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Pollutant removal by *Canna Generalis* in tropical constructed wetlands for domestic wastewater treatment

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ABSTRACT

Constructed wetlands have not been commonly used in Vietnam due to the lack of information in the selection of proper types of constructed wetlands, type of reeds, design parameters and performance efficiency, in tropical climates. This paper focuses on *Canna generalis,* which is a common reed and easy to grow both in water and wet land conditions. Two kinds of hybrid constructed wetlands were employed, including Facultative pond combined with free water sub-surface constructed wetlands system and horizontal subsurface flow combined with Aerobic pond system. It was found that the ponds played an important role in the hybrid system performance and enhanced the performance of constructed wetlands. The pollutant removal efficiencies of the hybrid systems were all higher than the single constructed wetlands. The BOD_5, TSS, NH_4-N and PO_4-P removal efficiencies averaged 81%, 85%, 93% and 77%, respectively for the hybrid horizontal subsurface flow constructed wetlands system operated at a hydraulic loading rate of 0.075 m/day, while they were 89%, 97%, 97%, and 68%, respectively for the hybrid free water sub-surface constructed wetlands system operated at a hydraulic loading rate of 0.1 m/day. The removal rate constants ($k_{BOD5,}$ $k_{NH4\text{-}N,}$ $k_{PO4\text{-}P}$) of the experimental hybrid constructed wetlands were similar to those in previous studies. However, these constants were higher for the hybrid free water subsurface constructed wetlands because of the modified structure flow of the free water subsurface constructed wetlands applied in this study, compared to conventional ones, as well as the additional benefits of the ponds in the hybrid systems.

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INTRODUCTION

Rapid urbanization and industrialization create critical pressures on the environment as well as urban infrastructure systems in developing countries (Yigitcanlar, and Dizdaroglu, 2015). Centralized wastewater treatment systems are often applied in densely populated urban areas, while in peri-urban areas, decentralized wastewater treatment with constructed wetlands is considered more suitable because of the greater land availability. With temperatures ranging from 20 to 45ºC and average rainfalls ranging from 1,700 mm to 2,400 mm, Vietnam, as well as other tropical countries, finds it more suitable for the application of ecological systems, in particular combination of stabilization ponds and constructed wetlands, for wastewater treatment (World bank, 2013; Shitu *et al.,* 2015). Construction wetland is a low-cost, natural technology for wastewater treatment, and is emerging as a useful technology for the treatment of a variety of wastewaters with the efficiency highly correlated with light intensity and temperature (Huang *et al.,* 2010; Huang *et al.,* 2013; Du *et al.,* 2017). It has many advantages, such as reducing flow velocity, increasing sedimentation capacity on the river bank, reducing erosion and sediment from the bottom, reducing the development of floating plants, enhancing redox potential in the CW, facilitating the decomposition of organic matter and nitrogen (N), phosphorous (P) removal, and killing pathogenic bacteria (Huang *et al.,* 2013; Karbassi and Pazoki, 2015; Daliry *et al.,* 2017; Shitu *et al.,* 2015). Many previous studies revealed that the performance of constructed wetlands varied with different plant species and their productivities (Zhang *et al.,* 2014). The total nitrogen (TN) and total phosphorous (TP) removal rates were 58.6% and 66.5% for *Typha angustifolia*; 45% and 81.7% for *Thaliade albata*; 52.8% and 40% for *Anthurium andreanum*, respectively; while they were 15% and 52% for *Canna indica*. It should be noted that the plants' productivities rely greatly on the weather and soil conditions. The wetlands in the tropical areas, which are exposed to higher temperatures and direct sunlight, have higher plant productivity and more efficient pollutant removal, accordingly, than those in the sub-tropical areas (Zhang *et al.,* 2012). For instance, with the same kind of Canna plants, the TN and TP removal rates varied from 15% and 52% in Wuhan, China (subtropical weather) to 39% and 46% in Chiangmai, Thailand (tropical weather) (Singh *et al.,* 2009). Vietnam, like other tropical countries, has found many plants can be used for constructed wetlands. They are usually perennial aquatic plants, porous herbs, bunch roots, floating on the surface or completely submerged in water, most commonly are grass candles, reeds, rush, wicks, and stalks (Tran, 2006). These plants are quite easy to find in nature and they also have strong vitality. Among them, *Canna generalis* is a mixture of tropical and subtropical plant, which can create ecological landscapes for urban areas, especially peri-urban areas, in additional to its high potential for wastewater treatment. Besides plant species, the flow direction forms different types of CWs and influences the performance to some extent. According to Kadlec and Knight (1996), the main kinds of CWs are free water subsurface (FWS) CWs and subsurface flow (SSF) CWs, in which, SSF CWs are further classified into vertical subsurface flow (VSSF) and horizontal subsurface flow (HSSF) systems; and the latest is floating treatment wetland (FTW). Stand only FTWs were reported to have better treatment efficiency than FWS CWs. Besides, it has the advantages over conventional sediment-rooted wetlands (FWS or SSF CWs) in their ability to cope with variable water depth, so it is appropriate to apply in areas with frequent storm weather or in those areas critically impacted climate change conditions (i.e., high storm intensity and flooding tendency). The removal efficiencies of FWS CWs were unstable and not so high (<50%) for total suspended solid (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), TP and TN (Zhang *et al.,* 2014) while, more than 70% removal for those pollutants were reported in previous studies (Kadlec and Wallace, 2008). The removal efficiency depends on many factors including inflow concentration, chemical form of nitrogen, water temperature, season, organic carbon availability, and dissolved oxygen concentration (Kadlec, 2009; Kim *et al.,* 2011). Among the SSF systems, the HSSF CWs show the best performance as the substrate is constantly immersed and there is less fluctuation in redox potential in the bed is observed (Vymazal, 2007; Vymazal, 2009). To improve the performance of this low cost technology, CWs are often combined in many ways, such as hybrid FWS-SSF CWs, two or three step SSF CWs, or combined with waste stabilization pond (WSP) (Vymazal, 2007). The hybrid was most commonly used in Asia and the performance was moderate and reliable with more than 60% for TN and TP removal and above 80% for organic and solid removal (Zhang *et al.,* 2014). The aims of this study were to evaluate the pollutant removal capacity of *Canna generalis* with hybrid CWs and stabilization ponds. Two kinds of hybrid CWs systems, including Facultative pond combined with free water sub-surface constructed wetlands (Hybrid FWS CW system) and horizontal subsurface flow combined with Aerobic pond system (Hybrid HSSF CW system), were employed. The mass growth rate of *Canna generalis* and the kinetics of pollutant removals of different hybrid models were determined and discussed in details. This study was carried out in Thai Nguyen province, Viet Nam, from 2014 to 2016.

