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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).

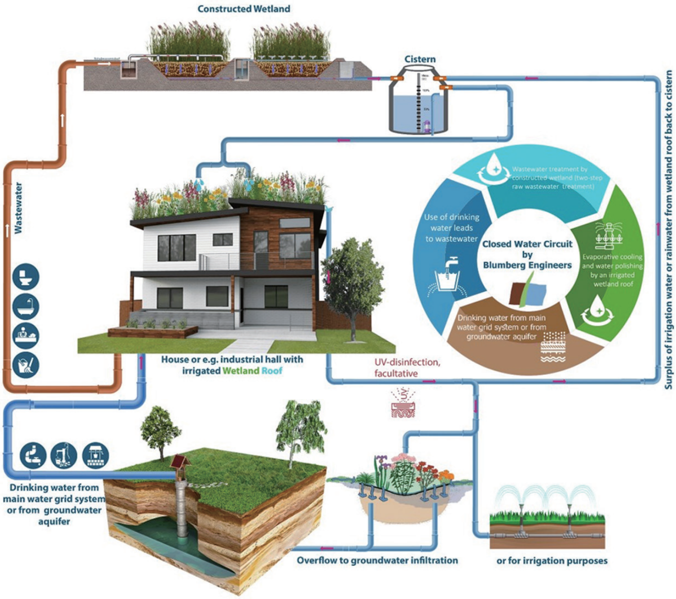

Figure 1. Diagram of wetland roofs for wastewater treatment.
Source: Ingenieurbüro Blumberg

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.

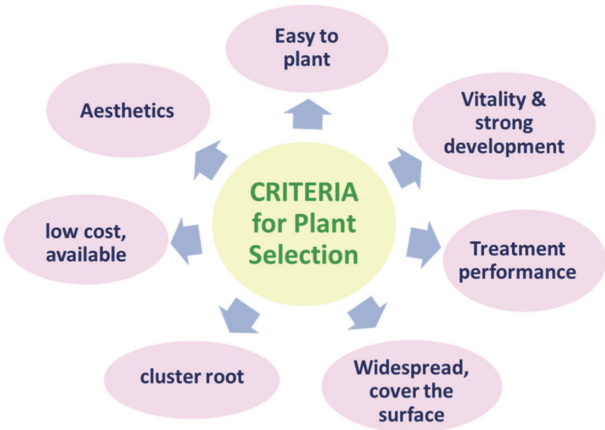

Figure 2: The criteria for plant selection.
Source: Author

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.

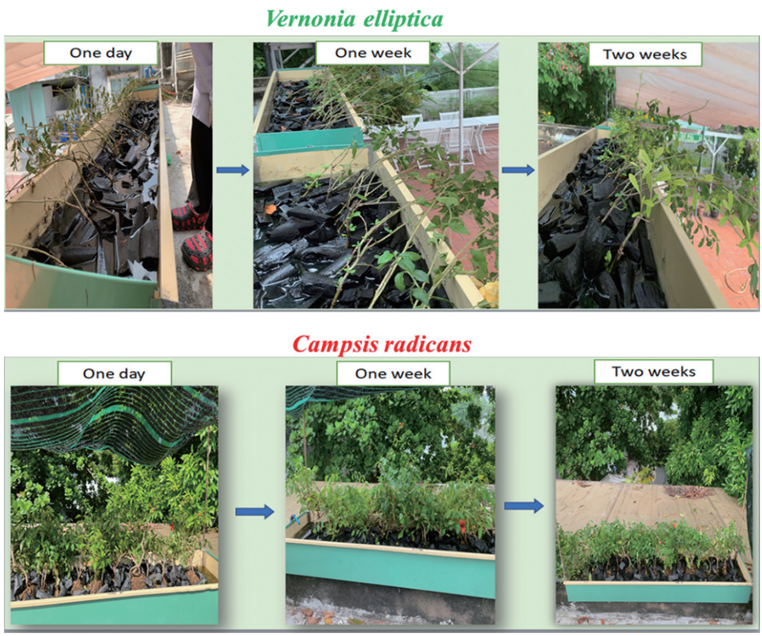

Figure 3: The adaptation of Vernonia elliptica and Campsis radicans for two weeks of the experiment. Source: Author

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

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