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A Study on Using Cyperus Alternifolius for Horizontal Subsurface Flow Constructed Wetland in Municipal Wastewater Treatment

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Constructed wetlands (CWs) are engineered systems that utilize natural materials including wetland vegetation, soils and their associated microbial assemblages. Horizontal Subsurface flow (HSSF) as a kind of subsurface flow CW, used commonly in the world since the 1990s but its application in municipal wastewater treatment in Vietnam is still limited. *Cyperus alternifolius* is wetland plants in HSSF CW to remove pollutants such as N, P and heavy metals. This study aimed at evaluating pollutants removal efficiency of HSSF CW using *Cyperus alternifolius as* in wetlands under Vietnamese conditions. Experimental model included HSSF CW and aerobic pond (AP) in municipal wastewater treatment systems operated from December 2014 to May 2016. The results of the research show that *Cyperus alternifolius* grow quickly, remain young and average humidity of the tree is 80.28 %. The growth of *Cyperus alternifolius* promotes the conversion of organic matter (BOD_5) and nutrients ($NH_4^+ - N$, $NO_3^- - N$, $PO_4^{3-} - P$) with decomposition kinetics coefficients k_{BOD_5} is 0.084-0.150 m/d; $k_{NH_4^+-N}$ is 0.022-0.046 m/d; $k_{NO_3^--N}$ is 0.029-0.059 m/d; $k_{PO_4^{3-}-P}$ is 0.011-0.030 m/d. The BOD_5 removal efficiency reaches 75.30 %; TN, $NH_4^+ - N$ and $NO_3^- - N$ removal efficiency are 53.92 %; 58.32 % and 62.82 %; $PO_4^{3-} - P$ removal efficiency is 62.85 %.

1. Introduction

Centralized wastewater treatment system (WWTP) is appropriate for densely populated urban areas. Technologies applied to these systems including aerobic tank, oxidation trench, sequencing batch reactor, etc. required large capital and operational costs. Decentralized treatment is more suitable solution for suburban areas and rural areas. CW and AP are low-cost municipal wastewater treatment technologies for urban areas and suburban residential areas. Surface water bodies such as ponds and lakes, can be utilized as a biological treatment facility as well as ecological landscape. The combination of these two technologies in a treatment system improve pollutants removal efficiency, overcome certain disadvantages of each facility.

CW have been widely used in the world since 1990 such as Germany, North America; UK; Italy; Denmark; Czech Republic; Netherlands, Portugal, Slovenia, France, Estonia, Norway, Switzerland (Vymazal and Kröpfelová, 2008) but the application is still limited in Viet Nam. Cui et al. (2009) used *Cyperus alternifolius* in simulated VFCWs to remove TN in wastewater. Nascimento et al. (2017) studied on oily wastewater treatment by CWs. Bilgin (2014) indicated that activated sludge-vertical flow subsurface constructed wetland systems (VFSCW) with planted *Cyperus alternifolius* was an economical option for N and P removal in the effluent of secondary treatment such as activated sludge, trickling filter of oxidation ponds. *Cyperus ligularis and Echinocloa colona*¸ planted in Constructed Wetlands in two local plants of Colombian Caribbean region, was highly effective in removal of dissolved organic matter (COD) and nutrients ($NH_4^+ - N$, $NO_3^- - N$, $PO_4^{3-} - P$) from domestic wastewater (Lizcano et al., 2017). CWs was utilized as an economically and energetically efficient unit process to treat greywater for reuse purposes (Arden and Ma, 2018). CW provided a sustainable

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solution to manage resource needs for food and energy production (Avellán and Gremillion, 2019). Wetland roof (WR), a combination of shallow constructed wetlands (SCWs) and green roof is a promising secondary treatment technology to adapt to climate changes and in accordance with the development strategy of green cities (Bui et al., 2019). Tran et al. (2019) studied on pollutant removal by *Canna Generalis* in tropical CW for domestic wastewater treatment and proved that the technology was highly effective.

The HSSF CW is a promising engineering technique to remove excess nutrients and certain pollutants from wastewater. *C. articulatus* could be a promising wetland vegetation for domestic wastewater treatment in the Colombian Caribbean region (Osorio et al., 2017). *Cyperus alternifolius* has been widely used in wetlands due to its cost-effectiveness. It can also be ultilized as forage for livestock and aquaculture(Ebrahimi et al., 2017). The HSSF CWs using *T. geniculata* and *C. articulatus* as wetland vegetation achieved significant removal effciciency of ammonium, phosphates and COD. CWs using *T. geniculata* removed higher proportions of $\mathrm{NH_4^+ - N}$ and $\mathrm{PO_4^{3-} - P}$, CWs using *C. articulates* generated more biomass (Lizcano et al., 2019).