MATERIALS AND METHODS

Characteristics of influent wastewater

The influent was taken from the 31-m^3/day wastewater treatment system in Bach Quang ward of Thai Nguyen city, a city in the Northern mountainous area of Vietnam. After screening, the value of SS, COD, BOD_5, NH_4^+, NO_3^-, PO_4^{3-}, Coliform were 67.0±3.5 mg/L; 154.6±7.8 mg/L; 85.0±9.2 mg/L; 23.4±5.8 mg/L; 1.73±0.3 mg/L; 0.61±0.15 mg/L; 91000±6740 MPN/100 mL, respectively. It can be said that the input concentrations of pollutants varied quite significantly. They reflect quite well the characteristics of wastewater (WW) from combined sewage system, in which, organic concentrations are low and diluted due to the mixture of domestic wastewater and rainwater and some of them are degraded in the sewers and canals. It is worth noting that more than 90% of municipal sewage system in Vietnam is collected by the combined sewer system and partly connected with open channels (World Bank, 2013). The compositions of the WW vary over the year, which correspond to dry and rainy seasons of the tropical climate.

CW Plant for testing

The selected plants for testing in constructed wetland were *Cannas generalis* reeds. The reed is a perennial shrub, rhizome, with broad leaves that grow from the stem in a tight roll, long in the trunk and commonly grow in wet and dry soil. Most cannas plants are immune to pests and used in constructed wetlands for wastewater treatment in tropical and subtropical weather. They can grow as high as 75-300 cm, with different colors as ivory, yellow, pink, red, creating beautiful landscapes in the city (Vymazal *et al.,* 2008). In this study, the seeding plants (Fig. 1) had the average height of 20 cm with 2-3 seed leaves. The *Cannas generalis* was planted every 20cm in distance, with density of 16 plants/m^2. For the determination of dry biomass, *Cannas generalis* was harvested and delivered to the lab after a certain time. They were cut into 20-30 cm pieces, then weighted before and after drying in the oven at $103^0C \div 105^0C$ until the weight was unchanged. The difference in fresh weight and dry weight is the moisture content of biomass. The difference in initial dry biomass (before planting) and those after harvesting time is the total dry biomass.

Fig. 1: Seeding *Cannas generalis* plants

Experimental set up

The purpose of this study is to test the combination of CWs and WSP. The first model used Facultative pond and FWS CW (Fig. 2a) while the second model employed HSSF CWs and aeration pond (Fig. 2b). A note should be mentioned here that effluent of FWS CW was taken from the bottom, not the top as other conventional FWS CW, thus, higher removal efficiency should be expected as the wastewater was filtered and adsorbed on sand and gravels on the way down.

The two models were designed to operate in parallel with the same inlet wastewater flow (Q) of 0.096 m^3/d. In the first model, the pond played the role of a secondary treatment unit, so the facultative pond was selected, and the FWS CW was considered as a polishing step afterward. In the second model, the CW had the role of a secondary treatment facility, so HSSF CWs were selected, while the pond played a role as a polishing treatment unit, aeration pond was therefore employed. The SSF CW normally performs better than FWS CW due to the flow structure (Zhang *et al.,* 2014). Based on the selection of hydraulic loading rates of the CWs and the required retention time of the ponds, the necessary dimensions of these two models were determined as in Table 1. The models were constructed of reinforced concrete in the corner of wastewater treatment plant in Bach Quang ward. Automatic pumps and wastewater pipelines were used to pump WW from the treatment plant to the influent WW tanks of the pilot. Inside the CWs were filled with sand and gravels with the height and media's sizes referred from previous studies (Watson *et al.,* 1989; Kayombo *et al.,* 2004; USEPA, 2000).

The model was started up in December, 2014. The hydraulic retention time (HRT) of both CWF and HSSF was 20 days, while the Hydraulic loading rates (HLR) were altered during the test to evaluate the impact of HLRs on the hybrid system's performance (effluent quality and plant growth rate). Table 2 presents the different HLRs and corresponding average input pollutants' loading rates.

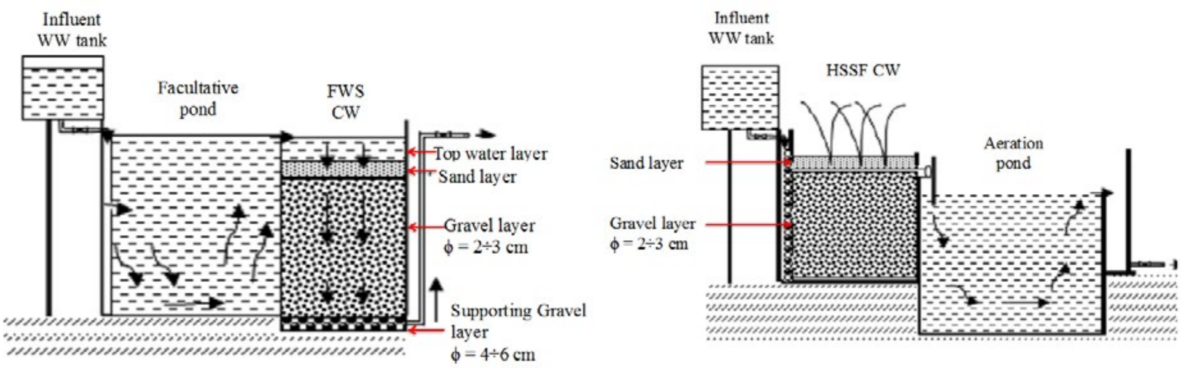

Fig. 2: Experimental pilots installed in wastewater treatment plant in Bach Quang ward

Table 1: Description of FWS and HSSF CWs
(Watson *et al.,* 1989; Kayombo *et al.,* 2004; USEPA, 2000)

