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Nutrient removal by different plants in wetland roof systems treating domestic wastewater

Phan Thi Hai Van[a], Nguyen Thanh Tin[a], Vo Thi Dieu Hien[a], Thai Minh Quan[a], Bui Xuan Thanh[a,*], Vo Thanh Hang[a], Dinh Quoc Tuc[a], Nguyen Phuoc Dan[a], Le Van Khoa[a], Vo Le Phu[a], Nguyen Thanh Son[b], Nguyen Duc Luong[c], Eugene Kwon[d], Changgyu Park[d], Jingyong Jung[d], Injae Yoon[d], Sijin Lee[d]

[a]*Faculty of Environment, Ho Chi Minh City University of Technology (HCMUT), Vietnam Building B9, 268 Ly Thuong Kiet Street, District 10, Ho Chi Minh City, Vietnam, emails: phanhaivan@gmail.com (P.T.H. Van); thanhtin201@yahoo.com (N.T. Tin); hien.ic.tracodi@gmail.com (V.T.D. Hien); thaiminhquan0909@gmail.com (T.M. Quan); bxthanh@hcmut.edu.vn (B.X. Thanh); hang_vothanh2003@yahoo.com (V.T. Hang); quoctuc@yahoo.com (D.Q. Tuc); npdan@hcmut.edu.vn (N. P. Dan); vkhoa2020@gmail.com (L.V. Khoa); volephu@hcmut.edu.vn (V.L. Phu)*
[b]*Centre for Space and Remote Sensing Research, National Central University, Jhongli, Taoyuan 32001, Taiwan, email: ntsonait@hotmail.com (N.T. Son)*
[c]*Institute of Environmental Science and Engineering (IESE), National University of Civil Engineering (NUCE), 55 Giai Phong, Hanoi, Vietnam, email: luongnd1@nuce.edu.vn (N.D. Luong)*
[d]*Korea Environment Corporation (KECO), General Environmental Research Complex, Gyeongseo-dong, Seo-gu, Inchon 404-170, South Korea, emails: rossete@naver.com (E. Kwon); cg2020@keco.or.kr (C. Park); kimgiyou@keco.or.kr (J. Jung); yooninjae@keco.or.kr (I. Yoon); leesj@keco.or.kr (S. Lee)*

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ABSTRACT

This study evaluated nutrients removal from domestic wastewater by five plants in wetland roof systems (WR). The study plants include *Arachis duranensis* (1), *Evolvulus alsinoides* (2), *Cosmos Bipinnuatus* (3), *Cyperus alternifolius* Linn (4), and *Philodendron hastatum* (5). The WRs were acclimatized at hydraulic loading rates (HLR) of 220 m^3/ha d and operated at HLR of 300 m^3/ha d. The plants (1), (2), (4), and (5) had the ability to grow under the rooftop conditions with domestic wastewater as a nutrient source while the plant (3) was not suitable and dead after 20 d of operation. Generally, *A. duranensis* (1) and *C. alternifolius* Linn (4) were the most suitable plants treating domestic wastewater under the conditions of WR. The average phosphorus removal efficiencies of (1) and (4) were approximately 75 and 89%, respectively, while the average nitrogen removal efficiencies were 69 and 92%. The phosphorus accumulation in plants (1) and (4) during operation was 20.4 and 29.4%, respectively, while the nitrogen accumulation was 21.5 and 93%. It is concluded that *C. alternifolius* Linn (4) has best nutrient removal among the study plants under the conditions of shallow bed WR treating domestic wastewater (24 ± 4 and 2.0 ± 0.4 kg TP/ha d).

*Corresponding author.

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1. Introduction

Constructed wetland is popularly described as "green," "environmentally friendly," and "sustainable" wastewater treatment technology. In this research, wetland roof system (WR) has been designed, constructed, and operated like conventional constructed wetlands with the subsurface flow (SSF) mode and the natural processes involving wetland plants, soils, materials, and their associated microbial community to treat organic matter and nutrient in municipal wastewater. The organic matters are decomposed primarily by micro-organisms under anoxic conditions/anaerobic when the dissolved oxygen concentration in the limited filtration layer. Suspended solids are retained by filtration, sedimentation, and often achieve very high efficiency [1].

