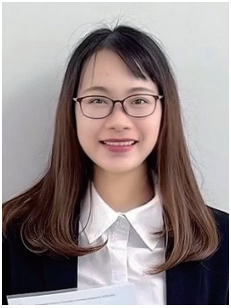

Chapter 5. Constructed Wetlands Planted with Iris for Mine Drainage Treatment: Effects of Domestic Wastewater Feeding on the Removal of Multiple Heavy Metals

Dr. Nguyen Thi Thuong is a Senior Researcher at Asia-Japan Research Institute, Ritsumeikan University, Japan. She obtained her Ph.D. in Advanced Architectural, Environmental, and Civil Engineering from the Graduate School of Science and Engineering, Ritsumeikan University, Japan. Her research primarily focuses on sustainable water and wastewater pollution treatment, nutrient removal and recovery, biological treatment processes, heavy metal removal, and constructed wetlands.

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Chapter 6. The Applications and Performances of Biochar in Constructed Wetlands for Sustainable Wastewater Treatment

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7. Dr. Shiromi DISSANAYAKA

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

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8. Dr. Van Tai TANG

Chapter 8. Application of Permeable Concrete Material in Constructed Wetlands for Urban Stormwater Runoff Treatment

Dr. Van Tai Tang did his Ph.D. program in Municipal Engineering at the School of Civil Engineering Southeast University, China. He is currently a lecturer at the Faculty of Technology, Dong Nai Technology University in Bien Hoa City, Vietnam. He also serves as a special scientific advisor to CEC Construction and Environmental Safety Investment Joint Stock Company in Hanoi, Vietnam. His research focuses on several issues and technical aspects of water and wastewater treatment technologies as well as eco-restoration technologies.

Chapter 1
Removal Optimization and Material Balance of Antibiotics from Freshwater and Seawater Aquaculture Tailwater in Constructed Wetlands

Dan A

1. Introduction

I would like to introduce my study on using CWs for antibiotic removal. As you may know, aquaculture is very important in the global food source. In 2020, aquatic production was 123 million tons in the world, of which China accounted for 67 million tons. China was also the largest aquaculture country in the world from 1991 to 2020. With the rapid development of aquaculture, veterinary antibiotics are frequently employed throughout the culturing process and are released directly into the nearby estuaries and sea. Figure 1 illustrates the concentration of antibiotics detected in water and sediment samples in the major mariculture sites in China, where sulfanilamide antibiotics (SAs) are frequently detected in seawater aquaculture with a detection rate of 100% and a concentration of 2.3–291 ng/L in Southeast China (Chen et al. 2017). In Guangdong Province, the exact location of our study, the detection rate is 85–100% with a detection concentration of 0.08–2.09 ng/L (Xu et al. 2019). In addition, sulfanilamide is also detected in freshwater aquaculture ponds and nearby rivers with a maximum concentration of 2.39 mg/L (Le and Munekage 2004).

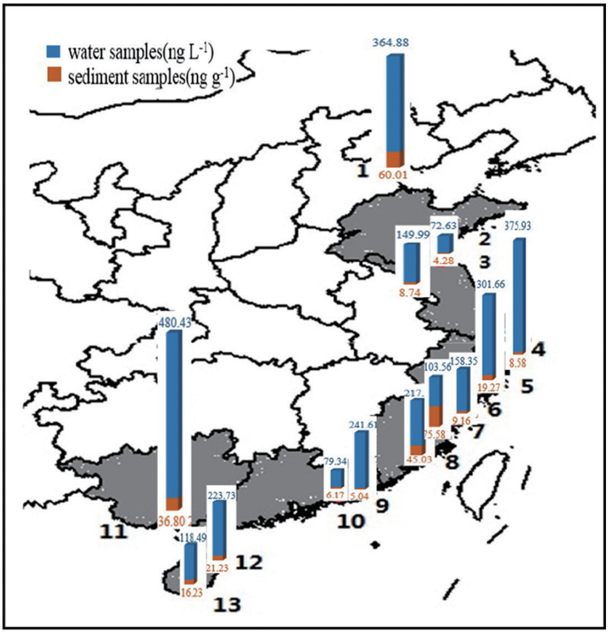


Figure 1: Antibiotics detected in water and sediment samples from key mariculture locations in China.
Source: Chen et al. 2017

The addition of feeds, feces, and veterinary waste led to an excessive content of organic matter, nitrogen, phosphorus, and antibiotics in aquaculture tailwater. Moreover, seawater aquaculture tailwater with different salinity levels was produced. Among them, salt ions cause danger to biological cells and bacteria, resulting in the limitation of the application of biotechnology (Cao et al. 2022; Tang et al. 2019).

CWs are proposed as a cost-effective technology for treating various kinds of wastewaters, including aquaculture tailwater. CWs have also been demonstrated to be effective in the removal of nutrients and antibiotics. Reportedly, when various wetland plants were used for treating aquaculture tailwater in CWs, it was found that the root exudates of common reed and iris had different effects on antibiotic biodegradation (Huang et al. 2019). Furthermore, different types of substrates can also impact the removal efficiency of antibiotics (Liu et al. 2021). This means that the configuration of CWs plays an important role in antibiotic biodegradation.

Figure 2 shows the results of searching for relevant papers by using Web of Science. We found only 23 papers that were related to CWs' aquaculture and antibiotics. Hence, it is necessary to more deeply investigate the removal behavior and mechanism of antibiotics from aquaculture tailwater in CWs.

Figure 2: The searched results in relevant papers using Web of Science.
Source: Web of Science <https://www.webofscience.com/>

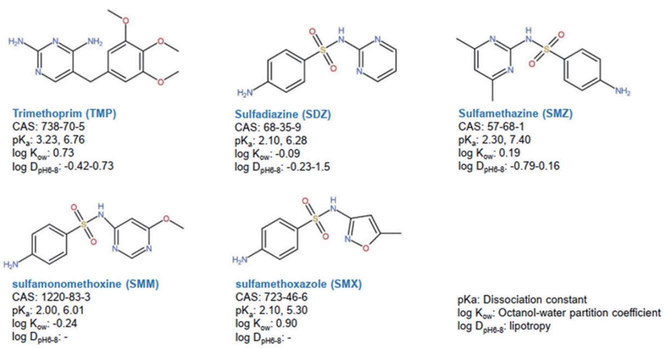
In this research, we prepared three topics, including "The optimization and microbial response mechanism of antibiotic removal from freshwater aquaculture tailwater by CWs," "The optimization and microbial response mechanism of antibiotic removal from seawater aquaculture tailwater by CWs," and "The removal pathways and material balance of antibiotics from freshwater and seawater aquaculture tailwater in CWs," with the three objectives of "The configuration of CWs that affect antibiotic removal by changing environmental factors optimized by orthogonal experiments," "The biodegradation and microbial response mechanism of antibiotics were analyzed by high-throughput sequencing," and "The material balance of antibiotics from aquaculture wastewater in CWs was described by mass balance analysis," respectively.

2. Experimental Setup and Investigation

Topic 1: Optimization and Microbial Response Mechanism of Antibiotic Removal from Freshwater Aquaculture Tailwater by CWs.

To the best of our knowledge, this marks the inaugural in-depth exploration of the correlation between antibiotic removal and microbial reaction within CWs employed for the treatment of aquaculture wastewater. Trimethoprim (TMP) and sulfonamides [sulfamethoxazole (SMX), sulfadiazine (SDZ), sulfamethazine (SMZ), and sulfamonomethoxine (SMM)] were selected as the targeted antibiotics in this study. Their physicochemical properties are shown in Figure 3a. For synthetic aquaculture wastewater, its composition was prepared according to the actual aquaculture tailwater in Guangdong province, China, by using tap water, fish feed, and veterinary drugs. The fish feed and chemicals are shown in Figure 3b.

(a)



(b)

Figure 3: (a) Physical and chemical properties of trimethoprim and sulfonamide antibiotics, (b) Fish feed, sea salt, and veterinary drugs used in this study.
Source: Author

The average inlet concentrations of TMP, SDZ, SMZ, SMM, and SMX were 6.4 ± 0.7, 15.5 ± 0.3, 3.3 ± 0.3, 5.7 ± 0.2, and 6.6 ± 0.5 mg/L, respectively. While the pH, water temperature (WT), dissolved oxygen (DO), oxygen reduction potential (ORP), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP), were kept around 7.9 ± 0.1, 19.8 ± 1.9, 9.3 ± 0.3, 90.0 ± 55.0, 326.0 ± 22.0, 10.0 ± 1.1, 1.2 ± 0.1, respectively.

The experimental setup is presented in Figure 4. Nine different CWs were prepared according to the orthogonal test design with three different factors: Factor 1 was the substrate (coral sand, gravel, zeolite), Factor 2 was the plant (reed, canna, yellow flag), and Factor 3 was hydraulic retention time (HRT_1, 2, and 3 days). This experiment was conducted in batch mode. The inlet and outlet samples were collected to determine antibiotic concentrations and measure other water parameters. Additionally, the microbial community from the water samples was analyzed.

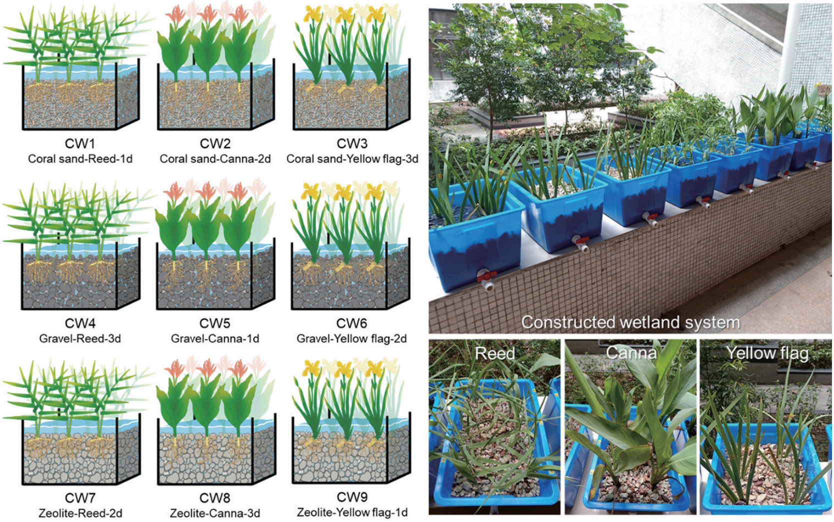


Figure 4: CWs system for antibiotic removal from freshwater.
Source: Author

During the experimental period, the effluent pH and WT reached 7.2–7.8 and 16.8–17.0 °C, respectively. The DO concentration after the CW treatment was reduced to 4.7–5.7 mg/L, implying the high oxygen demand for microbial activities and organic decomposition. The ORP values ranged from -107 to -7 mV. The COD and TP were removed effectively by all CWs, representing 69–76% and 52–85%, respectively. However, TN removal efficiency (4–40%) was quite low. The low temperature probably adversely affected the TN elimination. According to Becerra Jurado et al. (2010) and Du et al. (2016), the nitrification and denitrification rates dropped significantly at 20.0°C and 15.0°C, respectively.

For antibiotic removal, throughout the experiment, we found that the removal efficiency of TMP, SMX, SMM, SDZ, and SMZ were, respectively, 26–96%, -23–87%, -46–86%, -55–80%, and -62–84%

in all CWs. In general, all CWs showed higher TMP removal than SAs. Negative SAs removal was recorded in all CWs. This is probably because SAs can be easily returned to their original forms through the biochemical processes. This was confirmed by Li et al. (2021). The elimination efficiency of SMX was found to be the greatest among SAs. The highest treatment performance was recorded at CW4, which was employed with gravel, common reed, and HRT of 3 days. Its treatment performance was 89%, 61%, 20%, 20%, and 12%, for TMP, SMX, SMM, SMZ, and SDZ, respectively. The substrate was the most important factor for removing antibiotics in this study, followed by the plant and HRT. In addition, aerobic bacteria such as *Hydrogenophaga* and *Pseudomonas* were found to negatively affect TMP and SAs removal. In contrast, the anaerobic bacteria such as *Lacihabitans* and *Ilumatobacter* promoted these antibiotics elimination. The mechanisms of antibiotic removal from freshwater in CWs were summarized and displayed in Figure 5.

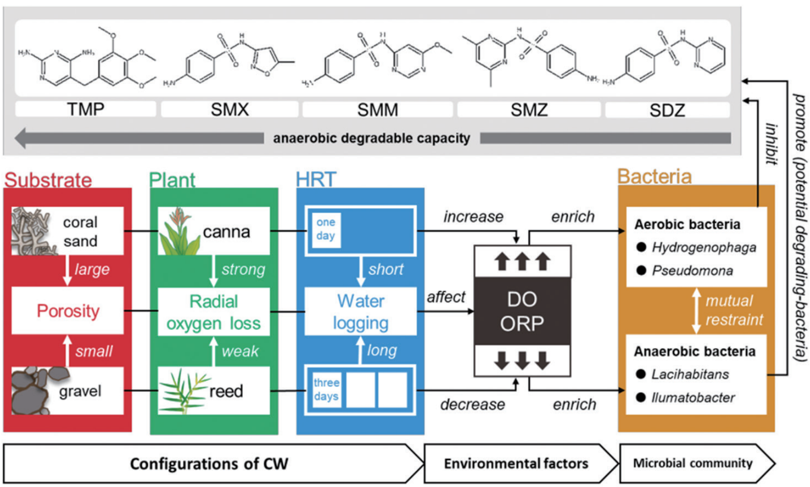


Figure 5: Antibiotic removal mechanisms from freshwater in CWs.
Source: Author

Overall, anaerobic degradation was regarded as the major removal pathway of antibiotics. The specific configuration of CW changed dominant and functional microbes in CWs. The CW configurations using small-porosity gravel, common reed with weak radial oxygen loss, and the longest HRT (3 days) resulted in a drop in the oxygen level. This enriched the anaerobic bacteria, which promoted antibiotic degradation. Conversely, the ones employed with large porosity coral sand, canna, having strong radial oxygen loss, and the short HRT (1 day) led to an increase in the oxygen level, which enhanced aerobic bacteria activities, inhibiting antibiotic degradation.

Topic 2: Optimization and Microbial Response Mechanism of Antibiotic Removal from Seawater Aquaculture Tailwater by CWs

In this study, we carried out an experiment in the greenhouse of Zhongkai University of Agriculture and Engineering in Guangzhou. The materials used in this experiment were the same as in Topic 1, except for Factor 3. In this experiment, Factor 3 was salinity, including three salt levels of 4‰ (low), 8‰ (middle), and 12‰ (high). The experimental design is shown in Figure 6.

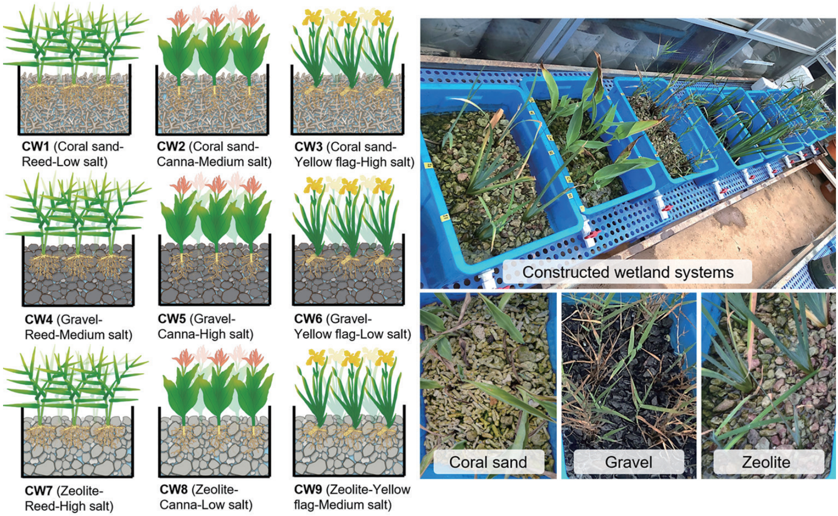


Figure 6: CWs system for antibiotic removal from seawater.
Source: Author

Unlike Topic 1, the HRT in this topic was fixed within 2 days. The tidal flow constructed wetlands (TFCWs) in this experiment were operated in intermittent mode, one day with synthetic wastewater (wet phase), and the other day without wastewater (dry phase), for the purpose of improving aerobic conditions in TFCWs, besides the water parameters mentioned in Topic 1. In this experiment, electrical conductivity (EC) and salinity (SAL) were also measured.

The results showed that during the experiment, the TFCWs demonstrated effectiveness in SAs removal with a removal efficiency of 59–92% for SMX, 38–97% for SMM, 30–94% for SDZ, and 34–92% for SMZ. In contrast, it was ineffective in TMP removal (-88–7%). The best treatment performance was recorded at CW9 (zeolite-yellow flag-12‰) for SAs, while CW4 (gravel-reed-8‰) showed the highest TMP removal. The TMP removal was dependent on anaerobic conditions and substrate adsorption. The zeolite improved pH, salt neutralization, and oxygen enrichment, which had the ability to enrich potential aerobic degrading bacteria (such as *Enterobacter* and *Sulfuritalea*). Among wetland plants, yellow flag performed the best in antibiotic removal in TFCWs. It enhanced bacteria with aerobic function and stress tolerance. Unlike with substrate and plant, salinity had no significant influence on antibiotic removal. The biodegradation mechanism of antibiotics from seawater in CW systems was summarized in Figure 7.

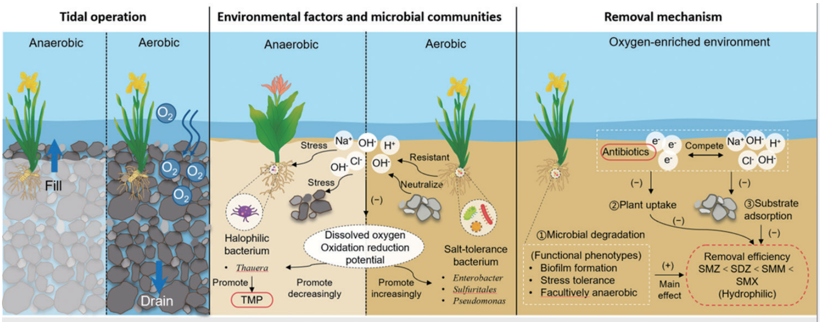


Figure 7. Biodegradation mechanisms of antibiotics in CWs.
Source: Author

In general, microbial degradation was regarded as the primary route for eliminating antibiotics from seawater in TFCWs. The substrate adsorption and plant uptake had minimal direct impacts on antibiotic elimination. Nevertheless, the ion exchange capacity of the substrate, the salinity tolerance of plants, and the salinity level each impacted the pH and EC values of the system, as well as the formation of rhizosphere biofilm, microbial functional characteristics, oxygen levels, and the structure of the microbial community. These factors determined the types and distribution of crucial functional bacteria, thereby indirectly influencing antibiotic biodegradation.

Topic 3: Removal Pathways and Material Balance of Antibiotics from Freshwater and Seawater Aquaculture Tailwater in CWs.

The main purpose of this experiment was to evaluate the removal pathways and material balance of antibiotics from freshwater and seawater in CWs. In order to achieve this purpose, we installed CW systems for fresh and seawater treatment. The experimental setup diagram is presented in Figure 8.

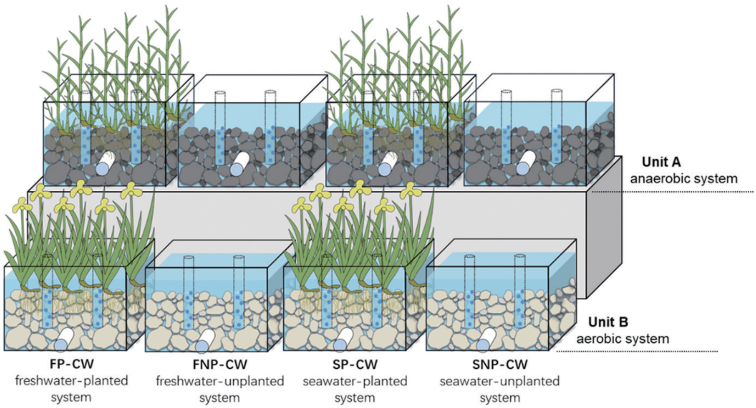


Figure 8: Design of the hybrid CWs.
Source: Author

The tidal flow series CW includes two units A and B. Unit A was designed similarly to the CW with the best treatment performance in Topic 1, employing gravel, common reed, and wetting mode. While Unit B was designed similar to the best performing treatment in Topic 2, with zeolite, yellow flag, and alternate wetting and drying modes. A control subunit without plants was prepared for each unit. This experiment was operated in sequencing batch modes with freshwater or seawater. The planted or unplanted CWs operated with freshwater were referred to as FP-CW and FNP-CW, while those with seawater were termed SP-CW and SNP-CW.

After the CW treatment, we observed that the removal efficiency of SAs from freshwater ranged from 7% to 87%, while it ranged from 7% to 94% for seawater. The planted CWs showed higher SAs removal efficiency (7–94%) than unplanted CWs (5–89%). Additionally, Unit B exhibited better SAs treatment performance. For TPM removal, its elimination efficiency from freshwater (>90%) was higher than that from seawater (-28–80%). Unlike SAs, TPM was removed more effectively in the unplanted CWs (52–98%) than planted CWs (-28–98%). Unit A removed TMP at a rate of 14–93% TMP, which was better than Unit B (-48–91%). Figure 9 shows the substrate adsorption and plant accumulation of antibiotics in CWs of freshwater and seawater.

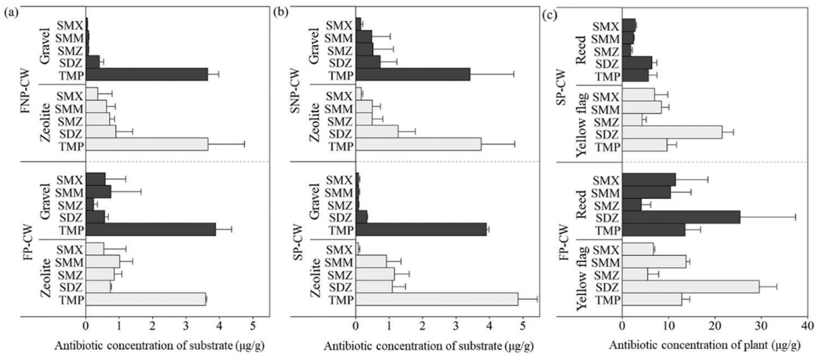


Figure 9: Distribution of antibiotics in substrates from the (a) freshwater and (b) seawater systems, and (c) in plants.
Source: Author

In general, zeolite demonstrated better antibiotic removal than gravel, as evidenced by the higher concentration of antibiotics absorbed in zeolite. The highest concentration of antibiotics found in the substrate was recorded for TMP in both systems. The TMP level in substrates was approximately 7 times higher than that of SAs. Also, we found that there were no significant differences between the treatment performances in freshwater and seawater systems, indicating that substrate adsorption of antibiotics is not impacted by salinity stress. For plant accumulation, the yellow flag showed a higher accumulation of antibiotics than the common reed. The antibiotic concentrations in plants from the freshwater system were around two times higher than those from the seawater, suggesting that plant uptake was inhibited by salinity stress. The antibiotic removal pathways were depicted in Figure 10.

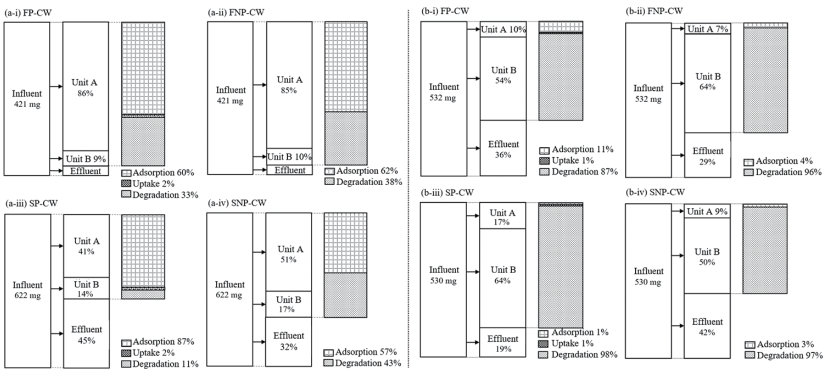


Figure 10: Mass balance model of (a) TMP and (b) SMX in the (i) FP-CWs, (ii) FNP-CWs, (iii) SP-CWs and (iv) SNP-CWs.
Source: Author

During the experiment, substrate adsorption was exhibited as the main pathway for TMP removal, representing 62–87%, followed by degradation (11–48%) and plant uptake (approximately 2%). Whereas degradation was the principal mechanism for removing SAs, accounting for 72–98%, followed by adsorption (1–24%), and plant uptake (only 1–6%).

3. Conclusion

In this research, we conducted three experiments to evaluate how different configurations of CWs influence the removal of antibiotics, elucidate the mechanisms of biodegradation and microbial response to antibiotics, and conduct a mass balance analysis. Our findings demonstrated that CWs were effective in removing antibiotics, with SAs and TMP showing higher removal efficiency in seawater and freshwater CWs, respectively. The specific configuration of CWs influenced the composition of dominant and functional microbes within them. Microbial degradation emerged as the primary pathway for SAs removal, accounting for 72% to 98% of removal, while substrate adsorption was the primary mechanism for TMP removal, accounting for 62% to 87% of removal. These results provided valuable insights for the utilization of CWs in the advanced purification of aquaculture wastewater containing veterinary drugs.

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Chapter 2
Shallow-Bed Constructed Wetland System: A Promising Innovative Nature-Based Solution Towards Circular and Resilient Cities

Thi Dieu Hien VO

1. Introduction

I would like to begin by briefly introducing some environmental hazards that are especially found in tropical countries. Domestic wastewater is often discharged directly to the environment or not properly treated. The percentage of untreated domestic wastewater released directly into the environment differs across continents: In Africa it stands at 99%, in South America at 86%, in Asia at 65%, in Europe at 34%, and in North America at 10% (Amábile-Cuevas 2016). Areas with a high percentage are a big concern. Additionally, rapid economic growth, industrialization, and urbanization have led to extremely severe air pollution that causes increasing negative effects on human health, visibility, and climate change. Each year, global greenhouse gas (GHG) emissions total about 50 billion tons. In many megacities, air pollution has been increasing by around 8–14% annually. This rate is up to three times as high as the national or regional increase. The largest contributors to air pollution are industrial and transportation sources. Furthermore, the lack of green space is a problem that many cities are facing. The World Health Organization (WHO) suggests that every city should aim to offer at least $9m^2$ per person of accessible, secure, and functional urban green areas.

However, many cities still lack sufficient green space, especially in tropical countries with 20–50% having low green area coverage (Russo and Cirella 2018).

Therefore, sustainable technology that can address the aforementioned problems is urgently needed. One such solution is the green roof, a roof partially or entirely covered with vegetation and a growing medium, planted over a waterproofing membrane. It can enhance green space, mitigate flooding, conserve energy, improve air quality, and provide aesthetic landscaping (Bui et al. 2019). In 2010, we introduced wetland roof solutions aimed at treating domestic wastewater by integrating shallow-bed CWs with green roofs. In addition to harnessing the benefits of green roofs, wetland roofs have proven effective in rainwater management. A schematic of our experimental system is presented in Figure 1. The primary goal of this research is to achieve sustainable water management through blue-green infrastructure solutions and to contribute to the creation of resource-efficient urban areas and commercial zones. The outcomes of our project have been documented in several journals (Thanh et al. 2012; Bui et al. 2014; Van et al. 2015; Bui et al. 2019; Nguyen et al. 2021).