	FWS CW			HSSF CW		
		Unit	Value		Unit	Value
Number of CWs	N1	system	1	N2	system	2
Flowrate	Q	m^3/day	0.096	Q	m^3/day	0.048
Surface area (A_s = 100Q/HLR)[2]	A_s	m^2	0.96	A_s	m^2	0.96
CW length	L	m	1.2	L	m	1.2
CW width	B	m	0.8	B	m	0.8
CW height	H	m	1.45	H	m	0.75
Top Water level height[1]	h_1	m	0.2	-	-	-
Medium for plant growing (sand ϕ = 1÷2 mm)[2]	h_2	m	0.15	h_1	m	0.15
Middle layer of medium gravel (Gravel ϕ = 2÷3 cm)	h_3	m	0.9	h_2	m	0.6
Bottom layer of coarse gravel (Gravel ϕ =4÷6 cm)[3]	h_4	m	0.1	-	-	-

Sample analysis

Water sampling and analysis were carried out from 8th of March, 2015 to 29th of May, 2016 with a two-week frequency. The samples were taken from the inlet, after the CWs and after the ponds. The sampling and sample storage were complied with standard method ISO 5667-2:2006 of Vietnam (Water quality - Sampling - Part 1: Guidance on the design of sampling programes and sampling techniques) and standard method ISO 5667-3:1985 of Vietnam (Water quality - Sampling - Guidance on curing and treatment of samples), respectively. They were then analyzed in terms of SS, BOD_5, NH_4-N, and PO_4-P. Standard Methods for the Examination of Water and Waste Water (SMEWW) were SMEWW 2540.D for SS determination; SMEWW-5210.B-2012 for BOD_5 analysis; SMEWW-4500-NH3F.2012 for NH_4-N, and SMEWW-4500-P.E:2012 for PO_4-P determination. The statistical analysis was also conducted to evaluate the impact of HLRs on the organic removal efficiency. This step was performed using one-way analysis of variance (ANOVA) as the only variable was HLR. The level of significance was α = 0.05 in all cases. The software StatPlus:mac LE version 6.7.1 (AnalystSoft Inc, USA) was used for this statistical analysis.

Kinetic study

To determine the kinetic coefficients of decomposition of pollutants by using *Canna generalis* in the hybrid systems, it was assumed CW is a bioreactor, in which the decomposition of organic matters (i.e., BOD_5) and nutrients (i.e, NH_4-N and PO_4-P) shall follow the first-order reaction modeling. Fitted values of k were derived from the following plug-flow k–X* model (Kadlec and Knight, 1996) using Eqs. 1 to 3.

$$ln\left(\frac{X_e - X^*}{X_i - X^*}\right) = \frac{-k}{q} \quad (1)$$

$$ln\left(\frac{X_i - X^*}{X_e - X^*}\right) = \frac{k}{q} \quad (2)$$

$$q = \frac{Q}{A_S} \quad (3)$$

In which, A_S: surface area of CW (m^2); X_e: effluent pollutant concentration (mg/L); X_i: influent pollutant concentration (mg/L); X*: background pollutant concentration in CW; k: first-order area-based removal rate constant (m/day); q: hydraulic loading rate (m^3/m^2.day or m/day) and Q: the average flowrate into CWs (m^3/day). Fittings were carried out using the non-linear regression procedure with k as unknown parameter. Typical X* background concentrations of BOD_5 were from 2-20 mg/L, and for NH_4-N, NO_3-N, PO_4-P were 0 mg/L (Kadlec and Knight, 1996; Kadlec, 2009). In this study, the X* values for BOD_5 were assumed and applied in the HSSF CW and FWS CW as 5 mg/L and 2 mg/L respectively. For the case of FWS CW, it was placed after facultative pond, which had treated part of organic matters, hence, the concentration of BOD_5 was selected with the lowest value (2 mg/L). The X* values for NH_4-N, NO_3-N, PO_4-P were 0 mg/L according to the reference.

RESULTS AND DISCUSSION

Biomass growth rate in tested CWs

The biomass growth is one of the concerned factors

Table 2: Testing HLRs and input pollutant loading rates

CWs	Testing period	HLR	Average BOD loading rate	Average NH_4^+ loading rate	Average PO_4^{3-} loading rate
		m^3/m^2/day	kg/ha/day	kg/ha/day	kg/ha/day
HSSF *	Phase 2	0.050	41.73	11.77	1.77
	Phase 3	0.075	63.08	25.41	11.63
	Phase 4	0.088	72.86	29.65	21.18
	Phase 5	0.100	81.95	43.67	28.40
FWS	Phase 1	0.100	46.91	5.24	1.75
	Phase 2	0.125	41.11	18.51	10.34
	Phase 3	0.150	39.47	16.73	13.31
	Phase 4	0.175	57.14	36.02	33.08
	Phase 5	0.200	60.80	41.50	35.40

Note: Phase 1 (7/12/2014-29/8/2015); Phase 2 (26/9/2015- 3/1/2016); Phase 3 (3/1/2016-21/2/2016); Phase 4 (21/2/2016-10/4/2016); Phase 5 (10/4/2017-29/5/2016).
*For the HSSF CWs, no *Canna generalis was planted during Phase 1 so this was omitted in the results and discussion.*

as it can explain to some certain extent the organic and nutrient removal efficiency of the CWs system. Higher biomass growth can relate to better nutrient absorption or plant uptake. Monitoring the growth of *Cannas generalis* plants during the experimental period revealed that the first month after planting (December 7, 2014) was the time for plants to adapt to environmental conditions, and create roots. In the second and third months after having roots, the plants began to produce new young leaves, but the growth rate was slow. In the 4th month, the plant started to grow faster and produced more new young leaves. The time to start harvesting biomass was in March 29, 2015 (after almost 4 months). It is worth noting that the longer time was expected for plants to adapt and grow because the test started in winter (March and April, 2015) with temperature of 18 ÷ 23°C.

During the testing period, 19 batches of *Cannas generalis* plants were harvested from the two hybrid models. Harvested *Cannas generalis* plants were measured in size, and weighed both the fresh biomass and dry biomass. Moisture was calculated from those data. The biomass growth of *Cannas generalis* plants in CWs were fluctuated over time, as shown in Figs. 3 and 4.