Over the past 20 years, there are thousands of constructed wetland systems (CWSs) being used in Europe and China in ecological engineering for individual houses or small communities, especially for treating the domestic wastewater [2,3]. Since 1990s, organic and nutrients have been removed effectively by secondary biological treatment process (normally $BOD_5 <$ 10 mg/L, NH_4-N < 10 mg/L) [2]. The processes of removal and accumulation of nitrogen in CWSs include ammonia volatilization, nitrification, denitrification, nitrogen fixation, plant development, microbial synthesis, ammonification, and anaerobic ammonia oxidation [4]. However, the main nitrogen removal mechanism of SSF is denitrification process [5]. Ammonia removal is limited by the lack of oxygen in the layer of filter material as frequently flooded conditions. Phosphorous in wastewater is eliminated mainly by the exchange reactions, phosphate substitute water or hydroxyl radicals from the surface of the iron oxide and aluminum. Without the use of special materials, phosphorus removal efficiency is rather low in the SSF wetlands. Removal of total nitrogen (TN) in previous studies of CWSs varied from 40 to 55% with removed load ranging from 250 to 630 g N/m^2 [4].

Green roofs, which are developed in many countries such as Germany, China, Taiwan, and Singapore, improve urban hydrology; reduce building energy consumption, air pollution, storm water quality, ecological habitat, and carbon dioxide emission [3,6–8]. WRs are integrated with green roofs and wetlands involve growing plants on rooftops and treating wastewater. The WRs with various plants such as *Melampodium paludosum* (Aster daisy) and *Axonopus compressus* could treat domestic wastewater effectively [9]. The shallow horizontal SSF WR system with aster daisy can effectively remove COD, TN, and Total phosphorus (TP) with the average efficiency of 29, 17, and 1.8 kg TP/ha d [10]. Wong et al. [11] and Rowe [12] used WR systems to remove nutrients from domestic wastewater. It is described that the green area of plants could also alleviate the influence of air pollution, carbon dioxide emission such as global warming and climate change.

This study aims to evaluate adaptability and nutrient removal of pilot-scale WR systems at hydraulic loading rate (HLR) of 300 m^3/ha d. The plants used for the WRs were *Arachis duranensis* (1), *Evolvulus alsinoides* (2), *Cosmos Bipinnuatus* (3), *Cyperus alternifolius* Linn (4), and *Philodendron hastatum* (5).

2. Materials and methods

2.1. Experimental setup

Each WR system was located in a tin container which is 1.8 m in length × 0.6 m in wide × 0.15 m in height (Fig. 1). Each container includes two baffles to create three separated zic-zac channels, creating plug-flow condition (L:W = 27). The layers of materials are placed in order from top to bottom (10 mm of surface sand; 20 mm of natural soil; 70 mm of sand; and 20 mm of small rock). Water level is maintained 100 mm during operation. This works like a shallow bed wetland, which is developed by our research group mentioned in [9,10]. At the two ends of each channel, gravel is packed in block to avoid clogging. The porosity of the filtration bed is 0.26. Wastewater flowed gravitationally from the elevated buckets into the WRs. Flow rate of wastewater were adjusted by needle valves daily to achieve the constant flow during operation.

Plants were grown on 5 May 2012 (day 1). Tap water was used for watering the plants for the first 5 d. Then, domestic wastewater was introduced to the system from the day 6 onwards. Four WRs were operated at the two average HLRs of 220 m^3/ha d (day 5–63) and 300 m^3/ha d (day 64–172).

Fig. 1. Model of the WR systems.

2.2. Domestic wastewater

Domestic wastewater was taken from the last chamber of a septic tank in a residential building in Ho Chi Minh City. The characteristics of wastewater was 162 ± 42 mg COD/L, 70 ± 15 mg TN/L, 0.11 ± 0.07 mg NO_3-N/L, and 6.1 ± 2 mg TP/L. Wastewater pH varied between 7.0 and 8.5 during the study period.

2.3. Experimental plants

Selected plants for WRs should be easy to plant; strong growth and vitality in tropical conditions; ability to grow in nutrient-rich conditions. Preferentially, the plants are available in local and low price. The used plants are described in Table 1.

