Wastewater treatment and biomass growth of eight plants for shallow bed wetland roofs

Thi-Dieu-Hien Vo[1,2], Xuan-Thanh Bui[3]*, Dinh-Duc Nguyen[4], Van-Truc Nguyen[5], Huu-Hao Ngo[6], Wenshan Guo[6], Phuoc-Dan Nguyen[3], Cong-Nguyen Nguyen[7] & Chitsan Lin[8]

[1]*Environmental Engineering and Management Research Group, Ton Duc Thang University, Ho Chi Minh City, Vietnam.*

[2]*Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam. Email: vothidieuhien@tdt.edu.vn.*

[3]*Faculty of Environment and Natural Resources, University of Technology, Vietnam National University – Ho Chi Minh, Viet Nam. Email: bxthanh@hcmut.edu.vn.*

[4]*Department of Environmental Energy & Engineering, Kyonggi University, 442-760, Republic of Korea.*

[5]*Institute of Research and Development, Duy Tan University, 03 Quang Trung, Da Nang, Vietnam.*

[6]*School of Civil and Environmental Engineering, University of Technology Sydney, Broadway, NSW 2007, Australia.*

[7]*Faculty of Environment and Natural Resources, Da Lat University, Da Lat, Vietnam.*

[8]*Department of Marine Environmental Engineering, National Kaohsiung Marine University, Kaohsiung 81157, Taiwan.*

Abstract

Wetland roof (WR) could bring many advantages for tropical cities such as thermal benefits, flood control, green coverage and domestic wastewater treatment. This study investigates wastewater treatment and biomass growth of eight local plants in shallow bed WRs. Results showed that removal rates of WRs were 21-28 kg COD ha^{-1} day^{-1}, 9-13 kg TN ha^{-1} day^{-1} and 0.5-0.9 kg TP ha^{-1} day^{-1}, respectively. The plants generated more biomass at lower hydraulic loading rate (HLR). Dry biomass growth was 0.4-28.1 g day^{-1} for average HLR of 247-403 m^3 ha^{-1} day^{-1}. Green leaf area of the plants was ranging as high as 67-99 m^2

leaves per m^2 of WR. In general, the descent order of *Kyllinga brevifoliaRottb* (WR8), *Cyperus javanicus Houtt* (WR5) and *Imperata cylindrical* (WR4) was suggested as effective vegetations in WR conditions in terms of wastewater treatment, dry biomass growth and green coverage ratio.

Keywords: wetland roof, domestic wastewater, biomass, green area.

1. Introduction

Water source is important for the life of human and other organisms in ecosystems. However, in developing countries, wastewater treatment is of less concern compared with other developments such as the economy and society (Konnerup et al., 2011). Only 2-30% of domestic and municipal wastewater was treated, while some small rural had a few or no wastewater treatment plants (Qadir et al., 2010). In urban areas, 75-80% of the domestic wastewater is preliminarily treated by septic tanks and then discharged into water bodies such as lakes, rivers and stream (Cao et al., 2016). This polluted effluent seriously affects human health. Diseases relative to the waterborne pathways, such as dengue, malaria or trypanosomiasis, are serious problems all over the world, especially for developing countries. Consequently, about 3,900 children die daily from waterborne diseases through unsafe water (Shannon et al., 2008).

There are many different biological treatment technologies for domestic and municipal wastewaters such as activated sludge process, trickling filter, moving bed biofilm reactor, constructed wetland, membrane bioreactor, etc. Constructed wetland (CW) is known as an ecological technology with low cost, easy operation and maintenance, no chemical requirement and effective ecological tool (Rai et al., 2013; Jiang et al., 2016). CW mainly consist of subsurface flow and surface flow types. By combining physical, chemical and biological processes, CW can remove organic matters and nutrients from wastewater naturally (Wu et al., 2015). This technology is able to treat domestic, municipal and industrial wastewaters as well as polluted river water. Recently, several investigations showed that CW effectively removed organics and nutrients from domestic wastewater and effluent from a septic tank (Camacho et al., 2007; Jácome et al., 2016; Bohórquez et al., 2016).

Wetland roof (WR) is designed as a shallow horizontal subsurface flow CW. This design helps to limit problems about nuisance odors and infectious diseases (Jácome et al., 2016). In addition, green roof is interested by many architects and environmental specialists because of its benefits such as rainwater quality and quantity control, energy saving, air pollution, green area, roof longevity extension, heat island effect and biodiversity (Li et al., 2010; Gregoire and Clausen, 2011). Currently, domestic wastewater treatment is a challenge in the urban cities of developing countries. Generated domestic wastewater from a building or a house is not treated or only treated by a septic tank. Thus, effluent quality does not often comply with standard limits of discharge regulations. Therefore, WRs were designed with different plant species and located on the roof is a potential solution because they inherit the benefits of both green roof and constructed wetland to solve some typical problems in an urban city such as thermal benefits, flood control, green coverage and domestic wastewater treatment. Song et al. (2010) found that WR helped decrease temperature of the zone below the roof on hot sunny days. Our previous studies were conducted to investigate the pollutant removal from domestic wastewater by WRs using various plants such as *Axonopus compressus, Tradescantia spathacea compacta, Catharanthus roseus (L) G. Don, Melampodium paludosum, Arachis duranensis, Evolvulus alsinoides, Cosmos Bipinnuatus, Cyperus alternifolius Linn* and *Philodendron hastatum, etc*. The pollutant removal of WRs achieved 55-86% of COD, 22-91% of TN and 12-89% of TP (Bui et al., 2012 & 2013; Phan et al., 2014; Vo et al., 2017). Furthermore, Zapater-Pereyra et al. (2016) reported that domestic wastewater treatment efficiencies of the wet roofs with *Lolium perenne, Festuca rubra* and *Poa pratensis* were 91.3% for TSS, 82.5% for COD, 96.6% for BOD, 99.7% for NH_4^+-N, 92.6% for TN and 97.2% for TP. With a target to find out the best local plants for roof vegetation, this study investigated the adapting capacity, green area coverage and wastewater treatment performance of eight WRs planted by eight local available plants (*Cyperus rotundus L., Zenith zoysia grass, Cynodon dactylon, Imperata cylindrical, Cyperus javanicus Houtt, Eleusine indica (L.) Gaertn., Struchium sparganophorum (L.) Kuntze* and *Kyllinga brevifolia Rottb).* The criteria for plant selection in the wetland roof are local availability, short plant (or grass type), suffering with natural conditions of high roof (windy, sunny, rainy), high green area coverage and wastewater treatment.

