A mini-review on shallow-bed constructed wetlands: A promising innovative green roof

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Abstract

Shallow-bed constructed wetland (SCW) has been used as a secondary wastewater treatment technology with low cost, less maintaining and operational requirements and environmental friendliness. Green roof has been considered an effective solution in saving energy, enhancing green space, providing landscape aesthetics, limiting stormwater runoff causing flooding, and purifying air pollutants. Recently, a wetland roof (WR) has been interested as a good integration of these two technologies. To gain an insight understanding of this combination, this review aimed to provide the potential applications of SCW on the roof as a WR. Factors affecting

performance, benefits and challenges of SCW were also discussed. The literature data showed WR was a promising green technology that needed to be investigated and scaled-up in the future.

Keywords:

Shallow-bed constructed wetland, Green roof, Wetland roof, Wetroof.

Introduction

Urbanization has been threatening water and air quality, urban climate, green space, and energy consumption. For example, more than 99% of municipal wastewater in Africa has not been treated, followed by 86% in Latin America, 65% in Asia, 34% in Europe, and 10% in Canada and United States [1]. Residential and household wastewater was reported to be untreated or uncompletely treated by a simple system like a septic tank, then discharged directly into the receiving sources [2]. Air pollutants and dust generated from the vehicles and stacks of factories have worsened urban air quality [3,4]. Besides, the frequent occurrence of urban heat-island phenomenon for which temperature of the urban center is higher than that of neighboring areas has limited the diffusion of air pollutants, resulting in the unhealthy air quality at the ground-level [5]. The rapid occupation and development of buildings have been narrowing the city's green space, leading to suffocation and discomfort for human [6]. Indeed, the current green space densities in some cities (e.g. 11 m^2 $person^{-1}$ in Hanoi, 5 m^2 $person^{-1}$ in Manila, 3 m^2 $person^{-1}$ in Bangkok and 0.7 m^2 $person^{-1}$ in Ho Chi Minh) are significantly low compared to the average green space index (39 m^2 $person^{-1}$) proposed by the Economist Intelligence Unit [7]. Another issue concerned in urban areas is energy security. According to the International Energy Agency report in 2018, the total world energy consumption increased by 2.3% compared to 2017 and 4% compared to the ten-year period 2005 - 2015 [8]. The above-mentioned challenges have adversely affected human activities and health as well as the ecosystem.

In order to deal with these problems, in recent years, wetland roof (WR), a combination of shallow constructed wetlands (SCWs) and green roof, has been investigated and developed. This technology is not only low-cost and effective in terms of domestic wastewater treatment [9-12] but also highlights the potential for purifying air pollutants, improving green space, reducing flood, conserving biodiversity, saving energy and providing landscaping aesthetic [13,14]. The benefits achieved from this combined technology have not reviewed yet. So far generally the WRs have not been developed to meet above-mentioned benefits, except wastewater treatment. Thus, this review aims to provide currently available knowledge originating from scientific research, such as an overview of SCWs, their potential application as WRs, their associated influence factors, benefits, challenges, and potential solutions for the future applications.

Shallow-bed constructed wetland (SCW) and associated influence factors

Shallow-bed constructed wetland

Constructed wetland (CW) have been used to treat a variety of wastewaters including urban runoff, municipal, industrial, agricultural and acid mine drainage [15,16]. For the free flow CWs, typical substrate bed and water depths are 0.2 - 0.3 m and 0.3 - 0.6 m, respectively. For the subsurface flow CWs, typical substrate bed depths are 0.5 - 1.0 m and water depths are maintained below the substrate bed [16,17]. In order to improve nitrogen treatment efficiency, shallow-bed constructed wetland (SCW) has been developed in recent years. The substrate bed of SCWs is shallower than those of CWs. Several studies indicated that oxygen transfer into SCW could be optimized without aeration by simply limiting the effective depth of the media layers to the maximum depth of the plant roots [18-20]. Garcíaet al. [18] found that horizontal subsurface flow CW with shallow bed (0.27 m) had a better performance than a deeper one (0.5 m) in removing nitrogen and organic compounds. Besides, in comparison with conventional CWs, SCW reduced the gravity load of the whole system and the quantities of materials used, leading to the lower cost of operation and maintenance. With reduced weight, SCW has been investigated and developed with roof conditions (called wetland roof - WR) for the purpose of treating domestic wastewater and taking advantage of other environmental benefits such as green space, energy saving, etc. In order to develop and apply WR successfully, the following influencing factors should be considered throughout the design and operation processes.