For the HSSF CWs hybrid model, the harvested biomass achieved the highest value of 526.15g on May 17, 2015 and the lowest value of 95g on March 29, 2015. The average biomass per plant ranged from 12.53 to 42.76 g with the average value of 29.81 g/plant. The average height of all harvested trees from HSSF CWs reached 1.44m. During the study, *Cannas generalis* grew quite stable with many new sprouts. For FWS CW hybrid model, the biomass reached the highest value of 1182.96 g on April 12, 2016 and the lowest value of 22.84 g on 29th of March, 2015 when it was newly planted. The average biomass per plant ranged from 22.84 to 71.69g, averaging 41.49 g/plant. The average height of all harvested trees of the FWS CW system reaches 1.58m. During the study period, the reeds in the FWS filter area had a fairly stable growth with more new sprouts and longer leaves. The fluctuation of biomass and plant height in the hybrid FWS CS system was more significant than those in the hybrid HSSF CS system. This was proved in Kadlec (2009) study that HSSF CWs were typically much less sensitive to cold water than FWS CWs, in other words, FWS CWs are more temperature sensitive. As the season changed from spring (average temperature of 20°C) to summer (average temperature of 30°C) and then

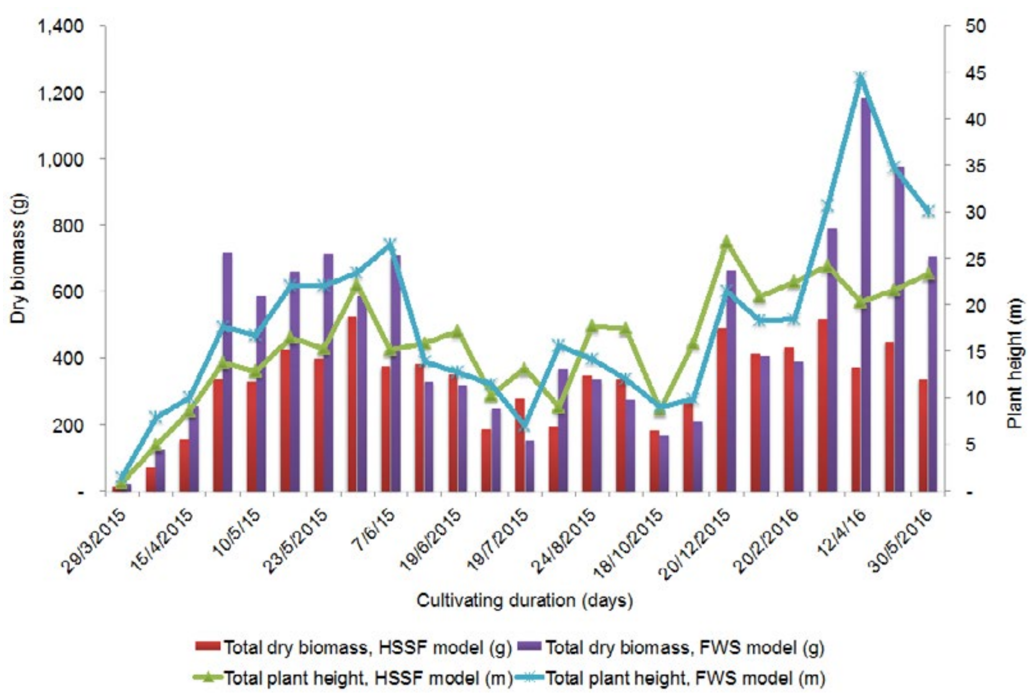

Fig. 3: Dry biomass and total height of *Cannas generalis* in the hybrid CWs

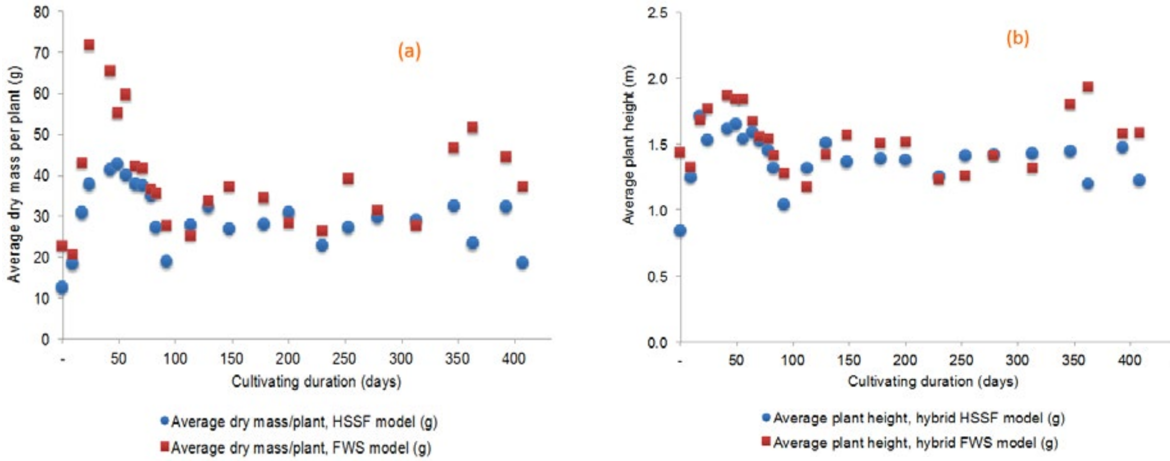

Fig. 4: Average dry biomass per plant (a) and average plant height (b) in the CWs

Fig. 5: *Canna generalis* on 12/4/2016 in HSSF CW (left) and FSW CW (right)

autumn (average temperature of 23°C), the changes in performance of HSSF CW was less severed (Figs. 3 and 4). The water layer on top of the planting media was the key factor affecting this phenomenon as water response to temperature more readily than sand. This water layer of FWS CW creating by combination with WSP may add some extra benefits for WFS in term of pollutant removal.