2. Materials and methods

2.1. Experimental setup

Eight pilot-scale WR systems with similar bed layers were used to conduct the experiments. In each WR, there were three consecutive channels to create a high length and wide ratio (L/W = 9). Each channel was designed with the dimensions of 1.8 m in length, 0.2 m in width and 0.2 m in depth. From the top, the bed layers consisted of a layer of soil (5 mm), a layer of sand (95 mm) and a layer of small rocks (20 mm). At the two ends of each WR, there was a layer of gravel (120 mm) to avoid jamming at the inlet and outlet. Water depth was maintained at 100 mm. The influent flowrates of each WR were controlled by dosing pumps (Pulsafeeder). The WR was designed with a slope of 1% from the inlet through outlet. It has specific weight of 163 kg m^{-2}. The experimental systems were located in an empty land zone in the campus of Ho Chi Minh City University of Technology ($10^0$46'31.3"N, $106^0$39'35.2"E). Therefore, WRs suffered fully natural tropical conditions such as rain, sunlight and wind. The annual average temperature and precipitation varied from 29.5^{0}C and 1,400-2,400 mm, respectively (Son et al., 2017).

2.2. Operating conditions of wetland roofs

During acclimatization phase, the unplanted WRs were operated at HLR1 with tap water for 30 days for stabilizing the bed layers. Subsequently, the selected plants were planted and the systems were fed with tap water for 10 days more. In the next 30 days, the tap water was then replaced by the effluent from a septic tank. Since the first operated HLR was started and the performance of the WRs was monitored. The length/height of plants was controlled to prevent windy condition and mosquitos. The initial height/length of the plants was trimmed to 20 cm at each started experimental HLR. The performance of WRs was investigated at two different HLRs as presented in Table 1.

The influent and effluent samples were simultaneous collected three times per week at the fixed time between 8 am and 9 am. Analytical parameters of TSS, alkalinity, COD, TKN, NH_4^+-N, NO_2^-N, NO_3^-N, TP and pH based on standard methods (APHA, 1998).

2.3. Feed wastewater characteristics

Wastewater from a canteen toilet was treated by a typical three-chamber septic tank whose effluent was then stored and fed into eight WRs. The influent wastewater was similar for all WRs. There was the slight difference in HLR or OLR among the WRs due to control of flowrates by different influent dosing pumps. However, the average coefficients of variation (CV) among WRs were 0.5-5.5% for HLR and 4.1-9.3% for OLR. The CV values vary from 1 to 10%, a comparison of WR performance is possible (Carballeira et al., 2016). Average concentrations of the septic tank effluent (feed wastewater) during the experimental period were shown in Table 2. The effluent quality of the septic tank does not comply with the national discharge standards (both level A and level B), thus post treatment for the effluent such as a wetland roof is necessary.

2.4. Investigated plants in wetland roofs

Eight WRs were planted with different vegetal species such as *Cyperus rotundus L.* (WR1), *Zenith zoysia grass* (WR2), *Cynodon dactylon* (WR3), *Imperata cylindrical* (WR4), *Cyperus javanicus Houtt* (WR5), *Eleusine indica (L.) Gaertn* (WR6), *Struchium sparganophorum (L.) Kuntze* (WR7) and *Kyllinga brevifolia Rottb* (WR8) (Table 3). These plants are wild grasses and locally available, especially in the Mekong delta region of Vietnam. Firstly, they were grown with the density of the 187 plants/m^2. The initial height or length of vegetal plants was approximately 20 mm.

2.5. Determination of biomass growth

The above-ground biomass of the plants consisting of leaf, branch and stem were harvested at the end of every experimental period. Total above-ground biomass of each WR was weighed to determine a fresh weight. After that, this fresh biomass was cut to a size of about 10 cm. Three plant samples were selected randomly and dried at 70^0C until constant weight. These samples were weighed before and after drying. From the results of total fresh biomass and their sample weights, the total dried weight of the plants in every WR was estimated (Chung et al., 2008).

2.6. Measurement of green leaf area

For each WR, eight leaf samples were collected at eight different positions. Collected area for each position was 2.5 cm^2. Then, these samples were mixed together and weighed (m_1). Three small samples were taken randomly to weight (m_2) and determine the leaf area (A_1) by ImageJ2147software. The green leaf area of each WR was calculated as follows:

$$A = \frac{2\,A_0 \times m_1 \times A_1}{x \times y \times m_2} \qquad (2.1)$$

Where, A is the total leaf area of WR (cm^2), 2 is the two sides of leaf surfaces, A_0 is the area of WR (cm^2), A_1 is the leaf area corresponding to the weight of m_2 (cm^2), m_1 is the total weight of 8 samples (g), x is the specific area of a position (x = 2.5 cm^2) and y is the sample number (y = 8).

2.7. Nitrogen and phosphorous mass balance

Before and after each experimental period, plant and soil samples in each WR were collected from nine different positions. These sites were in the middle of the channel and distributed evenly along the length of the container. TN and TP accumulated in the plant biomass and bed layer were measured. In this study, the percentage of TN and TP mass were absorbed by plants against total TN and TP in the feed wastewater and total dry biomass of the plants during each stage (Chung et al., 2008; Bui et al., 2014).

2.8. Statistical analysis

The removal efficiency at each HLR was analyzed by SPSS 16 software. Differences in efficiency between the WRs and the HLRs were identified using one-way ANOVA with Bonferroni and Tukey procedure. With the *p*-value < 0.05, the efficiencies were considered a significant difference. Pearson's correlation coefficient test was used for correlation analysis between biomass production and wastewater treatment efficiency of studied plants.