Effects of plant

Plants – macrophytes stabilize the surface of the material layer and provide a green area. The plant root system could facilitate physical filtration, prevent clogging, uptake nutrients and metals, and work as a media for attached bacteria [21]. Plants have been proved to have a significant impact on the pollutant treatment performance of CWs. Carballeiraet al. [22] found that the planted CWs had higher removal efficiencies (92.3% for COD and 49% for N) than the unplanted CWs (65.7% for COD and 25% for N) in the same operating conditions. Besides, when increasing surface loading rate (SLR) or hydraulic loading rate (HLR), the organic removal efficiency of CW with *Phragmites australis* had a smaller decrease (from 95% to 94%) compared to unplanted CW (from 93% to 78%). Similar results were also observed with *Cyperus javanicus Houtt* in WR system [10]. However, Vymazal [23] reported that nutrient removal efficiency of CWs insignificantly increased with the presence of macrophytes. So far, *Phigateites australis* (Common Reed) was used most frequently for SCWs (Table 1). In addition, *Bryum muehlenbeckii, Iris pseudacorus,* and *Juncus effucus* were also used [22,24]. Recent studies (Table 1) of SCWs or WRs focused on studying other plant species, which could adapt to rooftop conditions and increase landscape aesthetics [10,12,25]. Generally, plants have positive effects on the performance of SCWs. Moreover, nutrient uptake capacity of plants is different and depends on the characteristic of species.

Effects of hydraulic loading rate

Another important factor influencing the performance of SCW is the hydraulic loading rate (HLR). Based on literature data depicted in Table 1, HLRs applied for SCWs varied from 160 to 450 m^3 ha^{-1} day^{-1}, excepted in the study of Taniguchiet al. [26]. In general, lower HLRs resulted in higher nutrient removal rates. In higher HLRs, increased water velocity reduced the contact time between wastewater and microorganisms, resulting in lower treatment efficiency. Similar results were demonstrated in many conventional CWs [27-29]. However, Taniguchiet al. [26] stated that higher HLRs resulted in higher nitrogen removal rate. Higher HLRs could lead to better volumetric phosphorus adsorption in extremely SCW because of some condition depended on HLR such as oxidation-reduction potential. In fact, a favorable range of HLR must be considered during designing.

Effects of feeding pattern

SCW has two feeding strategies: intermittent and continuous. The feeding pattern can influence the CW performance by enhancing oxygen transfer and diffusion in the system. Some studies have been carried out to fully evaluate the effects of feeding pattern on the performance of SCW. Caselles-Osorioet al. [30] reported that the feeding strategies did not significantly influence the COD removal performance of SCW. Meanwhile, intermittent feeding pattern was observed to accelerate the ammonium removal (average 80 to 99%) better than the continuously fed system (average 71 to 85%) as it provided the more oxidized condition [30,31]. However, with the same reason, this feeding method was less effective than the continuous pattern in removing sulfate. The rich oxygen condition of intermittent feeding was considered to be the result of water depth fluctuation which gave the bed media opportunities to be exposed to the atmosphere, enhancing oxidization and wastewater – biomass contact [30]. These findings led to the consideration of the application of intermittent feeding in SCW or WR which aimed at enhancing ammonium removal and reducing energy consumption for pumping water, especially high capacity system.