2.4. Sampling and analysis

2.4.1. Sampling

The influent and effluent samples were collected 2–4 times per week, from 8 to 9 am to determine parameters of pH, COD, TP, TN, ammonia, nitrate, and nitrite. The analytical methods were according to standard methods [13]. Influent flow was measured daily by graduated cylinder and stopwatch to calculate the HLR of WRs [9,10]. Based on the time and duration of the rain flowing to the systems, the samples were reported as collected in rainy or sunny days. The rate of survival, fresh weight, and dry weight of plants were measured for each pre-defined period.

2.4.2. Nitrogen and phosphorous mass balance

Soil and plant samples were collected from WRs on the 132th day to determine TN and total phosphorous (TP) accumulated in the soil media and plant biomass, respectively. Samples were dried at 70°C until constant weights, refined and sieved at 0.2 mm. The concentrations of TN and TP in dry biomass were analyzed to calculate total accumulated nutrients in plant for whole operation period. Nitrogen and phosphorus mass balance is calculated according to Eqs. (1) and (2) [14].

$$TN_{influent} - TN_{effluent} = (TN_{Final\,soil} - TN_{Initial\,soil})(g) + (TN_{Final\,plant} - TN_{Initial\,plant})(g) + Loss\,(g) \quad (1)$$

$$TP_{influent} - TP_{effluent} = (TP_{Final\,soil} - TP_{Initial\,soil})(g) + (TP_{Final\,plant} - TP_{Initial\,plant})(g) + Loss\,(g) \quad (2)$$

The average ratio of nutrient uptake by plants was estimated based on the accumulated nutrient in plant over the accumulated load of nutrients into the WR system for the operation period according to Eqs. (3) and (4) [5].

$$\text{Nitrogen uptake ratio} = (TN_{accumulated\,in\,plants})(g)/\sum(TN_{influent} - TN_{effluent})(g) \quad (3)$$

Table 1
Experimental plants on WRs

Plant	(1)	(2)	(3)	(4)	(5)
Scientific name	*Arachis duranensis*	*Evovulus alsinoides*	*Cosmos Bipinnuatus*	*Cyperus alternifolius* Linn	*Philodendron hastatum*
Density	255 plants/m^2	253 plants/m^2	27 plants/m^2	187 plants/m^2	15 plants/m^2

$$\text{Phosphorus uptake ratio} = (\text{TP}_{\text{accumulated in plants}})(\text{g}) / \sum (\text{TP}_{\text{influent}} - \text{TP}_{\text{effluent}})(\text{g}) \quad (4)$$

3. Results and discussion

3.1. Plant growth and nutrient acclimatization

3.1.1. Acclimatization

Plants (1)–(4) were grown in acclimatization period from day 5. Plants (1), (2), and (3) grew rapidly with more blooming buds and flowers. Until day 14, survival of plant (3) reduced stronger and on day 20 all died with rotted root and stem. After that, plant (3) was grown again to check its vitality in WR conditions. However, after next 10 d, plant (3) continued to die. It can be concluded that plant (3) cannot adapt with wastewater under WR conditions. On week 4, the survival rate of (1) and (4) plants was approximately 98%, more buds growing on stems. On day 63, plant (5) was started growing to replace plant (3). During two weeks after planting (5), buds seem grow slowly and some leaves became yellow. However, on week 6, leaves changed to dark green and some new buds appeared. After that plant (5) continued to grow through the experimental period. For plant (2), they remained but reduced slowly during first 3 months; the survival rate was just only 85% on day 100, 50% on day 118, and 10% on day 148. In general, plants (1) and (4) had the best development under the conditions of WR systems treating domestic wastewater. They also could create the large green area covering whole the wetland surface.

3.1.2. Biomass growth

The plants were harvested after 60 d growing in the WRs. The fresh and dried plants were weighted. Biomass of plant (3) was not analyzed because of death after 2 months of operation. Plant biomass consisted of stem, leave, and root. Fig. 2 shows that the capacity of biomass growth according to the fresh weight of (1) increased to 958 g (296%); (2) to 133 g (31%); (4) to 451 g (93%); and (5) to 4,077 g (189%). It means that the growth rates in fresh biomass compared to initial biomass were following the descending order as (1), (5), (4), and (2). In terms of dry weight, plant (1) increased to 96 g (230%); plant (2) to 19 g (7%); plant (4) to 112 g (66%); and plant (5) to 663 g (141%). It indicates the growth rates in dry biomass compared to initial dry biomass were also following the same descending order of fresh biomass. Large amount of water was absorbed into the plants (1) and (5), contributing to their fresh weights after operation period. This correlates to the development of plant (1) of 3–5 buds/tree and plant (5) of 5–7 buds/tree.