Overall, it can be seen that the growth of Cannas *generalis* plants in CWs varied with routine that high in the winter and low in the summer under tropical weather. In general one expects that the plants would grow faster and better in the summer, as in the summer, the dissolved oxygen shall be more available (Zhang *et al.,* 2009). However, from June to August in Vietnam, the temperature can go up to 40-45°C, which actually limits the growth of these plants since the water evaporated more significantly, accordingly the water and nutrient supplied to plants was constrained. In addition, it can be found that the *Cannas generalis* in the FWS CW hybrid model grew consistently better than those in HSSF CW hybrid model, i.e., the total dry biomass was 1.5 times higher, dry biomass per plant was 1.4 times higher and the average height/plant was also 10% higher (Figs. 3, 4, 5 and Table 3). The explanation may lie in the fact that *Cannas* *generalis* prefers the wet and high humidity conditions as its biomass growth depends greatly on the water convection/exchange within the plant. With the high humidity, the rate of exchange was more significant. In addition, on top of the sand in FWS CW always maintained 0.2m layer of water, which promotes the nutrient and organic dissolution as well as oxygen dissolution more efficiency. This could help the absorption or assimilation of nutrients onto the plants, making them grow better (Table 3).

Organic and nutrient removal efficiencies

In the recent review of all kinds of CWs with various types of reeds for wastewater treatment in developing countries from 2000-2013, Zhang *et al.* (2014) found that all types of hybrid systems appeared more efficient in the removal of TSS (93.82%), COD (85.65%), BOD_5 (84.06%), NH_4-N (80.11%), and TN (66.88%), compared to single CW system. In addition, both HSSF and VSSF CWs showed superior TP removal (65.96% and 59.61%, respectively) compared to FWS CWs (49.16%). In this study, the effort for comparison only limits with *Cannas generalis* reeds and HLR of ≈100 mm/day. This would render a clearer picture of the impact of hybrid or single CWs on the pollutant removal efficiency providing that the same reed and relatively-fixed operation conditions. It is obvious from Fig. 6 that with the same type of reeds, the hybrid CW systems performed better than the single CWs (both SSF and FWS CWs), for most of the contaminants. This confirms the fact that WSPs in either form of facultative or aerobic ponds do support in degradation of organic matters or nutrient settling. They actually are biological treatment system with key advantages such as resistant to organic and hydraulic shock loads and high reduction of solids, BOD and pathogens (Tran, 2006).

In terms of performance of FWS CWs versus HSSF CWs, since in this study they were combined with WSP as hybrid systems in not the same order, it was hard to compare. Also, there was not many single FWS CW employed *Cannas generalis* reeds in previous studies for comparison with a single HSSF CW. One thing should be noted that the hybrid FWS CW system had higher biomass growth than that in the hybrid HSSF CW system (Table 3), and the nitrate uptake and the organic carbon supply from the roots increases with the growth of the plant (Wen *et al.,* 2010), thus, the nitrogen transfer and organic (BOD_5) removal in the hybrid FWS CW system were a bit better (Fig. 6).

Table 3: Comparison of biomass growth in the two hybrid CWs

Hybrid CWs	Total dry mass (g)	Average humidity (%)	Average dry mass/plant (g)	Average height/plant (m)
HSSF-WSP	8196.69	86.96±0.30	29.81±7.58	1.44±0.19
WSP-FWS	11908.96	88.84±1.33	41.49±13.13	1.58±0.21

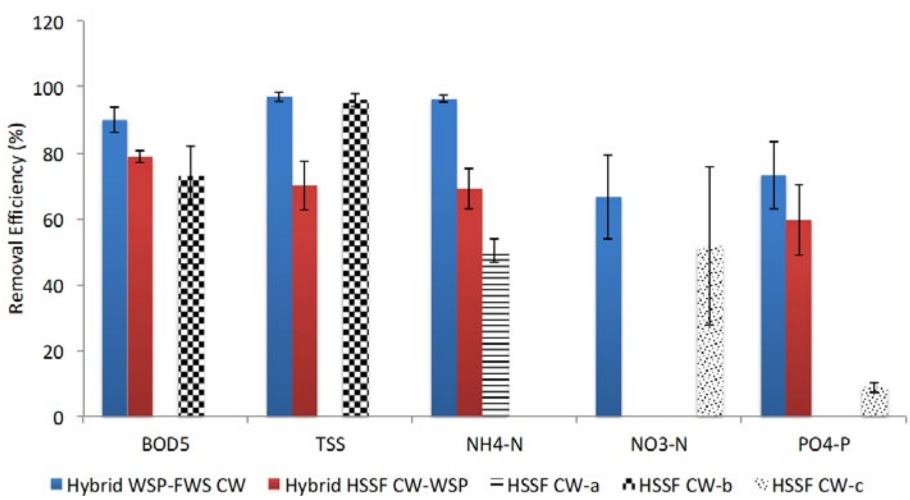

Fig. 6: Removal rate using *Canna generalis* reeds on different CWs
(*HSSF CW-a referred from Huang et al., 2013; HSSF CW-b referred from Konnerup et al., 2009; HSSF CW-c referred from Ojoawo et al., 2015*)

Impact of stabilization ponds in the hybrid systems

Previous studies with hybrid CWs in series (Zhang *et al.,* 2009) that the hybrid CW-WSP systems substantially enhanced the removal efficiencies. This study had similar results, Fig. 7 presents the average TSS, BOD_5, NH_3-N and PO_4-P removal of the WSP and the hybrid systems for the same type of reeds (Cannas *generalis)* and HLR of 0.1 m/day. In addition, it is obvious from Fig. 7 that the removal efficiency of facultative pond was always higher than aerobic ponds, resulting in higher overall efficiency of the hybrid WSP-FWS CW system.

Normally, FWS CW systems yield lower pollutant removals than HSSF CW systems due to their flow patterns and hydraulic retention times (Zhang *et al.,* 2014). However, in this study the hybrid FWS CW system performed better than the hybrid HSSF CW system presumably because of two reasons. Firstly, the flow pattern in the FWS CW was modified; the effluent was taken from the bottom of the system, not from the top of CW as in the conventional FWS CW. Thus, the wastewater was further filtered through media. Secondly, the facultative pond was deeper so there were aerobic, anoxic and anaerobic zones, where not only organic matter but also nitrogen and phosphorous were treated with the support of bacteria, algea and sunlight. While the aerobic pond was shallower than facultative pond to maximize the exposure to sunlight, hence, it is good for organic removal but it limits the nutrient and suspended solid removals.