Effects of bed media

The bed media is considered as a most important design factor for its strong impact on the performance of SCWs in terms of vegetation, physical and biochemical processes, hydraulics, wastewater treatment, and the other functions [16,21]. Bed media with porous structure material acted as pollutants absorbing material, provided an environment for macrophytes to grow and maintained good hydraulic conductivity [32]. According to Table 1, the most common bed materials for SCW were sand, soil and gravel. Results reported by Zapater-Pereyraet al. [11] showed that wastewater treatment efficiency of WR was significantly higher than others due to using light expanded clay aggregates (LECA) and polylactic acid beads (PLA) as bed materials. Recently, only a few studies provided the evaluation of the effects of bed media with different materials on CWs performance. For example, higher phosphorus removal (89%) was observed when using recycled brick while high nitrogen removal (≥ 86%), phosphorus removal (≥ 91%) and organic removal (≥ 92%) were reported in CWs that packed with sugarcane bagasse and biochar media [33,34]. Many studies have been done to assess the effects of various materials for enhancing contaminants removal performance. In fact, the materials such as organic wood-mulch, rice husk, zeolite, lightweight aggregates, alum sludge, slag, peat, maerl, compost, shale or even industrial wastes were introduced as potential bed media of CWs to optimize the removal of nitrogen, phosphorus, organics and the other pollutants [34,35]. The criteria for bed media would depend on the characteristic of materials, such as absorbing capacity, availability, porosity and permeability. These characteristics would be fit in significant scenarios, distributing in three main kinds included natural material, artificial material, and by-product from industrial (alum sludge, cinder, ash), agricultural (sugarcane bagasse) production [35,36]. Therefore, once SCWs are applied as WRs, the bed materials should be studied further in order to find high-performance alternative materials (lighter, high absorb capacity, long lifetime, etc.) instead of those common materials.

Potential benefits of shallow constructed wetland (applied as wetland roof)

Wastewater treatment and reuse

One of SCW's remarkable benefits is the contribution to wastewater treatment. Table 1 shows summary data of horizontal subsurface flow SCW applications for domestic wastewater treatment. Although its material depth is lower than that of CW, the pollutant treatment efficiency is relatively high. Generally, the average COD removal efficiency is over 70% with the rates up to 200 kg ha^{-1} day^{-1}. As discussed above, plants play a very important role in oxygen diffusion. *Phragmites australis* had higher oxygen transfer rate (up to 12 g m^{-2} day^{-1}) than other plants [20]. Therefore, SCW planted *Phragmites australis* showed significant higher organic removal. However, wherever appropriate *Phragmites australis* has fast-growing rate, high biomass production and height of 1- 3 m [21]. Therefore, it should be carefully considered for WR application. The shallow bed depth facilitated the nitrification process in SCW [18], resulting in relatively high efficiency in the treatment of total nitrogen (up to 93%, 53 kg ha^{-1} day^{-1}). Generally, the COD, BOD and TN concentrations in the effluent were lower than 100 mg L^{-1} which was considered for water reuse of agricultural purposes [37]. From the overview results, SCW, when applied as wetland roof, can handle domestic wastewater of households/buildings as well as has the potential to supply water for purposes that do not require high-quality water such as watering plants, washing floor or flushing toilet. In addition, the effluent of SCW, under better control of trace pollutants and bacteria (e.g. oxidation), can be reused for vegetable irrigation purposes or even adding for tap water.

Table 1. Summary of applications for horizontal subsurface shallow-bed constructed wetlands (SCWs) and wetland roofs (WRs) treating domestic wastewater