3.2. Treatment performance

3.2.1. COD removal

COD were removed in CW due to the biodegradation, accumulation, and filtration through media layers which was similar to the removal mechanism of constructed wetlands. Both aerobic and anaerobic processes contributed to reduction in organic matters in CWs. Root system created an ideal environment for the development of adhesive micro-organism. Biodegradation occurred when dissolved organic matter is brought in the adhesive micro-organism layer on the

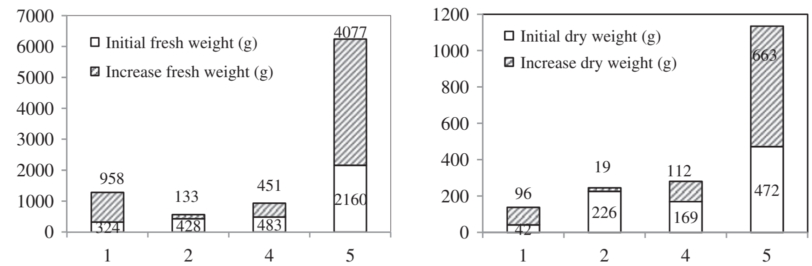

Fig. 2. Increase in dry and fresh weight of plants in WR systems after 60 d of operation.

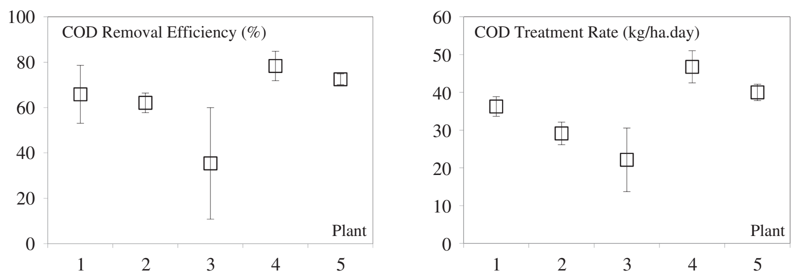

Fig. 3. COD removal and COD removal rate in the acclimatization period of WRs.

submerged body of plant, root systems, and filter bed layers [15].

In the acclimatization period with average HRT_o of 220 m^3/ha d (day 5–63), COD removal of the plants was relatively stable in decreasing order was (4) (78 ± 6% or 47 ± 4 kg COD/ha d); (5) (70 ± 4% or 40 ± 2 kg COD/ha d); (1) (66 ± 13% or 36 ± 3 kg COD/ha d); (2) (62 ± 4% or 29 ± 3 kg COD/ha d); (3) (35 ± 25% or 22 ± 8 kg COD/ha d) (Fig. 3). As a result, plant (4), i.e. *C. alternifolius* Linn achieved highest COD removal efficiency and removal rate during the acclimatization period.

Fig. 4 presents the influent COD concentrations at the HLR_1 (from day 64 to 172) varied from 120 to 200 mg/L. The average effluent COD concentrations were ranging from 7 to 88 mg/L for both rainy and sunny days that lower than the effluent standard limits (100 mg/L) for domestic wastewater (Viet Nam national technical regulation for domestic wastewater treatment—QCVN 14:2008/BTNMT, level B [16]). The effluent COD concentrations were lowest for the cases of plant (1) and plant (4). The highest removal efficiency was belonged to plant (4) (86 ± 11%). The plants (1), (2), and (5) were 86 ± 6, 64 ± 17, and 75 ± 5%, respectively.