3. Results and discussion

3.1. Growth of plant biomass

Initially, most of the plant species adapted quite well under WR operating conditions with tap water. In the adaptation period with wastewater at low HLR of 200-250 m^3 ha^{-1} day^{-1}, all plants were survival. However, its growth rates tended to decrease gradually when average HLR increased from 288±19 m^3 ha^{-1} day^{-1} (HLR1) to 394±13 m^3 ha^{-1} day^{-1} (HLR2). The plants of *Zenith zoysia grass* (WR2) and *Cynodon dactylon* (WR3) were stunted and yellowed leaves. While the plant *Struchium sparganophorum (L.) Kuntze* in WR7, the only one having big size leaf type, died gradually and maintained a survival of 50% till the end of experiment. The capacity of biomass growth of the plants reduced at HLR2 in all WRs (Fig. 1). This means these plants could not stand with a high HLR of 394±13 m^3 ha^{-1} day^{-1} (equivalent to organic loading rate (OLR of 52±22 kg COD ha^{-1} day^{-1}). The dry biomass reduced 18-72% (except WR7) when average HLR increased from 288 to 394 m^3 ha^{-1} day^{-1}. At the HLR of 288±19 m^3 ha^{-1} day^{-1}, the dry biomass in wetland roofs follows the descent order as WR8>WR3>WR5>WR4>WR2>WR1>WR6>WR7. While at the HLR as high as 394 m^3 ha^{-1} day^{-1}, the dry biomass in wetland roofs follows the descent order as WR8>WR5>WR2>WR3>WR4>WR1>WR6>WR7. The *Struchiumsparganophorum* (*L.) Kuntze* plant species in WR7, which was the only used plant, had big size leaves. This type of plant species is not suitable for rooftop wetland because of its negligible biomass growth under both HLRs. In addition, the *Kyllinga brevifolia Rottb* plant in WR8 always gained the highest growth rate in terms of fresh and dry biomass under both HLRs. This could be the best plant for dry biomass growth among studied vegetation for wetland roof systems.

The generated biomass from WRs can be a food source for herbivores. If bacteria and toxic organic compounds such as antibiotics in the feed wastewater are controlled, plant biomass can also be one of potential medicine sources. For example, *Kyllinga brevifolia Rottb* rhizomes are used in Paraguayan traditional medicine with digestive, diuretic, sedative and antispasmodic properties (Hellión-Ibarrola et al., 2016).

The growth of fresh and dry biomass of *Kyllinga brevifoliaRottb* was 1.1-2.1 times and 1.0-2.6 times higher than those of *C. Alternifolius Linn* described in our previous study (Phan et al. 2015). For dry biomass, most of the WRs (excepted WR6 and WR7) were 1.3- 25.5 times higher than other species (*Baumea Articulata*, *Carex Fascicularis*, *Philydrum Lanuginosum* and *Schoenoplectus Mucronatus*) cultivated in the conventional constructed wetlands investigated by Browning and Greenway (2003). However, compared with the results of Morari et al. (2015), the biomass growth of studied plants in the WRs were 3.9-17.9 times lower than those of common vegetation in conventional constructed wetlands such as *Typha Latifolia L.* and *Phragmites Australis L.*

3.2. Green leaf area of wetland roofs

Vegetation on a rooftop not only helps contribute to cooling roof underneath of building and absorbs carbon dioxide through plant photosynthesis but also increase a green space in an urban area (Li et al., 2010; Mirzaei et al., 2012). According to the report of the Economist Intelligence Unit, the current green space area per person (m^2 $person^{-1}$) is very limited in urban cities of developing countries such as Ha Noi (11), Manila (5), Bangkok (3). Ho Chi Minh's green space is only 0.7 m^2 $person^{-1}$. Meanwhile, the average green space index is 39 m^2 $person^{-1}$ (EIU, 2012). Therefore, a specific green area of plant leaves for each WR was measured to estimate their added green coverage in this study. The highest specific green area of WRs was 99 (WR8), followed by 98 (WR5), 92 (WR4), 86 (WR3), 78 (WR2), 72 (WR1), 72 (WR7) and 67 (WR6) m^2 m^{-2} WR. In which, the green coverage of WR8, WR5 and WR4 are higher than those of remaining WRs. If WRs are applied to urban cities, these best plant species will help improve the current lack of green area.

3.3. Mass balance of nitrogen and phosphorous

Nitrogen in the wastewater decreased mainly by loss (31-80% at HLR1 and 56-76% at HLR2) (Table 4). This loss of nitrogen was mostly through denitrification as similar as Chung et al. (2008). Oxygen is transported to the rhizosphere by the plant. Thus, aerobic zones are established next to the roots and rhizomes where ammonia is oxidized to nitrite and then to nitrate by nitrifying microorganisms. The bed medium always exists anaerobic zones where denitrification occurs. Consequently, nitrate is changed into nitrogen gas and released into the atmosphere.

Nitrogen accumulation in soil varied from 0.6-30% at HLR1 and 0.4-4.6% at HLR2. Meanwhile, nitrogen uptake by plants was 0.0-11.3%. Plants primarily use nitrate and ammonia nitrogen forms through their roots and leaves. Nitrogen helps plants to enhance photosynthetic processes, leaf growth as well as biomass assimilation rate (Leghari et al., 2016). No nitrogen uptake is due to the growing-less plant species in WR7. The nitrogen absorption of plants at HLR2 was in descent order as WR8, WR5, WR4 and WR6. The nitrogen absorption of the four WR plants was significantly higher than that of the remaining ones (i.e., WR1, WR2, WR3 & WR7). As observed, the nitrogen absorption is likely with the trend of specific green area of the WRs. Nitrogen accumulation based on dry biomass of WRs at HLR1 (0.0-1.1%) was lower than that at HLR2 (0.0-3.2%). Regarding nitrogen uptake based on the influent load and dry biomass for a WR, there is no significant difference between two operated HLRs.

Phosphorus plays an important role for plant growth as well. Its major contributes to key functions of plants such as photosynthesis, energy transportation, nutrient transmission and transferring of genetic characteristics (Waraich et al., 2011). Phosphorus was primarily removed by loss (36-81% in HLR1 and 17-59% in HLR2) and uptake in soil (14-32% in HLR1 and 7-57% in HLR2) (Table 5). Meanwhile, phosphorus in the plant uptake was only 0.2-27.6% and 2.8-20.6% for HLR1 and HLR2, respectively. The phosphorus absorption of plants at HLR2 was also similar with nitrogen absorption, in descent order as WR8, WR5, WR4 and WR6. The phosphorus uptake based on dry biomass for a WR was not significantly difference in both operated HLRs.

The results of this study were similar with previous study by Mc Jannet et al. (1995). Nitrogen and phosphorus accumulation in dry biomass of 41 emerged wetland plant species were 0.25-2.14% for nitrogen and 0.13-1.07% for phosphorus.