Cyperus alternifolius is a kind of tropical and subtropical vegetation with high nutrient and cellular metabolism (Mburu et al., 2015). This perennial shrub grows quickly in wet or swampy areas, prefers sunlight and resistant to shade. Aquatic plants can be easily propagated by seeds or a plant part. It is utilized for landscapes, fences, harvested to produced paper, hats, bags and also preventing soil erosion. Aquatic vegetation were studied as wetland plants in CWs for wastewater pollutants removal, especially, nutrients as N, P and heavy metals (Liao et al., 2005).

This paper focused on studying the feasibility of applications of combined HSSF CW with *Cyperus alternifolius* and aerobic pond in the low-cost domestic wastewater treatment plant in Viet Nam. The pilot experiment was conducted in suburban residential areas of Cau river basin, Bac Ninh province Viet Nam.

2. Materials and methods

2.1 Experimental model set-up and operation

The experimental set-up was described in Figure 1 and previous publication of co-authors (Tran et al., 2019).

To assess the capacity of *Cyperus alternifolius* in removal of pollutants ($\mathrm{BOD_5}$, TN, $\mathrm{NH_4^+ - N}$, $\mathrm{NO_3^- - N}$ and $\mathrm{PO_4^{3-} - P}$). The experiments were designed in two stages and divided into 5 phases, from December 2014 to May 2016. Stage 1 includes 1 phase (phase 1), evaluating the efficiency of pollutants removal of CW without Cyperus alternifolius. Water sampling and analysis were conducted from March 8th, 2015 to August 29th, 2015 with a two-week frequency. Stage 2 included 4 phases (phase 2,3,4,5), assess the bearing capacity of the model when changing the inflow of wastewater and the efficiency of pollutants removal of CW with *Cyperus alternifolius* planted. Water sampling and analysis were conducted in 4 periods November 8th, 2015 – December 13th, 2015; December 27th, 2015 – January 31st, 2016; February 28th, 2016 – April 3rd, 2016 and April 17th, 2016 – May 29th, 2016 with a weekly frequency.

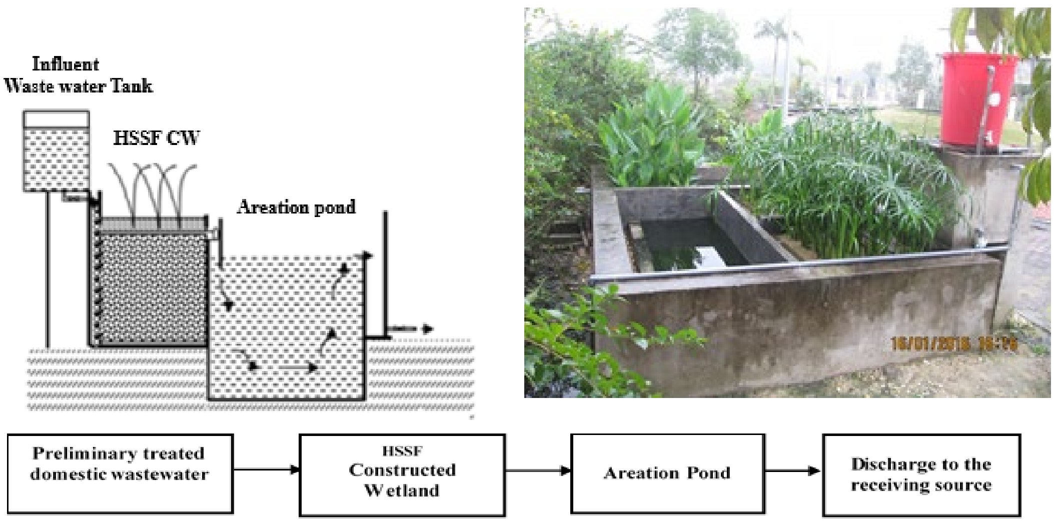

Figure 1: Experimental model

Experimental operating parameters and average pollutant loading rates of inlets were presented in Table 1 and Table 2. HF1 is HSSF without *Cyperus alternifolius*. HF1’ is HSSF which planted *Cyperus alternifolius*.