For rainy days, the COD removal efficiencies were ranging from 37 to 96%. The highest removal efficiency was also for the case of plant (4) (94 ± 2%). For the case of plant (1), COD removal efficiency increased more than at the acclimatization period. The removal efficiencies of (2) and (5) were 66 ± 18 and 76 ± 6% (Fig. 4(a)). For sunny days, the COD removal efficiencies were ranging from 19 to 94%. The highest one was at the case of plant (1) 84 ± 6% and the second one is for plant (4) (80 ± 12) (Fig. 4(b)). The COD removal efficiencies in rainy days were slightly higher than those in the sunny days. This was due to the dilution effect of rainwater.

The average COD removal rates of plants (1), (2), (4), and (5) in sunny days (rainy days) was 49 ± 9 (53 ± 8), 36 ± 10 (42 ± 7), 57 ± 10 (60 ± 9), and 38 ± 8 (41 ± 7) kg COD/ha d, respectively. The removal rate of plant (4) was the highest one (Fig. 4(c), and (d)). The average COD in effluents of plant (4) was lowest, ranging from 10 to 40 mg/L for both rainy and sunny days, compared to other studied plants.

3.2.2. Nitrogen removal

In this study, the average influent TN concentration of WRs was 75 ± 13 mg/L for the study period. The effluent TN concentrations in WR (1), (2), (4), and (5) were 25 ± 10, 35 ± 12, 6 ± 4, and 19 ± 7 mg/L, respectively. The average nitrogen removal efficiencies in (1), (2), (4), and (5) were 65 ± 12, 52 ± 11, 92 ± 5, and 72 ± 8%, respectively. While their average removal rates in (1), (2), (4), and (5) were 19 ± 3, 13 ± 2, 24 ± 4,

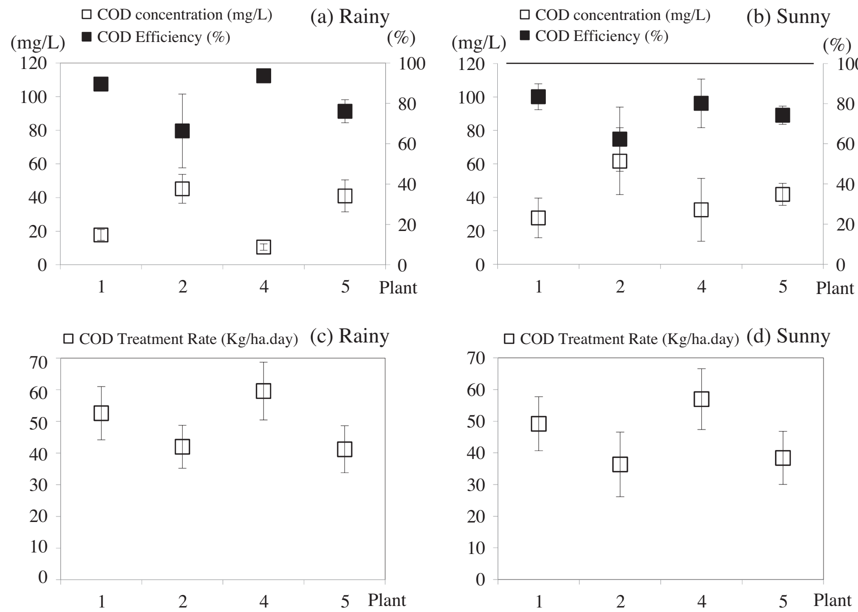

Fig. 4. COD removal and removal rate for rainy days (a,c) and for sunny days (b,d) of WRs.