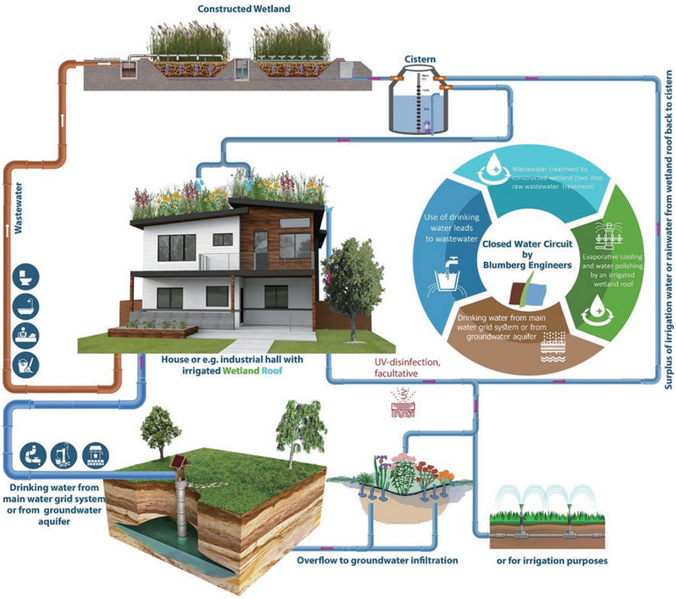

Figure 1. Diagram of wetland roofs for wastewater treatment.
Source: Ingenieurbüro Blumberg

2. Wetland Roofs

(1) Benefits of Wetland Roofs

Before delving into the research results of using the wetland roof system for domestic wastewater treatment, I would like to briefly summarize the benefits of wetland roofs. As you may know, the CW treatment technology offers advantages such as low cost, low energy requirements, and simple operation. Additionally, it can provide solutions for water reuse, natural landscape enhancement, and biodiversity promotion. Meanwhile, green roofs effectively utilize rooftop space, contribute to mitigating urban heat island effects, improve air quality, conserve energy, provide opportunities for environmental education, and enhance architectural interest.

(2) Factors Influencing the Performance of Wetland Roof

Several factors influence the treatment effectiveness of wetland roofs, including vegetation, hydraulic loading rate, feeding pattern, and bed media.

1) Plant

In a wetland roof, vegetation helps stabilize the surface of the material layer, provides greenery, enhances landscape aesthetics, facilitates physical filtration, prevents clogging, absorbs nutrients and metals, and serves as a medium for attached bacteria (Shelef et al. 2013). Thus, plants used in CWs should be selected carefully to achieve higher treatment performance. The factors influencing plant selection are shown in Figure 2.

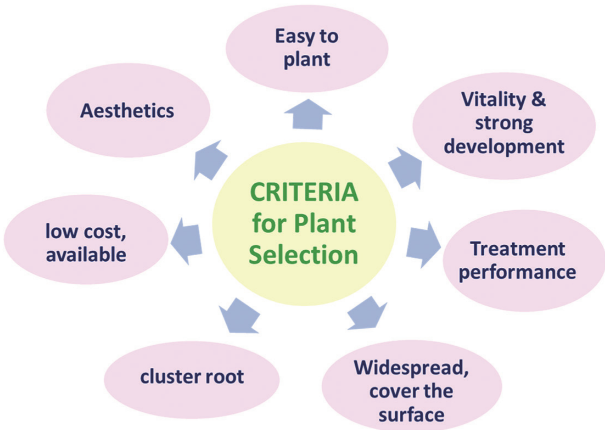

Figure 2: The criteria for plant selection.
Source: Author

2) Hydraulic Loading Rate

The hydraulic loading rate (HLR) refers to the volume of water applied to a treatment system per unit of time. HLR can indeed affect the performance of a wetland roof treatment system. It can influence the residence time of water within the treatment system. Higher loading rates may reduce the amount of time water spends in the system, potentially decreasing the effectiveness of pollutant removal processes such as sedimentation, filtration, and biological degradation. In some cases, higher HLR can result in better phosphorus removal due to certain conditions dependent on HLR, such as oxidation-reduction potential. In addition, wetland roof systems often incorporate vegetation to enhance treatment efficiency and provide additional ecological benefits. HLR can stress or damage vegetation by limiting root oxygenation, washing away soil, or causing waterlogging, thereby compromising the long-term viability of the system (Taniguchi et al. 2009). Therefore, when designing or operating a wetland roof treatment system, it is essential to consider the HLR and its potential impacts on treatment performance, as well as to implement appropriate measures to optimize system efficiency and longevity.

3) Feeding Pattern

The feeding pattern, which refers to how water is distributed across the wetland roof, can impact several aspects of the performance of systems. The feeding pattern determines how quickly water moves through the wetland roof system. A longer residence time allows more time for physical, chemical, and biological processes to occur, enhancing pollutant removal efficiency. Additionally, a well-controlled feeding pattern promotes healthy plant growth throughout the wetland roof, maximizing treatment efficiency. Whereas an uneven feeding pattern may lead to some areas of the wetland roof receiving more water than others, resulting in uneven treatment efficiency and the potential for clogging or sediment accumulation in certain areas. The intermittent pattern is recognized for enhancing oxygen transfer and diffusion in the system, reducing energy consumption for pumping water, especially in high-capacity systems, and accelerating ammonium removal (averaging 80–99%) better than the continuous system (averaging 71–85%). However, it is less effective than the continuous pattern in removing sulfate (Taniguchi et al. 2009). Overall, optimizing the feeding pattern in a wetland roof treatment system is essential for maximizing treatment efficiency, promoting healthy ecosystem functioning, and ensuring long-term performance and sustainability. This optimization often involves careful design and monitoring to achieve the desired hydraulic and ecological outcomes.

4) Bed Media

The bed media play a critical role in enhancing the treatment efficiency of CWs by providing a suitable environment for microbial activity and plant growth, promoting pollutant removal processes, and facilitating effective water treatment through physical filtration and biological degradation. The common bed media often used in CWs are gravel, sand, stone, and soil. In recent years, there has been a growing interest in exploring alternative bed media options for CWs, including charcoal, recycled brick, bagasse, biochar, and oyster shell. These alternative bed media offer unique properties and potential advantages for wastewater treatment in CW systems, such as lighter weight, strong absorbability, and ion exchange capacity. To achieve high treatment performance and meet the diverse needs of CW systems, continued research and development efforts are necessary. These efforts may involve testing various materials, including natural, synthetic, and recycled options, to assess their suitability for wastewater treatment applications. Additionally, optimization techniques can be employed to enhance the performance of alternative bed media and address specific treatment objectives, such as nutrient removal, organic matter degradation, and pathogen reduction. Furthermore, considerations such as cost-effectiveness, environmental sustainability, and scalability should also be taken into account when evaluating alternative bed media options for CWs.

3. Results

(1) Water Quality

Table 1 shows several applications of using shallow-bed CWs and wetland roofs for domestic wastewater treatment, comparing them with our research (Bui et al. 2014; Van et al. 2015; Vo et al. 2018; Nguyen et al. 2021).

Table 1: Treatment performance of several shallow-bed CWs and wetland roofs for treating domestic wastewater

Plants	Substrate/water depth (m)	Bed materials	OLR (kgCOD/ha/day)	HLR (m^3/ha/day)	Removal rate (kg/ha/day)			Reference
					COD	TN	TP	
Phragmites australis	0.35/ 0.30	Gravel	60	182 – 364	38 – 60	0.9 – 2.6	NA	Caselles-Osorio and García, 2006
Phragmites australis	0.35/ 0.30	Gravel	230	364	179 – 202	6.6 – 8.7	NA	Caselles-Osorio et al. 2007
Phragmites australis	0.30/ 0.02	Sand	19.4 – 90.7 (TN)	1500, 4500, 7500	NA	14.8 – 38	1.4 – 2.5	Taniguchi et al. 2009
Phragmites australis	0.075/ 0.02		2 – 10 (TP)		NA	14 – 53	0.5 – 1.6	
Phragmites australis	NA/ 0.20	Gravel	20.7	400	146	9	NA	Albuquerque et al. 2009
Phragmites australis	0.30/ 0.25	Gravel	47 (BOD)	285	69	5	NA	Pedescoll et al. 2011
Bryum muehlenbeckii	0.20/ NA	Gravel	41	120	35 – 36	5.2 – 6.5	0.3 – 0.4	Wang et al. 2012

Phragmites australis; Iris pseudacorus, Juncus effusus	0.35/ 0.30	Crushed granitic gravel	29 – 77	230 – 260	NA	NA	NA	Carballeira et al. 2016
Melampodium Paludosum	0.20/ 0.10	Soil, sand, small rock	36	340	28	19	1.4	Bui et al. 2014
Arachis Duranensis; Evovulus Alsinoides; Cyperus Alternifolius Linn; Philodendron Hastatum	0.20/ 0.10	Soil, sand, small rock	49	340	36 – 49	13 – 24	0.7 – 2.0	Van et al. 2015
Cyperus rotundus L.; *Zenith zoysia grass; Cynodon dactylon; Imperata cylindrical; Cyperus javanicus Houtt; Eleusine indica* (L.) *Gaertn.; Struchium sparganophorum* (L.) *Kuntze; Kyllinga brevifolia Rottb*	0.20/ 0.10	Soil, sand, small rock	30 – 60	260 – 400	16 – 33	9 – 21	0.2 – 0.6	Vo et al. 2018
Axonopus Compressus; Wedelia Trilobata	0.20/ 0.10	Soil, sand/ charcoal, small rock	34 – 58	257 – 299	25 – 34	11 – 20	0.4 – 0.9	Nguyen et al., 2021

NA: not available

In general, the common reed (*Phragmites australis*) was often used in shallow-bed CWs in previous studies. This plant demonstrated a higher ability to diffuse oxygen than other submerged plants, at approximately 12 g/m^2/day. Thus, the wetlands planted with common reed exhibited greater organic removal. Nevertheless, the rapid growth rate, high biomass, and towering height (1–3 m) of common reeds may pose challenges when considering them for use as roof vegetation in wetland systems. Therefore, careful consideration should be given before incorporating common reeds into wetland roofs. The shallow bed depth of shallow-bed CWs has been instrumental in facilitating the nitrification process, leading to relatively high efficiency in total nitrogen treatment. The removal of COD has been consistently high, ranging from 35 to 202 kg/ha/day. Our studies (Bui et al. 2014; Van et al. 2015; Vo et al. 2018; Nguyen et al. 2021) also demonstrated significant removal rates for COD, TN, and TP, ranging from 16 to 49 kg/ha/day, 9 to 24 kg/ha/day, and 0.2 to 2.0 kg/ha/day, respectively, in wetland roof systems. The treated wastewater can be repurposed for various applications such as toilet flushing, irrigation, car washing, or recharging underground water for potential potable reuse. Additionally, findings from Nguyen et al. (2021) suggested that novel charcoal media can substantially reduce the gravitational loading of wetland roofs. Systems utilizing charcoal media with intermittent feeding patterns showed the best performance.

(2) Air Quality Improvement

Wetland roofs can contribute to improving air quality, such as carbon dioxide (CO_2) absorption, oxygen production, particulate matter filtration, volatile organic compounds removal, and a cooling effect. The adsorption capacity of green roofs was 0.36–3.21 g/m^2 for PM_{10}, 0.52–4.4 g/m^2 for O_3, 0.27–2.28 g/m^2 for NO_2, 0.10–0.59 g/m^2 for SO_2. Vegetation plays a crucial role in influencing CO_2 concentration through absorption and emission processes. During daylight hours, the rate of CO_2 absorption was found to be nine times higher than the rate of emission during nighttime. It was found that approximately 48.19 kg of CO_2 was annually absorbed by 102 pots of *Ipomoea pes-caprae* planted on a flat roof in Malaysia (Bui et al. 2019).

(3) Enhancement of Green Spaces

It has been noted that green trees possess the capacity to absorb radiation and transpire, thereby cooling and refreshing the urban atmosphere. Nevertheless, the rapid pace of urbanization has led to a reduction in urban green spaces, particularly in developing countries. For instance, while Latin American countries boast an average of 255 m^2 per person, Asian countries typically offer only around 39 m^2

per person. Notably, the availability of green spaces in certain Asian cities is exceedingly low, such as Ho Chi Minh City (Vietnam), with a mere 0.7 m^2 per person, Bangkok (Thailand) with 3 m^2 per person, and Manila (Philippines) with 5 m^2 per person. Consequently, utilizing shallow-bed CWs as wetland roof systems could not only aid in wastewater treatment but also contribute to expanding green spaces.

Our study also examined the feasibility of integrating green spaces with eight different plant species into wetland roof systems. The findings revealed that each square meter of wetland roof could potentially yield between 67 and 99 square meters of specialized green leaf area. This implies that wetland roofs hold significant promise in addressing the limitations of urban green space. However, research in this area remains limited, and there is a notable lack of studies assessing the capacity of shallow-bed CWs or wetland roof systems to purify air pollutants and mitigate noise. Hence, it is imperative to conduct further research focusing on these aspects in order to achieve a more comprehensive evaluation in the future.

4. Current Work

In recent years, we have implemented pilot-scale wetland roof systems atop Ho Chi Minh City University of Technology in Vietnam. In this study, we integrated rock, charcoal, and oyster shells as substrates within the wetland roof systems to improve the removal of nutrients from domestic wastewater. For vegetation, we opted for ornamental flowering plants, namely Campsis radicans and Vernonia elliptica, within the wetland setup.

The average influent concentrations of COD, TN, and TP were 305±50, 15±10, and 0.62 ± 0.48 mg/L, respectively. After two months of operation, it was observed that COD removal was moderate in both wetland roof systems, with approximately 78% removal in the Vernonia elliptica planted systems and 52% removal in the Campsis radicans planted systems. The COD concentrations (ranging from 42 to 90 mg/L) in both systems remained well within the effluent standard requirements. More than 90% of nitrogen was effectively removed by both wetland roof systems, with no significant difference between the Vernonia elliptica and Campsis radicans planted systems. Regarding phosphorus removal, the Vernonia elliptica planted system exhibited a higher removal efficiency (73%) compared to the Campsis radicans planted system (34%). Figure 3 shows the adaptation of Vernonia elliptica and Campsis radicans in the startup phase. Generally, these plants adapted and grew well throughout the experiment.

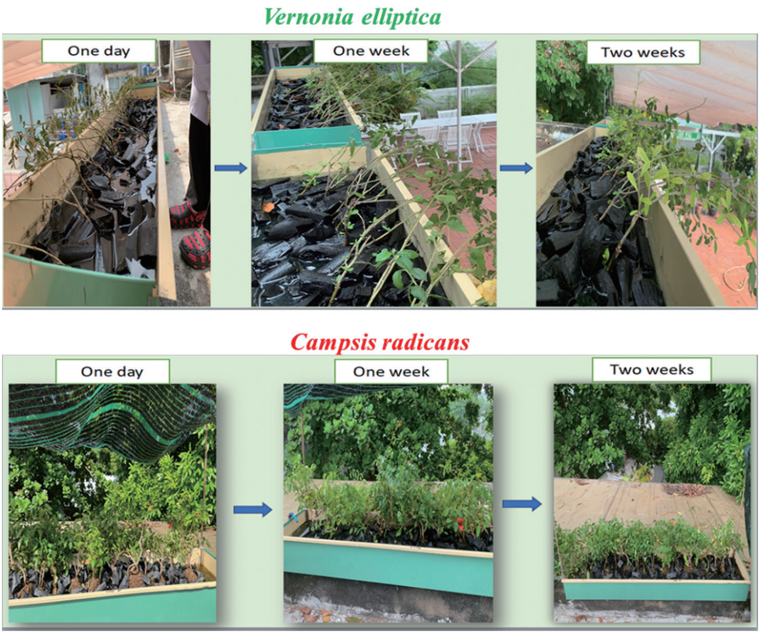

Figure 3: The adaptation of Vernonia elliptica and Campsis radicans for two weeks of the experiment. Source: Author

5. Challenges and Solutions in Implementing Wetland Roof Applications

Despite the evident advantages, there are still certain constraints to consider when using wetland roof systems. For instance, the gravitational load of the shallow CW systems may impact the load-bearing capacity roofs. While previous studies have designed wetland roofs with a gravitational load of 163 kg/m^2, it is advisable to use lighter bed materials instead of traditional ones like sand, stone, and gravel to enhance safety (Vo et al. 2018). Besides, the potential for odor issues arising from wastewater and the decomposition of organic matter within the CWs is a concern. To address this, wastewater can be contained in closed tanks. Additionally, wetlands employing horizontal subsurface flow, with water levels situated beneath the bed material layer, can minimize the risk of odors and infectious microorganisms. Wetland lands utilizing down-to-up vertical subsurface flow can also deter odor problems and the proliferation of organisms like flies and mosquitoes. Furthermore, regularly harvesting plants and maintaining them at a height of approximately 20cm can significantly limit mosquito breeding.

The financial aspect, covering investment, installation, operation, and maintenance costs, is a key concern regarding wetland roof applications. However, no studies have yet conducted a cost-benefit analysis specifically for these applications. Thus, further studies should investigate the benefits assessment for actual wetland roofs to better understand their full potential and accuracy.

6. Conclusion

Shallow-bed constructed wetlands (CWs) have been effectively employed for wastewater treatment across various regions globally, yet their additional potential advantages are often overlooked. The integration of shallow-bed CWs and green roofs through wetland roofs could offer both economic and environmental benefits, particularly in developing nations where cost-effective wastewater treatment solutions are crucial. Once challenges such as gravitational loads, selection of bed materials, odor control, management of infectious organisms, and biomass harvesting are addressed, wetland roofs could emerge as a promising secondary wastewater treatment technology. Furthermore, their adaptability to climate change and alignment with the development strategies of green cities enhance their potential significance.

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Chapter 3
Design and Performance Assessment of Subsurface Constructed Wetlands for Pollutant Removal

Saurabh SINGH

1. Introduction

In this chapter, my focus will be on the design and performance assessment of CWs for pollutant removal. I will discuss the constraints of using wetlands, their advantages, and how we can overcome their disadvantages through wetland implementation. The structure of today's presentation comprises six parts: (1) Introduction to CWs and the customized design of Horizontal Flow Constructed Wetlands (HFCWs) focusing on organic removal, (2) Optimization of nitrogen and phosphorus removal in wastewater deficient in organics using HFCWs, (3) Optimization of HFCWs design through Machine Learning, (4) Metagenomics analysis of NIH Roorkee HFCWs, (5) Optimization of filler media depth in HFCWs to maximize removal rate coefficients of targeted pollutant(s), and (6) Importance of Deep HFCWs. Firstly, we will take a look at CWs, which replicate natural wetland processes and offer cost-effectiveness and ease of operation. However, a major drawback or limitation is the substantial land area required, which limits their widespread adoption. In my country, India, there are currently no guidelines for constructing wetlands, making it essential for our research group to work towards providing design and performance assessment guidelines. Wetlands play a crucial role in pollutant removal, both kinetically and dynamically. The advantages of using wetlands include their capability, particularly when constructed as deep and HFCWs, to facilitate improved pathways for antibiotic removal, and nutrient removal, anaerobic conditions for sulfate reduction, as well as reduced land area requirements. These systems represent energy-sustainable solutions. CWs can be categorized into three types: traditional, hybrid, and enhanced (as shown in Figure 1).

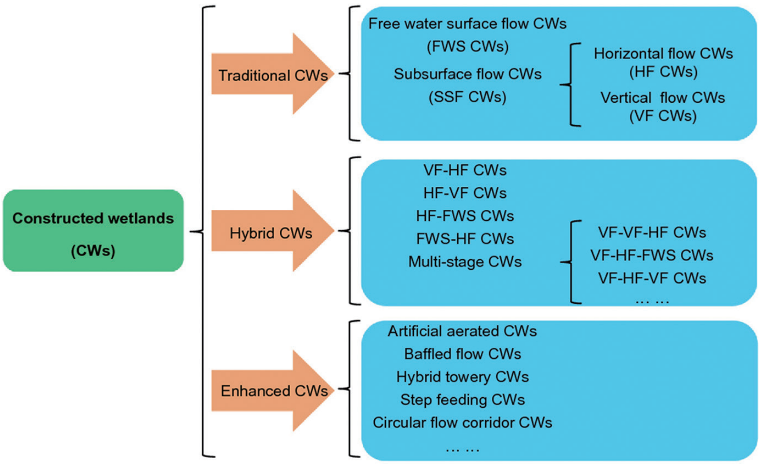

Figure 1: CWs classification.
Source: Wu et al. 2015

Traditional CWs can be categorized into subsurface and surface systems. In this chapter, we will specifically focus on subsurface HFCWs and VFCWs. These subsurface systems are designed to treat wastewater by promoting the removal of various pollutants through natural biological processes. Subsurface CWs are particularly effective in removing organic material, suspended solids, and nitrogen. The primary mechanisms involved include autotrophic denitrification and nitrification. Autotrophic denitrification is a process where bacteria convert nitrogen compounds into nitrogen gas under low oxygen conditions, effectively reducing nitrogen levels in the water. Nitrification, on the other hand, involves the conversion of ammonia into nitrate by aerobic bacteria, which is then followed by denitrification. The advantage of subsurface systems lies in their ability to maintain a more controlled environment for microbial activity, which enhances the efficiency of these biological processes. The water flows horizontally or vertically through a porous medium, such as gravel or sand, where microorganisms colonize and form biofilms. These biofilms play a crucial role in breaking down pollutants.

Currently, significant research is focused on optimizing CWs for not only nitrogen removal but also for phosphorus and pathogen removal. Phosphorus is a critical nutrient that can cause eutrophication in water bodies, leading to excessive growth of algae and deterioration of water quality. Pathogen removal is essential for ensuring that treated water is safe for discharge or reuse. Studies are exploring various configurations and operational strategies to enhance the removal of these contaminants, making CWs more versatile and effective in different environmental conditions. By understanding and improving the design and operation of subsurface HFCWs and VFCWs, researchers aim to develop more efficient and sustainable wastewater treatment solutions that can be widely adopted to address various water pollution challenges.

(1) Problems Associated with HFCWs

In a previous study conducted by Rampuria et al. (2020; 2021), deep CWs were assessed for treating both domestic and hospital sewage over an extended period. These systems were primarily designed to meet organic removal requirements specified in Indian standards. The study found a linear relationship between biological oxygen demand (BOD) removal and loading rates of Aakanksha, with linearity observed up to very high loading rates (as shown in Figure 2). Additionally, it was observed that the existing CWs fell well below the curve's flattening point (Figure 2), indicating highly underloaded systems in terms of organic loading (Soti et al. 2024). This highlighted an opportunity to address a major drawback of such systems, namely the area requirement.

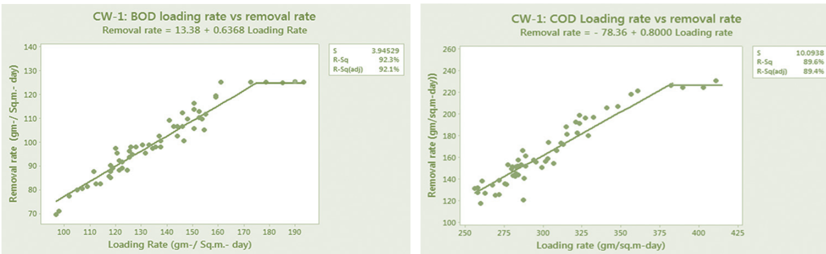

Figure 2: BOD and COD loading rate and removal rate.
Source: Rampuria et al. 2020

As shown in Figure 2, in the first curve, the x-axis represents the loading rate, which is the areal loading rate, and the y-axis represents the removal rate. As the loading rate increases up to a certain level, the removal rate also increases. However, beyond a certain point, increasing the loading rate in terms of organic loading does not result in a proportional increase in the removal rate. Instead, the removal rate reaches a plateau. This indicates that the system has reached an optimum condition, where further increases in the loading rate do not significantly improve system efficiency.

To find the maximum removal efficiency of the system, we increased the loading rates. We utilized the P-k-C* approach to customize the design of CWs and minimize area requirements. The areal loading rate coefficient values were calculated using the P-k-C* approach as shown in the equation as follows:

$$k = \frac{PQi}{A}\left[\left(\frac{Ci - C*}{Co - C*}\right)^{\frac{1}{P}} - 1\right] \qquad \text{(Eq1)}$$

where Co, Ci, and C* (mg/L) are outlet, inlet concentration, and background concentration, respectively. k (m/d) is the first-order areal rate coefficient. P represents apparent number of tanks in series (TIS) dimensionless, Qi (m^3/d) is influent flow rate.

First-order areal removal rate coefficient (K, m/d) at any temperature (T°) was calculated by:

$$k_{T^\circ} = k_{20^\circ}(1.047)^{(T^\circ - 20^\circ)} \qquad \text{(Eq2)}$$

Essentially, in Equation 1, we observed that the area of the CWs depends on the first removal rate coefficient. Therefore, higher values of k, which represent the first removal rate coefficient and indicate the degradability of organics, result in higher removal efficiencies of the system. We will discuss removal rates for BOD, TN, TK, and TP.

(2) Customized Design of HFCWs Based on Removal of Organics

In this study, our primary objective was to reduce the area required for the CWs. Initially, we aimed to achieve this by optimizing the k-values. We collected data and assessed the k-values using the P-k-C* approach and the plug flow equation, subsequently optimizing them. Then, we classified the CWs based on the organic loading rate (OLR), temperature, and depth, as these parameters vary according to the k-values in different geographical conditions. Next, we conducted area calculations using the P-k-C* approach, aiming to determine judicious land use for CWs. The optimization approach is described in Figure 3.

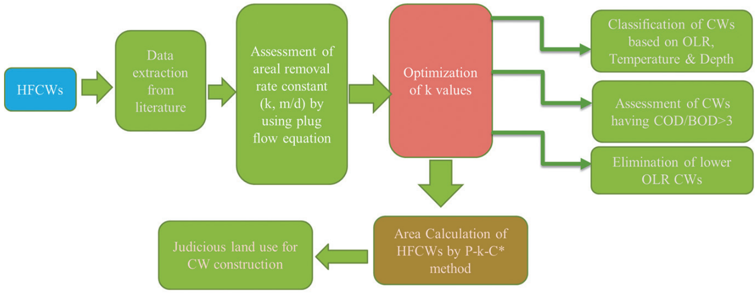

Figure 3: Optimization approach.
Source: Singh et al. 2022a

We calculated the k-values based on organic loading rate, temperature, and depth, categorizing loading into low organic, medium organic, and high organic systems (Figure 4). As depicted in Figure 4A, the higher the loading rate, the higher the organic loading rate, and consequently, the higher the k-values. This indicates that the removal of organics is more efficient under conditions of higher removal rates. We evaluated 111 VFCWs and HFCWs and found that most wetlands are underloaded, as the actual area of the wetland exceeds the calculated area using the P-k-C*approach. These systems can enhance removal efficiency by increasing the depth of the media or increasing the loading rate.