Table 1: Operating parameters of the experimental model

Experimental phase	Work	Q (L/h)	HRT (d)	HLR ($m^3/m^2/d$)
Phase 1: December 7th, 2014 - August 29th, 2015	HF 1 Aerobic pond	2 4	5.72 20	0.05 -
Phase 2: September 26th, 2015 - December 13th, 2015	HF 1' Aerobic pond	2 5	4.572 16	0.05 -
Phase 3: December 13th, 2015 - February 21st, 2016	HF 1' Aerobic pond	3 6	3.05 13.33	0.075 -
Phase 4: February 21st, 2016 - April 3rd, 2016	HF 1' Aerobic pond	3.5 7	2.61 11.43	0.0875 -
Phase 5: April 3rd, 2017 - May 29th, 2016	HF 1' Aerobic pond	4 8	2.29 10	0.1 -

Table 2: The average pollutant loading rates of the inlet

No	Pollutants	Average of pollutants concentration (mg/L)
1	BOD_5	83.39 ±13.62
2	TN(*)	35.19 ± 8.84
3	$NH_4^+ - N$	33,17 ±10.71
4	$NO_3^- - N$	2.07 ±0.70
5	$PO_4^{3-} - P$	1.51 ±0.98

2.2 Research method

The samples were taken from inlet and outlet of the HSSF, then analysed in the laboratory of National University of Civil Engineering using Vietnamese. Standard methods applied including: TCVN 6001-1995: Water quality – Determination of biochemical oxygen demand after 5 d - Dilution and seeding method for BOD_5 concentration; TCVN 5988-1995 (ISO 5664-1984) – Water quality - Determination of aminonium - Distillation and titration method for $NH_4^+ - N$ determination; TCVN 6180-1996 (ISO 7890-3-1988) - Water quality - Determination of nitrate - Spectrometric method using sulfosalixylic acid for TN and $NO_3^- - N$ determination; TCVN 6202:2008 (ISO 6878:2004) - Water quality - Determination of phosphorus - Spectrometric method using ammonium molybdate for $PO_4^{3-} - P$ determination

Determination of kinetic coefficients: Decomposition coefficients of pollutants (BOD_5, $NH_4^+ - N$, $NO_3^- - N$, $PO_4^{3-} - P$) in HSSF in the experimental model was determined based on the kinetic equation of Kadlec and Knight (1996). Kadlec and Knight (1996) consider plant constructed wetlands as adhesive bioreactors. Kadlec and Knight created a first-stage reaction flow model for all pollutants. The model is based on constant coefficients on first stage reaction, without depending on the temperature. As a result, the Kadlec and Knight models are less sensitive to different climatic conditions. The coefficient of reaction speed was presented in Eq (1) to (3) calculated the speed of hydraulic loading.

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

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

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

Where, As is treatment area of HSSF (m^2); X_e is the concentration of pollutants in the outflow (mg/L); X_i is the concentration of pollutant in the inflow (mg/L); X* is average concentration of pollutants (mg/L); k is the coefficients of reaction speed of stage 1 (m/d); q is the speed of hydraulic loading (m^3/m^2.d or m/d) and Q is the average flow rate through the constructed wetlands (m^3/d).

Average concentration X* of $NH_4^+ - N$, $NO_3^- - N$ and $PO_4^{3-} - P$ equalled to 0 mg/L. That of BOD_5 in HSSF was determined by Eq(4):

$$X^* = 3.5 + 0.053.X_o \quad (4)$$

Where, X_o is concentration of BOD_5 in the sewage and selected as 2 mg/L with HF (Ebrahimi et al., 2013).

3. Results and discussion

3.1 The results examining the development of Cyperus alternifolius

The results reflecting the development of *Cyperus alternifolius* at HF1' during the research period is shown in Table 3. *Cyperus alternifolius* began to be planted in HF1' from October 4th, 2015. In November 2015, the tree began to produce the first young branches. In December 2015, the tree grew rapidly, with dozen of new sprouting. During the study period from October 2015 to May 2016, biomass harvest was conducted only twice times on February 28th, 2016 and March 20th, 2016. The total amount of biomass obtained was 2,297.38 g, with an average height of trees in the two harvest periods was 1.28 m and 1.6 m. Thus, the *Cyperus alternifolius* have adapted and grown well in the HF1'.