Type	Subtrate/ Water depth (m)	Bed materials	Plant species	OLR	HLR	HRT (h)	Removal (%)	Removal rate (kg ha^{-1} day^{-1})	Effluent (mg L^{-1})	References
WR	0.20/0.10	Soil, sand, small rock	*Melampodium Paludosum*	36 (COD) 21 (TN) 2 (TP)	340	18	71 (COD) 89 (TN) 74 (TP)	28 (COD) 19 (TN) 1.4 (TP)	25-65 (COD) < 10 (TN) < 2 (TP)	Bui et al. [25]
WR	0.20/0.10	Soil, sand, small rock	*Arachis Duranensis* *Evovulus Alsinoides* *Cyperus Alternifolius Linn* *Philodendron Hastatum*	49 (COD) 22.5 (TN) 1.8 (TP)	340	NA	64-86 (COD) 52-92 (TN) 20-88 (TP)	36-49 (COD) 13-24 (TN) 0.7-2.0 (TP)	7-88 (COD) 6-35 (TN) < 6 (TP)	Phan et al. [12]
WR	0.20/0.10	Soil, sand, small rock	*Cyperus rotundus L.* *Zenith zoysia grass* *Cynodon dactylon* *Imperata cylindrical* *Cyperus javanicus Houtt* *Eleusine indica (L.) Gaertn.* *Struchium sparganophorum (L.) Kuntze* *Kyllinga brevifolia Rottb*	30-60 (COD) 15-39 (TN) 1.1-1.2 (TP)	260-400	23-30	61-90 (COD) 62-90 (TN) 54-92 (TP)	16-33 (COD) 9-21 (TN) 0.4-0.9 (TP)	29-34 (COD) 6.8-32.3 (TN) 0.2-0.6 (TP)	Vo et al. [10]
WR	0.90/NA	Sand, organic soil, LECA, PLA	*Lolium perenne,* *Festuca rubra,* *Poa pratensis*	12 (COD) 5 (TN) 0.6 (TP)	160	91.2	83 (COD) 93 (TN) 97 (TP)	NA	132 (COD) 19 (TN) 1 (TP)	Zapater-Pereyra et al. [11]
SCW	NA/0.27	Coarse, small granitic gravel	*Phragmites australis*	49-77 (COD) 26-63 (BOD_5) 11-17 (NH_3)	200-450	57.6-132	33-79 (COD) 18-37 (BOD_5) 13-38 (NH_3) 5-10 (DRP)	16-43 (COD) 6-22 (BOD_5) 1.8-4.7 (NH_3) 0.1-0.2 (DRP)	9.3-29 (TOC) 5.9-35 (NH_4^+-N) 0.68-19 (NO_3^-)	García et al. [18]
SCW	0.35/0.30	Gravel	*Phragmites australis*	60 (COD)	182-364	72-144	70-94 (COD) 20-57 (NH_4^+-N)	38-60 (COD) 0.9-2.6 (NH_4^+-N)	10-45 (COD) 7.6-14.2 (NH_3-N)	Caselles-Osorio and García [38]
SCW	0.30/0.25	Gravel	*Phragmites australis*	74-100 (COD) 6.7-10 (NH_4^+-N)	260-390	50.4-79.2	70-84 (COD)* 71-85 (COD)** 71-85 (NH_4^+-N)* 80-99 (NH_4^+-N)**	NA	63-125 (COD) 0.3-12 (NH_4^+-N) 59-127 (SO_4^{2-})	Caselles-Osorio and García [31]
SCW	0.35/0.30	Gravel	*Phragmites australis*	230 (COD)	364	72	91-92 (COD) 43-57 (NH_4^+-N)	179-202 (COD) 6.6-8.7 (NH_4^+-N)	50 (COD) 18-24 (NH_4^+-N)	Caselles-Osorio et al. [30]