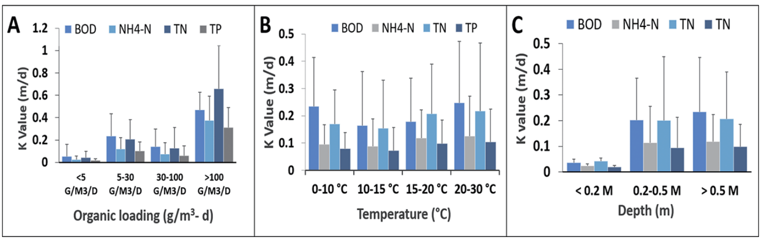

Figure 4: Variation in $K_{20^\circ C}$ values at different OLRs (A), temperatures (B), and depths (C) computed using the Plug flow equation.
Source: Singh et al. 2022a

Similarly, we have determined the k-values through area calculation (refer to Figure 5). Negative values indicate that the systems are underloaded, while positive values indicate overloaded systems. Therefore, efficiency is highest in normally loaded or overloaded systems.

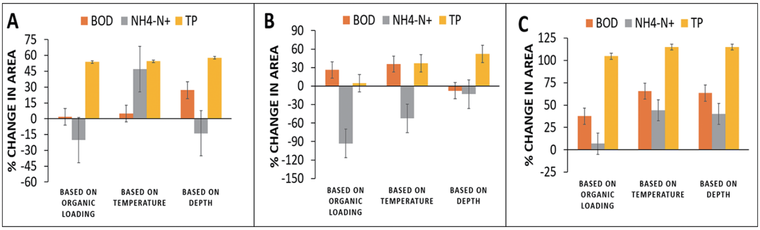

Figure 5: The area percentage error bars in column plots of BOD removal using Plug flow equation for (A) Lab-scale, (B) Pilot-scale, and Full-scale HFCWs.
Source: Singh et al. 2022a

This study concludes that the k-values, calculated based on the P-k-C* equation for different pollutants, exhibited wide variations (ranging from 0.006 to 0.40 m/day), influenced by both environmental factors and operational conditions. The error bars in the column plot highlight the importance of subclassifying the CWs based on loading, environmental conditions (such as temperature), and compliance norms. This subclassification would lead to more meaningful k-values, facilitating customized design approaches. Reducing the standard deviation of the k-value could be achieved by categorizing datasets according to inlet conditions, such as depth and substrate loading rates, for different pollutants. Furthermore, the calculation of HFCWs based on required discharge standards revealed that the actual area of existing CWs exceeds the calculated area, indicating significant underloading of these systems. The areal rate constants derived in this study could provide valuable support for designing HFCWs to optimize land use more effectively, ensuring better pollutant removal and system efficiency.

2. Optimization of Nitrogen and Phosphorous Removal in Wastewater Deficient in Organics of HFCWs

In the first phase, we assessed 74 HFCWs and classified them into higher-loading systems and lower-loading systems. Higher-loading systems showed higher k-values and better removal efficiency, indicating that they are more effective at treating pollutants. Conversely, lower-loaded organic systems can also be beneficial in achieving maximum removal efficiency in HFCWs by optimizing conditions for microbial activity. Deeper wetland systems, in particular, create an anoxic zone in the bottom layer. This anoxic environment is conducive to important biochemical processes such as nitrification and denitrification, which are crucial for nitrogen removal. Additionally, the anoxic conditions support the activity of phosphorus-solubilizing bacteria, which helps in the effective removal of phosphorus. By facilitating these processes, deeper HFCWs can enhance the overall pollutant removal efficiency, making them a valuable option for wastewater treatment.

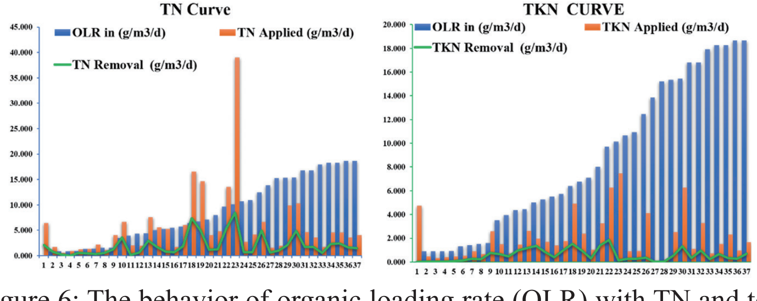

Figure 6: The behavior of organic loading rate (OLR) with TN and total kjeldahl nitrogen (TKN).
Source: Singh et al. 2022a

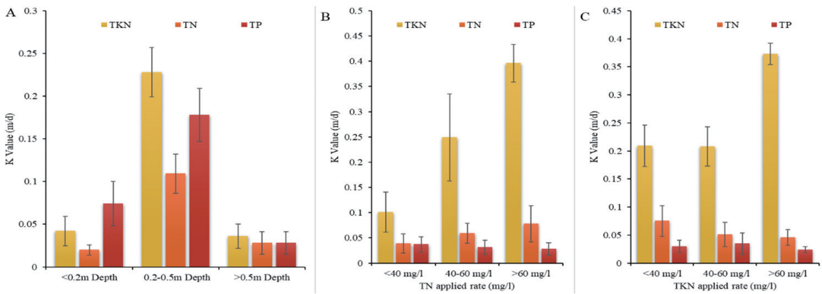

Figure 7: Optimization of k-values through depth classification of HFCWs (A) and optimization curve of k-based on TN (B) and TKN (C) applied rates.
Source: Singh et al. 2022a

Curves were plotted to observe the behavior of biological reactions, as shown in Figure 6. These curves demonstrated that increasing the organic loading rate along the x-axis initially resulted in higher removal efficiency of total nitrogen. However, beyond a certain point, further increases in the organic loading rate did not improve removal efficiency, indicating that the system had reached optimum conditions.

Figure 7 shows the optimization of k-values through depth classification of HFCWs, and the optimization curve of k based on TN and TKN applied rates. It is evident from these curves that the k-values in low-organic systems varied with depth and the applied TN and TKN loading rates. This variation highlights the importance of considering these factors when optimizing HFCWs for maximum removal efficiency.

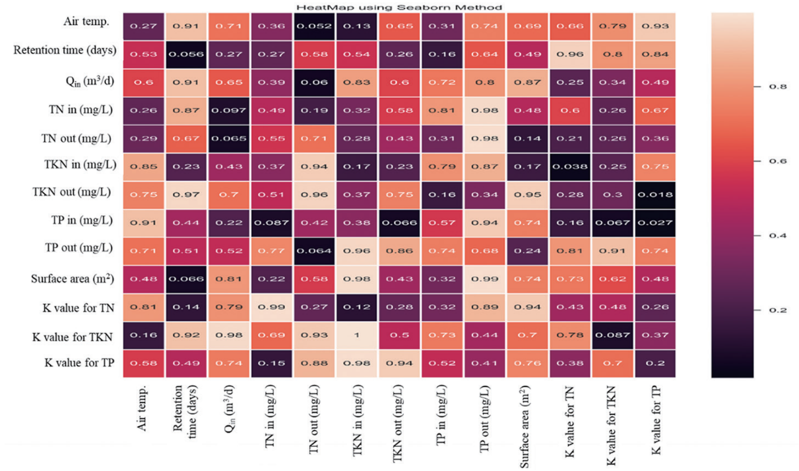

Figure 8: Pairwise correlation Heatmap of influent and effluent parameters.
Source: Singh et al. 2022b

It has been identified that the k-value of the system is not solely dependent on any empirical relationship. Factors such as retention time, discharge, and air temperature significantly influence removal efficiency, with surface area and depth playing crucial roles in maximizing the efficiency of constructed wetlands. Therefore, relying solely on empirical relationships is insufficient to accurately predict wetland removal efficiency. To address this, we applied machine learning techniques. Initially, we utilized 12 parameters to identify and predict k-values using both multi-linear regression and artificial neural networks (ANN) approaches. The correlation between influent and effluent parameters is illustrated in the heatmaps (Figure 8).

Table 1: Comparison between the root mean square error (RMSE) and Standard deviations (SDs) of k-values

Prediction output	P-k-C* Approach		SVR on unseen datasets		RF on unseen datasets		ANN on unseen datasets	
	R^2	SDs	R^2	RMSE	R^2	RMSE	R^2	RMSE
k_{TKN}	0.657	33.80%	0.512	9.70%	0.635	8.70%	0.768	6.70%
k_{TN}	0.711	36.95%	0.6	8.50%	0.701	6.20%	0.835	4.30%
k_{TP}	0.637	34.86%	0.429	16.50%	0.596	13.10%	0.723	8.70%

(SVR: Support vector regression, RF: Random Forest, R2: Coefficient of determination).
Source: Singh et al. 2022b

Table 1 displays the root mean square error (RMSE) and standard deviations (SDs) of k-values. The results indicate that the ANN algorithm achieved a higher R^2 and lower RMSE compared to other methods. Initially, actual k-values were calculated using the P-k-C* approach, resulting in an SD of 33.80%, which was deemed unacceptable. Additionally, the R^2 of these k-values was relatively low. To enhance system efficiency and accuracy, we implemented a machine learning approach. The ANN demonstrated superior performance in terms of accuracy, with errors consistently below 6.7% variation compared to the actual k-values. Figure 9 shows the real data and predicted data of the k-values curve for TKN, TN, and TP by using various machine learning algorithms.

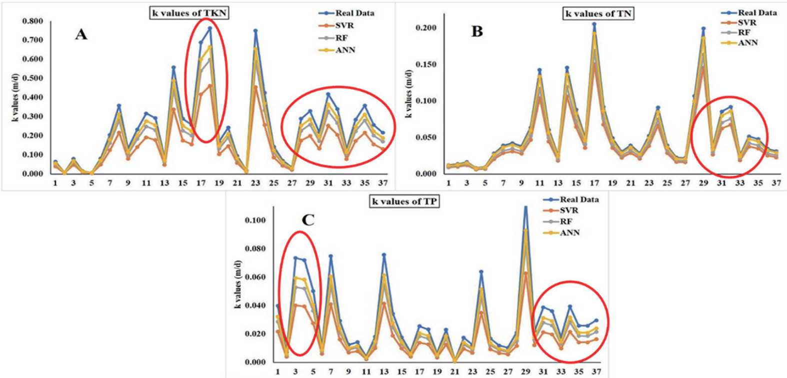

Figure 9: Real data and predicted data of k-values Curve for TKN (A), TN (B), and TP (C).
Source: Singh et al. 2023a

Overall, a strong direct correlation was observed between TN applied (R^2 0.77) and TKN applied (R^2 0.83). The initial large variations (ranging from 0.01 to 0.54 m/day; SD of 83.41%) observed in k-values calculated by the reverse P-k-C* approach could be reduced through dataset classification. Classification based on wetland depth, COD/TN, COD/TKN, TN application rate, and TKN application rate led to a reduction in SD to 30.32%, 38.21%, 39.21%, 34.83%, and 21.98%, respectively. HFCWs with COD/TN and COD/TKN ratios of 12 and 16.6 demonstrated the highest nitrogen removal efficiency of 84.45%. This study contributes to the customized design of HFCWs for TN, TKN, and TP pollutant removal from low-organic wastewater, with minimal area requirements.

3. Optimization of HFCWs design through Machine Learning

This study aims to assist in the design process by analyzing the treatment dynamics of 111 HFCWs using secondary datasets comprising 1232 data points. Essentially, wastewater biological reactions exhibit non-linear behavior, often characterized by exponential variations. Machine learning tools prove highly valuable in identifying fundamental relationships between input variables and k-values, and for understanding these k-values vary in response to input variables. Table 2 shows the R^2 for SVR and multiple linear regression (MLR) algorithm.

Table 2: The R^2 of k-values for the SVR and MLR-based model

Effluents \ R^2	**R^2 of k_1-Values (effluent in mg/l)**		**R^2 of k_2-Values (effluent in ($g/m^3/d$)**	
	MLR	SVR	MLR	SVR
BOD	0.921	0.982	0.911	0.954
COD	0.901	0.968	0.885	0.948
NH_4^+-N	0.782	0.845	0.626	0.782
TN	0.810	0.889	0.722	0.819
TP	0.592	0.612	0.369	0.518

Source: Singh et al. 2023a

Among the two models, SVR resulted in better predictions of all effluent concentrations, measured in mg/L as well as in $g/m^3/d$. The prediction of NH_4^+-N ($g/m^3/d$) and TN ($g/m^3/d$) achieved the highest accuracy, with R^2 and RMSE values of 0.847 and 0.44%, and 0.947 and 0.18%, respectively. The areal removal rate (k, m/d) values computed by the reverse P-k-C* approach, using the predicted effluent concentrations, exhibited high correlation with actual k-values of BOD, COD, and TN, with R^2 values of 0.954, 0.948, and 0.819, respectively. The SVR algorithm demonstrates promising potential for predicting k-values for BOD, COD, and TN with high confidence, thereby aiding in optimizing the design of HFCWs in terms of area requirements for organics and nitrogen removal. This enhanced predictive capability is crucial for developing more efficient and effective CW designs that maximize pollutant removal while minimizing land use.

4. Metagenomics Analysis of NIH Roorkee HFCWs

Building upon previous findings, this study conducted a metagenomics analysis of HFCWs at the National Institute of Hydrology (NIH) in Roorkee, India, referred to as NIH Roorkee HFCWs. At NIH Roorkee, eight cells were constructed in a decreasing order of depth, from 1.5 m in cell 1 to 0.8 m in cell 8. The arrangement and depths of these HFCWs are illustrated in Figure 10.

Figure 10: Diagram of HFCWs (A) and actual site photographs (BandC). Source: Singh et al. 2023b

These studies identified the role of media depth in pollutant removal within HFCWs. The focus was on HFCWs due to their effectiveness in removing nitrogen through denitrification, as well as phosphorus and other nutrients. In these systems, the anaerobic zone at the bottom aids in the removal of these pollutants. Wastewater samples were collected from both deep and shallow cells of the sequential CW for physicochemical analysis. Subsequently, the areal rate coefficients (k) were calculated, followed by metagenomic analysis. Tables 3 and 4 present the performance assessment results of the NIH Roorkee wetlands and the areal removal rate coefficients in HFCWs.

Table 3: Performance assessment results of NIH Roorkee HFCWs

HSSFCW	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8
Temperature (ºC)	24.24	24.04	23.66	23.71	23.17	22.96	22.8	22.64
Surface area (m^2)	35	35	35	35	35	35	35	35
Wetland depth (m)	1.5	1.4	1.3	1.2	1.1	1	0.9	0.8
Volume (m^3)	52.5	49	45.5	42	38.5	35	31.5	28
Sewage inflow (m^3/d)	32	32	32	32	32	32	32	32
BOD_{in} (ppm)	99	47	37	17	14	14	13	11
BOD_{out} (ppm)	29	21	17	14	14	13	11	10
COD_{in} (ppm)	137	61	36	38	25	23	20	16
COD_{out} (ppm)	49	36	28	25	23	20	16	15
NO_3-N_{in} (ppm)	4.1	2.29	1.68	1.53	1.51	1.37	1.42	1.2
NO_3-N_{out} (ppm)	2.29	1.68	1.53	1.51	1.37	1.42	1.2	1.12
TKN_{in} (ppm)	25.8	18	16	15	14.4	13.3	12	11
TKN_{out} (ppm)	18	16	15	14.4	13.3	12	11	8.5
$Phosphate_{in}$ (ppm)	10.23	9.29	9.41	8.41	7.22	6.46	6.21	5.34
$Phosphate_{out}$ (ppm)	9.29	9.41	8.41	7.22	6.46	6.21	5.34	4.78
DO_{in} (ppm)	0.37	0.66	0.8	0.77	0.93	1.21	1.1	1.49
DO_{out} (ppm)	0.66	0.8	0.77	0.93	1.21	1.1	1.49	3.85

Source: Singh et al. 2023b

Table 4: Areal removal rate coefficients in NIH Roorkee HFCWs, CW1 and CW2

Wetland	k_{BOD} (m/d)	k_{TKN} (m/d)	k_{TN} (m/d)	$k_{NH4\text{-}N}$ (m/d)	k_{TP} (m/d)
NIH-CW Cell 1	0.627	0.155	0.166	NA	0.148
NIH-CW Cell 2	0.483	0.051	0.059	NA	0.048
NIH-CW Cell 3	0.522	0.028	0.028	NA	0.026
NIH-CW Cell 4	0.208	0.018	0.016	NA	0.016
NIH-CW Cell 5	0.000	0.033	0.034	NA	0.031
NIH-CW Cell 6	0.099	0.043	0.037	NA	0.04
NIH-CW Cell 7	0.339	0.036	0.04	NA	0.033
NIH-CW Cell 8	0.476	0.109	0.099	NA	0.097
CW1 (2.2m)	0.35	0.27	0.21	0.15	NA
CW2 (2.51m)	0.41	0.25	0.16	0.13	NA

(NA: not available).
Source: Singh et al. 2023b

We calculated the k-values and observed that the k-values of the Cell 1 system are notably high, given the system's depth of 1.5 m. As the depth of the media decreases, the k-values also decrease accordingly. Our findings suggested that increasing the depth of media enhances pollutant removal efficiency, but only up to a certain level (1.5 m in Cell 1). We also conducted a similar study on wastewater field-scale HFCWs for treating residential wastewater (CW1) and hospital wastewater (CW2) to compare with NIH Roorkee HFCWs. The depth of these wetlands was 2.2 m and 2.51 m, respectively. The k-values of NIH Roorkee, CW1, and CW2 are presented in Table 4. The results indicated that the organic loading rates (OLR) for Cell 1, CW1, and CW2 fall within the range of 30-100 g/m^3/d. The customized k_{BOD} value for this OLR was 0.395 ± 27.74%. Therefore, the k_{BOD} value for the experimental data exceeded the range of customized k-values according to the organic loading classification. This could be attributed to the considerably greater depth of the experimental wetlands (1.5 m, 2.2 m, and 2.51 m) compared to the wetlands data available in the literature used for customization. In deep wetlands, there is a possibility of developing anoxic zones at the bottom, which could aid both denitrification and anammox processes. The former process would facilitate BOD removal (Rampuria et al. 2020). OLR values for Cell 2 to Cell 8 lie within the range of 5–30 g/m^3/d. The k-values for this OLR were 0.268 ± 29.11%. Consequently, the k_{BOD} value for experimental data falls within the range of customized k-values according to the organic loading classification (Singh et al. 2022a). The k_{TN} and k_{TP} values for all cells fall within the range of customized k-values according to their organic loading classification (Singh et al. 2022a).

In the metagenomics analysis, we conducted 16S rRNA amplicon sequencing on samples collected from the inlet and outlet of both deep and shallow cells. The genera present in the three samples are shown in Figure 11A. The bacterial diversity was found to be significantly different among the samples. The bacterial diversity was considerably reduced from 164 species at the inlet to 76 species at the outlet, and there were 114 species in the deep-cell wetlands. The inlet sample had 59 unique genera, while the deep cell and shallow cell consisted of 11 and 7 unique genera, respectively. The reduction in bacterial diversity during the CW treatment indicates the selective nature of the system. In addition, in the phylum level analysis (Figure 11B), we also identified Bacteroidetes, Firmicutes, and Proteobacteria, which play crucial roles in nutrient removal.

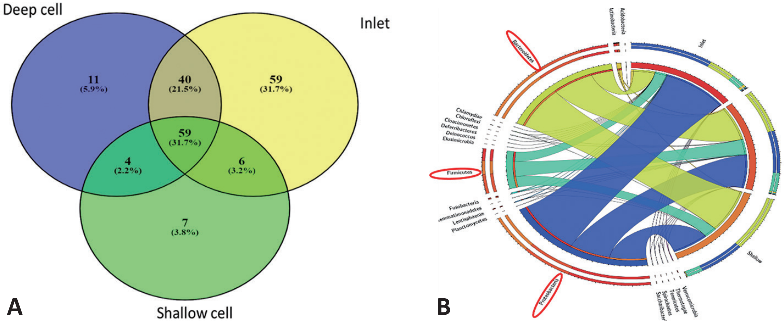

Figure 11: (A) Venn diagram of the genera present in the three samples, (B) Phylum level identification. Source: Singh et al. 2023b

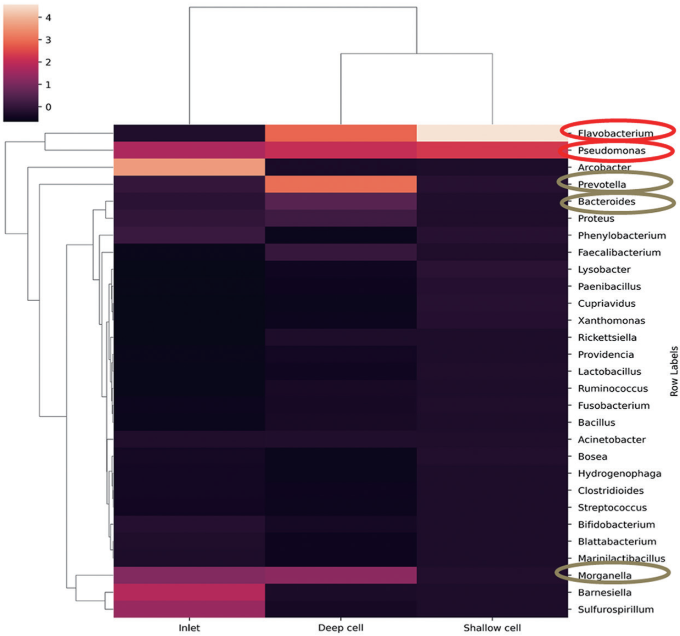

Figure 12: Relationship between the inlet and outlet samples in both deep and shallow cells at the Genus level. Source: Singh et al. 2023b

Figure 12 depicts the relationship between three samples at the genus level. The inlet sample appears relatively distantly related to the deep and shallow cell samples in terms of the relative abundance of different bacterial genera observed. *Pseudomonas*, *Flavobacterium*, *Prevotella*, *Morganella*, and *Bacteroidetes* are present in deep systems. The functions of these genes are beneficial for heterotrophic nitrification, anaerobic denitrification, and phosphate accumulation. *Flavobacterium* contributes to aerobic denitrification, while *Prevotella* genes aid in anaerobic generation, which helps reduce phosphorus solubilizing bacteria (PSB). *Morganella* is found in both environments, often associated with animals and exhibiting high antibiotic resistance. *Bacteroidetes* are responsible for the catabolism of complex carbohydrates. Deep cells exhibit a significant presence of *Bacteroidetes*, correlating with better removal efficiency compared to shallow cells.

Overall, full-scale HFCWs utilizing sequential shallower depths was found to efficiently remove organics and nutrients. The areal removal rate coefficients of different cells in this system were higher for organics and within the expected range for nitrogen and phosphate, compared to the optimized removal rate coefficients calculated using secondary data. Metagenomic analysis supports the removal of organics and nutrients, as indicated by the presence of specific bacterial genera. The abundance of heterotrophic nitrifiers, aerobic denitrifiers and phosphate-accumulating bacteria demonstrates the effectiveness of such deep HFCW systems for combined organics and nutrient removal.

5. Optimization of Depth of Filler Media in HFCWs for Maximizing Removal Rate Coefficients of Targeted Pollutant(s)

In this study, the optimal depths for the removal of various organic compounds were identified. To determine the depth of media required for maximum removal rate coefficients, curves were plotted to show the relationship between increasing media depth and k-values using 111 secondary data points from HFCWs (as presented in Figure 13).

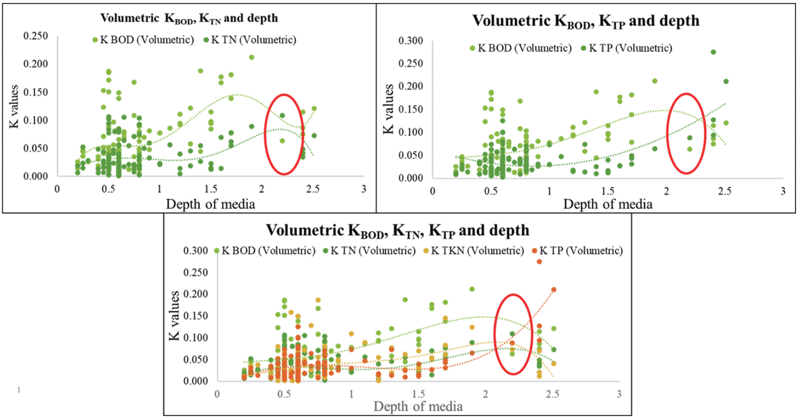

Figure 13: The optimum depth of media for the removal of combinations of pollutants.
Source: Singh et al. 2024

Observations indicated that as the media depth increases up to a certain level, typically around 2 m or 2.2 m, the k-values reach their maximum, with the peak occurring at 2 m. Beyond this depth, the k-values start to decrease. This suggests that for effective removal of both BOD and TN from wastewater, the ideal depth of the wetland should be around 2 m. Similarly, we found a common depth point for BOD, TN, and TP removal. If we aim to remove BOD, TN, and TP simultaneously, the depth should be 2.2 m. For exclusive BOD removal, the depth should be 1.6 m.

The optimal depths for BOD, TN, TKN, and TP pollutants are found to be 1.6 m, 2.2 m, 1.9 m, and 2.4 m, respectively, when the correlation curve is plotted between volumetric loading rate (k, 1/ day) and depth of media. This data was validated using Grey Wolf Optimization (GWO) in MATLAB software, which was run 1,000 times to determine the maximum depth for removing BOD and TN. Initially, GWO analysis was employed within MATLAB software. Subsequently, a novel equation was developed for predicting the depth of BOD and TN removal in terms of k, as k is a critical parameter for determining the maximum k-values to optimize the removal rate coefficients.

The equations of correlation were obtained using the curve as shown in equations (i) to (iv).

$$f(x) = (depth)_{BOD} = 0.203k_{\mathrm{BOD}}^4 + 0.114k_{\mathrm{BOD}}^3 - 0.095k_{\mathrm{BOD}}^2 + 0.101k_{\mathrm{BOD}} + 0.073 \quad \text{(i)}$$

$$f(x) = (depth)_{TN} = 0.081k_{\mathrm{TN}}^4 + 0.354k_{\mathrm{TN}}^3 - 0.041k_{\mathrm{TN}}^2 + 0.193k_{\mathrm{TN}} - 0.022 \quad \text{(ii)}$$

$$f(x) = (depth)_{TKN} = -0.042k_{\mathrm{TKN}}^4 + 0.195k_{\mathrm{TKN}}^3 + 0.297k_{\mathrm{TKN}}^2 + 0.156k_{\mathrm{TKN}} - 0.018 \quad \text{(iii)}$$

$$f(x) = (depth)_{TP} = 0.013k_{\mathrm{TP}}^4 + 0.038k_{\mathrm{TP}}^3 - 0.108k_{\mathrm{TP}}^2 + 0.159k + 0.088 \quad \text{(iv)}$$

After that, these equations were further used to run simulations in MATLAB software 1,000 times, and then we derived an equation to find the optimum depth for pollutant removal using GWO. The equation of depth of media was forecasted using the removal rate coefficients for nutrient removal by MLR model as shown in equation (v).

$$f(x) = \mathrm{Depth} = -0.8216(k_{\mathrm{BOD}}) + 6.170\,(k_{\mathrm{TN}}) - 2.011(k_{\mathrm{TKN}}) + 0.927(k_{\mathrm{TP}}) + 0.952 \quad \text{(v)}$$

The computed optimal depths were 1.48 m and 1.71 m for TKN removal, 1.91 m for TN removal, and 2.14 m for TP removal.