Table 3: Results of examining the development of Cyperus alternifolius at HF1'

No	Harvesting date	Wet weight (g)	Dry weight (g)	Water content (%)	Average height (m)	Hmax
1	28 February 2016	4,400	867.68	80.28	1.28	1.45
2	20 March 2016	7,250	1,429.7		1.6	1.8
Total		11,650	2,297.38			

3.2 Determination of pollutants decomposition coefficients

Results of determination of pollutants decomposition factors k_{BOD_5}, $k_{NH_4^+-N}$, $k_{NO_3^--N}$, $k_{PO_4^{3-}-P}$ in municipal wastewater in HSSF in the experimental model is shown in Table 4, Table 5. The coefficient of determination between k_{BOD_5} of the HSSF and HLR in the experimental model was close to 1, meant that k_{BOD5} and HLR were linearly correlated. The coefficient k_{BOD5} was from 0.084 to 0.150 m/d, reaching the highest at HLR as 0.10 m^3/m^2/d. This value is consistent with the published results as 0.101 m/d (37 m/y) (Kadlec, 2009); 0.1123 m/d (45 m/y) (Vymazal and Kröpfelová, 2008); 0.060-0.260 m/d (22-95 m/y) (Ngo et al., 2010).

Table 4: Coefficient of organic compound decomposition rate (k_{BOD_5})

HLR(m^3/m^2/d)	Load of pollutants (kg/ha/d)	k_{BOD_5}(m/y)	k_{BOD_5} (m/d)	R^2
0.05	42.42	31	0.084 ±0.005	0.87
0.075	62.54	35	0.095 ±0.019	0.94
0.088	72.86	47	0.127 ±0.001	0.95
0.1	81.95	55	0.150 ±0.036	0.98

The coefficient k_{NH4+-N} was negatively correlated with HLR, decreased from 0.046 to 0.022 m/d regarding HLR increased from 0.05 to 0.10 m^3/m^2/d (Table 5). This value was in accordance with the published results 0.024 m / day (Vymazal and Kröpfelová, 2008) and 0.031 m / day (11.4 m/y) (Kadlec, 2009). However, this result is lower than the published result of Kadlec and Knight (1996) with the value of $k_{NH_4^+-N}$ is 0.093 m/d (Liao et al., 2005). The same correlation was found between $k_{NO_3^--N}$ and HLR as well as $k_{PO_4^{3-}-P}$ and HLR.

Table 5: The coefficient of decomposition rate of $NH_4^+ - N$, $NO_3^- - N$ and $PO_4^{3-} - P$

HLR (m^3/m^2/d)	Load of pollutants (gN/m^2/d)	$k_{NH_4^+-N}$ (m/d)	R^2	Load of pollutants (gN/m^2/d)	$k_{NO_3^--N}$ (m/d)	R^2	Load of pollutants (gN/m^2/d)	$k_{PO_4^{3-}-P}$ (m/d)	R^2
0.05	15.98	0.046 ±0.005	0.89	6.35	0.055 ±0.008	0.81	5.75	0.030 ±0.003	0.99
0.075	26.85	0.029 ±0.010	0.91	11.03	0.059 ±0.008	0.91	11.63	0.013 ±0.003	0.99
0.088	29.65	0.022 ±0.002	0.96	19.69	0.029 ±0.019	0.84	21.18	0.014 ±0.003	0.99
0.1	43.67	0.019 ±0.005	0.97	24.3	0.033 ±0.02	0.84	28.4	0.011 ±0.006	0.99

The coefficient tended to decrease gradually as the HLR index increases into constructed wetlands, ranging around 0.011-0.030 m/d. This result of $k_{PO_4^{3-}-P}$ was consistent with previous studies of Kadlec and Knight (1996) and Kadlec (2009). These values were lower than in study of Ngo et al. (2010) from 0.112 to 0.230

m/d. These were also lower than the result of synthesizing the k value for TP of HSSF for all types of wastewater in general and for municipal wastewater with the values of 0.065 and 0.035 m/d (Vymazal and Kröpfelová, 2008).

3.3 Outcome water quality results after treatment of HSSF

The parameters of effluent quality after treatment of HSSF and pollutants removal efficiency are shown in Figure 2a and 2b, Figure 3. The ability of the HF1 's treatment degradable organic matter was lower than that of the HF1. This was because the HF1 formed a water layer on the surface, there was the growth of algae and an increase in the exchange of oxygen with the air, so an aerobic decomposition zone was formed in this water layer. The average BOD_5 treatment performance of HF1' decreased gradually from phase 1 to phase 5, with a slow speed (down from 75.30 % to 61.56 %). This proved that the HF1 was capable of removing BOD_5 stably in the studied HLR range from 0.05 to 0.10 $m^3/m^2/d$. (see Figure 2a)