3.4. Performance of wastewater treatment

The COD reduction varied considerably for each HLR. The average effluent concentration was 29±16 mg L^{-1} (HLR1) and 34±23 mg L^{-1} (HLR2). In HLR1, COD removal efficiency reached 16-30% (67-86 kg ha^{-1} day^{-1}). In HLR2, COD removal efficiency was 27-33% (61-

79 kg ha^{-1} day^{-1}) (Fig. 2). Although the COD removal efficiency in HLR2 was higher than HLR1, the removal rate in HLR2 was slightly lower than that in HLR1. This is due to shorter retention time which is insufficient time for uptake and decomposition by the plants and microorganism at such a high hydraulic loading rate.

Nitrogen is eliminated by denitrification, plant and microorganism uptake, adsorption and volatilization. Average total nitrogen (TN) concentrations in effluents varied 10±4 mg/L and 10±2 mg/L for HLR1 and HLR2, respectively. At WR8, WR5 and WR4, effluent TN was less than 10 mg/L. TN removal rates, as well as removal efficiencies, in HLR2 was higher than those in HLR1 (Fig. 3). WR8, WR5 and WR4 had performed better among others, especially the WR8 showed the best performance in terms of nitrogen removal capacity.

Phosphorus also plays an important role for metabolism and growth of microorganism and plants in WRs. Total phosphorus (TP) concentration in the treated wastewater was 0.7±0.3 mg L^{-1} (HLR1) and 0.4±0.3 mg L^{-1} (HLR2). All the wetland roofs had similar phosphorus removal rate at each HLR. This is due to the low phosphorus concentration in the feed wastewater (Fig. 4). The statistical analyses showed that there was not a significant difference in TP removal rates for HLR1 and HLR2 ($p > 0.05$).

In this study, a correlation of biomass production and nutrient uptake of WRs was also analysed statistically. The results showed that dry biomass production strongly correlated with fresh biomass production (R^2 = 0.886-0.898). Biomass production possitively correlated with TN and TP removal rates ($R^2 = 0.470-0.774$), excepted TP removal rates at HLR2. This indicates that biomass production could be an indicator for the nutrient uptake of the studied plants.

In general, the average removal efficiencies were 1.0-1.4 times (for COD, excepted WR8), 1.1-1.8 times (for TN) and 1.1-18 times (for TP) lower than that of a previous wet roof study (Zapater-Pereyraet al., 2016). The wet roof was designed with HLR of 160 m^3 ha^{-1} day^{-1} and water depth of 0.9 m. The wet roof bed materials included sand, crushed light expanded clay aggregates and polylactic acid bread. However, the results of TN removal in this study were 1.8-2.8 times higher than the findings from the green roof which was designed with the bed materials including lightweight expanded shale, composted biosolids and perlite (Gregoire and Clausen, 2011). In addition, removal of COD and TN for the WRs (namely WR8, WR5 and WR4) achieved greater compared with the WRs at similar operating hydraulic loading rate, water depth and bed media (Bui et al., 2014). These results showed that the nutrient removal efficiencies of the WR systems were strongly affected by the types of plants and their roots as well as the bed media structure.

In addition, treated wastewater quality of WRs in terms of organics and nutrients could comply with national standards on domestic wastewater discharge (QCVN 14:2008, level B) (MONRE, 2008).

4. Conclusions

Based on the achieved results, some concluding remarks can be withdrawn as follows:

- Among eight plant species, the descent order of *Kyllinga brevifolia Rottb* (WR8), *Cyperus javanicus Houtt* (WR5) and *Imperata cylindrical* (WR4) brings better environmental effects such as green area enhancement and wastewater treatment.
- Study plants (*Kyllinga brevifoliaRottb, Cyperus javanicus Houtt* and *Imperata cylindrical*) improve green space for tropical cities effectively.
- Wetland roof could be an ecological engineering solution for complete treatment of domestic wastewater in the urban buildings.

Acknowledgements

The authors would like to thank for the research grant from National Foundation for Science and Technology Development (NAFOSTED) No. 105.99-2011.03, Ministry of Science and Technology, Vietnam and Korea Environment Corporation (KECO), South Korea. Research collaboration between Ho Chi Minh City University of Technology and other Universities is very grateful.

References

1. APHA A. WEF, 1998. Standard methods for the examination of water and wastewater. American Public Health Association, Washington, DC.
2. Bohórquez, E., Paredes, D. and Arias, C.A., 2017. Vertical flow-constructed wetlands for domestic wastewater treatment under tropical conditions: effect of different design and operational parameters. Environ. Technol. 38(2), 199-208.

3. Bui, X.T., Phan, T.H.V., Nguyen, T.T., Vo, T.D.H., Nguyen, P.D., Koottatep, T., 2014. Performance of wetland roof with *Melampodium paludosum* treating septic tank effluent. Desalin. Water Treat. 52(4-6), 1070-1076.
4. Bui, X.T., Vo, T.D.H., Nguyen, P.D., Phan, T.H.V. and Nguyen, T.T., 2012. Performance of wetland roof treating domestic wastewater in the tropic urban area. J. Water Sustain. 2, 79-86.
5. Browning, K., Greenway, M., 2003. Nutrient removal and plant biomass in a subsurface flow constructed wetland in Brisbane, Australia. Water Sci. Technol. 48(5), 183-189.
6. Camacho, J.V., Martínez, A.D.L., Gómez, R.G. and Sanz, J.M., 2007. A comparative study of five horizontal subsurface flow constructed wetlands using different plant species for domestic wastewater treatment. Environ. Technol. 28(12), 1333-1343.
7. Cao, N.D.T., Nguyen, T.T., Bui, X.T., Vo, T.D.H., Truong, C.H.S., Son, N.T., Dao, T.S., Pham, A.D., Nguyen, T.L.C., Nguyen, L.H. and Visvanathan, C., 2016. Low-cost spiral membrane for improving effluent quality of septictank. Desalin. Water Treat. 57(27), 12409-12414.
8. Carballeira, T., Ruiz, I. and Soto, M., 2016. Effect of plants and surface loading rate on the treatment efficiency of shallow subsurface constructed wetlands. Ecol. Eng. 90, 203-214.
9. Chung, A.K.C., Wu, Y., Tam, N.Y. and Wong, M.H., 2008. Nitrogen and phosphate mass balance in a sub-surface flow constructed wetland for treating municipal wastewater. Ecol. Eng. 32(1), 81-89.
10. Economist Intelligence Unit, 2012. Best cities ranking and report. Available at http://pages.eiu.com/rs/eiu2/images/EIU_BestCities.pdf (visited 6th November 2016).