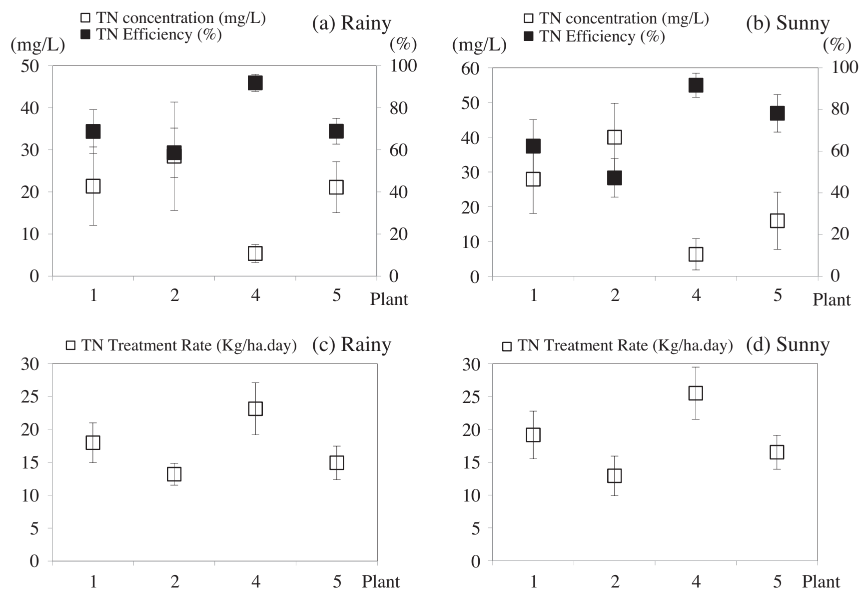

Fig. 5. Nitrogen removal and removal rate for rainy days (a,c) and for sunny days (b,d) of WRs.

and 16 ± 3 kg TN/ha d, respectively. This indicates plant (4) had the highest and excellent nitrogen removal capacity among the plants. The effluent TN concentrations in plant (4) WR was lower than 10 mg/L during operation period. The difference of nitrogen removal in the sunny days and the rainy days was insignificant. The TN removal efficiency of plant (4) was the highest with 92 ± 4% (rainy day) and 92 ± 6% (sunny day) (Fig. 5).

3.2.3. *Phosphorous removal*

For both seasons, average effluent TP concentrations were less than 6 mg/L which complies with Vietnam national technical regulation on domestic wastewater (QCVN 14:2008/BTNMT, level A) [16]. The TP removal efficiencies in rainy days increased slightly compared with the one in sunny days were (75 ± 14, 73 ± 13%), (21 ± 16, 23 ± 20%), (91 ± 6, 88 ± 10%), and (12 ± 12,

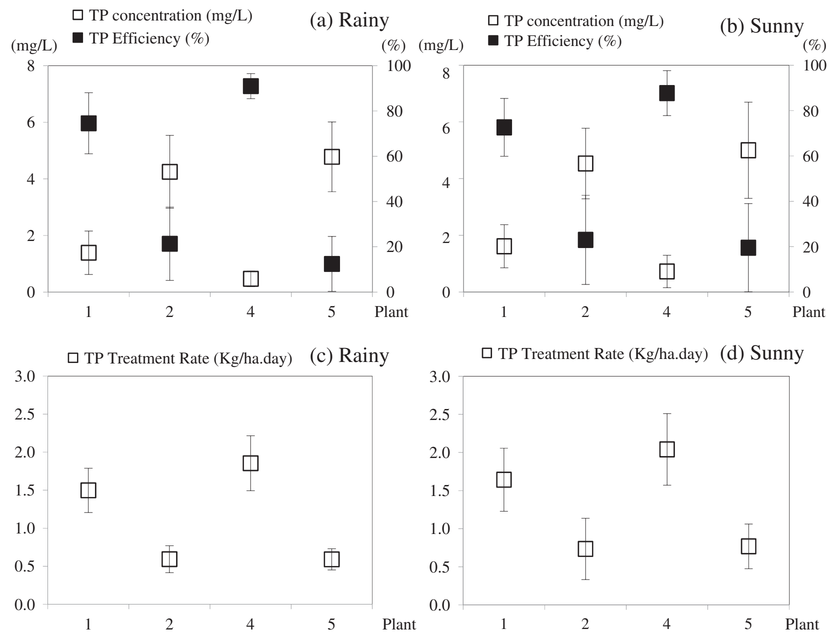

Fig. 6. Phosphorus removal for rainy days (a,c) and sunny days (b,d) in WRs.

20 ± 19%) for (1), (2), (4), and (5) respectively) (Fig. 6). While their average phosphorus removal rates in (1), (2), (4), and (5) were 1.6 ± 0.4, 0.7 ± 0.3, 2.0 ± 0.4, and 0.7 ± 0.2 kg TP/ha d, respectively. This indicates plant (4) also had the highest and excellent phosphorus removal capacity among the plants.

Compared with the results of Thanh et al. [9,10], the COD, TN, and TP removal efficiency of *C. alternifolius* Linn (4) was all higher than those of *M. paludosum* (Table 2).