Type	Subtrate/ Water depth (m)	Bed materials	Plant species	OLR	HLR	HRT (h)	Removal (%)	Removal rate (kg ha^{-1} day^{-1})	Effluent (mg L^{-1})	References
SCW	NA/0.20	Gravel	*Phragmites australis*	20.7 (COD)	400	122.4	70.5 (COD) 43 (NH_4^+-N)	146 (COD) 9 (NH_4^+-N)	154 (COD) 31(NH_4^+-N)	Albuquerque et al. [36]
SCW	NA/0.20	Filtralite NR	*Phragmites australis*	17.9 (COD)	350	136.8	94 (COD) 91.7 (NH_4^+-N)	148 (COD) 11 (NH_4^+-N)	32 (COD) 4 (NH_4^+-N)	Albuquerque et al. [36]
SCW	0.075//0.02	Sand	*Phragmites australis*	19.4 -90.7 (TN) 2-10 (TP)	1500, 4500, 7500	2.4-12	46-73 (TN) 6.5-9.6 (TP)	14-53 (TN) 0.5-1.6 (TP)	NA NA	Taniguchi et al. [26]
SCW	0.30/0.02	Sand	*Phragmites australis*	19.4 -90.7 (TN) 2-10 (TP)	1500, 4500, 7500	2.4-12	37-77 (TN) 12-61 (TP)	14.8-38 (TN) 1.4-2.5 (TP)	NA NA	Taniguchi et al. [26]
SCW	0.30/0.25	Gravel	*Phragmites australis*	47 (BOD)	285	3-5	80 (COD) 73 (NH_4^+-N)	69 (COD) 5 (NH_4^+-N)	55.8-63.3 (COD) 4.11-35.4 (NH_4^+-N) 4.84-5.58 (TN) 1.87-3.47 (TP)	Pedescoll et al. [39]
SCW	0.20/NA	Gravel	*Bryum muehlenbeckii*	41 (COD) 6.7 (NH_4^+-N) 7.1 (TN)	120	156	86-88 (COD) 83-92 (NH_4^+-N) 75-86 (TN) 91-92 (TP)	35-36 (COD) 5.4-6.6 (NH_4^+-N) 5.2-6.5 (TN) 0.3-0.4 (TP)	42.9-45.1 (COD) 4.5-9.1 (NH_4^+-N) 8.5-14.1 (TN) 0.27-0.31 (TP)	Wang et al. [24]
SCW	NA/0.25	Gravel	*Phragmites australis*	42-84 ($CBOD_5$) 13-26 (TN)	180-360	NA	71-82 ($CBOD_5$) 23-30 (TN) 3-9 (NH_4^+-N)	34-69 ($CBOD_5$) 3-8 (TN) 0.5-0.9 (NH_4^+-N)	43.4 ($CBOD_5$) 50.4 (TN) 49.5 (NH_4^+-N)	Nivala et al. [20]
SCW	0.35/0.30	Crushed granitic gravel	*Phragmites australis* *Iris pseudacorus* *Juncus effucus*	29-77 (COD) 17-50 (BOD) 9-19 (TN)	230-260	NA	69-95 (BOD) 20-52 (NH_4^+-N)	NA	4.9-64.5 (BOD_5) 29.8-35.8(NH_3)	Carballeira et al. [22]
SCW	0.25/0.20	Gravel	unplant	148 (COD) 67.8 (BOD)	300	67.2	60 (COD) 69 (BOD_5)	33 (COD) 27 (BOD_5)	< 80 (COD) < 60 (BOD_5)	De Matos et al. [40]

Remarks: OLR = organic loading rate (kg ha^{-1} day^{-1}); HLR = hydraulic loading rate (m^3 ha^{-1} day^{-1}); HRT = hydraulic retention time; * = continuous feeding; ** = intermittent feeding; LECA = light expanded clay aggregates, PLA = polylactic acid beads; DRP = dissolved reactive phosphorus

Air quality improvement

It was estimated that more than 50% of the world's population living in urban areas [41]. The rapid rate of industrialization and transportation has contributed to accelerating the growth of the economy, however, it also has worsened the urban air quality [42]. According to recent studies, the climate in the central of the cities was getting warmer than the surrounding area due to urban heat inversion. This phenomenon has made air pollutants unable to disperse vertical, resulting in poor ground-level air quality [4]. In fact, plants are known to be urban lungs as they help purify the air. According to the summary results of literature reviewed by Gourdji [43], air quality was significantly improved by green roof plants. In fact that adsorption capacity of green roof were 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, and 0.10-0.59 g m^{-2} for SO_2. Notably, vegetation significantly affects CO_2 concentration through the absorption and emission processes. For example, Li et al. [44] found that the CO_2 absorption rate at day time were nine times higher than the CO_2 emission rate at night time. Ismail et al. [45] also reported that approx. 48.19 kg CO_2 were annually adsorbed by 102 pots of *Ipomoea pes-caprae* planted on the flat roof in Malaysia.