11. Gregoire, B.G. and Clausen, J.C., 2011. Effect of a modular extensive green roof on stormwater runoff and water quality. Ecol. Eng. 37(6), 963-969.
12. Hellión-Ibarrola, M.C., Montalbetti, Heinichen, O.Y. Kennedy, M.L, Campuzano, M.A., Alvarenga, N., Ibarrol, D.A., 2016. Antidepressant-like effect of Kyllinga brevifolia rhizomes in male mice and chemical characterization of the components of the active ethyl acetate fraction. J. Ethnopharmacol. 194, 1005-1011.
13. Jácome, J.A., Molina, J., Suárez, J., Mosqueira, G. and Torres, D., 2016. Performance of constructed wetland applied for domestic wastewater treatment: Case study at Boimorto (Galicia, Spain). Ecol. Eng. 95, 324-329.
14. Jiang, L., Liu, Y., Hu, X., Zeng, G., Wang, H., Zhou, L., Tan, X., Huang, B., Liu, S. and Liu, S., 2016. The use of microbial-earthworm ecofilters for wastewater treatment with special attention to influencing factors in performance: A review. Bioresour. Technol. 200, 999-1007.
15. Konnerup, D., Trang, N.T.D., Brix, H., 2011. Treatment of fishpond water by recirculating horizontal and vertical flow constructed wetlands in the tropics. Aquaculture 313, 57-64.
16. Leghari, S.J., Wahocho, N.A., Laghari, G.M., HafeezLaghari, A., MustafaBhabhan, G., HussainTalpur, K., Bhutto, T.A., Wahocho, S.A., Lashari, A.A., 2016. Role of nitrogen for plant growth and development: a review. Adv. Environ. Biol. 10(9), 209-219.
17. Li, J.F., Wai, O.W., Li, Y.S., Zhan, J.M., Ho, Y.A., Li, J. and Lam, E., 2010. Effect of green roof on ambient CO 2 concentration. Build. Environ. 45(12), 2644-2651.

18. Mc Jannet, C.L., Keddy, P.A. and Pick, F.R., 1995. Nitrogen and phosphorus tissue concentrations in 41 wetland plants: a comparison across habitats and functional groups. Funct. Ecol. 231-238.

19. Mirzaei, P.A., Haghighat, F., Nakhaie, A.A., Yagouti, A., Giguère, M., Keusseyan, R. and Coman, A., 2012. Indoor thermal condition in urban heat Island–Development of a predictive tool. Build. Environ. 57, 7-17.

20. MONRE-Ministry of Viet Nam Natural Resources and Environment, 2008. National technical regulation on domestic wastewater treatment - QCVN 14:2008/BTNMT.

21. Morari, F., Dal Ferro, N. and Cocco, E., 2015. Municipal wastewater treatment with Phragmites australis L. and Typha latifolia L. for irrigation reuse. Boron and heavy metals. Water Air Soil Pollut. 226(3), 56.

22. Phan, T.H.V, Nguyen, T.T, Vo, T.D.H., Thai, M.Q., Bui, X.T., Vo, T.H., Dinh, Q.T., Nguyen, P.D., Le, V.K., Vo, L.P. and Nguyen, T.S, 2015. Nutrient removal by different plants in wetland roof systems treating domestic wastewater. Desalin. Water Treat. 54(4-5), 1344-1352.

23. Qadir, M., Wichelns, D., Raschid-Sally, L., McCornick, P.G., Drechsel, P., Bahri, A. and Minhas, P.S., 2010. The challenges of wastewater irrigation in developing countries. Agric. Water Manag. 97(4), 561-568.

24. Rai, U.N., Tripathi, R.D., Singh, N.K., Upadhyay, A.K., Dwivedi, S., Shukla, M.K., Mallick, S., Singh, S.N. and Nautiyal, C.S., 2013. Constructed wetland as an ecotechnological tool for pollution treatment for conservation of Ganga river. Bioresour. Technol. 148, 535-541.

ACCEPTED MANUSCRIPT

25. Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Marinas, B.J., Mayes, A.M., 2008. Science and technology for water purification in the coming decades. Nature 452, 301-310.
26. Son, N.T., Chen, C.F., Chen, C.R., Thanh, B.X. and Vuong, T.H., 2017. Assessment of urbanization and urban heat islands in Ho Chi Minh City, Vietnam using Landsat data. Sustain. Cities Society, 30, 150-161.
27. Song, U., Kim, E., Bang, J.H., Son, D.J., Waldman, B. and Lee, E.J., 2013. Wetlands are an effective green roof system. Build. Environ. 66, 141-147.
28. Vo, T.D.H, Do, T.B.N, Bui, X.T., Nguyen, V.T., Nguyen, D.D., Sthiannopkao, S. and Lin, C., 2017. Improvement of septic tank effluent and green coverage by shallow bed wetland roof system. Int. Biodeterior. Biodegrad (In press). DOI: 10.1016/j.ibiod.2017.05.012.
29. Waraich, E.A., Ahmad, R. and Ashraf, M.Y., 2011. Role of mineral nutrition in alleviation of drought stress in plants. Aust. J. Crop Sci. 5(6), 764.
30. Wu, H., Fan, J., Zhang, J., Ngo, H.H., Guo, W., Hu, Z. and Liang, S., 2015. Decentralized domestic wastewater treatment using intermittently aerated vertical flow constructed wetlands: impact of influent strengths. Bioresour. Technol. 176, 163-168.
31. Zapater-Pereyra, M., Lavrnić, S., van Dien, F., van Bruggen, J.J.A. and Lens, P.N.L., 2016. Constructed wetroofs: A novel approach for the treatment and reuse of domestic wastewater. Ecol. Eng. 94, 545-554.