Impact of hydraulic loading rates

Table 4 presents the pollutant removal efficiencies (%) at the different hydraulic loading rates to ascertain the impact of HLRs on CWs performance. Hydraulic conditions strongly influence the CWs biotic community composition, the biogeochemical processes, and the fate of pollutants. (Kadlec and Wallace, 2008). With the variation of HLRs in hybrid FWS CW, there was significant difference in the removal efficiency of all contaminants, so was with the hybrid HSSF CW, except for BOD_5 parameter (Table 4). For the case of hybrid

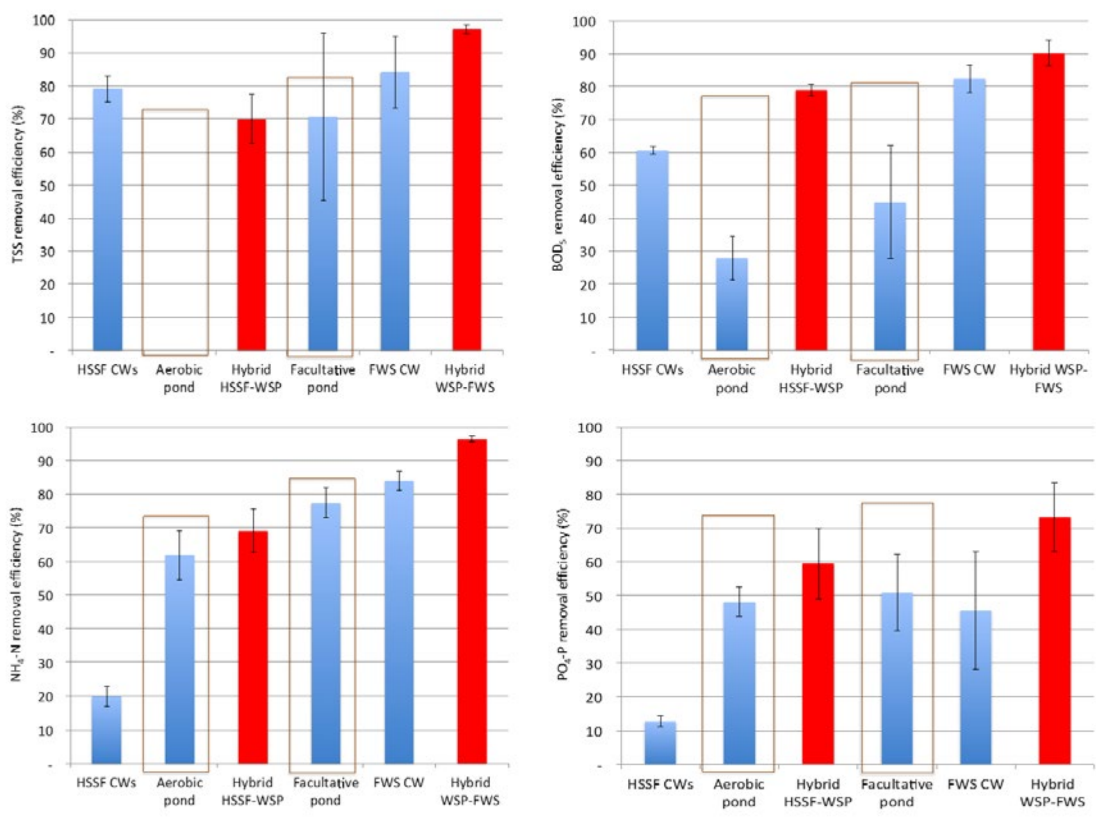

Fig. 7: Impact of waste stabilization pond (WSP) on hybrid WSP-CW system’s performance

WSP-FWS CW, the highest removal rate was at HLR of 0.1m/day while for the case of hybrid HSSF CW-WSP, the highest removal percentages for all contaminants was at a HLR of 0.075 m/day. In most cases, the removal rate decreased with increasing HLRs. Overall, the removal percentages of the hybrid FWS CW were higher than hybrid HSSF CW in terms of BOD_5, TSS; similar for NH_4-N but lower for PO_4-P. The best hydraulic loading rates for hybrid CWs ranged from 0.075-0.1m³/m²/d or 75 – 100 mm/d. Ngo *et al.* (2010) also found high removal rates for BOD, SS, and PO_4-P at a HLR of 104 mm/day. The HLR should not be too high as it may cause overflow from the planted bed, which reduces the plants and other biota's organic/nutrient absorption or storage. While the HLR should not be too low as it may not supply sufficient water and organic/nutrient for the reeds to maintain the best condition for active absorption.

Kinetics results

As mentioned in the previous section, the plug-flow k–X* model presented by Kadlec and Knight (1996) and constant background concentrations (X*) were used to fit the exponential decrease in pollutant concentration. The estimated first-order area-based removal rate constants (k) and coefficients of determination (R^2) for BOD_5, TSS, NH_4-N and PO_4-P are shown in Table 5. High R^2 for most of the cases proves that the plug-flow k–X* model fits well with the data.

Normally, the first-order area-based removal rate constants (k) represent the degradation rate of pollutants in the biological treatment system. Nevertheless, the high values of k do not necessarily indicate high removal efficiency when relating the value of k and removal efficiency (Fig. 8). Removal rate constants could increase slightly as HLRs increased for BOD_5 and COD, but not for TN and TP (Ngo *et al.,* 2010). Similar behaviors of constants k were observed in this study with the hybrid CW-WSP system. Only high correlations observed were for the NH_4-N and PO_4-P removals in the hybrid HSSF CWs system.