With an in-depth explanation using the correlation curve, it was observed that BOD increased with the increasing depth of media up to 1.6 m. This phenomenon occurs due to substrate and oxygen limitations for heterotrophic denitrification. Similarly, concerning the removal of TN, the depth of media increased up to 2.2 m, where the removal efficiency peaked at 2 m, and after 2.2 m, the rate did not increase further. This could be attributed to the generation of an anoxic zone in the deep stretches of the wetland, which may favor heterotrophic denitrification and anammox processes. Regarding PSB, an anaerobic bottom zone in deep wetlands may provide favorable conditions for their activity. PSBs play a vital role in solubilizing inorganic and organic insoluble phosphorus to form soluble phosphorus, which can then be assimilated by other phosphate-accumulating bacteria.

Metagenomic analysis provided further insights. The removal of organic matter in HFCWs primarily occurs in aerobic zones, where heterotrophic bacteria play a dominant role, typically up to a depth of 1.48 m. For TKN removal, the ideal depth of media is around 1.7 m. This removal process involves heterotrophic bacteria facilitating hydrolysis, alongside aerobic nitrifying microorganisms. However, increasing the depth of the media beyond approximately 1.908 m leads to the formation of an anoxic zone due to dissolved oxygen depletion. Within this anoxic zone, heterotrophic denitrification and anammox processes become predominant pathways, facilitating complete nitrogen removal in the form of nitrogen gas. Likewise, at greater depths, such as 2.14 m, anaerobic conditions may develop, potentially harboring phosphorus-accumulating organisms and phosphorus-solubilizing bacteria. This environment contributes to phosphorus removal within the CWs. Thus, understanding the interplay between media depth and microbial activity is crucial for optimizing pollutant removal in constructed wetlands.

6. Importance of Deep HFCWs

The deep HFCWs offer significant advantages over VFCWs, including reduced space requirements and enhanced removal of nitrogen, phosphorus, and sulfur compounds. This system features anaerobic zones at the bottom layer, facilitating efficient removal of phosphorus and nitrogen within the wetland. Additionally, deep-CWs exhibit a more pronounced redox gradient. The pollutant removal pathways in deep-CWs are summarized in Figure 14.

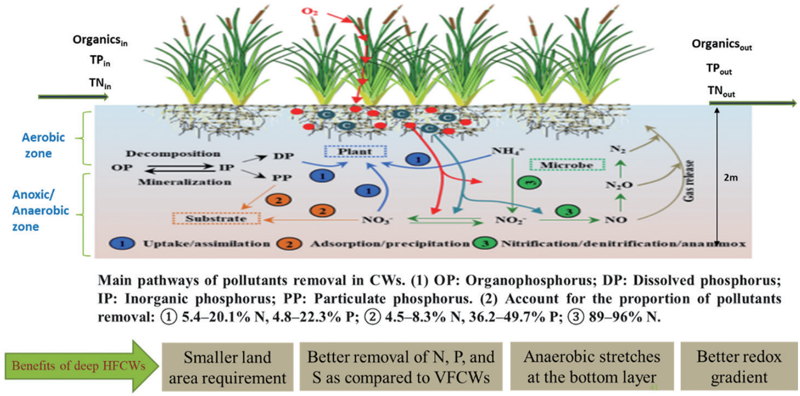

Figure 14: Pollutant removal pathways in deep-CWs.
Source: Soti et al. 2022; 2023

In general, the calculation of HFCWs based on required discharge standards reveals that the actual area of existing CWs exceeds the calculated area, indicating that HFCWs are significantly underloaded systems. The areal rate constants derived in this work may provide excellent design support for efficient land use planning. Deep-CWs reduce land requirements and offer effective organic removal efficiencies, along with improved nitrogen removal. Deep wetlands provide an optimal environment for the in situ growth and coexistence of diverse microbial populations, supporting contaminant and nitrogen removal, particularly anammox bacteria (Rampuria et al. 2021). Over a 20-year period, HFCWs demonstrate superior life cycle costs compared to VFCWs for pollutant removal.

Table 5. Comparison of k20 for BOD, TKN, TN and TP in different types of CWs

Field scale HFCWs	Type of wastewater	k_{BOD}	k_{TKN}	k_{TN}	k_{TP}
Shallow 0.5m MNIT HFCW	Primary	0.345	0.086	0.103	0.080
Shallow 0.8m NIH HFCW	Primary	0.476	0.099	0.109	0.089
Deep 1.5m NIH HFCW	Primary	0.627	0.166	0.155	0.072
Deep 2.51m Rajnish Hospital HFCWs	Primary	0.361	0.157	0.122	0.097
Shallow 0.85m VFCW	Secondary	0.183	0.152	0.120	0.148
Deep 2m Vishakhapatanam VFCW	Primary	0.314	0.220	0.140	0.088

Source: Author

Table 5 provides a comparative analysis of various field-scale VFCWs and HFCWs, detailing their depths, types of wastewater treated, and removal rate coefficients (k-values) for BOD, TKN, TN, and TP. The Shallow 0.5m MNIT HFCW, used for primary wastewater treatment, shows moderate removal efficiencies with k-values of 0.345 for BOD, 0.086 for TKN, 0.103 for TN, and 0.080 for TP. This system's moderate depth limits its capacity for nitrogen and phosphorus removal compared to deeper systems. In comparison, the Shallow 0.8m NIH HFCW, also used for primary treatment, exhibits higher removal rates with k-values of 0.476 for BOD, 0.099 for TKN, 0.109 for TN, and 0.089 for TP. The slight increase in depth enhances its efficiency in removing organic and nitrogenous compounds. The Deep 1.5m NIH HFCW, another primary treatment system, demonstrates the highest removal efficiencies for BOD (0.627), TKN (0.166), and TN (0.155), although its TP removal (0.072) is slightly lower compared to other systems. The greater depth allows for more effective denitrification and organic matter breakdown, but phosphorus removal remains less efficient. Meanwhile, the Deep 2.51m Rajnish Hospital HFCWs, treating primary wastewater from a hospital, show balanced removal efficiencies with k-values of 0.361 for BOD, 0.157 for TKN, 0.122 for TN, and 0.097 for TP. While effective, this system does not outperform the 1.5m NIH HFCW for BOD and TN removal, possibly due to the complex nature of hospital wastewater.

In the case of secondary treatment, the Shallow 0.85m VFCW demonstrates lower k-values for BOD (0.183) but shows comparable efficiencies for TKN (0.152), TN (0.120), and higher TP removal (0.148). This suggests that VFCWs, even at shallower depths, can be quite effective for nutrient removal when treating secondary effluent. Lastly, the Deep 2m Vishakhapatnam VFCW used for primary treatment presents k-values of 0.314 for BOD, 0.220 for TKN, 0.140 for TN, and 0.088 for TP, indicating effective removal rates, particularly for TKN. This depth allows for the development of anoxic zones conducive to nitrogen removal processes.

These observations highlight the impact of depth and type of wastewater on the pollutant removal efficiencies of constructed wetlands. Deeper systems generally offer better performance for nitrogen removal due to enhanced denitrification conditions, while the type of wastewater influences the efficiency of BOD and TP removal. This information is crucial for designing and optimizing HFCWs and VFCWs for specific wastewater treatment needs.

7. Conclusion

This study presents a comprehensive analysis of various field-scale HFCWs and VFCWs. Shallow HFCWs, such as the 0.5m MNIT HFCW, show moderate removal efficiencies, which improve with a slight increase in depth, as seen in the 0.8m NIH HFCW. Deeper HFCWs, like the 1.5m NIH HFCW, achieve the highest removal efficiencies for

BOD, TKN, and TN, although TP removal is slightly lower compared to shallower systems. This indicates that deeper wetlands enhance the removal of organic and nitrogen compounds due to the development of anoxic zones that favor denitrification and other nutrient removal processes. The 2.51m Rajnish Hospital HFCWs demonstrate balanced removal efficiencies, supporting effective nitrogen and phosphorus removal due to prolonged contact time and enhanced microbial activity. Secondary treatment VFCWs, such as the 0.85m VFCW, show lower BOD removal but are effective for TKN, TN, and particularly TP removal, likely due to aerobic conditions promoting phosphorus-accumulating organisms. The 2m Vishakhapatnam VFCW, used for primary treatment, shows effective removal rates, especially for TKN, with its depth creating a gradient of aerobic to anaerobic conditions, optimizing various pollutant removal processes. These observations underscore the importance of designing constructed wetlands with appropriate depths to maximize their treatment efficiency for different types of wastewater. Deeper systems generally provide better removal efficiencies for nitrogen compounds due to anoxic conditions, while phosphorus removal effectiveness varies depending on specific bacterial presence and treatment phase. This study contributes to the development of effective designs, helping to avoid the creation of under-loaded CWs, thereby conserving land areas. These findings offer valuable insights into customizing CW design and configuration to notably improve nutrient removal efficiency in both domestic and industrial wastewater treatment contexts. Additionally, the study provides optimization strategies tailored specifically for constructing wetlands within the Indian context. Notably, it emphasizes the advantages of deeper wetlands, which can facilitate in situ growth, minimize land requirements, and achieve superior removal efficiencies.

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Chapter 4
Towards Multifaceted Mitigation of Climate Change Impacts: Ensuring Sustainable Treatment Solutions with Constructed Wetlands

Nehreen MAJED

1. Background

This work begins by providing a comprehensive background overview. Afterwards, the discussion revolves around the role of CWs in climate change mitigation and their significance in sustainable treatment solutions. Following that, a further description and overview of the endeavors carried out in Bangladesh are presented. Finally, the challenges, opportunities, and future directions in this field are addressed. In the beginning, let us remind ourselves with the quote from Mahatma Gandhi: "The Earth does not belong to us; we belong to the Earth. It is our duty to protect and preserve this fragile planet for future generations." This encapsulates the essence of sustainable development.

The insufficient availability of clean water has become a pressing concern impacting human health in various countries globally, particularly in South Asia. Rapid urbanization and industrialization in South Asia have exacerbated water pollution issues, with alarming statistics revealing the extent of surface water contamination. According to the World Bank (2019), approximately 75% of surface water in Bangladesh is polluted, posing significant threats to public health and livelihoods. Costly and resource-intensive technologies have been proven ineffective in addressing the intricate water challenges arising from urbanization in these regions. Moreover, wastewater treatment plants produce substantial amounts of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), exacerbating climate change. Hence, there is a necessity for affordable, low-maintenance, and eco-friendly wastewater treatment solutions. CWs have emerged as a natural and efficient remedy for wastewater treatment.

As highlighted in previous presentations, CWs offer numerous environmental benefits by mimicking natural ecosystems. They provide a sustainable solution for wastewater treatment that can help mitigate climate change impacts globally, with particular relevance to South Asian countries facing unique environmental and socio-economic challenges. Integrating CWs into water management strategies can contribute to both climate change mitigation and adaptation efforts in the region. According to the United Nations Environment Programme (UNEP), wetlands can sequester up to 20 times more carbon per unit area compared to other terrestrial ecosystems. The biological carbon sequestration in wetlands is depicted in Figure 1.

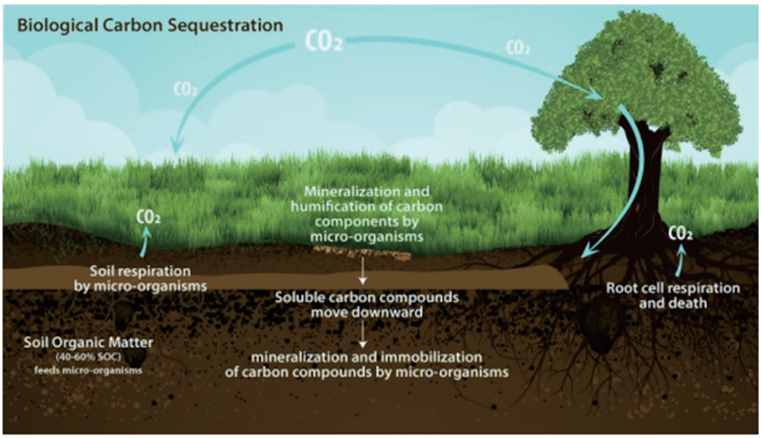

Figure 1: Carbon sequestration in wetlands. Source: calrecycle.ca.gov

Moreover, these wetlands offer invaluable solutions for managing flood control and stormwater, crucial for countries in South Asia vulnerable to climate-related disasters like floods and cyclones. The region experiences severe flooding during monsoon seasons, leading to extensive damage and disruption to millions of lives, as witnessed in Bangladesh in 2020, where over 5 million people were affected, resulting in substantial economic losses (The Guardian 2017). Figure 2 shows the potential applications of wetlands in urban areas.

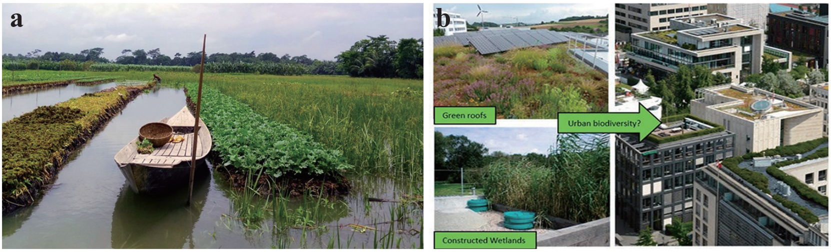

Figure 2: a) The remarkable floating gardens of Bangladesh, b) CWs as Eco-technologies in urban areas. Source: Author

In addition to their water purification functions, CWs play a pivotal role in conserving biodiversity by providing habitats for diverse plant and animal species, thus bolstering ecological resilience across South Asian countries. Research by Kadlec and Wallace (2009) underscored the importance of wetlands in supporting a wide array of species, contributing significantly to biodiversity conservation efforts.

Successful case studies from countries like India, Bangladesh, and Sri Lanka illustrate the potential of CWs in addressing water pollution, mitigating flood risks, and conserving biodiversity. For instance, in Chennai, India, the implementation of CWs for decentralized wastewater treatment has led to notable improvements in water quality and a reduction in pollution levels in surrounding water bodies, as documented by the United Nations Environment Programme (Obaideen et al. 2022). Thus, we need to focus our concerns and prioritize integration towards environmental protection. Global-level knowledge sharing and collaboration among researchers, policymakers, and communities are indispensable for amplifying the adoption of sustainable treatment solutions involving CWs, particularly in South Asian countries.

2. The Role of CWs in Climate Change Mitigation and Sustainable Treatment Solutions

(1) The Role of CWs in Climate Change Mitigation

Climate change impacts, such as increased water pollution and reduced water availability, can be effectively addressed by CWs. CWs play a crucial role in enhancing water quality by effectively removing pollutants such as nitrogen, phosphorus, heavy metals, and antibiotics from water bodies, thereby addressing the pressing challenges of water pollution. Mitsch and Gosselink (2015) have shown that CWs can achieve remarkable removal rates, with the potential to eliminate up to 90% of nitrogen and 70% of phosphorus from wastewater, thereby significantly enhancing water quality standards. Additionally, they play a significant role in water conservation efforts by promoting groundwater recharge and reducing water demand for irrigation (Vymazal 2013).

CWs offer a nature-based approach to mitigate the hazards linked to rising sea levels and escalating coastal erosion. Acting as natural barriers, wetlands serve as buffers against storm surges and tidal waves, safeguarding coastal regions (Gedan et al. 2011). Mangrove wetlands, in particular, play a crucial role in stabilizing coastlines and defending against erosion (Donato et al. 2011). CWs bolster resilience against extreme weather occurrences like floods and cyclones by enhancing water management and mitigating flood risks. Serving as natural flood buffers, they absorb surplus water during intense rainfall events. Moreover, they can be engineered as floodwater storage zones, curbing downstream flooding and shielding susceptible communities (Kadlec and Wallace 2009).

Wetlands can sequester significant amounts of carbon through the accumulation of organic matter in their soils and biomass. The anaerobic conditions found in wetland soils slow down the decomposition process, allowing organic matter to accumulate over time. According to the Ramsar Convention on Wetlands, which is an international treaty for the conservation and sustainable use of wetlands, wetlands cover only around 6% of the Earth's land surface but are estimated to store around 35% of global terrestrial carbon. Mitsch et al. (2012) also estimated that wetlands can sequester 50–100 g of carbon per square meter per year. This underscores the importance of wetlands in global carbon cycling and climate change mitigation efforts.

Furthermore, the incorporation of CWs into urban planning and landscape architecture yields numerous advantages, notably in climate change mitigation. CWs play a role in carbon sequestration, aiding in the reduction of greenhouse gas emissions. Additionally, CWs foster biodiversity conservation, providing habitats for diverse plant and animal species, thus fortifying ecosystem resilience.

(2) Sustainable Treatment Solutions with CWs

1) Water Treatment Benefits of CWs

CWs have demonstrated a remarkable ability to enhance water quality. A study conducted by Kadlec and Wallace in 2009 indicated that CWs removed up to 90% of nitrogen and 70% of phosphorus from wastewater, contributing to improved water quality. Another study conducted in South India demonstrated that a CW system effectively reduced the concentration of heavy metals, including copper and zinc, by up to 90% (Kumar et al. 2021). The natural processes within CWs, such as microbial degradation and plant uptake, play a vital role in pollutant removal (Vymazal 2013).

2) Climate Change Resilience Benefits of CWs

Wetlands act as natural buffers against rising sea levels and storm surges, protecting coastal communities and habitats from erosion and inundation. Each hectare of wetland can store an estimated 1.5 million liters of floodwater, helping to reduce the risk of downstream flooding (Ramsar Convention 2018). CWs have been shown to reduce downstream flooding by 20–30%, providing critical flood control during extreme rainfall events (Obaideen et al. 2022). The presence of wetlands in coastal areas can also dissipate wave energy, reducing the impact of coastal erosion (Gedan et al. 2011).

3) Economic Benefits of CWs

CWs have demonstrated cost-effectiveness compared to conventional treatment methods, with potential savings of up to 50% in capital and operational costs (Bui et al. 2018). For instance, a case study in China found that the revenue generated from ecotourism activities in a constructed wetland area amounted to approximately USD 35,000 per year (Li et al. 2020). In addition to cost savings, CWs can generate economic benefits through ecotourism and recreational activities, contributing to local economies (Li et al. 2020).

4) Social Benefits of CWs

CWs enhance biodiversity, providing habitats for various plant and animal species, and promoting ecological education and environmental awareness. Each square meter of wetland can support a diverse range of species, contributing to the conservation of local flora and fauna (Mitsch and Gosselink 2015). Wetlands can be integrated into urban landscapes, providing aesthetic and recreational spaces for communities to enjoy and connect with nature (Gedan et al. 2011).

5) Implementation Considerations for South Asian Countries

CWs can support fossil fuel divestment efforts by addressing environmental challenges associated with fossil fuel extraction and consumption, promoting sustainable land use practices, and raising awareness about the need for a transition to renewable energy sources and a low-carbon economy. South Asian countries, such as Bangladesh, with high population density and limited land availability, can benefit from the compact nature of vertical flow CWs for wastewater treatment (Bui et al. 2018). Additionally, CWs can complement and support the broader movement for climate justice, environmental sustainability, and youth empowerment. Engaging local communities and stakeholders in the planning and management of constructed wetlands is essential for ensuring their acceptance, success, and long-term sustainability (Obaideen et al. 2022). Furthermore, CWs can offer multifaceted benefits for commercial-scale plants, supporting their wastewater treatment needs, regulatory compliance efforts, environmental sustainability goals, and economic objectives. Customizing the design and operation of constructed wetlands to suit local conditions, including climate, water quality challenges, and available resources, is crucial for optimal performance and maximum benefits (Mitsch and Gosselink 2015).

3. Endeavors for a Sustainable Future through CWs in Bangladesh

In this section, I would like to delve into some studies conducted primarily by our research group. Our endeavors are directed toward shaping a sustainable future through the application of CWs for wastewater treatment.

(1) Biggest Floating CW System in Bangladesh

Firstly, I want to introduce a large-scale floating CW system in Bangladesh which was installed by our research team. This is a research project between University of Asia Pacific (UAP) and the Water Supply and Sewerage Authority (WASA) to improve water quality in the Dhaka-Narayanganj-Demra (DND) canal by employing floating constructed wetlands. We installed a significantly large-sized floating CW system in Bangladesh. The project aimed to minimize the treatment costs associated with the secondary treatment phase, thereby alleviating the burden before the wastewater flows into further treatment processes. In the project the estimated volume of treated water per day was nearly 50 m^3. Figure 3 shows the pilot application of the floating CW. However, it has not gone into large-scale operation yet.

Figure 3: The biggest floating CW system in Bangladesh. Source: Author

(2) Wastewater Treatment with Surface Flow CWs

Next, I will focus on the treatment solutions published by the research group at UAP already. The treatment for removing pollutants was accomplished using two CW systems (Saeed et al. 2019). The diagram of surface flow CWs is shown in Figure 4.

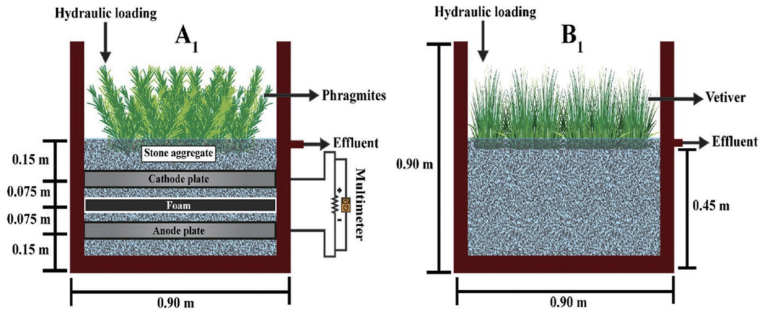

Figure 4: Schematic diagram of surface flow wetland arrangement.
Source: Saeed et al. 2019

In this experiment, two pilot-scale CWs were used employing two types of plants, namely Phragmites reeds and Vetiver grass, in both vertical and horizontal configurations. The CW systems were operated under constant and shock hydraulic load periods. The COD, nitrogen, and phosphorus input loadings varied 61–2181, 7–1040, and 2–194 $g/m^2/d$, respectively. After the treatment, the removal efficiency for COD, nitrogen, and phosphorus was, respectively, 39–97%, 20–100%, and 16–86% in the first stage. In the second stage, these values were 11–83%, 4–85%, and 1.4–100%, respectively. The plant accumulation for nitrogen was ≤7%, and for phosphorus, it was ≤14%.

(3) Wastewater Treatment with VFCWs

Another experiment conducted by the UAP research group investigated the removal of organic matter, nitrogen, and phosphorus by using VFCW configurations (Saeed et al. 2019). The diagram of the experimental setup is depicted in Figure 5.

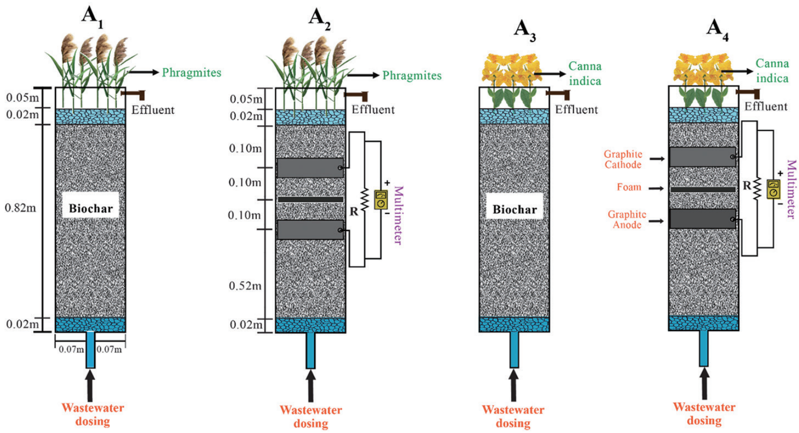

Figure 5: Schematic diagram of vertical flow wetland arrangement.
Source: Saeed et al. 2019

Phragmites and *Canna indica* were used as wetland plants in this research. The filter media used with different layers are shown in Figure 5. In the initial stage of VFCWs, the input loadings of nitrogen, phosphorus, and COD were 48–145, 1–7, and 56–191 g/m^2/d, respectively. The results showed that the decreased removal of organic matter in VF wetlands was attributed to the presence of recalcitrant compounds from the synthetic recipe. Furthermore, the adsorption of NH_4-N and carbon leaching properties of biochar stimulated nitrogen removal (ranged from 19–102 g/m^2/d) in partially saturated VFCWs. The removal percentages for biochemical oxygen demand, chemical oxygen demand, nitrogen, phosphorus, solids, and coliform from the drained wastewater were 96%, 99%, 89%, 99%, 98%, and 97%, respectively, across all systems. Partially wetland systems achieved removal rates exceeding 90% for biochemical oxygen demand, over 97% for nitrogen, and complete (100%) removal of phosphorus.

(4) Removal of Heavy Metals

Now, I am going to discuss the aspect of heavy metal removal, as demonstrated in the publication by Saeed et al. (2021). This study investigated the removal of four heavy metals — zinc (Zn), chromium (Cr), nickel (Ni), and lead (Pb) — from landfill leachate using two hybrid subsurface flow CW systems. The diagram of the experimental setup is presented in Figure 6.

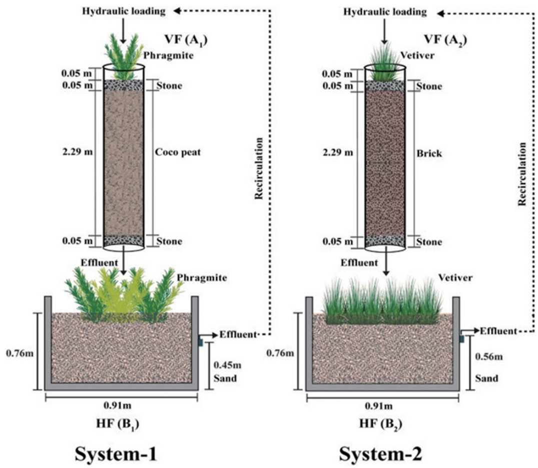

Figure 6: The diagram of pilot-scale hybrid CWs. Source: Saeed et al. 2021

Each system consisted of a vertical flow followed by a horizontal flow wetland. The wetland systems were filled with either organic materials (coco-peat) or construction materials (brick, sand), and planted with either *Phragmites australis* or *Chrysopogon zizanioides* (Vetiver). Both systems were operated with and without effluent recirculation protocols. The concentrations of Cr, Ni, and Pb accumulated on Phragmites were, respectively, 2–73, 3–12, and 0–27 mg/kg. In Vetiver, these concentrations were 8–34, 3–15, and 0–14 mg/kg, respectively. In vertical flow CWs, the presence of organic carbon and iron in coco-peat and brick substrates facilitated the removal of metals. However, this accumulation was not measured in sand-based HFCWs. The removal rates of heavy metals throughout the experiment are shown in Figure 7. In general, heavy metals can be removed effectively in the two-hybrid wetlands, representing 20–97%, 95–99%, 55–73%, and 69–83% for Zn, Cr, Ni, and Pb, respectively. During the effluent recirculation phase, the removal percentages of Zn, Cr, Ni, and Pb increased to varying degrees in vertical flow CWs, ranging from 75% to 98%, 29% to 41%, 14% to 48%, and 23% to 26%, respectively, compared to their removal without recirculation. In the recirculation phase, a decrease in heavy metal removal was observed in HFCWs.