Table 1. Operating conditions of WRs (mean ± SD)

System	WR1	WR2	WR3	WR4	WR5	WR6	WR7	WR8
HLR1 288 ± 19 m^3 ha^{-1} day^{-1} (33 days in operation)								
HLR	304 ± 11	306 ± 8	286 ± 29	312 ± 18	262 ± 21	287 ± 16	286 ± 17	286 ± 41
OLR	32 ± 4	32 ± 5	30 ± 5	33 ± 6	30 ± 12	33 ± 13	33 ± 13	33 ± 13
HRT	30 ± 1	30 ± 1	32 ± 2	30 ± 2	35 ± 2	32 ± 3	32 ± 3	32 ± 2
HLR2 = 394 ± 13 m^3 ha^{-1} day^{-1} (41 days of operation)								
HLR	394 ± 13	397 ± 10	395 ± 14	395 ± 11	391 ± 14	396 ± 12	393 ± 17	393 ± 12
OLR	47 ± 15	48 ± 16	47 ± 15	48 ± 16	56 ± 28	57 ± 27	56 ± 27	57 ± 28
HRT	23 ± 1	23 ± 1	23 ± 1	23 ± 1	24 ± 1	23 ± 1	23 ± 1	23 ± 1

Remarks: HLR: Hydraulic Loading Rates (m^3 ha^{-1} day^{-1}); OLR: Organic Loading Rate (kgCOD ha^{-1} day^{-1}); HRT: Hydraulic retention time (h)

Table 2. Studied wastewater characteristics

Parameters	Unit	Value (Mean ± SD)	National standard limits-QCVN 14:2008 (MONRE, 2008)	
			Level A	Level B
pH	-	6.3 – 7.8	5-9	5-9
COD	mg L^{-1}	108±53	-	-
TSS	mg L^{-1}	71±7	50	100
TKN	mg L^{-1}	42±7	-	-
NH_4^+-N	mg L^{-1}	38±2	5	10
NO_3^-N	mg L^{-1}	0.5±0.3	30	50
NO_2^-N	mg L^{-1}	0.4±0.2	-	-
TP	mg L^{-1}	1.5±0.7	6	10
Alkalinity	mgCaCO$_3$ L^{-1}	55±12	-	-

Remarks: Level A - maximum limits are discharged into the water bodies which using for domestic water supply purposes; Level B -maximum limits are discharged into the water bodies which not using for domestic water supply purposes.

Table 3. Characteristics of studied plants

Systems	WR1	WR2	WR3	WR4
Scientific name	*Cyperusrotundus L.*	*Zenith zoysia grass*	*Cynodondactylon*	*Imperata cylindrical*
Characteristics	Perennial plants, rhizomes, up to 140 cm in height, grows in moist areas.	Annual herbs can tolerate wide variations in temperature, sunlight and water.	Annual herbs, 1-30 cm in height, strong growth under full sunlight.	Perennial grass, rhizomes, 0.6-3 m in height.
Systems	**WR5**	**WR6**	**WR7**	**WR8**
Scientific name	*Cyperusjavanicus Houtt*	*Eleusineindica (L.) Gaertn.*	*Struchiumsparganophorum (L.) Kuntze*	*Kyllingabrevifolia Rottb*
Characteristics	Perennial herbs, short rhizomes, tufted, robust, 40-110 cm in height, survival in the alluvial sand and wet clay.	Annual herbs, extensive roots, 5-60 cm in height, survival in the 500-1200 mm rainfall range.	Annual herbs, local source of food and medicines, 10-30 cm in height, survival in the alluvial sand and wet clay.	Perennial herbs, rhizomes, 50 cm in height, weed in wet areas.

Table 4. Nitrogen mass balance in WRs at hydraulic loading rates

Nitrogen	WR1	WR2	WR3	WR4	WR5	WR6	WR7	WR8
	HLR1 = 288 ± 19 m^3 ha^{-1} day^{-1}							
Influent (g)	58.3	58.8	54.9	60.0	38.5	42.1	42.0	42.0
Effluent (g)	7.1	8.2	6.8	8.0	12.8	16.1	13.1	10.7
Soil uptake (g)	4.7	2.2	2.1	10.9	9.9	6.0	0.2	12.6
Plant uptake (g)	1.6	1.2	1.4	4.1	3.6	3.7	0.0	4.8
Loss (g)	45.0	47.1	44.6	37.0	12.1	16.4	28.6	13.9
Plant uptake based on dry biomass (%)	0.5	0.1	0.2	1.1	0.7	0.4	0.0	0.4
Plant uptake based on influent load (%)	2.7	2.1	2.5	6.9	9.4	8.7	0.0	11.3
	HLR2 = 394 ± 13 m^3 ha^{-1} day^{-1}							
Influent (g)	96.4	97.3	96.7	96.8	97.2	98.5	97.8	97.7
Effluent (g)	23.9	23.5	20.8	22.4	30.5	32.3	26.5	27.5
Soil uptake (g)	0.4	0.8	0.6	1.5	1.6	1.9	1.0	4.5
Plant uptake (g)	2.5	2.2	2.2	7.0	8.9	7.0	0.0	10.9
Loss (g)	69.5	70.8	73.1	65.9	56.2	57.3	70.3	54.7
Plant uptake based on dry biomass (%)	0.9	0.4	0.7	2.3	2.0	3.2	0.0	2.2
Plant uptake based on influent load (%)	2.6	2.3	2.3	7.2	9.2	7.1	0.0	11.2

Table 5. Phosphorus mass balance in WRs at hydraulic loading rates

Phosphorus	WR1	WR2	WR3	WR4	WR5	WR6	WR7	WR8
	HLR1 = 288 ± 19 m^3 ha^{-1} day^{-1}							
Influent (g)	3.3	3.4	3.1	3.4	4.0	4.4	4.4	4.4
Effluent (g)	0.6	0.2	0.4	0.3	0.2	0.2	0.2	0.3
Soil uptake (g)	0.9	0.7	0.6	1.1	1.2	0.9	0.6	1.3
Plant uptake (g)	0.3	0.3	0.3	0.8	0.9	0.7	0.0	1.2
Loss (g)	1.6	2.2	1.9	1.2	1.7	2.7	3.6	1.6
Plant uptake based on dry biomass (%)	0.11	0.02	0.06	0.21	0.18	0.07	0.05	0.10
Plant uptake based on influent load (%)	10.1	7.8	10.3	23.5	23.0	15.1	0.2	27.6
	HLR2 = 394 ± 13 m^3 ha^{-1} day^{-1}							
Influent (g)	98.5	2.9	2.9	2.9	2.6	2.6	2.6	2.6
Effluent (g)	0.7	0.5	0.5	0.6	0.8	1.1	0.4	0.6
Soil uptake (g)	1.1	0.5	1.6	0.7	0.9	0.2	1.1	0.4
Plant uptake (g)	0.3	0.2	0.2	0.4	0.4	0.3	0.1	0.5
Loss (g)	0.8	1.7	0.5	1.1	0.5	1.1	1.0	1.1
Plant uptake based on dry biomass (%)	0.10	0.03	0.05	0.12	0.09	0.38	0.02	0.11
Plant uptake based on influent load (%)	9.7	5.4	6.5	13.1	15.6	12.8	2.8	20.6