The organic removal rate constants (k_{BOD}) of hybrid HSSF CWs system tended to increase gradually when increasing the HLRs from 0.05 to 0.10 m³/m²/day with organic loading rates of 41.73-81.95 kg/ha/day. These values were quite in a range with the published results of the average k_{BOD} in previous studies (Kadlec, 2009; Vymazal, 2009; Ngo *et al.,* 2010) with the corresponding k_{BOD} values of 0.101; 0.123; 0.060-0.260 m/day (or 37; 45 and 22-95 m/year) for HSSF CW systems. The k_{BOD} of the hybrid FWS CW system ranged from 54-69 m/year (0.148 to 0.189 m/day). These values were higher than the average k_{BOD} for FWS CWs of 41 m/year reported by Kadlec (2009). Again the stabilization pond played an important role in this removal. In term of ammonium transformation rate constant (k_{NH4-N}), there was not a significant difference in the experimental phases and tended to decrease gradually when increasing HLR from 0.05-0.10 m³/m²/day. These values are consistent with the k_{NH4+-N} of HF filtration yards reported by Vymazal and Kröpfelová (2008) and Kadlec (2009), i.e., values of 0.024 and 0.031 m/day, respectively. In their study, Vymazal and Kröpfelová (2008) employed three stages CWs in series (saturated vertical-flow bed planted with *Phragmites australis*, followed by free-drained vertical-flow bed planted with *Phragmites australis* and ended with horizontal-flow bed that planted with *Phalaris arundinacea*), the overall efficiency of NH_4–N was from 68-78% and influent NH_4–N was quite fluctuated from 5-40 mg/L. In the current study, the influent NH_4–N concentration fluctuated less (23.4±5.8 mg/L) and achieved higher removal efficiencies (65%-92%). Thus, the stabilization pond in combination with CWs seemed to render better pollution control than the CWs-in-series. The superiority of the facultative stabilization ponds ammonium removal could be attributed to three NH_4-N removal mechanisms: evaporation, nitrification/denitrification and algae absorption. Ammonia removal by nitrification/denitrification occurs at a slow rate. The main

Table 4. Mean (±1 SD, n = 6) pollutant removal efficiencies (%) at the different hydraulic loading rates and results of one-way ANOVA statistic (F-ratio).

	Hybrid HSSF-WSP, HLRs (m³/m²/day)					Hybrid WSP-FWS, HLRs (m³/m²/day)					
	0,050	0,075	0,088	0,100	F ratio	0,100	0,125	0,150	0,175	0,200	F ratio
BOD_5	81±3.4	81±5.6	76±3.0	79±1.9	2.50^{NS}	89±5.2	87±2.8	88±3.1	81±1.1	82±2.9	6.90*
TSS	78±5.9	85±3.9	85±5.1	70±7.4	9.33*	97±1.1	96±1.0	93±1.4	87±6.5	84±5.0	14.9*
NH_4-N	92±4.3	93±4.2	72±9.4	69±6.3	23.5*	97±0.4	88±3.2	83±4.7	70±2.9	63±10	30.1*
PO_4-P	87±6.4	77±7.0	47±21	59±10.6	12.0*	68±8.6	67±13	53±8.6	40±10.5	51±9.9	7.37*

$p<0.001$; ^{NS}: not significant

Table 5: First-order area-based removal rate constants for different HLRs and hybrid systems

	CWs	HLR, $m^3/m^2/day$	X* (mg/L)	k m/year	k m/day	R^2
BOD_5	Hybrid HSSF-WSP	0.050	5	27	0.073	0.87
		0.075	5	35	0.097	0.80
		0.088	5	43	0.118	0.89
		0.100	5	48	0.131	0.90
	Hybrid WSP-FWS	0.100	2	64	0.175	0.97
		0.125	2	54	0.148	0.98
		0.150	2	62	0.171	0.97
		0.175	2	63	0.174	0.93
		0.200	2	69	0.189	0.86
NH_4-N	Hybrid HSSF-WSP	0.050	0	15	0.040	0.95
		0.075	0	10	0.028	0.89
		0.088	0	11	0.029	0.87
		0.100	0	8	0.023	0.99
	Hybrid WSP-FWS	0.100	0	79	0.216	0.90
		0.125	0	54	0.147	0.94
		0.150	0	49	0.134	0.84
		0.175	0	41	0.112	0.89
		0.200	0	32	0.087	0.84
PO_4-P	Hybrid HSSF-WSP	0.050	0	9	0.026	0.95
		0.075	0	6	0.017	0.88
		0.088	0	5	0.014	0.97
		0.100	0	4	0.012	0.99
	Hybrid WSP-FWS	0.100	0	9	0.024	0.97
		0.125	0	12	0.033	0.99
		0.150	0	17	0.047	0.99
		0.175	0	30	0.081	0.83
		0.200	0	21	0.056	0.93

mechanism of ammonium treatment is evaporation at pH≥9 (Zhang, 2014). During the daytime, when the intensity of sunlight is high, the strong photosynthetic algae activity consumes dissolved CO_2 and increase pH of pond water, the higher pH shifts NH_4^+ / NH_3 equilibrium towards more to NH_3. And at high pH, the NH_3 volatilizes and is removed from the water. The plant uptake of nitrogen was also found to be highly dependent on the environment inside the system (Ngo *et al.,* 2010). This helps explain the variation of nitrogen removal efficiency with time. This was partly resulting from the influence of temperature on nitrification bacteria activity. With an increase of temperature, the activity of nitrifying bacteria is gradually enhanced and their reproduction accelerates. The higher temperature also makes plants to grow more vigorously (Huang *et al.,* 2013). Nevertheless, too high a temperature will inhibit the nitrification bacteria activity (Jones and Hood, 1980). This was likely the case in this study during June and August, as the performance was slower as the temperature was higher than 35ºC. Phosphorous removal in CWs also occurs via some of the same mechanisms as nitrogen removal (adsorption and plant uptake), but in addition, precipitation is a significant mechanism (Vohla *et al.,* 2011; Du *et al.,* 2017). Similar to nitrogen removal, the phosphates removal rate constants (k_{PO4-P}) of hybrid HSSF CWs system tended to decrease gradually when increasing the HLR from 0.05 to 0.10 $m^3/m^2/day$ with P loading rates up to 28.40 kg/ha/day, however, the opposite trend was observed for the hybrid FWS CW system with phosphates loading rates up to 35.40 kg/ha/day. The average k_{PO4-P} from 0.012-0.026 m/day found in the current study are consistent with the results published by Kadlec and Knight (1996) in North America, Brix (1998) in Denmark, Kröpfelová and Vymazal (2008) in the Czech Republic using HSSF CWs with the corresponding values of 0.033; 0.0247 and 0.026 m/day, respectively. It is hard to determine which mechanism most influences the phosphorous removal in the hybrid CW system. One might assume that with the support of sand, gravel and reeds, the precipitation and/or adsorption of phosphorous in CWs might be more significant than in the stabilization pond. A fine medium, like the medium sand bed used in the CW systems could have a higher P sorption capacity compared to the coarser media (Konnerup *et al.,* 2009; Kantawanichkul *et al.,* 2009). In this study,