Green area improvement

Besides, green trees were also reported to have radiation and transpiration absorb abilities, making the urban atmosphere cooler and fresher [46]. However, the rapid urbanization trend has made urban green space become narrower, especially in developing countries. Specifically, green space of Latin American countries is up to 255 m^2 $person^{-1}$ while that of Asian countries is about only 39 m^2 $person^{-1}$. The actual situation in these Asian countries was very low, e.g. Ho Chi Minh City (Vietnam) with 0.7 m^2 $person^{-1}$, Bangkok (Thailand) with 3 m^2 $person^{-1}$ and Manila (Philippines) with 5 m^2 $person^{-1}$ [7]. Therefore, if SWCs used as WRs would contribute not only to wastewater treatment but also to enhance green space [47]. Vo et al. [10] also studied the possibility of providing green space of 8 different plant species on WR systems. The results showed that one square meter of WR could provide 67 - 99 m^2 of special green leaf area. This suggests that WR has a relatively high potential in improving the narrowed urban green space. However, these studies are very few. Besides, almost no research has been conducted to evaluate the ability to purify air pollutants as well as to reduce noise by SCWs or WRs systems. Therefore, more studies focusing on these aspects need to be done in the future to have a more comprehensive evaluation.

Energy saving

Another significant benefit of the SWC applied as WR is energy saving. SCW's flora system and bed materials contribute strongly to solar energy absorption and reducing heat transfer, leading to lower energy consumption for air-conditioning systems during hot days. There have been many studies proving the heat-saving potential of GR systems. For example, the findings of Jaffal et al. [48] showed that the average temperature inside a traditional building varied between 19 - 31℃ while that of GR ranged from 19 - 28 ℃. By the insulation function and the restriction of heat transfer by plants, the indoor temperature was 5.6 ℃ warmer than the outdoor temperature on cold days. This could save annually about 2.2 kWh per square meter of GR for cooling and heating. Ebadati and Ehyaei [49] also studied the benefits of GR in saving electricity in different areas in Iran. In tropical areas, GR helped to cool down the building and thereby reduce the energy consumption for air-conditioning systems. In cold areas, GR helped to warm up the building and thereby reduce the energy consumption for heating. The results indicated that the total annual electricity demand decreased up to 12.5% (cold areas) and 23% (tropical areas) depending on climate conditions. Energy saving potential in the tropical regions was more effective than the cold areas.

An emerging function of SCW is the synthesis of electrical power. In recent years, the combination of CW and microbial fuel cells (MFC) has been more concerned with wastewater treatment and energy production. According to the overview results of Doherty et al. [50], the energy produced by CW-MFC system ranged from 1.6 to 47.3 kWh kg^{-1} COD depending on the organic load, redox conditions, plants, and microorganisms. Overall, the energy saving of the GR system and the energy generation of the CW-MFC have been clearly demonstrated. However, the energy-saving function of WRs needs to be studied and evaluated because of the difference in plants, bed materials and bed depths between WRs, GRs and CWs. In addition, the energy consumed by pumping wastewater to the roof needs to be taken into account.

Other benefits

In addition to domestic wastewater treatment, WR was proved to be one of the effective rainwater management solutions, reducing flooding in urban areas where the drainage system was considered to be limited and old [51]. On the other hand, plants of WRs were proved to be effective in reducing the noise emitted by vehicles [52]. In terms of aesthetics, some plants (*Melampodium Paludosum*, *Arachis duranensis*, *Evolvulus alsinoides*, *Cosmos Bipinnuatus)* applied on WRs not only have the ability to treat wastewater but also produce good landscape aesthetic [12]. Compared to normal roofs, WR can give people a relaxing space after exhausting working hours. In addition, WR helps restore biodiversity as it provides a safe space that attracts harmless insects, for example, bees, butterflies, dragonflies [53]. The potential benefits achieved from WR is shown in Fig. 1.