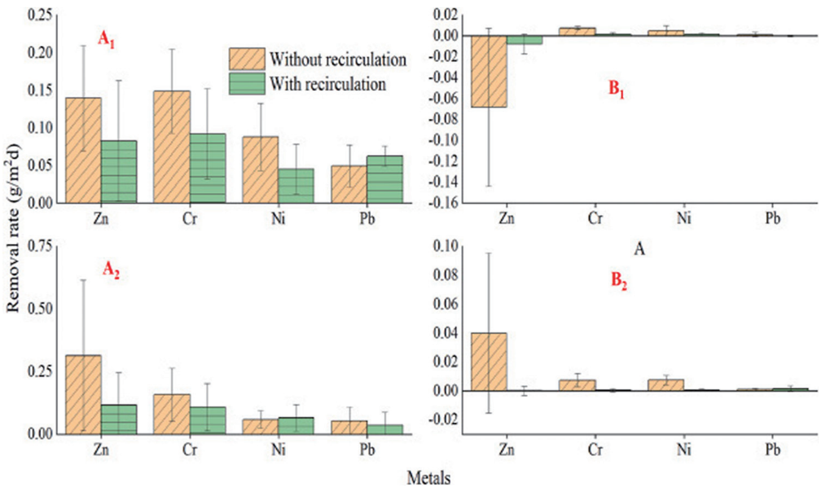

Figure 7: The average rates of metal removal in hybrid-CWs.
Source: Saeed et al. 2021

(5) Leachate Treatment

Leachate treatment represents a significant achievement accomplished by CWs. Leachate, the liquid that drains from landfills, often contains high concentrations of pollutants and contaminants, posing a considerable challenge for management. Table 1 presents the primary pollutant concentrations found in landfill leachate used in this study.

Table 1: The average composition of the leachate wastewater, with standard deviation values provided in parentheses

Parameters	**Unit**	**Concentration**
pH		6.9 (0.5)
Eh	mV	91.2 (107.0)
TKN	mg/L	186.6 (132.3)
NH_4-N		103.5 (80.0)
NO_2-N		0.7 (0.7)
NO_3-N		12.6 (11.3)
TN		201 (131.3)
TP		51.5 (36.0)
BOD		241.5 (149.0)
COD		1481 (693.0)

(Eh: Redox potential, TKN: Total Kjeldahl-Nitrogen, NH_4-N: Ammonium-nitrogen, NO_2-N: Nitrite-nitrogen, NO_3-N: Nitrate-nitrogen, TN: Total nitrogen, TP: Total phosphorus, BOD: Biochemical oxygen demand, COD: Chemical oxygen demand)

This study discovered that landfill leachate can be effectively treated by tidal flow CWs. The removal percentages for chemical oxygen demand, total nitrogen, total phosphorus, and coliform ranged from 96% to 99%, 82% to 93%, 91% to 98%, and 86% to 96%, respectively. These results remained consistent throughout the experimental period. The nitrogen and phosphorus accumulation percentages in wetland plant tissues were low, representing 0.4–2.2% and 0.04–0.8%, respectively. Additionally, the CW systems also provided power generation. During the continuous aeration period, the electrode-integrated tidal flow CWs achieved higher power density production, ranging between 859 and 1432 mW/m^3.

(6) Bioenergy Production

Constructed wetlands (CWs) can serve as multifunctional systems, simultaneously providing wastewater treatment and generating bioenergy. Implementing bioenergy production in CWs offers several advantages, including utilizing renewable resources, mitigating greenhouse gas emissions from waste treatment, and potentially offsetting energy costs associated with wetland maintenance. This accomplishment is also a highlight of our research group's work. The findings of this study were published in a highly respected journal, *Science of the Total Environment*, Asia Pacific (UAP), by a research group led by Professor Saeed (Saeed et al. 2022). In this study, four hybrid CW systems comprising vertical flow (VF) followed by horizontal flow (HF) configurations were utilized, with or without vegetation. Among them, two systems integrated planted electrodes into microbial fuel cells (MFCs). Figures 8 and 9 illustrate the microbial fuel cell wetland and the hybrid CW systems.

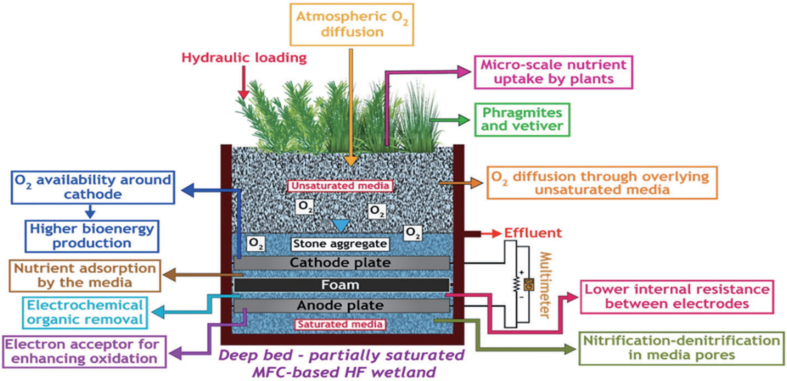

Figure 8: Microbial fuel cell wetland. Source: Author

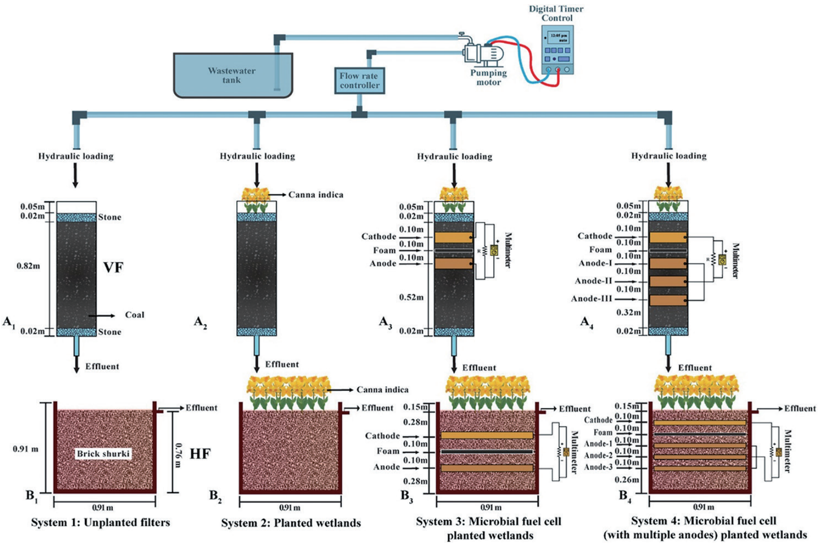

Figure 9: Operational arrangement of the CW systems.
Source: Saeed et al. 2022

The average initial pollutant concentrations of the real wastewater used in this experiment are shown in Table 1. The hybrid systems operated in a free-draining mode. After 33 weeks of operation, the hybrid CWs exhibited high removal efficiency for biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, and phosphorus, achieving percentages of 90%, 92%, 88%, and 89%, respectively, across all systems. Additionally, solid and coliform removal rates were 98% and 97%, respectively. The electrodes-integrated CWs demonstrated a 27% higher organic removal and a 14% higher nitrogen removal compared to those without electrode integration. The higher pollutant removal efficiency was observed in microbial fuel cell (MFC)-based CWs with vertical flow. This may be attributed to the contribution of dissolved oxygen from the atmosphere and oxygen released from the root zone. The physicochemical properties of the filter media also facilitated both biotic and abiotic mechanisms for organic matter and nutrient removal. During the second phase, the efficiency of organic matter and nutrient removal in HF-CWs decreased due to higher input loading and substrate saturation. The increased input loading rate in phases II and III also resulted in a decrease in bioenergy production across MFC-based hybrid CWs (as shown in Figure 10).

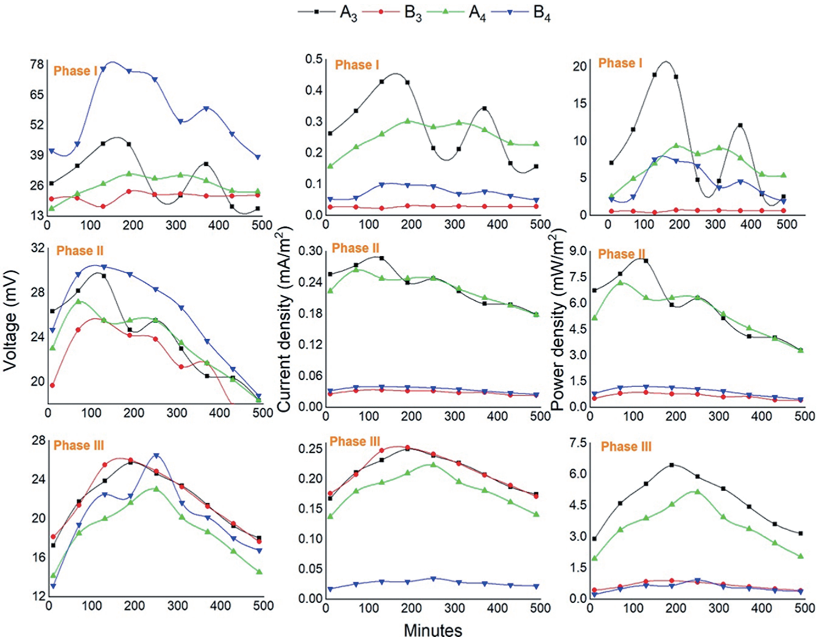

Figure 10: Profiles of bioelectricity generation during the experimental period. Source: Saeed et al. 2022

Activation, ohmic, and concentration losses affected the bioenergy generation in MFC-integrated wetlands. A maximum power density production rate of 60 mW/m^2 was recorded. The highest power density production was observed in phase I, reaching 294 mW/m^2 in the VF wetland with a single anode electrode, and 192 mV in the HF system (B4) with multiple anode electrodes.

(7) Mitigating the Challenges of Industrial Growth and Climate Change Impacts in Developing Countries

An important study that our group has accomplished specifically investigated the role of CWs in addressing the challenges posed by industrial growth and the impacts of climate change in developing countries (Islam et al. 2022). This study aimed to provide a comprehensive overview of various practices, uses, and research on CW systems for removing pollutants from wastewater in developing countries, placing them in the context of climate change, environmental resource planning, and sustainable wastewater treatment systems. Table 2 provides a summary of the operational features and treatment effectiveness of hybrid CW systems in several Asian countries, such as China, Nepal, Bangladesh, Indonesia, Turkey, and Thailand.

Table 2: Characteristics of hybrid CW systems used in several Asian countries

	Type of wastewater	**Treatment performance**						**Plant species**	**HLR**
		TSS	BOD_5	COD	NH_4-N	TN	TP		
China									$0.58 m^3/m^2/d$
Eff (mg/L)	Lake water	12.3	5.9	5.4	4.3	6.3	0.1		
RE (%)		99.1	77	67.4	52.8	99	77		
Nepal									$20 m^3/d$
Eff (mg/L)	Hospital wastewater	2.8	3.3	20.2	1.61	NA	4.2	*Phragmites karka*	
RE (%)		97.3	97	93.8	95.1	NA	46.6		
China									0.25m/d
Eff (mg/L)	Municipal wastewater	NA	59.9	22.5	0.4	1.5	NA	*Thpha orientalis*	
RE (%)		NA	62.8		80.7	51	NA		
Bangladesh									
Eff (mg/L)	Industrial wastewater	12.3	5.9	5.5	4.3	6.4	0.1	*Phragmites*	
RE (%)		99.1	77	67.4	52.8	99	77		
Nepal									0.13m/d
Eff (mg/L)	Municipal wastewater	37.8	173.3	319	45	NA	17.1	*Phragmites karka*	
RE (%)		97.5	89.1	89.1	68.3	NA	29.9		
Indonesia									$31 m^3/d$
Eff (mg/L)	Laboratory wastewater	15	4.75	5.32	3.1	2.1	1.6	*Phragmites*	
RE (%)		68.8	77.86	87.3	74.3	75	39.3		
Turkey								*Iris australis*	$60 L/m^2/d$
Eff (mg/L)	Municipal wastewater	NA	NA	NA	3.2	0.3	4.5	*Phragmites australis*	
RE (%)		NA	NA	NA	91.2	89	91.3		

Thailand									400
Eff (mg/L)	Municipal wastewater	16	25	NA	NA	33	4.5	*Canna, Heliconia Papyrus*	
RE (%)		90	91.5	8	NA	39	46.4		

(NA: Not available, Eff: Effluent, RE: Removal efficiency).

Source: Islam et al. 2022

Among the eight hybrid CW systems examined, four were designed for treating municipal sewage, while others targeted various types of wastewater such as lake water, and hospital and laboratory wastewater. These hybrid systems demonstrated impressive contaminant removal efficiencies, achieving up to 93.82% for total suspended solids, 85.65% for chemical oxygen demand, and 80.11% for ammonia nitrogen, which were comparable to or better than other viable alternatives. Regarding BOD removal, hybrid-constructed wetlands showed the highest elimination rate (84.06%) compared to free water surface CWs (65.34%), horizontal sub-surface CWs (75.1%), and floating treatment wetlands (55.29%). The removal efficiency for phosphorus and nitrogen was moderate, representing 54.75% and 66.88%, respectively. Their removal rates depended on factors such as system design, HLR, and plant species.

Table 3: The use of MFC-based CWs for electricity production in some countries

Country	**Wastewater flow**	**Volume (L)**	**Electrode**	**Initial COD (mg/L) and (% removal)**	**Electricity**
India	Vertical flow	5.4	Anode–Graphite Plate	1500 (74.8)	15.7 mW/m^2
India	Vertical flow	1.8	Anode–Granular, and Activated Carbon	770–887 (90.9)	43.63 mW/m^3
China	Vertical flow	1.5	Cathode–Granular Graphite, and Activated Carbon	500 (80)	87.79 mW/m^2

China	Vertical flow	12.5	Cathode–Granular Activated Carbon	205 (95)	12.42 mW/m^2
Malaysia	Vertical up flow		Cathode–Activated Carbon	625 (99)	93 mW/m^3
Bangladesh	Vertical flow		Anode–Powder, and Cathode–Granular Graphite	559.5 (79)	86 mW/m^2

Source: Islam et al. 2022

Table 4: A comparison of biofuel ecosystem production

Item	Bioenergy production (GJ/ha/yr.)	CO_2 sequestration	GHG emission
CWs	1836	31	28.8
Land grassland	88.8	4	0.3
Switchgrass	199.1	16.2	0.4
Corn	158.1	NA	0.7
Soybean	45.8	NA	0.7
WTP	NA	17.1	592.2

(NA: not available).

Source: Islam et al. 2022

Tables 3 and 4 present data regarding the results of a comparative assessment of studies employing CW-MFCs for electricity generation and a comparison of biofuel ecosystem production, respectively. In general, the MFC-based CWs showed high COD removal rates (74.8–99.0%), achieving a maximum power density generation of 86 mW/m^2 in Bangladesh and 93 mW/m^3 in China using vertical flow. Additionally, CWs showed the highest bioenergy production with 1836 GJ/hectare/year. Each year, WTPs produce approximately a hundred times more GHGs than CWs. In Nepal, a CW system was installed at Dhulikhel Hospital to treat hospital wastewater over five years, with a volume of 500,000 m^3 of treated wastewater. This system did not require any electric energy due to hydro-mechanical feeding into the beds. It was approximated that utilizing the CWs rather than a wastewater treatment plant could potentially result in savings of around USD 50,000.

In the present era of urbanization, the widespread installation of wastewater treatment plants can result in a considerable expansion of land use for upstream activities, exacerbating pressure on water resources and available land. Moreover, these technologies typically demand high energy and consistent maintenance. Thus, implementing CWs can alleviate these challenges. It was estimated that for every 1 m^3 of wastewater treated, the CW occupies 0.05 m^2 less space compared to the centralized water treatment system. Figure 11 illustrates the potential for land conservation and the per capita land savings for each province in 2017, under the assumption of replacing urban WTPs with CWs in China.

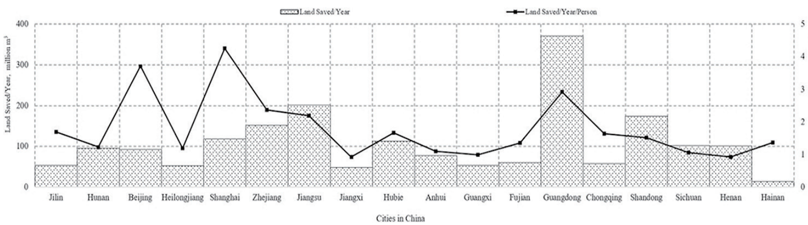

Figure 11: The amount of land saved annually, both in total and per person, by employing CWs in China. Source: Islam et al. 2022

(8) Life Cycle Analysis

Another study by our group (Alam et al. 2023) accomplished the life cycle analysis of various configurations of CWs and how the configurations influence CWs through the utilization of different media sources. We used five configurations of CW applications from previous studies (as shown in Figure 12) with different filter media including coco-peat, biochar, sand, gravel, sugarcane bagasse, cement mortar, brick chips, and scraped metals. The characteristics of five CWs and the quality of influent and effluent are presented in Table 5, while their diagrams are presented in Figure 12. This study employed life cycle assessment (LCA) through SimaPro software to measure the environmental effects of constructed wetland systems.

Table 5: Characteristics of the constructed wetland system and influent/effluent composition

	Unit	S1	S2	S3	S4	S5
System Characteristics						
Flowrate	L/d	38	4	4	4	6
Plants		*Phragmites australis*	*Phragmites australis*	*Cannaindica*	*Cannaindica*	*Phragmites australis*
Hydraulic retention time	D	12.5	32.8	27.9	27.9	28.3
No. of vertical CW cells		2	2	1	1	1
Vertical cell dimensions	m (H × D)	0.73 × 0.91	1.5 × 0.15	1.53 × 0.15	1.53 × 0.15	2.13 × 0.15
No. of horizontal CW cells		1	1	1	1	1
Horizontal cell dimensions	m (H × L × W)	0.78 × 1.32 × 1.01	0.5 × 1.22 × 0.61	0.92 × 0.90 × 0.30	0.92 × 0.90 × 0.30	0.91 × 1.22 × 0.61
Influent quality						
BOD	mg/L	4200 (43.5)	131.5 (3.4)	215 (6.1)	215 (5.5)	96.4 (4.5)
COD	mg/L	11500 (410.2)	420.3 (13.3)	1098 (32.5)	1098 (21.4)	171.5 (10.5)
TN	mg/L	100.3 (5.4)	31.3 (1.9)	17.3 (1.5)	17.3 (1.4)	59.3 (3.5)
TP	mg/L	30 (2.1)	2,3 (0.2)	4.6 (0.12)	4.6 (0.2)	14.1 (0.4)
Effluent quality						
BOD	mg/L	80 (3.5)	8.8 (1.5)	28.4 (3.5)	56.2 (4.8)	3.7 (0.5)
COD	mg/L	200 (5.1)	45.2 (3.9)	184 (4.2)	362.9 (8.2)	22.2 (1.5)
TN	mg/L	49.8 (5.2)	3.1 (0.15)	3.4 (0.2)	5.6 (0.3)	2.4 (0.2)
TP	mg/L	3 (0.25)	0	0.5 (0.05)	1.6 (0.01)	0.5 (0.01)

Standard deviations are enclosed in parentheses.

Source: Alam et al. 2023

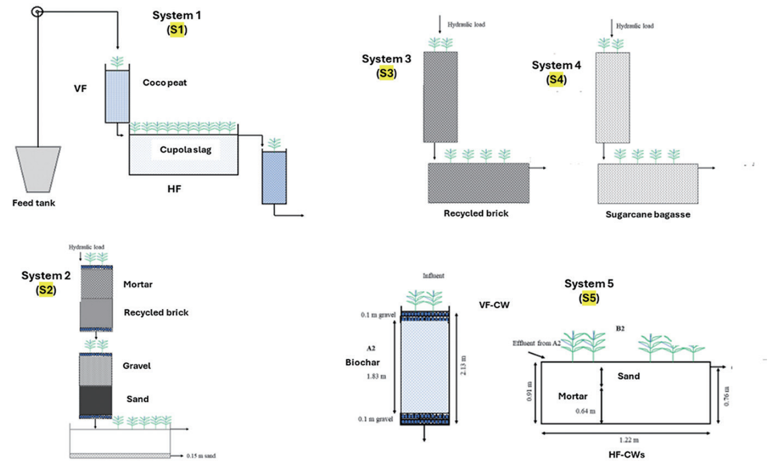

Figure 12: Diagrams of five CW systems. Source: Author

The findings indicate that all five CWs effectively remove organic matter and nutrients. The influence of the media materials used in CWs on global warming, fossil resource scarcity, terrestrial, and freshwater ecotoxicity categories is illustrated in Figure 13.

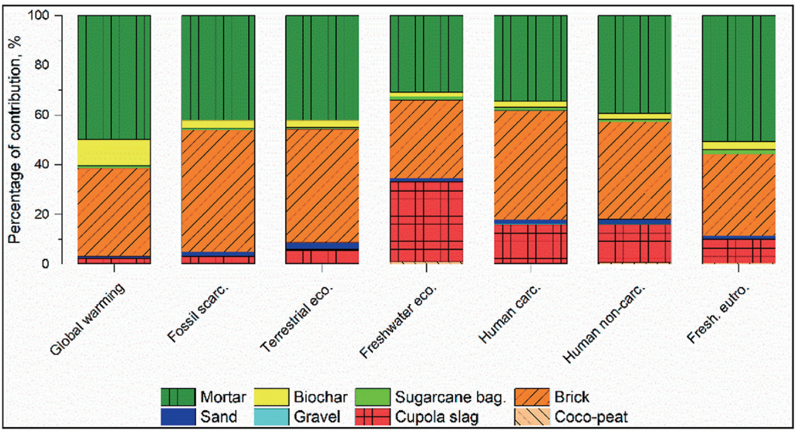

Figure 13: Comparative assessment of the impact of media materials throughout their life cycles on selected categories. Source: Alam et al. 2023

Among the CW systems studied, those utilizing cement mortar exhibited the highest environmental impact. Conversely, natural media options such as sugarcane bagasse and coco-peat have shown to be environmentally advantageous. Using recycled materials like brick and steel slag in media could significantly mitigate the previous environmental burdens associated with these materials, while also enhancing treatment efficiency. Overall, the assessments indicated that careful selection of media materials is crucial to ensure the sustainability of CWs. CWs demonstrate greater advantages and environmental friendliness compared to other treatment methods, particularly when designed at large scales.

4. Challenges and Opportunities

While CWs offer numerous advantages, their widespread implementation still encounters several challenges. One such obstacle is the limited availability of suitable land for CW construction, especially in densely populated urban areas. In regions like South Asia, such as Bangladesh, where population density is high, finding adequate space for CWs is particularly challenging (Byomkesh et al. 2009). Another challenge lies in the lack of awareness and understanding of the benefits and operations of CWs among policymakers, communities, and stakeholders. A survey conducted in India revealed that only 28% of respondents were aware of CWs as a wastewater treatment solution (Kumar and Dutta 2018). Furthermore, inadequate funding and financial resources pose significant barriers to the design, implementation, and maintenance of CW projects. A study conducted in Sri Lanka emphasized the financial constraints encountered in implementing CWs, with limited funding available for long-term maintenance and operation (Pathirana and Manatunge 2022). Moreover, climate change-induced alterations in precipitation patterns and extreme weather events may affect the performance and efficacy of CWs. Reports from the Intergovernmental Panel on Climate Change (IPCC) suggest an increase in the frequency and intensity of extreme weather events, such as heavy rainfall and droughts, which could disrupt the hydrological balance of CWs (IPCC 2021).

However, CWs also present numerous opportunities, such as their integration into urban planning and development strategies for sustainable water management. According to Kumar et al. (2022), incorporating CWs into urban development can offer cost-effective solutions for wastewater treatment and water resource management, thereby supporting sustainable urban growth. Furthermore, collaboration and partnerships among government agencies, local communities, researchers, and non-governmental organizations (NGOs) can promote the adoption and implementation of CWs. An example of successful collaboration is seen in Bangladesh, where the Municipality of Dhaka partnered with NGOs to implement CWs for wastewater treatment, demonstrating the potential of multi-stakeholder partnerships (Bui et al. 2018). Additionally, harnessing the potential of nature-based solutions, such as CWs, can contribute to achieving multiple Sustainable Development Goals (SDGs). CWs contribute to SDGs related to clean water and sanitation (SDG 6), climate action (SDG 13), and life on land (SDG 15), offering opportunities for integrated and holistic approaches to address various challenges. Incorporating CWs into climate change adaptation and mitigation strategies at national and regional levels is also important. The South Asian region, in particular, can benefit from including CWs in climate change adaptation plans, as they can help reduce the vulnerability of coastal areas to sea-level rise and provide natural infrastructure for flood management (Ramsar Convention 2018).

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Chapter 5
Constructed Wetlands Planted with Iris for Mine Drainage Treatment: Effects of Domestic Wastewater Feeding on the Removal of Multiple Heavy Metals

Thi Thuong NGUYEN

1. Introduction

In my presentation, I would like to introduce a case study on the utilization of constructed wetlands (CWs) for the removal of heavy metals from acid mine drainage (AMD) in Japan. First, I will provide a brief overview of the mining and metal pollution situation in Japanese mines. Japan boasts a rich mining heritage, having once been a premier global metal producer, contributing significantly to its wealth generation. However, this has also had negative impacts on the environment and human health. One of the prominent health risks associated with mining operations is the Itai-Itai disease, caused by exposure to cadmium (Cd). It is regarded as one of the top four pollution-related diseases in Japan. Since the 1970s, factors such as mineral reserve depletion, rising labor expenses, the liberalization of mineral resource imports, and environmental concerns have resulted in the closure or abandonment of the majority of mines in Japan. Nonetheless, the ongoing presence of mine drainage containing elevated levels of heavy metals, sulfates, and acidic pH remains a considerable hazard to both the ecosystem and human well-being. Presently, mine wastewater pollution is documented at 450 of the 7,000 nationwide. Among these, about 100 sites exhibit elevated levels of toxic heavy metals necessitating treatment before discharge (Nguyen et al. 2021; Ueda and Masuda 2005). The pH and ratio of metal concentrations to the effluent standards in Japan from 2014 to 2016 are presented in Figure 1.