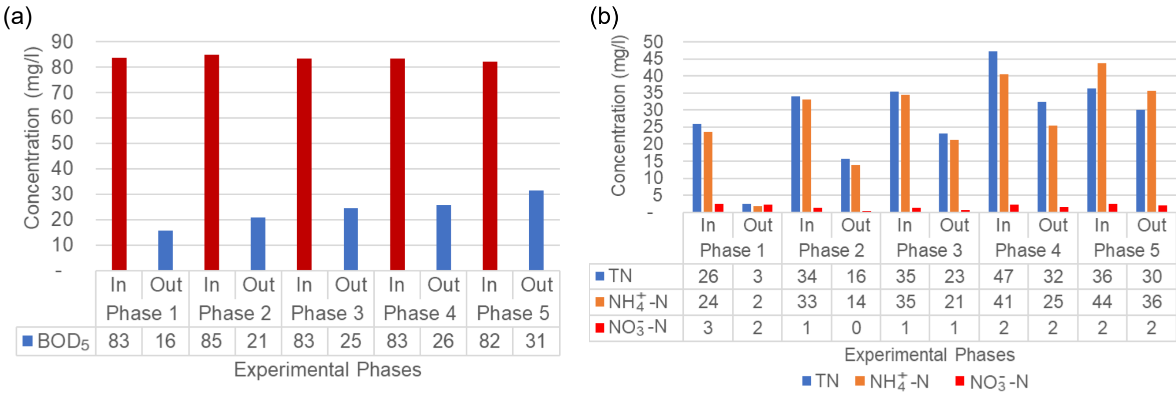

Figure 2: Efficiency of (a) biodegradable compound removal, and (b) Nitrogen compounds removal

Treatment efficiency of TN, $NH_4^+ - N$ and $NO_3^- - N$ in the HF1 and HF1' is (90.38 %; 92.82 %; 9.45 %) and (53.92 %; 58.32 %; 62.82 %). The HF1 has much higher treatment efficiency for TN and $NH_4^+ - N$ and has much lower efficiency of treating $NO_3^- - N$ than the HF1'. Treatment efficiency of TN, $NH_4^+ - N$ and $NO_3^- - N$ of HF1' is not high, it proved that the crop has a negligible influence on the nitrogen compounds treatment capacity of the HSSF (see Figure 2b).

The $PO_4^{3-} - P$ treatment efficiency of HF1' is higher than that of HF1. Because the HF1 without plants, there is no mechanism of absorption of plants like HF1'. The reason for HF1' is more efficient because the *Cyperus alternifolius* begins to grow in this experiment, biomass increases rapidly and the need to absorb nutrients also grows. It leads to Increase absorption of $PO_4^{3-} - P$ (see Figure 3).

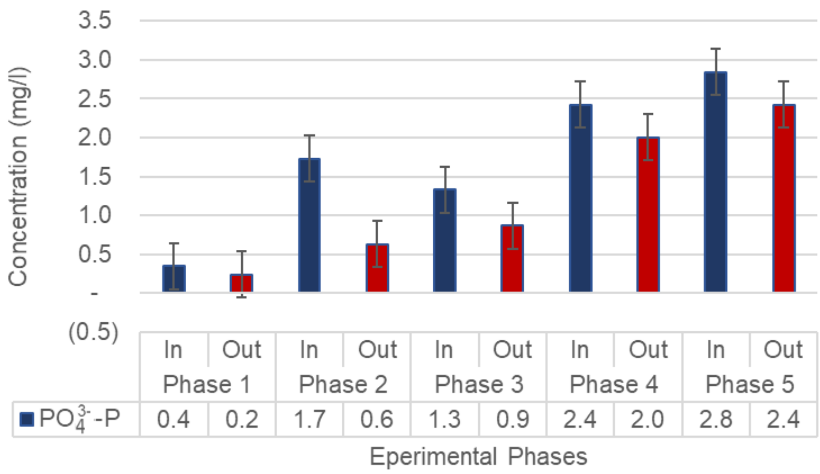

Figure 3: Efficient treatment PO_4^{3-} - P

4. Conclusions

The study found that Cyperus alternifolius had fast-growing speed and its growth promoted the conversion of organic matter (BOD_5) and nutrients ($NH_4^+ - N$, $NO_3^- - N$, $PO_4^{3-} - P$). The ability to treat degradable organic substances in HF1' is lower than that in HF1. The ability to treat nitrogen compounds in municipal wastewater. The removal performance in the model with Cyperus alternifolius was higher than that without this plant regarding $NO_3^- - N$ and — P. The TN and $NH_4^+ - N$ removal performance was lower in the model with *Cyperus alternifolius*.

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