Fig. 1. Potential benefits of wetland roof

Challenges and solutions for wetland roof

From the reviews discussed above, a better understanding of the importance when SCW applied as WR was given. Besides the obvious benefits, there are still certain limitations. For example, the gravity load of the SCW system can affect the load capacity of the roof. WRs in previous studies were designed with the gravity load of 163 kg m^{-2} [10]. However, to improve safety, light bed materials should be considered to replace traditional materials such as sand, stone, and gravel. One drawback concerned is that the odor nuisances arise from wastewater and during the process of decomposing organic matter from the SCW. To overcome this problem, wastewater can be stored in closed tanks. In addition, the SCW with the horizontal subsurface flow, which has the water level below the bed material layer, can minimize the risk of odor and infectious microorganisms [16]. The SCWs with the down-to-up vertical subsurface flow can prevent odor nuisances and infectious organisms such as flies and mosquitoes [54]. Moreover, the mosquito generation will be significantly limited when the plants are harvested regularly and maintained at a certain height of about 20 cm.

Cost for investment, installation, operation and maintenance is one of the top concerns of WR applications. To date, no studies have conducted a cost benefit analysis of WR. Because WR is the combination of SCW and GR, the cost benefit analysis of GR can be referred. Cost and benefit depend on different factors, e.g. number of roofs, type of used materials, location of buildings, etc. For example, the case study in Helsinki – Finland, benefit and cost ratio varied from 0.5 - 1.1 for a single GR installation and 0.9 - 2.2 for 50% infrastructure installed GR [55]. A cost benefit assessment should be conducted for the actual WR to understand it more fully and accurately.

Based on the above analysis of benefits and challenges, WR is feasible and promises to bring significant environmental benefits. Diagrams of typical wetland roofs with roof slope 0° and 15° proposed by Michael Blumberg is shown in Fig. 2. In order to provide valuable evidence and insights into these potential benefits, WR needs to be investigated more in further studies.