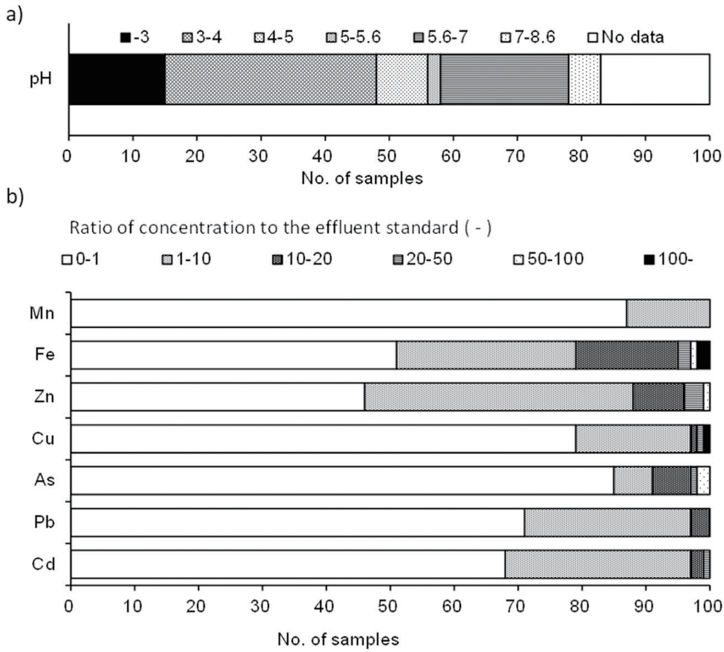

Figure 1: The average characteristics of 100 mine drainages in Japan, 2014–2016. (a) pH, and (b) ratio of metal level to the effluent standard (Cd 0.03 mg/L, Pb 0.1 mg/L, As 0.1 mg/L, Cu 3 mg/L, Zn 2 mg/L, Fe 10 mg/L, and Mn 10 mg/L). Source: Soda and Nguyen 2023.

In efforts to safeguard the environment and human health from mine wastewater pollution, the Japanese government annually allocates a substantial budget amounting to billions of yen for treatment purposes. Various physicochemical techniques such as precipitation, flocculation, and neutralization have been utilized for mine wastewater treatment. However, these methods often require high costs in maintenance, operation, and secondary waste management (Nguyen et al. 2022). Therefore, prioritizing the development of cost-effective and environmentally friendly technologies is crucial to minimize the treatment burden and ensure sustainable mine wastewater treatment practices. CWs present a promising passive solution for mine drainage treatment due to their simplicity in operation and maintenance, and cost-effectiveness. Metals removal in CWs primarily results from the collaborative interaction of three elements: plants, substrates, and microorganisms.

In our previous study (Nguyen et al. 2022), we found that CWs filled with limestone and planted with cattails exhibited a remarkable ability to remove heavy metals from AMD. The presence of sulfate-reducing bacteria (SRB) suggested metal removal occurred through sulfide precipitation. However, the contribution of SRB to metal removal was limited due to the low concentration of nutrients and carbon sources required for SRB activities. Hence, stimulating SRB activity by supplementing external carbon sources is feasible for sustainable AMD treatment. Domestic wastewater (DW) contains organic substances and nutrients that can serve as external carbon inputs to enhance bacterial activity. Additionally, these nutrients can greatly stimulate the growth of plants in constructed wetlands. Careful selection of plant species for CWs is crucial to attain optimal metal removal efficiency. Furthermore, integrating ornamental plants into wetlands is encouraged due to the potential for economic and social advantages, such as improved landscaping and decreased environmental pressure. Iris species, commonly grown for ornamental purposes in many countries, exhibit metal absorption capabilities, robust tolerance, and visual appeal. Nevertheless, there remains insufficient data on their efficacy in treating AMD.

In that context, in this study, we designed lab-scale CWs employed with iris (*Iris pseudacorus*) for AMD treatment. DW was introduced into AMD to stimulate the bioprocesses. The primary aims of the present study are to assess how effectively CWs remove heavy metals from AMD mixed with DW, and to examine the effectiveness of utilizing an ornamental flowering plant (iris) as a wetland plant for removing heavy metals from AMD.

2. Methodology

(1) Synthetic Wastewater

AMD and DW used in this study were prepared based on the annual average chemical composition of real mine drainage in Kyoto and domestic wastewater in Shiga Prefecture, Japan, respectively. The heavy metal concentrations of stimulated AMD were 0.07 mg/L for cadmium (Cd), 0.22 mg/L for copper (Cu), 37.2 mg/L for iron (Fe), 0.89 mg/L for manganese (Mn), 0.09 mg/L for lead (Pb), and 7.61 mg/L for zinc (Zn). While DW contained 32.0 mg/L of total organic carbon (TOC), 10.1 mg/L of total nitrogen (TN), and 1.75 mg/L of total phosphorus (TP).

(2) Setup and Operation of CWs

We conducted this experiment at the greenhouse on the BKC campus of Ritsumeikan University, Japan. Each CW system was filled with limestone and loamy soil and covered with aluminum foil to prevent light from penetrating the substrate. Cattails and irises were utilized as wetland plants. Cattail, a typical wetland plant, was employed for comparison with iris in heavy metal removal. Systems with cattails and irises were referred to as CW-cattail and CW-iris, respectively. Additionally, a control system (referred to as CW-UP) without plants was also prepared. The experiment was operated in four phases with different HRTs. Phases I to III exclusively utilized AMD. Prior to the commencement of phase IV, 400 mL of pond sediment and 100 mL of activated sludge were added to the CWs to inoculate microorganisms for 2 weeks. In phase IV, DW was supplied to the CWs along with AMD. The experimental diagram and time of operation are shown in Figure 2.

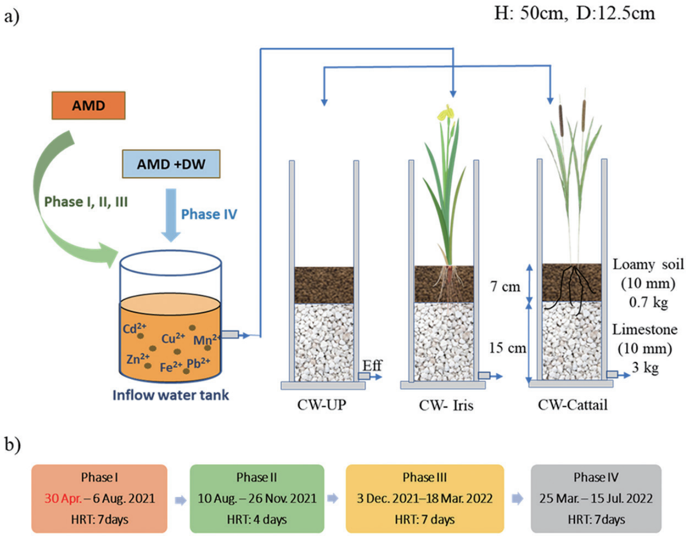

Figure 2: a) Diagram of CWs, b) Time of operation for four phases. Source: Author

We collected samples from both the inlet and outlet to analyze heavy metal concentrations and other water parameters such as pH, DO, ORP, sulfate (SO_4^{2-}), sulfide (S^{2-}), TOC, TN, and TP. At the end of the experiment, samples of plants and substrate were also collected to determine the accumulation of heavy metals.

3. Results and Discussion

(1) Water Quality

During the experimental period, the pH levels of the effluent ranged from 6.5 to 8.3, with a slight increase observed in Phase IV, likely due to the buffering capacity of the supplied DW and the bicarbonate production from SRB activities. Effluents from planted CWs exhibited lower DO levels compared to unplanted ones, indicating enhanced oxygen consumption by roots and microorganisms in the rhizosphere. DO levels experienced a significant drop in Phase IV as a result of heightened oxygen requirements for organic matter decomposition. While ORP values were mostly positive in the first three Phases, they experienced a notable drop in the last Phase, ranging from -179 mV to -20 mV after one month. Sulfate concentrations decreased in CW effluents, with a marked reduction in Phase IV. Dissolved sulfide concentrations remained minimal (0–0.01 mg/L) in Phases I-III but gradually increased (0.037–0.21 mg/L) in Phase IV, indicating the reduction of sulfate to sulfide by SRB.

During Phase IV, all CWs demonstrated effective removal of organic matter and nutrients, achieving removal rates of 84.0–88.5% for TOC, 80.6–100% for TN, and 80.0–99.0% for TP. Nitrogen removal in CWs primarily occurred through microbial nitrification and denitrification processes, while phosphorus removal was mainly achieved through adsorption and precipitation processes. Additionally, plant presence enhanced nutrient uptake, evident from higher removal rates observed in planted CWs. These findings affirm the capability of CWs to effectively eliminate multiple contaminants from both AMD and DW simultaneously.

(2) Heavy Metal Treatment

The average concentration of heavy metals for each phase is presented in Figure 3. In Phases I, II, and III, there was a general decrease in heavy metal concentrations post-treatment. The most effective removal was observed in Phase I, with a 7-day hydraulic retention time (HRT). However, in Phase II, where the HRT was reduced to 4 days, removal efficiencies decreased. Despite maintaining a 7-day HRT in Phase III, removal efficiencies slightly decreased. These findings suggest that the substrate became increasingly saturated with metals in the absence of an external carbon source. Additionally, diminished plant vitality and reduced evaporation during late autumn and winter months adversely affected treatment performance in Phases II and III. Planted CWs exhibited superior removal efficiency for all investigated metals, except for Mn.

As observed in Figure 3, the influent concentrations of Cd and Zn exceeded the effluent standards. During Phase I, the Zn and Cd concentrations from outlet samples met the standards well. However, in Phase III, Zn concentrations in effluents exceeded the standard. The dominant process for Cd removal in CWs was identified as adsorption, and the decrease in HRT in Phase II resulted in lower Cd removal efficiency. Among the investigated heavy metals, Fe had the highest level in the influent, with an average concentration of 37.4 mg/L, approximately four times higher than the Japanese effluent standard of 10 mg/L. Hara et al. (2021) indicated that Fe can be easily removed through the formation of insoluble oxides, precipitation, and co-precipitation processes in CWs. In the current study, more than 99% of

Fe from AMD was removed by all CWs after treatment.

Cu, Mn, and Pb were effectively removed post-treatment. However, Mn removal efficiency (37.9–95.8%) varied significantly across all CWs during the three phases, possibly due to its lower sensitivity to pH changes and susceptibility to leaching with variations in ORP. Treatment performance for Mn notably declined in Phase III, particularly in planted CWs. Pb was effectively eliminated in Phase I but exhibited less than 50% removal efficiency in Phases II and III, except for those in the iris-CWs. Substrate saturation likely contributed to the reduced treatment performance of CWs. To achieve sustainable and effective AMD remediation, stimulating biogenic processes through supplementation with sludge and DW was deemed necessary.

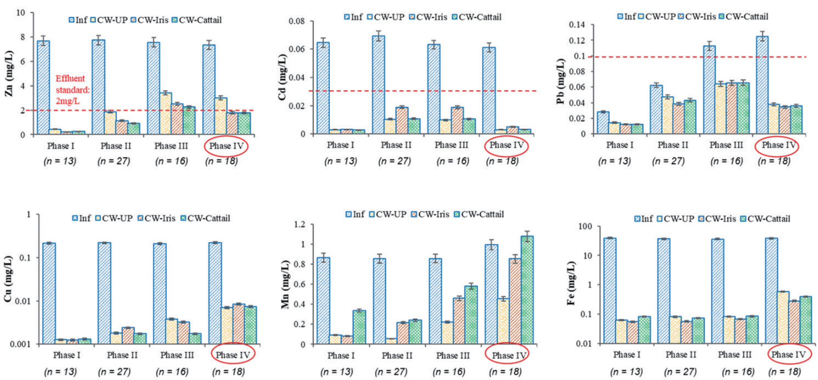

Figure 3: Heavy metal concentrations (avg. ± SD) in influent synthetic AMD and effluents in four phases. Source: Author

In Phase IV, we found that after adding sludge and DW, the effectiveness of heavy metal removal significantly enhanced, especially in the planted CWs. The stimulation of microbial activities facilitated the removal of heavy metals through their adsorption onto the mucus generated by microorganisms around plant roots. Additionally, the addition of DW as electron donors, particularly for SRB, encouraged the conversion of sulfate to sulfide. Subsequently, the sulfide reacted with soluble metals in the wastewater, precipitating them out. Nguyen et al. (2021) and Soda et al. (2021) also reported that metals can be removed in CWs through bacterial metabolism when they serve as trace elements. Furthermore, the supplementation of nutrients from DW promoted plant growth, leading to significant contributions to heavy metal removal from AMD. Throughout Phase IV, a gradual decrease in the Zn concentration was observed in the effluent, particularly noticeable in the planted CWs. The Zn concentration fell below the effluent standard, averaging approximately 1.7 mg/L. The efficiency of Zn removal increased from 57.0–72.2% in Phase III to 67.6–88.4% in Phase IV. Similar to Zn, there was a notable decline in the effluent Cd levels during Phase IV, reaching only 0.002–0.003 mg/L. Cd removal efficiency in Phase IV improved by 11.3–19.8% compared to Phase III. Unlike Cd and Zn, the effectiveness of Cu and Mn decreased after the addition of sludge and DW. Cu was likely predominantly removed in Phases I-III through binding sites on the media, which might have been diminished by the addition of sludge and microbial-produced mucus in Phase IV. Despite this, Cu removal efficiency remained high (97.5–98.5%) across all systems, whereas Mn removal ranged from 35.4–65.1% in Phase IV. Fe removal remained consistently high, with more than 99% removal in all systems during this phase.

(3) Metal Accumulation in Substrate

It is recognized that substrates play a crucial role in removing heavy metals from mine wastewater in CWs. Most metals are removed from AMD primarily through interaction with substrates such as gravel, soil, and limestone (Wang et al. 2020; Yang et al. 2018). Therefore, selecting substrates with high filtration and adsorption capacities, as well as high ecological activity, is important.

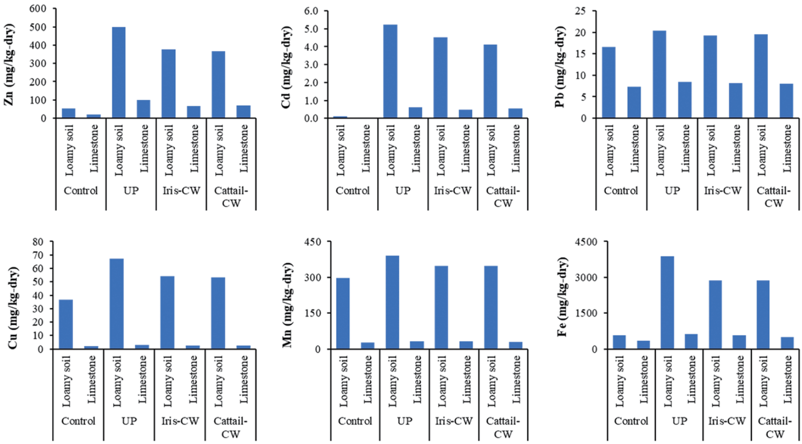

Figure 4: Heavy metal contents in loamy soil and limestone before and after the treatment. Source: Author

In the present study, loamy soil and limestone were used as substrates in CWs. Loamy soil has the characteristics of high permeability, porosity, and water retention. In addition, its chemical composition includes many metal oxides such as SiO_2, Al_2O_3, FeO, CuO, K_2O and CaO, thus, it has the potential to adsorb metals and exchange ions. Soda et al. (2021) reported that soil adsorption was the main mechanism in CWs for removing Cd from neutral mine drainage. Limestone has been widely used as a substrate in CWs for mine drainage treatment because of its high durability and adsorption capacity. The main component of limestone is calcium carbonate which generates ion hydroxides leading to increased pH. With the increase of pH, metal can be removed through neutralization or precipitation as metal hydroxides. Figure 4 presents the heavy metal contents in the loamy soil and limestone before and after treatment. Overall, the concentrations of examined heavy metals in the substrates increased across all CWs during the experimental duration.

(4) Plant Growth and Metal Uptake

Irises and cattails exhibited robust growth during Phase I and the early stages of Phase II. However, the aboveground parts started to wither towards the end of Phase II and continued through Phase III due to the cold winter weather. With the onset of warmer spring weather in Phase IV, the underground roots began to sprout again. Alongside nutrient supplementation, the plants thrived during Phase IV.

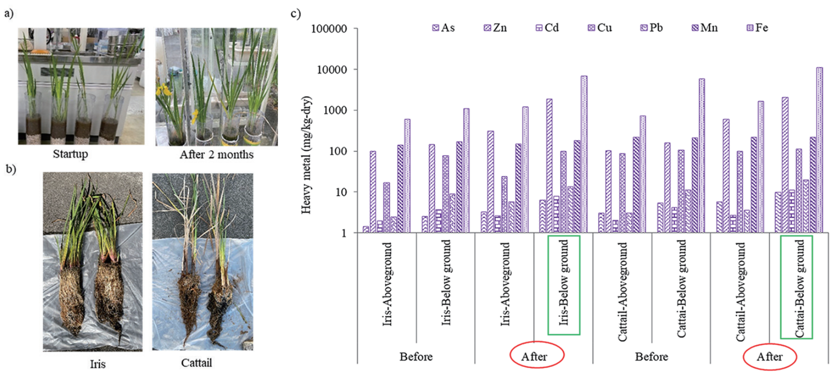

Figure 5: a) Irises and cattails on the first day and after two months of operation, b) the aboveground and belowground parts of plants after the experiment, c) heavy metal contents in Iris and Cattail biomass before and 14.5 months after AMD treatment. Source: Author

At the end of Phase IV, irises and cattails were harvested. Each iris-CW yielded 250 g-dry of iris biomass, with 81 g-dry from the aboveground part and 169 g-dry from the belowground part. Similarly, each cattail-CW produced 208 g-dry of cattail biomass, including approximately 60 g-dry from the aboveground part and 148 g-dry from the belowground part. The heavy metal concentrations in iris and cattail biomass before and after treatment with AMD are depicted in Figure 5c. During the experiment, the metal levels in both irises and cattails notably increased, particularly in the belowground part. Essential elements such as Zn, Cu, Fe, and Mn exhibited higher concentrations than Pb and Cd in the plant biomass.

In this research, iris and cattail were likely to generate roots and rhizomes, serving as substrates for bacteria attachment. Moreover, these roots and rhizomes play a role in oxygenating the surrounding areas and absorbing pollutants from the wastewater. These plants possess the ability to absorb metals through mechanisms such as phytostabilization, phytovolatilization, phytoextraction, and rhizofiltration. The uptake of metals by plants was acknowledged as the primary biological process for metal removal in CWs (Sandoval et al. 2019). During the experiment, the amount of accumulated metals in iris was comparable to that of the typical wetland plant, cattail, suggesting that iris possesses a strong capability for heavy metal removal. Furthermore, the higher biomass of iris provides an advantage for metal accumulation.

(5) Sulfate-Reducing Bacteria Population

Figure 6 illustrates the presence of SRB in effluent samples throughout the experiment. Initially, only a small number of SRB (ranging from 0 to 4×101 CFU/mL) were detected in effluent samples during Phases I-III. However, by Phase IV, the population increased to a range of 102 to 3×103 CFU/mL in the effluent. The introduction of sludge and DW acted as a stimulant for the growth of SRB. In CWs, SRB plays a critical role in removing heavy metals, as highlighted in previous study (Sheoran and Sheoran 2006).

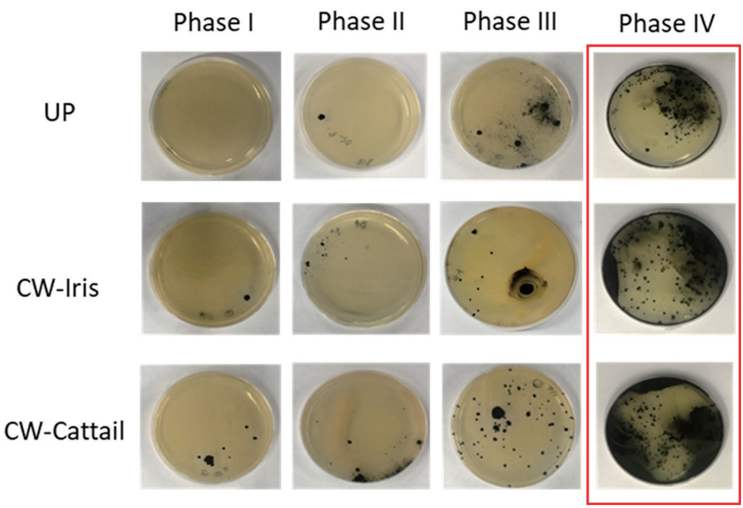

Figure 6: SRB population in effluent samples during four Phases. Source: Author

In this study, SRB was found to enhance the conversion of sulfate to sulfide, as indicated by a significant decrease in sulfate concentration and an increase in dissolved sulfide concentration during Phase IV. The produced sulfide reacted with dissolved metals, resulting in the formation of highly insoluble metal sulfides. Nguyen et al. (2021) also indicated that metal sulfide precipitation is recognized as an effective method for removing metals in CWs. Furthermore, the sulfate reduction by SRB also contributed to an increase in pH during Phase IV, promoting the precipitation of metal hydroxides and sulfides.

4. Conclusion

The laboratory-scale experiment aimed at co-treating AMD and DW effectively demonstrated the efficiency of the CW microcosm. It showcased improvements in effluent pH and the removal of heavy metals, sulfate, organic matter, and nutrients. Stimulating SRB activities by adding external carbon sources proved to be an effective method for enhancing heavy metal removal. Iris, when used as a wetland plant, showed significant efficacy in heavy metal removal. Additionally, incorporating ornamental flowering plants such as iris into CWs can enhance aesthetic appeal, creating visually pleasing landscapes and offering additional economic value.

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Chapter 6
The Applications and Performances of Biochar in Constructed Wetlands for Sustainable Wastewater Treatment

Obey GOTORE

1. Introduction

In many developing countries, both point and non-point sources of pollution are increasingly significant concerns. These sources include industrial activities, wastewater treatment plants, and urban agricultural practices, all contributing to environmental degradation. The consequences of this pollution are evident in the eutrophication of surface water resources. Despite efforts to mitigate these issues, implementing measures to improve the trophic status of surface waters remains challenging. Various technologies have been explored for this purpose, yet their application faces hurdles, particularly in developing countries, due to high energy requirements and monitoring costs. However, constructed wetlands (CWs) offer a promising solution for wastewater treatment in such contexts. Their natural and passive treatment approach makes them relatively easy to implement compared to other technologies, providing an effective means of addressing water pollution.

In this study, I initially explored locally available materials in developing countries, focusing on corncob waste from agricultural activities. My emphasis was on developing materials that provide optimal conditions for removing pollutants from wastewater, particularly for application in constructed wetlands. In the first phase of my research, I investigated the impact of various pyrolysis conditions on the production of adsorbents or biochar for removing Ciprofloxacin (CFX), Delafloxacin (DLX), and Ofloxacin (OFX). Initially, I determined the surface area of the biochar post-production and measured its adsorption capacity through isotherms for removing CFX, DLX, and OFX from wastewater. Subsequently, I characterized the physiochemical properties of this corncob under different pyrolysis conditions through proximate analysis, Field emission scanning electron microscopy- energy dispersive X-ray (FESEM-EDX) analysis, Fourier-transform infrared spectroscopy (FTIR) spectroscopy, and determination of effective pore volume. Following these analyses and obtaining results, I further explored the application of this biochar in CWs, both as part of the substrate and as a habitat for microorganisms.

2. Investigating the Effect of Different Pyrolysis Conditions on the Adsorbent and Exploring the Adsorption Properties of Fluoroquinolones

Antibiotic residues are recognized as emerging pollutants in the environment due to their widespread use, release into ecosystems, and biological activities (Ohoro et al. 2019). Unlike many other organic pollutants, antibiotic residues in aquatic environments pose a significant concern due to their complex nature and their ability to hinder the degradation of other organic matter. Moreover, the continuous discharge of antibiotic compounds can contribute to the development of drug resistance among native bacterial populations (Gotore et al. 2022.; Liu et al. 2021; Manaia et al. 2016). Among the antibiotics commonly employed in medical treatment, CFX, DFX, and OFX belong to the fluoroquinolone (FQs) group, ranking fourth in terms of human usage. To mitigate health risks and protect ecosystems, antibiotic removal is crucial. Traditional wastewater treatment processes struggle to effectively remove antibiotics, highlighting the need for alternative treatment approaches.

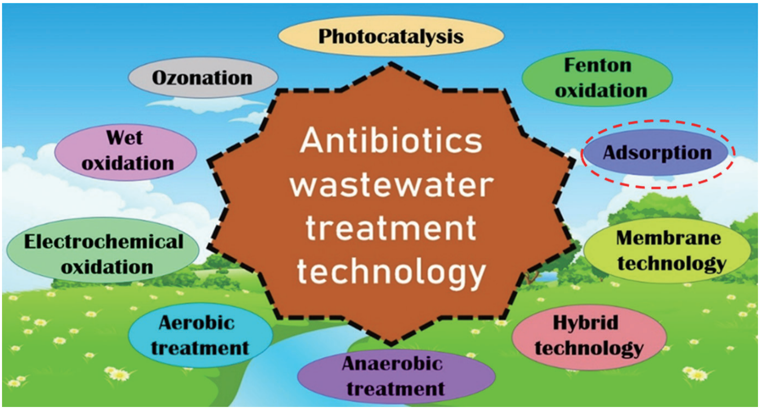

Figure 1: Antibiotic wastewater treatment technology.
Source: Phoon et al. 2020

Various methods are available for addressing antibiotic removal (as illustrated in Figure 1), but I specifically focused on adsorption. My objective was to pinpoint a cost-effective approach applicable in CWs. We sought to integrate this adsorption process into a substrate using biochar and evaluate its effectiveness. Moreover, we emphasized the use of locally sourced materials to ensure affordability and suitability for remote areas in both developing and developed countries, while also prioritizing environmental friendliness.

Several biochar materials or resources are available, such as coconut or wood, corn cobs, tree barks, peanut shells, and rice husks, with numerous studies conducted on their potential. However, their utilization in CWs for antibiotic removal has been limited, which prompted our research focus.

In this research, we utilized corncobs. The laboratory experiment was conducted in Nagasaki, Japan. The corncobs were sourced from a local farmer in Nagasaki and were subsequently packed into small ceramic cups. These cups were then placed inside a microwave oven and subjected to pyrolysis under three different temperature conditions: 900°C, 700°C, and 600°C for durations of one and two hours. After pyrolysis, the corncobs were ground into small granules ranging from 0.25 to 1.00 mm. However, these granules were only utilized for the adsorption experiment and were not used in the constructed wetland. The pyrolysis process is illustrated in Figure 2.

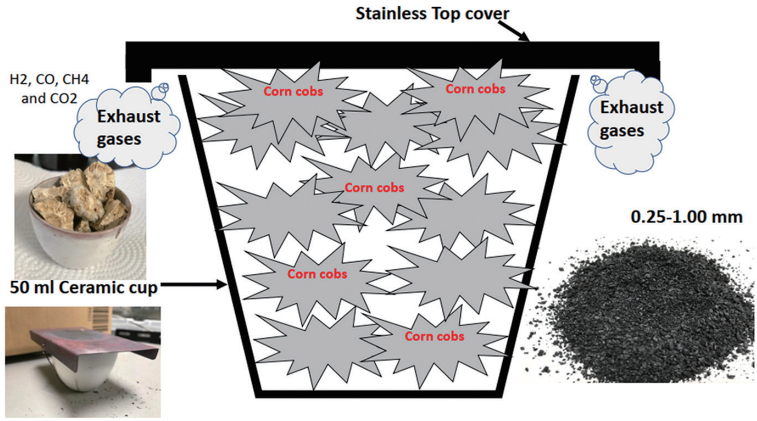

Figure 2: Pyrolysis process. Source: Author

After producing materials under three different temperature and duration combinations — 600°C for one hour, 600°C for two hours, 900°C for one hour, and 900°C for two hours — we conducted proximate analysis. The target parameter was fixed carbon content, aiming to ascertain the yield from pyrolysis. Table 1 shows the properties of corn cob biochar were derived from proximate analysis under different pyrolysis conditions.