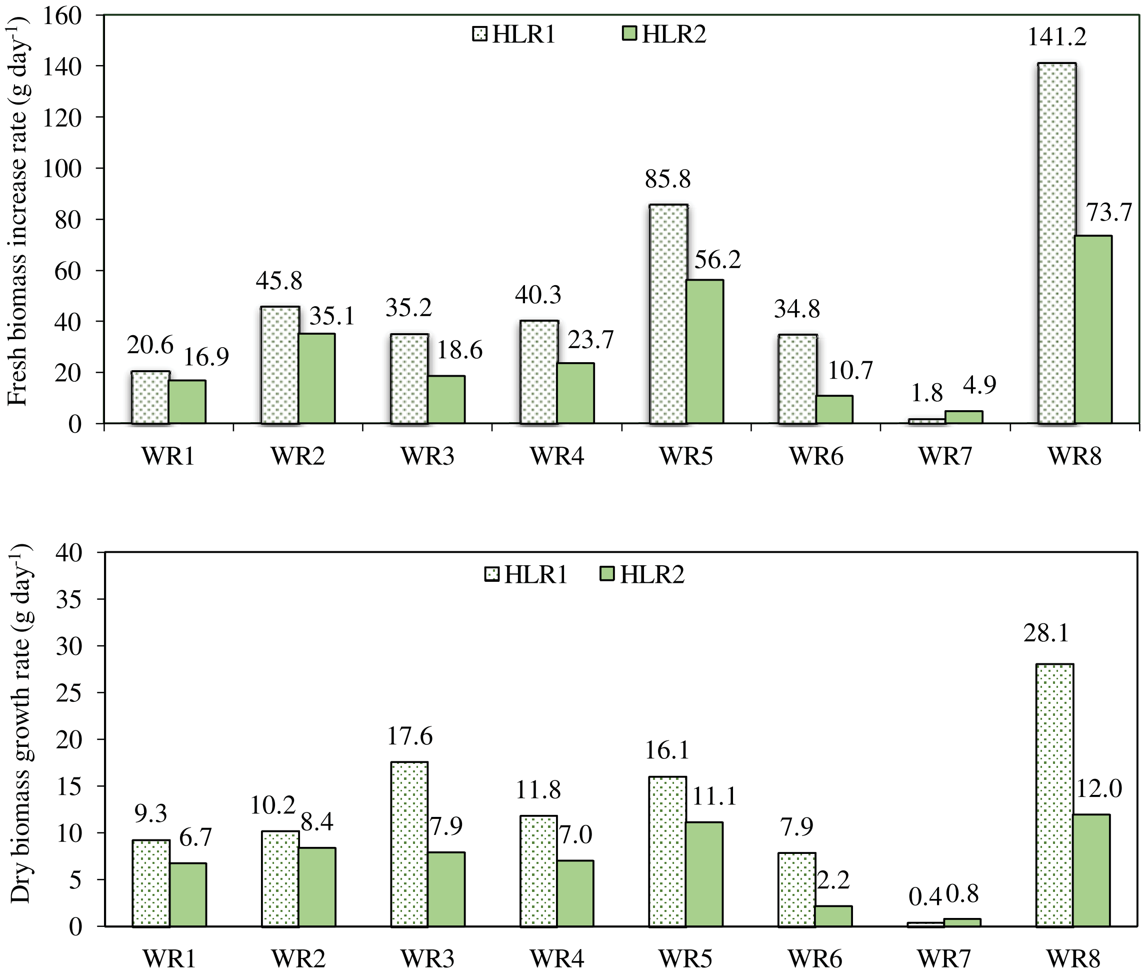


Fig. 1. Fresh (above) and dry (below) biomass increase rate of the plants

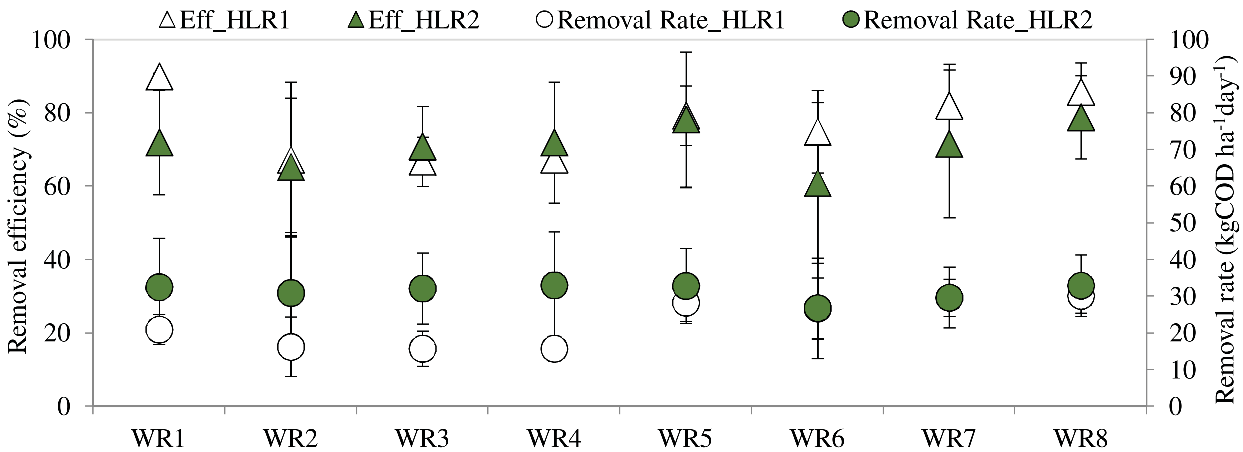


Fig. 2. COD removal rate and efficiency of WRs at hydraulic loading rates (HLRs)