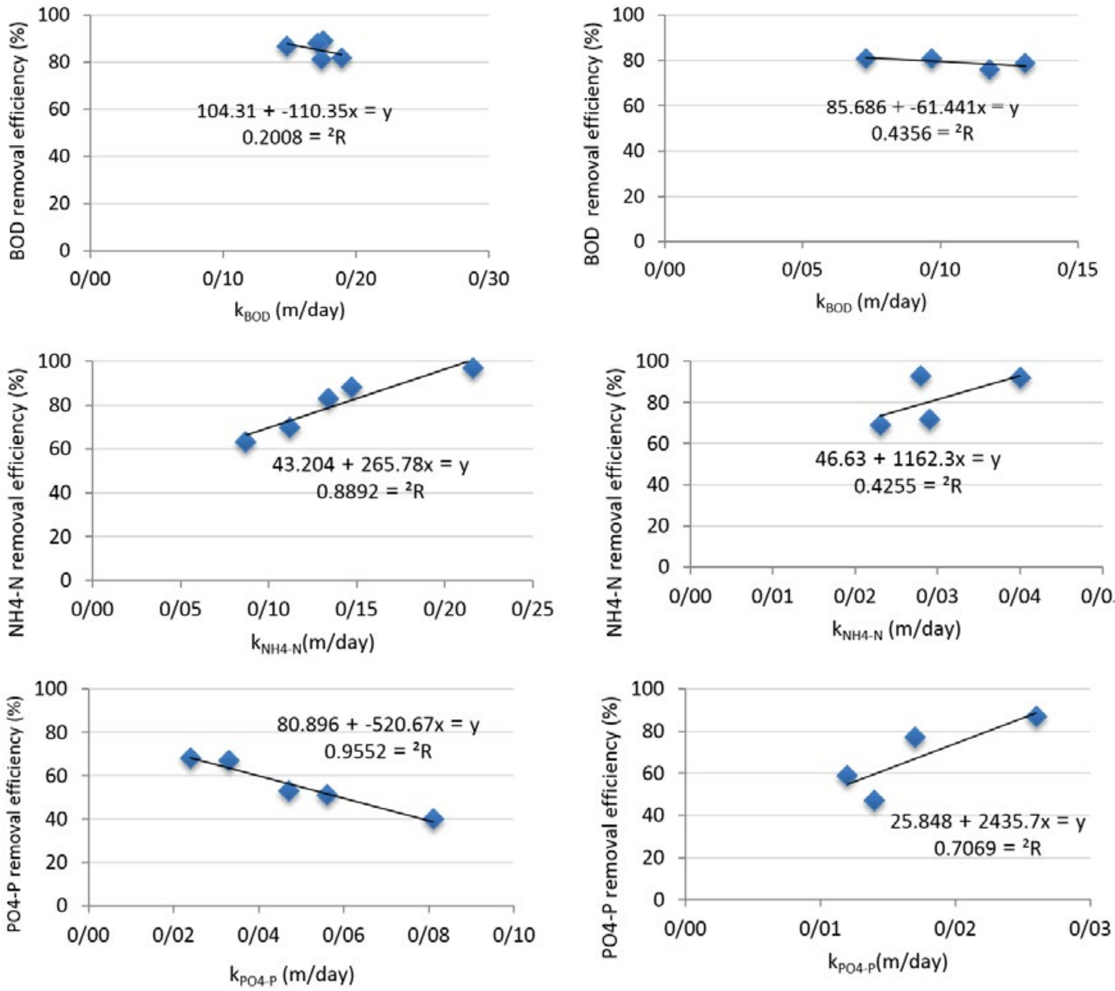

Fig. 8: Correlation between pollutant removal efficiency and removal rate constant “k”

it was found that additional coarse medium layer in hybrid FWS CWs did not help enhance the P sorption/precipitation compared to hybrid HSSF CWs (Table 4).

CONCLUSION

The study of *Canna generalis* on tropical hybrid WSP-CWs revealed that the *Canna generalis* reeds were adapted well and treated pollutants successfully on both hybrid HSSF and FSW CWs. However the average dry biomass and average plant height of *Canna generalis* by the hybrid FSW system were higher than those for the hybrid HSSF CW system. The pollutant removal efficiencies of the hybrid systems were all higher than the single constructed wetlands. For the hybrid horizontal subsurface flow constructed wetland system operated at a hydraulic loading rate of 0.075 m/day the BOD_5, TSS, NH_4-N and PO_4-P removals averaged 81%, 85%, 93% and 77% for, respectively. While they were 89%, 97%, 97% and 68% for BOD_5, TSS, NH_4-N and PO_4-P, respectively at hydraulic loading rate of 0.1 m/day for the hybrid free water sub-surface constructed wetland system. The removal rate constants (k_{BOD}, k_{NH4-N}, k_{PO4-P}) of the experimental hybrid CWs were similar to those in previous studies. However, these constants were higher for the hybrid FWS CW possibly because of the modified flow pattern within the CW used in this study, as well as the additional benefits of WSP in the hybrid system.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percentage
α	Alpha
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CW	Constructed Wetland
FWS	Free Water Sub-surface
g	Gram
HLR	Hydraulic Loading Rate
HRT	Hydraulic Retention Time
HSSF	Horizontal Subsurface Flow
k	Removal rate constants
kg/ha/day	Kilogram/hectare/day
m	Meter
m/day	Meter/day
m/year	Meter/year
m^2	Square meter
m^3/day	Cubic meter/day
$m^3/m^2/day$	Cubic meter/square meter/day
mg/L	Milligram/Litter
mL	Milliliter
mm	Millimeter
mm/day	Millimeter/day
MPN/100mL	Most Probable Number of viable cells in 100 mL
NH_4-N	Ammonium-Nitrogen
NO_3-N	Nitrate-Nitrogen
PO_4-P	Phosphate-Phosphorous
R^2	R Squared value
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solid
VSSF	Vertical Subsurface Flow
WSP	Waste Stabilization Pond
WW	Wastewater

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