Table 1: Properties of corn cob biochar under different pyrolysis conditions.

	Pyrolysis temperatures (℃) /time (h)					
	600℃ /1 h	600℃ /2 h	700℃/1 h	700℃/2 h	900℃/1 h	900℃/2 h
Vpore (%)	80.0 ± 0.589	79.9 ± 0.588	80.0 ± 0.590	79.3 ± 0.589	80.7 ± 0.587	84.0 ± 0.589
Biochar recovery (%)	36.7 ± 0.052	32.2 ± 0.062	30.6 ± 0.041	26.9 ± 0.023	27.7 ± 0.044	26.0 ± 0.013

It was observed that approximately 25% of the material remained as fixed carbon, indicating that about 75% comprised volatile components, water, and other substances decomposable at higher temperatures. Subsequently, pore volume was measured, revealing approximately 80% for the 600°C condition. As pyrolysis conditions intensified, both porosity and pore volume increased to 83%, suggesting a higher pore density within the biochar. Lastly, biochar recovery was assessed, showing a decrease as pyrolysis temperature increased.

The next experiment aimed to evaluate kinetic adsorption, focusing on achieving a material balance between the adsorbate and the adsorbent utilized in this kinetic study. Our objective was to determine whether a 1st order or 2nd order, among other nonlinear equations, best described the rate of removal of various adsorbates. For instance, iodine was employed to assess the surface area. Initially, methylene blue was also considered for surface area measurement; however, it was ultimately disregarded due to its tendency to overestimate the surface area. Consequently, only iodine was utilized to accurately determine the surface area of the produced biochar, as iodine provides a more precise estimation compared to methylene blue. The iodine estimation is closely aligned with BET analysis, which might be prohibitively expensive for implementation in developing countries. Hence, nonlinear regression equations were employed for this analysis, utilizing nonlinear least squares. Alongside the kinetic experiments, we also conducted isothermal experiments. For the isotherm analysis, we considered both Langmuir and Freundlich models to determine the Q_{max}, which represents the maximum absorption capacity of this biochar. The kinetic adsorption and isothermal experiments were conducted and calculated according to Dang et al. (2022). Figure 3 shows the iodine on biochar and the maximum adsorption capacity of CFX, OFX, and DLX

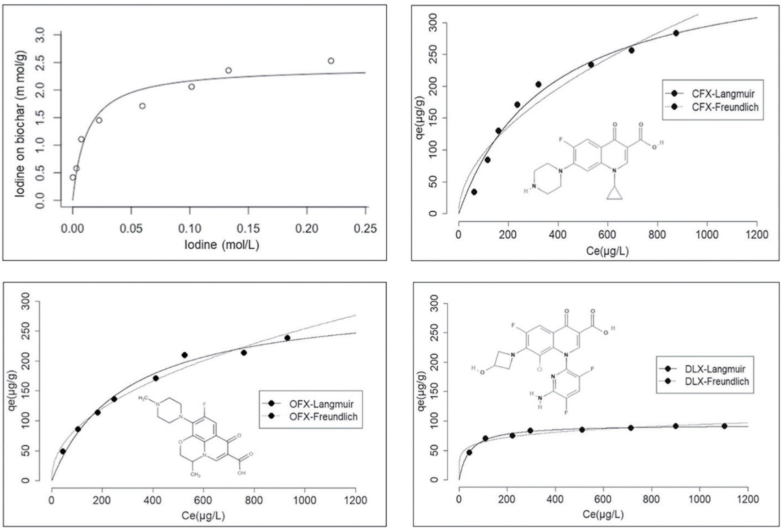

Figure 3: Iodine on biochar and the maximum adsorption capacity of CFX, OFX, and DLX. Source: Dang et al. 2022

After undergoing pyrolysis, higher levels of carbonization resulted in the formation of more pores and voids, particularly evident at 900°C where the abundance of pores surpassed other conditions. Variances in honeycomb structures were observed across different pyrolysis conditions. Typically, surface voids ranging from 12–30 µm were observable, alongside numerous pores measuring 1 to 2 µm on the walls of these voids, facilitating percolation diffusion. The formation of large porous structures was attributed to the rapid volatilization occurring at temperatures exceeding 500°C. As evidenced in Figure 4, images of biochar under various pyrolysis conditions illustrate the development of pores post-pyrolysis. This observation suggests a potential habitat for microorganisms or bacteria within CWs, which could concurrently facilitate the removal or biodegradation of nutrients present in wastewater during CW treatment.

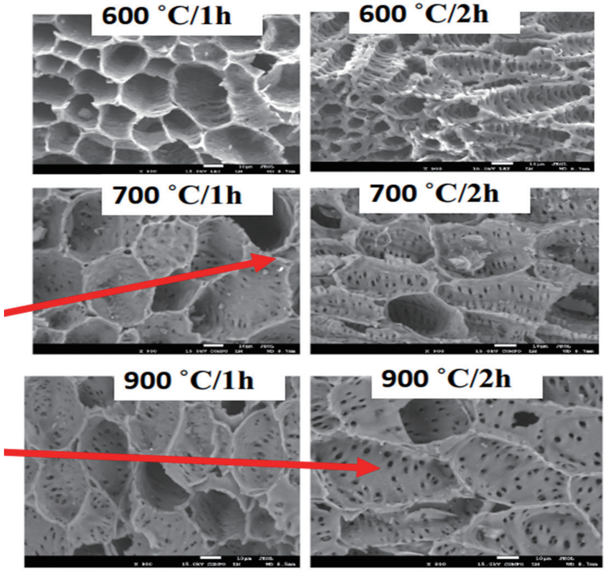

Figure 4: FESEM images showing the surface morphology of corn cob biochar under various pyrolysis conditions. Source: Gotore et al. 2022

Another characterization technique employed was FTIR, as illustrated in Figure 5A. We identified distinct functional groups on the surface of the biochar, notably the CFX antibiotic (Figure 5B). Due to the presence of fluorine, these functional groups could be easily removed owing to the higher electronegativity of fluorine towards the biochar.

Furthermore, DLX was analyzed (Figure 5C), revealing the presence of three fluorine charges. Consequently, we observed an increase in electronegativity, facilitating the easy removal of these functional groups.

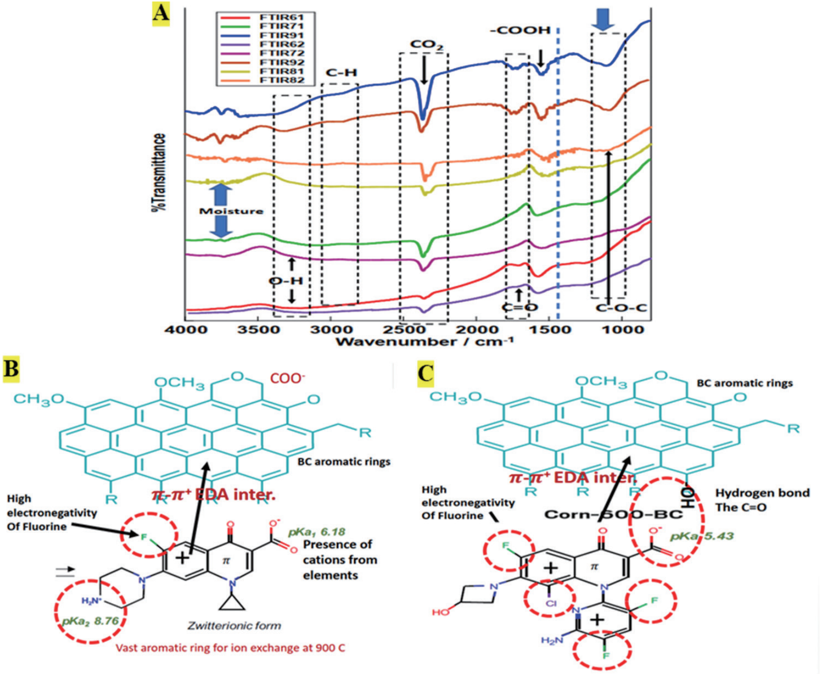

Figure 5: FTIR spectra of corncob biochar under various pyrolysis conditions (A), and the detection of CFX (B) and DLX (C) on the surface of the biochar.
Source: Gotore et al. 2022; Candel and Peñuelas 2017

Figure 6 illustrates the CFX and DLX adsorption isotherms. Regarding CFX removal, it was apparent that higher pyrolysis temperatures facilitate ciprofloxacin removal, while it proved challenging under lower pyrolysis conditions. Increased pyrolysis led to the formation of numerous functional groups capable of removing such contaminants, particularly antibiotics. Similarly, with DLX removal, a comparable trend was observed wherein higher pyrolysis temperatures were more effective in removing delafloxacin from wastewater. Consequently, biochar produced at 900°C demonstrate efficacy in antibiotic removal, even at lower temperatures.

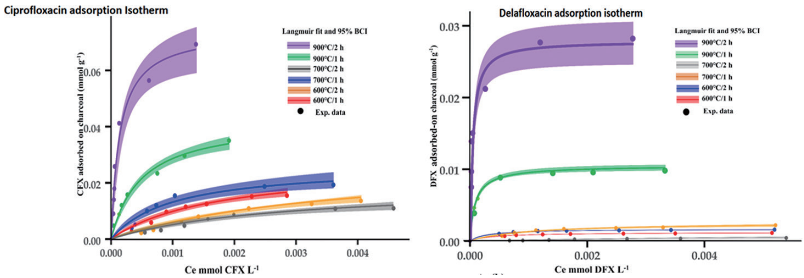

Figure 6: CFC and DFX adsorption isotherms.
Source: Gotore et al. 2022

Figure 7 presents KL, representing the energy present on the surface of the biochar, similar to binding energy. This energy influenced the adsorption and attraction of contaminants in wastewater. The impacts of iodine, CFX, and DLX were compared. In the case of iodine, higher pyrolysis conditions did not lead to its removal from the surface, with higher energy observed under smaller or lower pyrolysis conditions. Conversely, for antibiotics, the opposite trend was observed due to the higher electronegativity of these contaminants. These findings align with those reported by Dang et al. (2022).

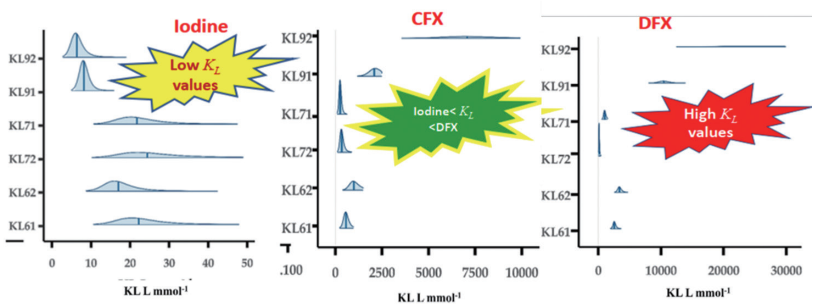

Figure 7: KL distribution parameters of iodine, CFX, and DLX.
Source: Gotore et al. 2022

3. Application of Corncob Biochar as A Substrate in CWs

Once we had obtained data on adsorption, we proceeded with the application of corncob biochar as a substrate in CWs for treating wastewater. This experiment was conducted in Chiang Mai City, northern Thailand. The corncobs were obtained from a local farmer and pyrolyzed at 600°C. We opted for this lowest effective temperature to save energy and reduce the cost of the constructed wetland. After pyrolysis, the biochar was produced over two hours, then washed and dried to prepare it for wetland application. The size of the biochar particles after pyrolysis ranged from approximately 1.5 millimeters to around 3 millimeters in diameter, which was considered relatively large. The fieldwork biochar pyrolysis process is shown in Figure 8.

Figure 8: Preparation of biochar for constructed wetland applications. Source: Author

The CW setup for treating pig manure or swine wastewater was implemented. This experiment was conducted at Maejo University, Chiang Mai, Thailand. The diagram of the experimental setup and operational parameters is presented in Figure 9. In this study, we utilized gravel and biochar as substrates in CWs, which were planted with common reed (*Phragmites australis*).

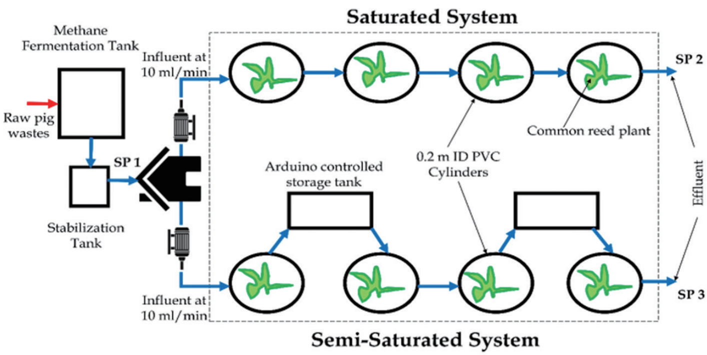

Figure 9: Schematic layout of the integrated constructed wetland system. Source: Gotore et al. 2022

After setting up the experiment, we managed to automatically control the CW, dividing it into two sections: saturated and semi-saturated wetlands. Within the CW, we measured a flow rate of approximately 14.4 liters per day from the pig manure waste. The cylinder volume in the area was calculated to be around 0.03 square meters per column, totaling approximately 0.12 square meters per system. The HRT was approximately 3.5 days for each system (Gotore et al. 2022).

As discussed in the previous chapters, plants play a crucial role in wastewater decontamination through processes such as transpiration and respiration. They contribute to aeration within the root system, facilitating the exchange of carbon dioxide and oxygen during their growth. As plants mature, they supply oxygen to microorganisms residing within the biochar, fostering a favorable environment for microbial activity. This ongoing interaction with microorganisms enables them to biodegrade nutrients present in wastewater, effectively decomposing and removing pollutants. The reeds served as a key component of the treatment process in the CWs. Additionally, leveraging its high porosity and large surface area, corncob biochar can provide a habitat for microorganisms and aid in adsorbing pollutants.

After four months of operation, we found that organic matter and nutrients were effectively removed by CWs, meeting the effluent quality standards for discharge into surface waters. The effluent ammonia and nitrate levels were below approximately 10 mg/L and 2 mg/L, respectively. Both effluent phosphorus and nitrite levels were maintained around 1 mg/L.

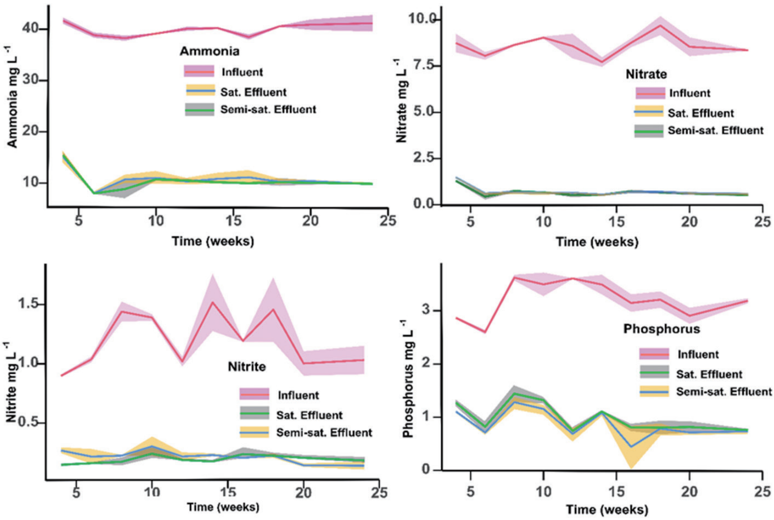

Figure 10: Inlet and outlet concentrations of ammonia, nitrate, nitrite, and phosphorus. Source: Gotore et al. 2022

The COD was also effectively removed in both saturated and semi-saturated CWs, achieving an average removal rate of approximately 70%. Figure 11 shows the concentration of COD in raw wastewater and after treatment with CWs, as well as the COD removal efficiency over time.

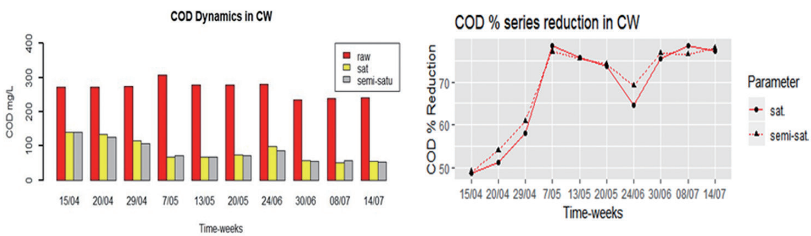

Figure 11: The concentrations of COD in influent and effluent samples, as well as the COD removal efficiency. Source: Gotore et al. 2022

4. Conclusion

In general, corncob biochar demonstrated favorable adsorptive properties and potential suitability as a substrate in CWs. The semi-saturated CWs utilizing corncob biochar and common reeds exhibited higher removal efficiency. With all locally available materials used in the study, the implementation of this approach for wastewater reclamation could prove cost-effective, offering a practical solution to ongoing challenges in rural areas of developing countries. Moreover, we aim to employ this passive technology for treating mine wastewater, particularly targeting the removal of manganese, zinc, and iron from mine drainage systems. Japan has approximately 100 mines still requiring heavy metal processing, and given its mountainous terrain, establishing large artificial wetlands proves challenging, especially in mountainous mining areas. Consequently, we are actively exploring the potential of bioremediation and the application of small-scale CWs for treating metal contamination in these mines' wastewater.

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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.

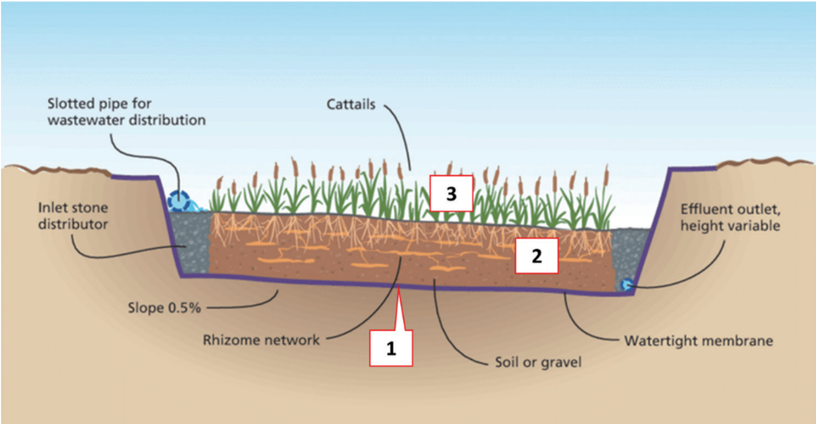

Figure 2: Three main components of CWs. Source: Author

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.

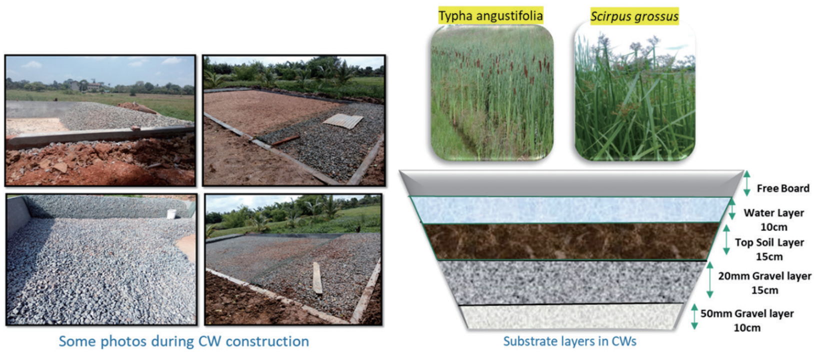

Figure 3: Substrates and plants used in CWs. Source: Author

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.

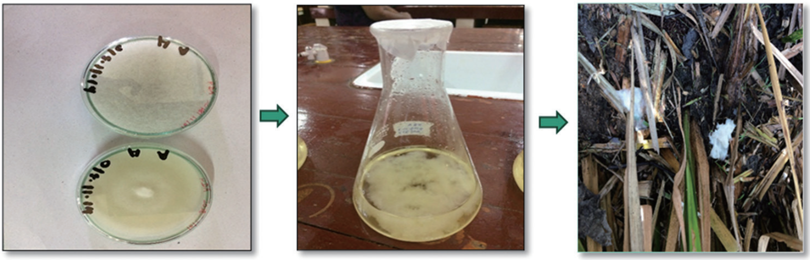

Figure 4: Procedure for fungal inoculum into CWs. Source: Author

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.

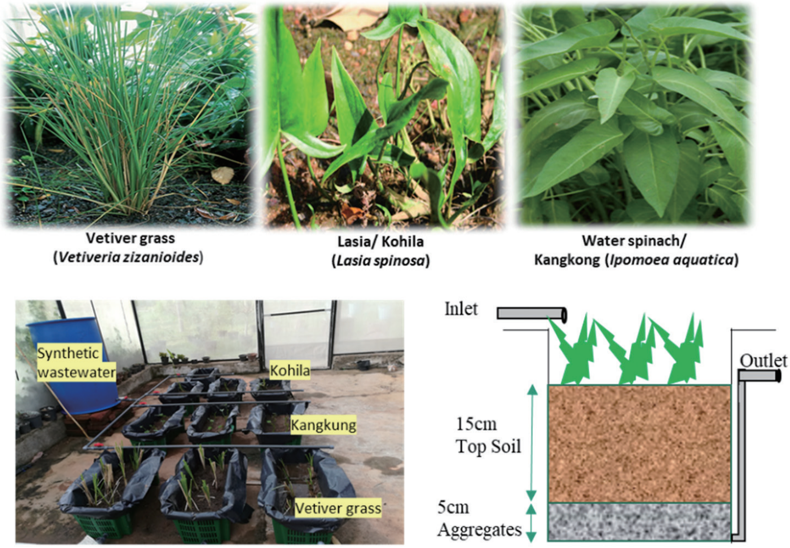

Figure 5: Plants and diagrams of CW treatment units. Source: Author

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.

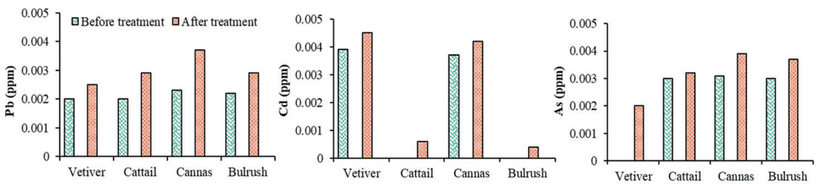

Figure 6: The concentration of trace elements in four plants.
Source: Author

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

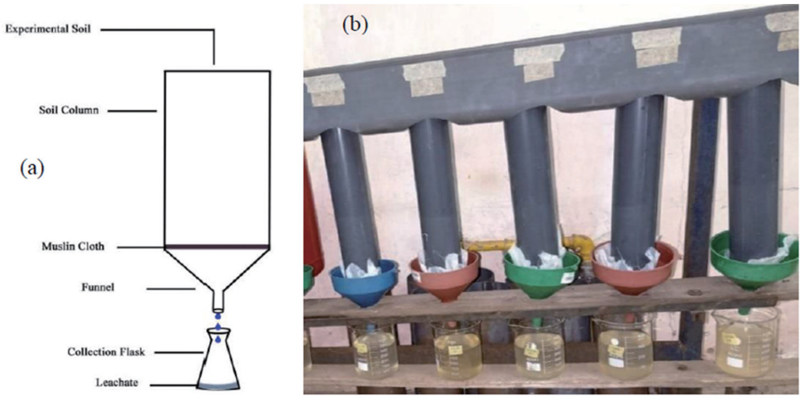

Figure 7: (a) Diagram of a typical column, and (b) laboratory arrangement of the columns. Source: Author

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.

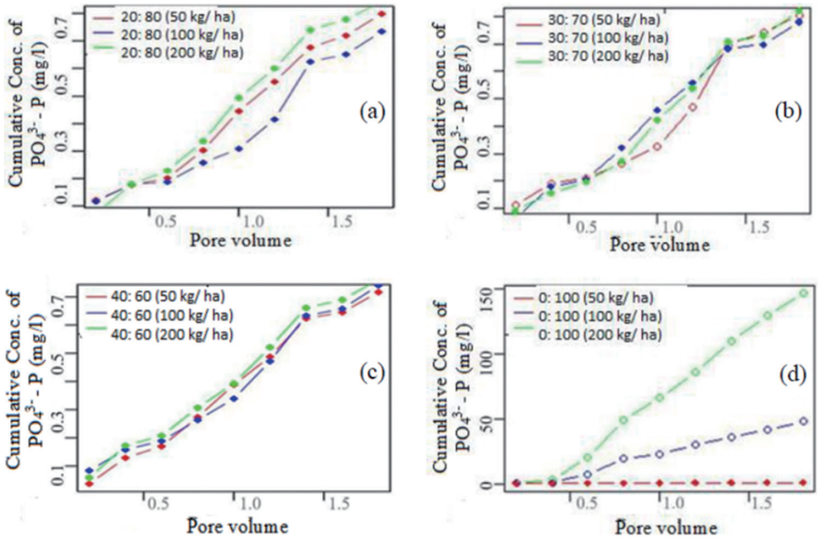

Figure 8: Cumulative concentration of phosphate in leachate from various clay and sand mixture media: (a) 20:80 clay–sand mixture media, (b) 30:70 clay–sand mixture media, (c) 40:60 clay–sand mixture media, and (d) 0:100 clay–sand mixture media. Source: Author

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)
Clay brick	0.5	0.036±0.00	2.45	6.04±0.23	0.31±0.01	20.87±0.35
	1.0	0.032±0.00		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
Laterite brick	0.5	0.004±0.01	3.07	5.08±0.10	3.24±0.10	18.30±0.50
	1.0	0.005±0.00		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.

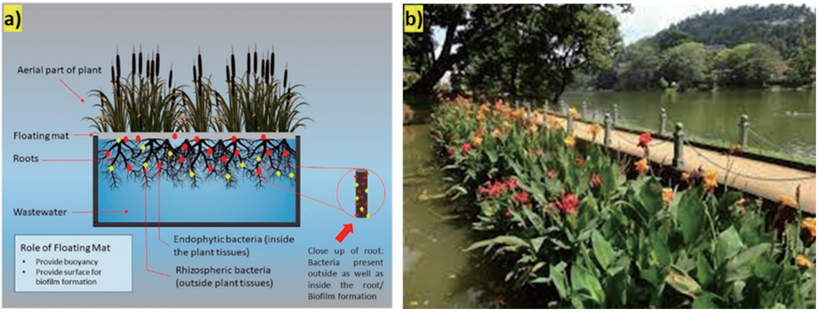

Figure 9: (a) The main components in the FCW, and (b) an actual scale FCW image. Source: Author

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 8
Application of Permeable Concrete Material in Constructed Wetlands for Urban Stormwater Runoff Treatment

Van Tai TANG

1. Introduction

I would like to introduce a case study using novel advanced porous concrete in constructed wetlands (CWs) for urban storm runoff treatment in Vietnam. The findings of this research were published in Water Science and Technology (Tang and Pakshirajan 2018). First, I will share the research background. As you may know, the current infrastructure construction technology fails to meet the requirements for collecting and treating urban stormwater adequately, leading to two major challenges: urban river pollution and urban flooding. Furthermore, the increase in sea levels, heavy rainfall, and the extensive use of impermeable concrete surfaces in urban areas have exacerbated this problem. Figure 1 illustrates the impervious surface and the percentage of infiltration in various residential density areas.