3.3. Nutrient mass balance

3.3.1. Mass balance of nitrogen in WR systems

Nitrogen uptake by plants differs according to the systems, loading ranges, pollutant concentrations in wastewater, and environmental conditions. The contribution of plants has been reported within the range 0.5–40% of the TN removal [5]. In conventional wetland, nitrogen is mainly accumulated in soil media and lost through denitrification [15]. While the plant uptake ratios for WR (1), (2), (4), and (5) were 21.5, 1.3, 93.0, and 16.8%, respectively (Table 3). The results show that the highest nitrogen accumulation was for plant (4) (255.17 g) (i.e. *C. alternifolius* Linn). The nitrogen uptake ratio in plant (4) was much higher than the others (with the uptake ratio of 93%). This was probably due to the growth rate of plant biomass in the systems. The plants need a large amount of nitrogen for their growth process. This result was in line with the observed growth density in plant (4) WR systems and the biomass formation. The plant biomass increased each 11.1 g per day during operation period (observed in 60 d of operation) (Fig. 2). According to the research results of [17], the TN removal of the plant (4) in the horizontal SSF wetland was mainly through plant uptake. The other plants also range within 0.5–40% as the period studies.

Table 2
Comparison of treatment performance of different plants in WR systems

Parameters	COD (%)	TN (%)	TP (%)
This study (HLR of 300 m^3/ha d)			
Arachis duranensis (1)	86	65	73
Evovulus alsinoides (2)	64	52	22
Cyperus alternifolius Linn (4)	86	92	89
Philodendron hastatum (5)	75	72	15
Thanh et al. [10] (HLR of 338 m^3/ha d)			
Melampodium paludosum	77–78	88–91	72–78

3.3.2. Mass balance of phosphorus in WR systems

Phosphorous in soil of (2) and (4) increased during the experiment period but (1) and (5) was opposite. TP accumulated in plants (1), (4), and (5)

Table 3
Mass balance of nitrogen and phosphorus in WR systems

	Plant	Influent/effluent (g)	Initial soil/ final soil (g)	Initial plant/ final plant (g)	Loss (g)	Uptake ratio (%)
Total nitrogen	(1)	247.42/53.62	40.81/62.26	0.66/37.65	135.36	21.5
	(2)	232.61/75.69	40.81/45.10	3.97/5.94	150.66	1.3
	(4)	268.40/2.55	40.81/32.12	5.92/261.09	19.37	93.0
	(5)	61.64/10.09	40.81/60.17	4.12/9.52	26.79	16.8
Total phosphorus	(1)	23.26/4.37	17.71/16.72	0.06/2.02	17.92	10.4
	(2)	21.87/13.11	17.71/21.12	0.42/0.40	5.37	−4.8
	(4)	25.23/0.28	17.71/16.06	0.51/7.94	19.17	29.8
	(5)	5.79/3.48	17.71/18.70	0.27/0.35	1.24	3.5

increased 10.4, 29.8, and 3.5%, respectively. There was no phosphorus uptake in plant (2) and this is in line with the result of nitrogen uptake of this plant. This plant was not well growing in the WR condition presented in the above results of biomass growth. The final TP mass in soil media of (1) and (4) was lower than that in the initial soil media because of the fast growth of the plants which required more phosphorus from wastewater. Therefore, the plants used a part of phosphorus in soil to develop. The rate of absorption of plant phosphorus of (4) was highest 29.78% (Table 3).

4. Conclusion

As the conclusion, the removal efficiency of *A. duranensis* (1) and *C. alternifolius* Linn (4) was much higher than the other three plants at the HLR of 220–300 m^3/ha d. The plant *C. Bipinnuatus* (3) was not suitable for the working conditions of WR treating domestic wastewater. The nutrient removal efficiencies as well as nutrient removal rates of plant (4) were the highest among the study plants (24 ± 4 and 2.0 ± 0.4 kg TP/ha d). The uptake of nitrogen and phosphorus of *C. alternifolius* Linn (4) was higher than those of *A. duranensis* (1). In addition, the shallow WRs with *C. alternifolius* Linn (4) and *A. duranensis* (1) are effective in terms of removing the nutrients in domestic wastewater and improving the green area in the top roof of urban cities.

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