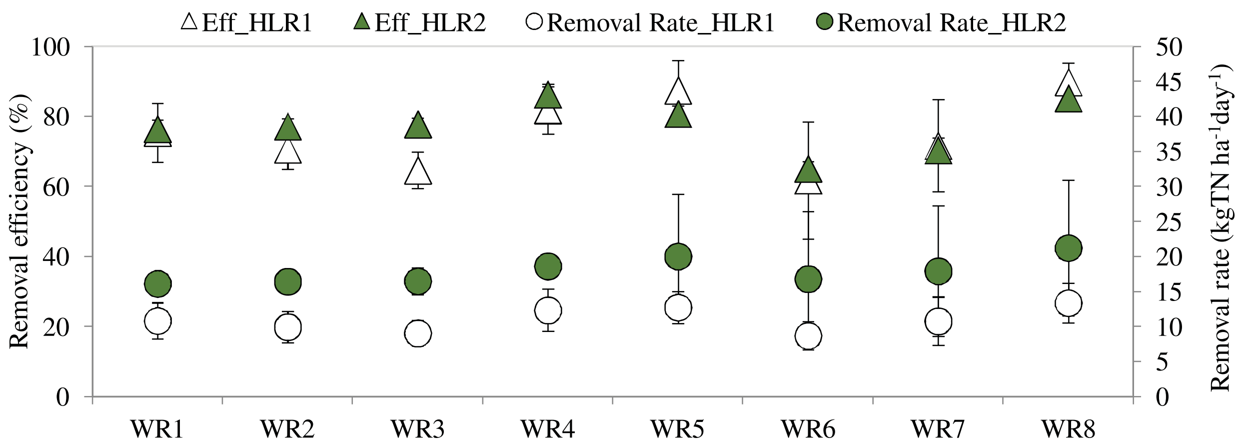


Fig. 3. Total nitrogen (TN) removal rate and efficiency of WRs at hydraulic loading rates (HLRs)

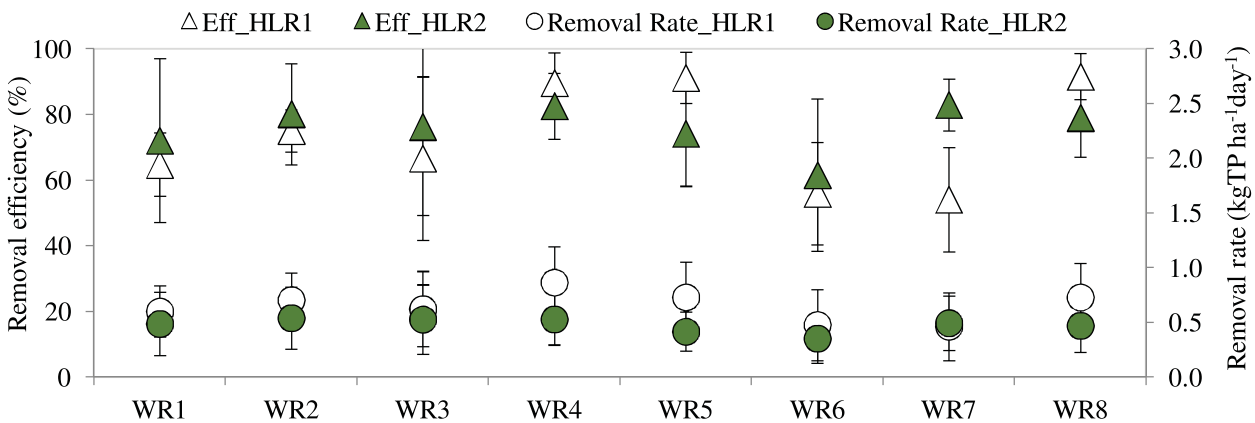
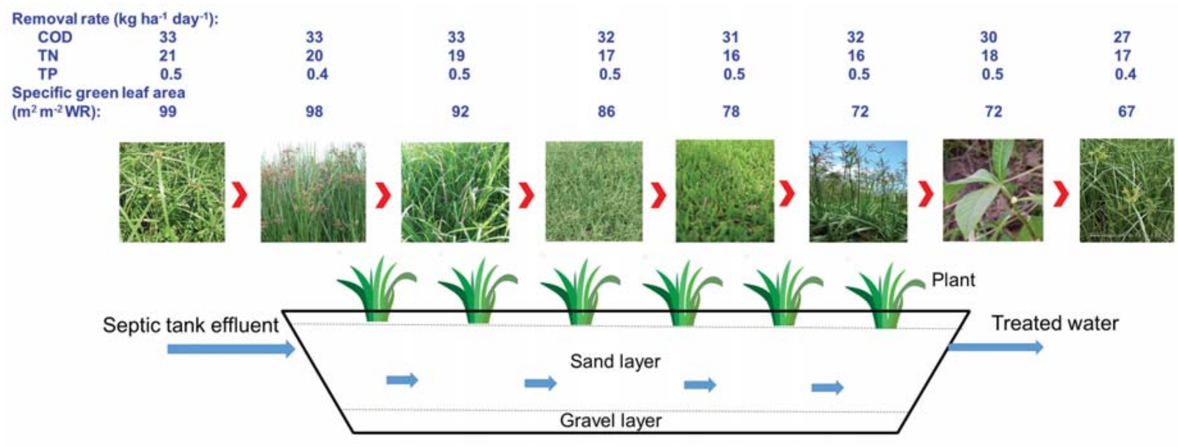


Fig. 4. Total phosphorus removal rate and efficiency of WRs at hydraulic loading rates (HLRs)

Highlights

- Wetland roof (WR) is an ecological treatment solution for tropical urban cities.
- WR contributes to enhance specific green coverage for urban cities.
- Tree among eight studied plants reveals as effective vegetation for WR system.
- *Kyllinga brevifolia Rottb* was the best for green area and wastewater treatment.

ACCEPTED MANUSCRIPT


Removal rate (kg ha-1 day-1):
COD 33 33 33 32 31 32 30 27
TN 21 20 19 17 16 16 18 17
TP 0.5 0.4 0.5 0.5 0.5 0.5 0.5 0.4
Specific green leaf area
(m2 m-2 WR): 99 98 92 86 78 72 72 67
Plant
Septic tank effluent
Treated water
Sand layer
Gravel layer