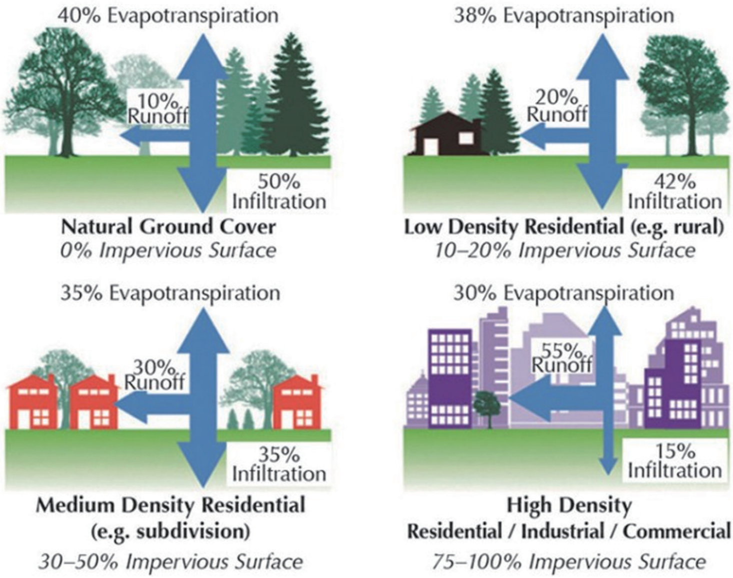

Figure 1: The impervious surface and the percentage of infiltration in various residential density areas. Source: Author

Estimates suggest that under natural ground cover, approximately 50% of stormwater infiltrates into the soil, with only 10% resulting in runoff. However, in low-density residential areas, the infiltration rate decreases to 42%, and in medium-density residential regions, it further reduces to 35%. In high-density residential areas, this rate drops significantly to only 15%, leading to approximately 55% of stormwater runoff reaching the river surface and causing flooding in urban areas. Figure 2 shows the urban river pollution and urban flooding in Ho Chi Minh City, Vietnam.

Figure 2: The urban river pollution and urban flooding in Ho Chi Minh City, Vietnam. Source: Author

Due to the inability of rainwater to penetrate the soil, it accumulates and forms large streams. Storm runoff resulting from heavy rainfall leads to the erosion and dissolution of surface pollutants like organic matter, nutrients, and heavy metals into riverbeds, resulting in significant pollution. Addressing these challenges requires comprehensive strategies such as promoting sustainable urban planning and development practices, enhancing green infrastructure, implementing flood mitigation measures, and reducing greenhouse gas emissions to mitigate climate change impacts. Additionally, it is crucial to urgently develop sustainable urban stormwater treatment systems to minimize the contribution of impermeable surfaces to urban flooding and pollution. To control pollution from stormwater, the term Best Management Practices (BMPs) has been introduced into stormwater management in the US and Canada. Stormwater management BMPs can typically be categorized into four basic types: Storage practices, Vegetative practices, Filtration/Infiltration practices, and Water-Sensitive Development. By this approach, we provided an urban stormwater treatment method utilizing novel advanced porous concrete in CWs. This method offers advantages such as permeable pavements, bioretention areas, and wetlands.

CWs can be used to control urban floods and water sources pollution caused by stormwater. The porous structure of CWs with high permeability can effectively absorb floodwater. The complex interaction of three main components — absorption material, plants, and microorganisms — within CWs facilitates the removal of pollutants from stormwater runoff. Also, CWs offer a cost-effective and sustainable solution for treating stormwater pollution, providing numerous benefits for water quality improvement, habitat enhancement, and ecosystem restoration. By harnessing natural processes and ecological functions, CWs can efficiently mitigate the impacts of urbanization and land development on water resources. Figure 3 shows a CW designed for stormwater treatment and landscape creation in Ho Chi Minh City, Vietnam.

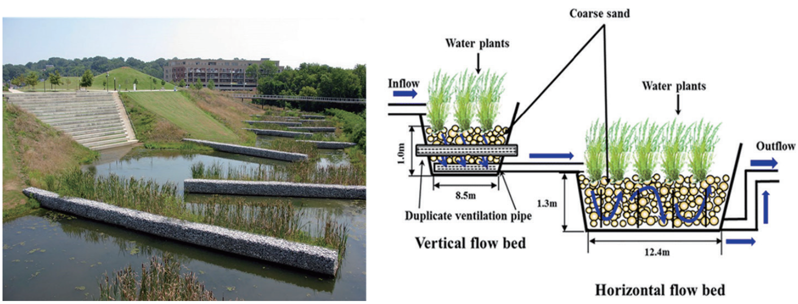

Figure 3: A CW designed for stormwater treatment and landscape creation. Source: Author

2. Methodology

(1) Materials

In this study, to prepare porous concrete, we used ceramics, cement, and water with a ratio of 348:272:83 kg/m^3, respectively. Porous concrete aggregates, ranging from 5 to 15 mm in size, were chosen, with a water-cement ratio of 0.24. To ensure the growth of plant biomass, permeability, strength, and stormwater purification capability of the CWs, the void ratio of porous concrete was set at 35%, as reported by Kim and Park (2016). For the sake of simplified installation, both the common porous concrete templates (CPCT) and advanced porous concrete templates (APCT) were prepared in a modular format with dimensions of 60 × 30 × 12 cm^3 each. In the case of APCT of the same volume, holes measuring 50 × 20 × 4 cm^3 were incorporated at the center for filling with a mixture of zeolite, slag, and activated carbon in a ratio of 4:1:11. This was aimed at boosting pollutant removal efficiency, determined based on the ratio of pollutants present in stormwater (Maniquiz et al. 2010). Figure 4 shows the photos of CPCT and APCT.

Common porous concrete templates (CPCT) | Advanced porous concrete templates (APCT) | CPCT and APCT were planted with *Festucaelata* grass

Figure 4: Photos of CPCT and APCT. Source: Author

The planting capacity of the porous concrete was evaluated through the incorporation of *Festuca elata* grass. *Festuca elata* seeds were mixed with soil, and the resulting mixture was spread evenly over the surface of the dried porous concrete. After a period of one month, samples of *Festuca elata* grass were collected from 15 different points from each porous concrete template to measure both their height and weight.

(2) CW Experimental Setup and Operation

We utilized two plastic containers, each measuring 84 × 30 × 60 cm^3, housing porous cement templates as CW units for the removal of pollutants from stormwater. These units were equipped with two valves positioned at 5 and 45 cm heights to manage stormwater discharge and regulate water levels within the constructed wetland. A sampling outlet at a height of 20 cm was utilized for stormwater analysis. Two CWs, one containing six CPCT units and the other with six APCT units, were set up to assess their effectiveness in removing pollutants from stormwater runoff. Schematics displaying the dimensions of both units and CW treatment systems are presented in Figure 5.

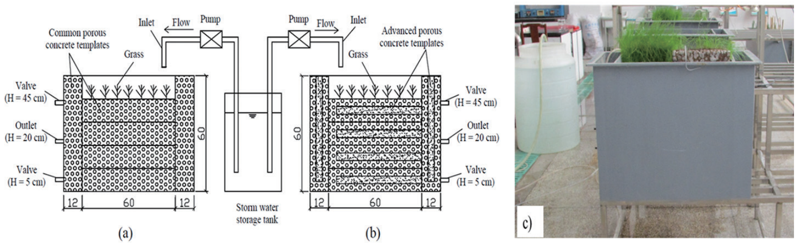

Figure 5: Diagram of (a) CPCT-CW unit and (b) APCT-CW unit, (c) CW treatment systems. Source: Author

For each CW treatment unit, *Festuca elata* grass was planted on top of the CW. In this study, we set the flow rate to 0.25 L/min, simulating the actual flow rate of rainwater as per previous studies (Hettler 2010; Maniquiz et al. 2010), with an HRT of 24 hours. This HRT was also utilized in the study conducted by Li et al. in 2015.

Stormwater was collected at Chengxianjie Road, Xuanwu Area, Nanjing City, Jiangsu Province, China, during rainfall events from April 17 to September 12, 2017. The stormwater was collected using a 500 L plastic tank and subsequently transferred to the laboratory for analysis and other experiments. In total, we obtained 13 stormwater samples.

3. Results

(1) Plant Growth on Porous Concretes

After one month from sowing, *Festuca elata* grass exhibited heights ranging from 12.6 to 16.9 mm and weights from 63.4 to 95.4 mg, indicating that the high porosity of the porous concrete provided sufficient space for root growth. Additionally, the voids within the porous concrete create favorable conditions for microbial reproduction. It is well recognized that bacteria contribute significantly to nutrient cycling processes in CWs, supporting plant growth and maintaining ecological balance. These findings highlight the robust growth potential of plants on the surface of the porous concrete.

(2) CW Treatment Performance

The treatment performance of CPCT-CW and APCT-CW is shown in Table 1. The CPCT-CW system achieved pollutant removal rates of 20.6% for COD, 30.1% for NH_3-N, and 35.4% for TN, primarily attributed to the formation of a biofilm on the porous concrete surface, facilitating microbial decomposition of organic matter and nutrients in stormwater. Additionally, grass planted atop the porous concrete aided in storm runoff pollution treatment by providing a nutrient-rich environment and moisture for microbial and plant growth, ultimately improving water purification efficiency. Overall, the combination of porous concrete and vegetation in CPCT-CW significantly contributed to pollutant removal from urban stormwater. In comparison, the APCT-CW system exhibited higher removal rates of 49.6% for COD, 52.4% for NH_3-N, and 47.7% for TN, outperforming CPCT-CW by 2.41, 1.74, and 1.34 times, respectively. This superior performance was attributed to the high pollutant absorption capacity of APCT, composed of activated carbon, zeolite, and slag, which provided ample space for nutrient, heavy metal, and organic matter adsorption. Additionally, the high void ratio of the filler material created an ideal habitat for microbial growth and biofilm formation on the surface of activated carbon, zeolite, and slag grains. Previous studies confirmed the effectiveness of biofilm in absorbing pollutants such as COD, BOD, and nutrients. Furthermore, each advanced porous concrete unit contained filler space acting as an independent bio-filter to retain and treat pollutants in stormwater. These findings emphasized the necessity of combining grass, porous concrete, and filler materials for achieving high water purification efficiency in APCT-CW systems.

Table 1: Pollutant removal efficiencies of CPCT-CW and APCT-CW

Water quality parameters (n = 13)	Water runoff quality (mg/L)	Influent	CPCT-CW		APCT-CW	
			Effluent (mg/L)	Average removal (%)	Effluent (mg/L)	Average removal (%)
COD	26-273	158.5± 65.9	125.8± 64.4	20.6	79.9± 27.2	49.6
TSS	23-217	126.2± 52.3	88.6± 58.7	29.8	51.9± 23.1	58.9
NH_3-N	0.9-7.2	4.21± 1.52	2.94± 1.96	30.1	2.01± 1.12	52.4
TN	2.6-18.3	10.35± 3.92	6.69± 3.00	35.4	5.42± 2.51	47.7
TP	0.35-3.21	1.73± 0.67	1.27± 0.65	26.9	0.95± 0.38	45.5
Pb	0.27-0.53	0.45± 0.12	0.32± 0.09	28.9	0.22± 0.06	51.1
Ni	0.11-0.31	0.24± 0.06	0.16± 0.03	33.3	0.09± 0.02	62.5
Zn	0.15-0.36	0.26± 0.05	0.15± 0.04	42.3	0.12± 0.03	53.8
pH	6.8-7.7	7.2 ± 0.3	7.9 ± 0.7	-	7.5 ± 0.5	-
Temperature (^{o}C)	18.5-30.2			25.7 ± 3.3		

Filtration serves as the primary mechanism for removing TSS and particulate phosphorus in CWs. Since heavy metals in storm runoff are mainly in particulate form, their removal is closely linked to TSS removal. Therefore, CWs are likely to remove heavy metals by adsorbing them onto attached suspended solids in stormwater. The removal of TSS, TP, and heavy metals by CPCT-CW and APCT-CW is presented in Table 1. In stormwater, the removal of TSS, TP, Pb, Ni, and Zn using APCT-CW exceeded that of CPCT-CW by factors of 1.98, 1.69, 1.77, 1.88, and 1.27, respectively. APCT incorporates a mixture of filler materials — zeolite, slag, and activated carbon — that effectively absorb pollutants in stormwater. These small-sized filler materials on the concrete created numerous continuous small pores, allowing for the accumulation of suspended solids, organic matter, and heavy metals present in stormwater. The biofilm formed in the voids of the filler mixture contributed to the transformation and absorption of dissolved phosphorus and organic matter in stormwater. Robust microbial growth on the voids of porous concrete and filler decomposed organic matter and absorbs phosphorus particles, thereby reducing TSS in stormwater. Extracellular polymeric substances (EPS) in a biofilm enhanced the removal of particulate matter and heavy metals in wastewater through increased flocculation and adhesion properties. These findings highlighted the superior efficiency of APCT-CW over CPCT-CW in removing TSS, TP, and heavy metals from stormwater.

Temperature and pH play vital roles in the removal of pollutants within CWs. In this study, the experimental temperature range of 18.5 to 30.2 °C provided favorable conditions for the essential bacterial processes of nitrification and denitrification, crucial for nitrogen removal from stormwater. Previous studies have highlighted the optimum temperature range for these processes as between 22 and 27 °C (Yoo et al. 1999). The pH levels measured in CPCT-CW and APCT-CW units were 7.9 ± 0.7 and 7.5 ± 0.5, respectively. The slightly higher pH observed in CPCT-CW compared to APCT-CW can be attributed to the larger quantity of porous cement utilized in CPCT preparation. When the porous concrete was immersed in water, it released alkaline minerals that might hinder bacterial activity and disrupt the structure of EPS within the biofilm. Consequently, the decreased efficiency in removing nutrients and TSS observed in CPCT-CW with higher pH values was likely due to a reduction in microbial populations and disruption of EPS structure.

4. Conclusion

This study has shown the role of porous concrete in ensuring the stability of CWs due to its high compressive strength. The APCT-CW unit, which combined porous concrete with absorption materials like zeolite, slag, and activated carbon, showed outstanding effectiveness in removing nutrients, suspended solids, and heavy metals from stormwater compared to the CPCT-CW unit that solely relies on porous concrete. Moreover, both CPCT-CW and APCT-CW units demonstrated durability and supported plant and microbial growth effectively for pollutant removal from stormwater. These findings highlight the potential of utilizing advanced porous concrete templates in CWs to effectively address urban stormwater runoff pollutants. Incorporating such templates offers a sustainable and efficient approach to managing urban stormwater runoff, thereby contributing to the improvement and preservation of water quality in urban environments.

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Concluding Remarks

Thi Thuong NGUYEN

Through rapid development with inadequate water treatment facilities, a dilemma frequently found in developing countries, substantial volumes of wastewater laden with various pollutants are being discharged into water sources, resulting in adverse health and environmental consequences. Conventional wastewater treatment processes face limitations due to their high energy requirement, elevated costs, and limited feasibility for widespread adoption in rural areas. Consequently, ecological technologies are garnering increased attention as alternative solutions for wastewater treatment. constructed wetlands (CWs) have emerged as prominent and optimal methods within ecological technologies for sustainable, cost-effective, and environmentally friendly waste treatment solutions. However, achieving sustained removal performance and meeting acceptable wastewater standards necessitates the development of appropriate strategies and techniques.

The content of this volume is a record from the international workshop named "New Challenges in Constructed Wetlands for Sustainable Wastewater Treatment: Intensification Strategies Based on Asian Experiences" that was held in July 2023, hosted by the Asia-Japan Research Institute (AJI), Ritsumeikan University. We express our sincere gratitude to all the presenters who contributed to this volume, for generously sharing their knowledge and experience in utilizing CWs for wastewater treatment, as well as strategies for enhancing the treatment performance of CWs in specific operating conditions and areas.

Following each presentation, we conducted Q & A sessions, followed by a final discussion session. Our discussions focused on the following main issues discussed below.

1. CWs as an Affordable and Sustainable Wastewater Treatment Method

CWs offer a cost-effective and eco-friendly approach to wastewater treatment, showcasing numerous advantages over conventional treatment plants. This was underscored by all eight researchers in their respective presentations during the workshop. Throughout the event, the potential of CWs to address diverse wastewater types — including aquaculture wastewater, hospital wastewater, domestic wastewater, mine drainage, swine wastewater, greywater, landfill leachate, RO concentrate, and urban stormwater runoff — was thoroughly explored and discussed.

Their low construction and operation costs make them an appealing option, as they utilize simple materials like gravel, sand, and native plants, which are both readily available and inexpensive. This affordability makes them accessible for various applications, from individual households to larger communities or industrial settings.

One of the key benefits of CWs is their reliance on natural treatment processes. By harnessing filtration, adsorption, and microbial degradation, they efficiently remove pollutants from wastewater. Plants and microorganisms within the wetland ecosystem play crucial roles in breaking down organic matter, removing nutrients like nitrogen and phosphorus, and trapping sediment and contaminants. This natural approach not only enhances water quality but also minimizes the need for mechanical aeration and energy inputs, making CWs highly energy efficient. Moreover, CWs contribute to biodiversity conservation and habitat creation. By creating diverse ecosystems, they support a variety of plant and animal species, including birds, insects, and aquatic organisms. This biodiversity not only enriches local ecosystems but also provides ecological benefits such as habitat restoration and wildlife preservation.

The scalability and flexibility of wetland systems further add to their appeal. They can be designed and constructed to accommodate various scales of wastewater treatment, making them suitable for a range of applications. Additionally, their adaptability to different site conditions allows them to be integrated into existing landscapes seamlessly. Treated effluent from CWs is often of high quality and suitable for non-potable reuse, such as irrigation, groundwater recharge, or recreational purposes. This water reuse not only conserves valuable freshwater resources but also improves overall water quality by removing pollutants and enhancing aesthetic characteristics.

CWs also offer resilience to climate change impacts. By acting as buffers against flooding and storm surges, they mitigate the risk of water pollution and provide valuable ecosystem services in the face of increasing precipitation and extreme weather events. Furthermore, these systems provide opportunities for community engagement and education. By serving as educational resources and recreational amenities, they foster a sense of stewardship and environmental awareness among local communities. This engagement helps raise awareness about the importance of wetlands in water management and ecosystem health, empowering communities to take proactive steps towards conservation and sustainability.

2. Techniques and Strategies for Enhancing Performance in CWs

While CWs offer numerous benefits over conventional technologies, their effectiveness can vary significantly depending on the nature and design of the CW system. Achieving sustainable removal performance and meeting stringent effluent requirements, especially when treating wastewater with complex pollution characteristics and variable pollutant loadings under extreme conditions, necessitates the development of more suitable strategies and techniques. This was the primary focus of discussion at the workshop. Eight Asian researchers presented methods aimed at enhancing the treatment efficiency of CWs tailored to the specific conditions of each region.

Dr. Dan A implemented a tidal flow operation strategy featuring an intermittent mode: one day with wastewater (wet phase) followed by a day without wastewater (dry phase). This approach aims to enhance aerobic conditions in CWs for antibiotic removal because oxygen plays a critical role in controlling nitrification and the biodegradation of organics.

To address urban wastewater treatment challenges in densely populated cities with limited land availability, such as Ho Chi Minh City, Vietnam, Dr. Thi Dieu Hien Vo proposed installing shallow-bed CW systems on the rooftops of buildings for wastewater treatment. She utilized shallow-bed CW systems integrated with rock, charcoal, and oyster shells as substrates to enhance the removal of nitrogen and phosphorus from domestic wastewater. Additionally, she integrated ornamental flowering plants, specifically Campsis radicans and Vernonia elliptica, into the CW system to further improve wastewater purification and create an aesthetically pleasing landscape.

Coming from South Asian countries such as India, Bangladesh, and Sri Lanka, which are facing significant challenges related to rapid population growth, climate change, water pollution, and water shortages, South Asian researchers have proposed CWs as suitable solutions to treat wastewater. To enhance wastewater treatment and reduce land requirements, Dr. Saurabh Singh from India used an algorithm to predict k-values, the first-order areal rate coefficients, to optimize the design of Horizontal Flow Constructed Wetlands (HFCWs) in terms of area requirement for organics and nitrogen removal from wastewater. He found that the use of deep HFCWs provides a conducive environment for in situ growth and the coexistence of diverse microbial populations supporting contaminant and nitrogen removal, specifically anammox bacteria. Dr. Nehreen Majed from Bangladesh introduced her endeavors to improve wastewater treatment, such as using hybrid CW systems and electrodes-integrated CWs for landfill leachate treatment. Notably, the electrodes-integrated CWs showed excellent treatment performance attributed to providing additional surface area for microbial attachment and electron transfer, thereby promoting the degradation of organic matter and the removal of pollutants from wastewater. Additionally, microbial fuel cells (MFCs) harness the microbial metabolism of organic matter to produce electricity, which can potentially be harvested for various applications, thereby offsetting energy costs associated with wastewater treatment. Besides these, planted electrodes offer a stable and durable substrate for microbial attachment and biofilm formation, ensuring the longevity of the microbial community within the MFCs, leading to consistent and reliable performance over time. From Sri Lanka, Dr. Shiromi Dissanayaka incorporated native plants, namely Thunhiriya, and fungal inoculum into CWs to enhance greywater treatment. Fungi, particularly mycorrhizal fungi, can absorb and assimilate nutrients such as nitrogen and phosphorus from wastewater. Introducing fungal inoculum can enhance the nutrient removal efficiency of CWs, thus improving water quality. Additionally, fungi form symbiotic relationships with plant roots, promoting wetland plant growth and health. She also investigated the use of native materials such as Grumusol in Sri Lanka and recycled materials (clay brick, laterite brick) as substrates in CWs to enhance nutrient and metal removal, respectively.

Dr. Thi Thuong Nguyen inoculated microorganisms into the CW system by adding pond sediment. In addition, an external carbon source from domestic wastewater was also added to the wastewater to promote the biological processes for heavy metal removal from acid mine wastewater in Japan. The results showed that CW treatment performance increased by around 20% compared to the period without external carbon source supplementation.

Another strategy for improving wastewater treatment involves utilizing materials with high adsorption capacity. Dr. Obey utilized corncobs, an agricultural byproduct, to produce biochar, which was then examined as a filter material in CWs to enhance wastewater treatment. Corncob biochar, with its high surface area, porous structure, and cation exchange capacity, proves effective in adsorbing contaminants and providing a habitat for beneficial microorganisms. These microorganisms aid in organic matter degradation and contaminant transformation, thereby boosting pollutant removal efficiency. Additionally, corncob biochar buffers pH fluctuations, maintaining an optimal environment for microbial activity and nutrient uptake by plants. Furthermore, its resistance to decomposition improves the longevity and stability of CWs, ensuring sustained treatment performance over time. Dr. Obey's research revealed that corncob biochar exhibits a high capacity to adsorb antibiotics (CFX, OFX, and DLX). A pilot-scale CW filled with corncob biochar was conducted for treating swine wastewater, demonstrating effective removal of organic matter and nutrients, and meeting effluent quality standards for discharge into surface waters.

Similarly, focusing on the substrate, one of the three main components of CWs, Dr. Van Tai Tang developed advanced porous concrete combined with filler materials such as zeolite, slag, and activated carbon to enhance the treatment performance of CWs for urban stormwater runoff. Additionally, durability, high water infiltration, and support for plant growth are also advantages of advanced porous concrete in stormwater decontamination and management, as well as in creating urban landscapes.

3. CWs Challenges and Future Perspectives

In recent years, there has been a significant and rapidly growing interest in utilizing new strategies and techniques to improve removal efficiency in CWs. Pollutant removal in CWs involves a complex interplay of physical, chemical, and biological processes, which can be greatly affected by various environmental and operational factors. However, the primary mechanisms and pathways responsible for removing pollutants remain unclear. Further studies are required to elucidate these mechanisms and pathways, particularly focusing on understanding the structure and distribution of microbial communities. Identifying associated bacteria that aid in the removal process will also be crucial for optimizing the treatment performance of CW systems. Additionally, it is essential to assess the influence of operational factors and optimize design parameters to encourage the development of new removal pathways within the system.

Another significant challenge of CWs is assessing their long-term performance. Existing studies primarily focus on small-scale and short-term assessments, which makes it difficult to comprehensively evaluate the effectiveness of CWs over extended periods, such as 10 or 20 years. To advance CW technology, there is a need for more research on large-scale CWs treating real wastewater. Furthermore, studies should prioritize the evaluation of long-term performance.

Using industrial materials like fly ash, steel slag, or mortar in CWs showed promise for enhancing pollutant removal. These materials often boast ample surface areas, providing ideal habitats for microbial communities crucial in breaking down pollutants such as heavy metals or organic contaminants. Furthermore, repurposing industrial waste as substrates offers an eco-friendly solution for waste disposal, alleviating pressure on landfills and curbing environmental pollution. However, potential adverse effects warrant attention. Some industrial materials may leach harmful substances into water, jeopardizing water quality and aquatic life. Additionally, evaluating the long-term stability and durability of these materials in wetland settings is imperative. Substrate degradation or structural failure could lead to pollutant release or disrupt wetland functions. Thus, thorough risk assessment and monitoring are vital to mitigate adverse effects and optimize artificial wetland systems' efficacy.

Additionally, to ensure the sustainability of CWs in wastewater treatment, it is essential to incorporate economic, social, and environmental protection aspects. While technical strategies have been successfully developed to improve treatment efficacy in CWs, the assessment of CW sustainability has been overlooked. Hence, there is a necessity for comparative analysis and evaluation of these CWs to better comprehend environmental and social sustainability. Moreover, specific cost-benefit analyses for these applications are largely absent. Therefore, further research should focus on investigating and evaluating this aspect in real-scale applications to enhance understanding of their full potential and accuracy.

The widespread implementation of CWs faces several challenges, including limited land availability, lack of awareness among policymakers and stakeholders, and inadequate funding. Moreover, climate change-induced alterations may affect CW performance. Thus, integrating CWs into urban planning and development strategies for sustainable water management, alongside supportive policies and regulations, is crucial. Promoting knowledge sharing and capacity building among stakeholders is essential to facilitate best practices and innovation in CW implementation and management. Incorporating CWs into climate change adaptation and mitigation strategies at national and regional levels, particularly in Asia, can help reduce coastal vulnerability and provide natural flood management infrastructure.

ONLINE ISBN 978-4-910550-06-0
PRINT ISBN 978-4-910550-07-7

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