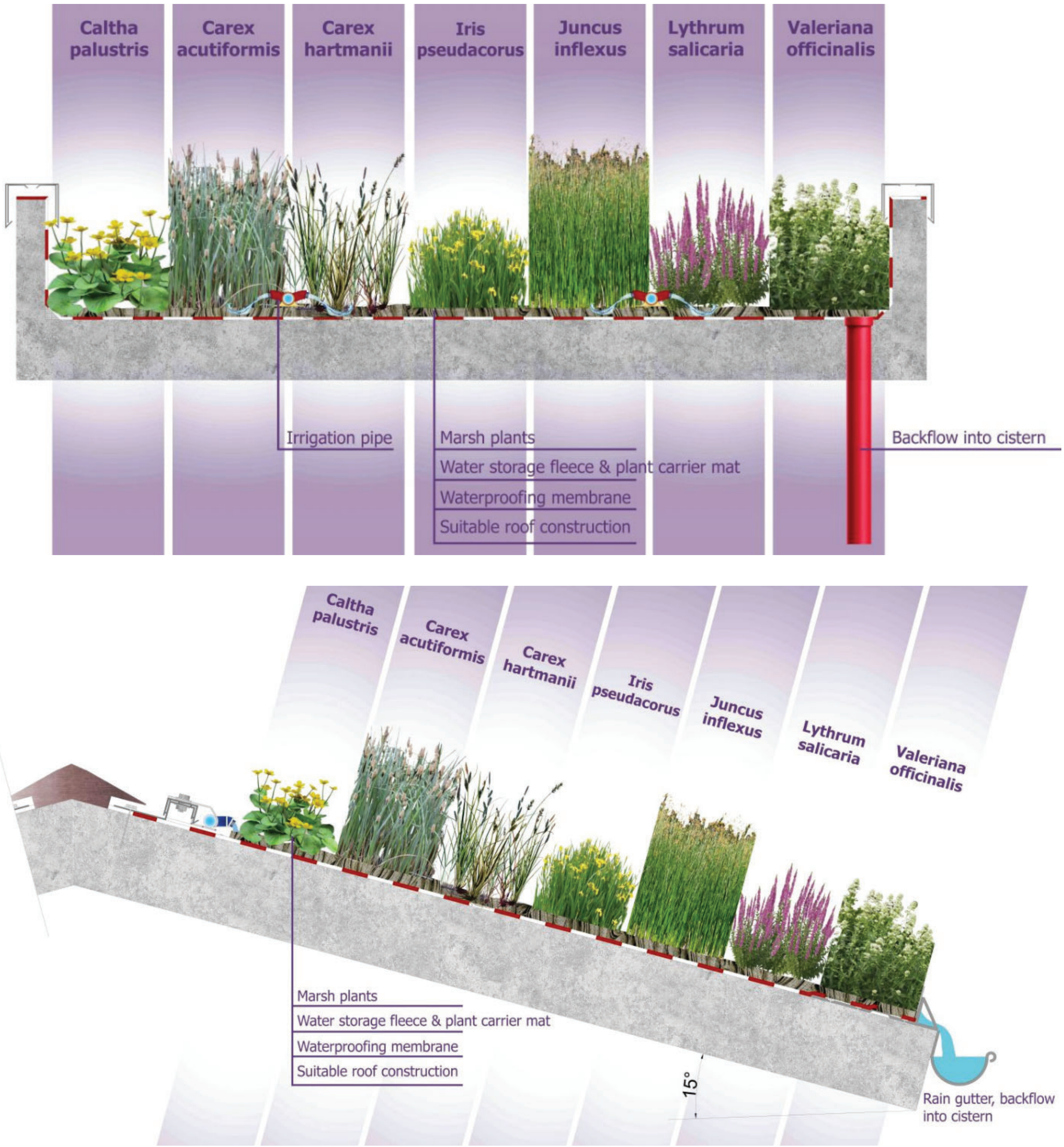

Fig. 2. Diagrams of typical wetland roofs with roof slope 0° and 15°(*https://rhizotech.de/en/131/wetland-roof*)

Conclusions

Shallow-bed constructed wetland (SCW) is successfully used for wastewater treatment in many parts of the world but their other potential benefits seem to be ignored. From the results of the review, SCW in the form of wetland roof (WR) can be an economical and environmental option, especially for developing countries where low-cost wastewater treatment strategies are critical. Once it overcomes barriers including gravity loads, bed materials, odors, infectious organisms, and biomass harvest, WR will become a promising secondary treatment technology, which is able to adapt to climate changes and in accordance with the development strategy of green cities.

Conflict of interest statement

The authors declare no conflict of interest.

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September 6th, 2019

Prof. D. Barceló
Editor-in-Chief,
Current Opinion in Environmental Science & Health

Declaration of interest

Dear Prof. D. Barceló,

I am writing to submit the following manuscript entitled ***"A mini-review on shallow-bed constructed wetlands: A promising innovative green roof"*** for publication in the **special issue of Green Technologies for Environmental Remediation** as a review article. The paper is jointly prepared by Thi-Dieu-Hien Vo, Xuan-Thanh Bui*, Chitsan Lin, Van-Truc Nguyen, Thi-Khanh-Dieu Hoang, Hong-Hai Nguyen, Phuoc-Dan Nguyen, Huu Hao Ngo, Wenshan Guo.

Declaration of interest:

After consulting with all authors, we would like to inform that
"No conflict of interest. Also there are no funding agencies are provised to this review paper."

In addition, we confirm that the manuscript has been read and approved by all authors. We also guarantee that other authors agreed to this submission. I declare that this manuscript has not been published and not under consideration for publication elsewhere. We have formatted the original article based on the Instructions to Authors of the journal.

I really appreciate your time and consideration. We are looking forward to hearing from you soon.

Yours sincerely,

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