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Developing a composite vertical flow constructed wetlands for rainwater treatment

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Abstract. The worldwide shortage of water resources is a major environmental issue. Using pure water for drinking and domestic purposes is a bigger issue than other environmental issues. Industrialization and Urbanization have even polluted rainwater. In China, when it rains, rainwater is stored on the roof or other sources of storage for daily use resulting in pollution. Several studies have been conducted to treat rainwater. The objective of this study is to evaluate the efficiency of constructed wetlands by using ACF as a medium. So, this study aims to treat rainwater in Wuhan city through a Composite Vertical Flow Constructed Wetlands. First, rainwater was stored in the tank while it flows out of the roof, further it is processed in constructed wetlands. The constructed wetlands is consisted with plants Calamus and Chives, adding ACF (prepared from luffa) has achieved great results in this study. Results show that the pollutants have been removed to a considerable level, there were significant differences in removal rates under different HRT at 6h, 9h and 12h respectively. Therefore, Composite Vertical Flow Constructed Wetlands is recommended for total nitrogen and Ammonia nitrogen and total phosphorus.

Keywords: CVFCW, ACF, wetlands-plants, water treatment, rainwater, Wuhan-China

1. Introduction

The increasing scarcity of water around the globe has been documented as a big issue. Several studies confirmed that the most of the watercourses are polluted and quantity of wastewater has increased along with population growth and rapid industrialization. Therefore, to avail pure water for drinking and household purpose is a big issue. Utilizing natural water resources is recommended option while doing proper water management practices (Shi-Kuan Jiang *et al.* 2017, Rouhullah *et al.* 2017, Notaro *et al.* 2016, Abdel-Halim *et al*. 2008).

Many countries around the world are utilizing rainwater due to water shortages because the available water resources are limited and/or seasonal, which made the experts working in the water sector to search for solutions to the water shortage (Eckart *et al.* 2017, Mohammed *et al.* 2006). Rainwater is relatively stable in water quality and low in bacterial/chemical contamination rate. The full use of purified rainwater resources can effectively alleviate the increasingly serious water use conflicts (Notaro *et al.* 2016). Recently, LID (Low Impact Development) is widely used at home in several countries around the world. Environmental agencies are applying several techniques to utilize rainwater resources such as BMP (Best Management Practice), SDS (Sustainable Discharge System), and WUSD (Water Sensitive Urban Design). Rainwater harvesting and utilization around the world has been increasing. Up-to-no; Germany, China, Singapore, Philippines, Thailand, Japan, Bangladesh, Indonesia, Botswana, Togo, Mali, Malawi, South Africa, Namibia, Zimbabwe, Mozambique, Sierra Leone Tanzania, Brazil, Bermuda and USA are collecting rainwater on the roofs and utilize for household even for drinking purpose. This technique is promoted to mitigate water shortages, secure water for emergencies and control floods. Collected roof water is kept in separate cisterns on the roofs for non-potable uses, but for the potable uses (include drinking, bathing, and cooking and washing) rainwater must be treated to remove the contaminants (Junyu Gao 2017, Mohammed *et al.* 2006, Notaro *et al.* 2016, Eckart *et al.* 2017)

China is big country with highest population. A serious problem for clean water shortage has been documented. It caused great economic and environmental losses. In China, environmental company has investigated to develop better rainwater utilization and pollution control strategies for cities with water shortages so that it should not be hit by drinking water pollution scare (Asit Biswas and Kris Hartley 2017, Mulan *et al.* 2010, Eckart *et al.* 2017). Rainwater utilization is better option to save the cities from floods as in 2016 floods overwhelmed drainage systems in Wuhan, Nanjing and Tianjin. The Wuhan City focuses on reducing waterlogging and increasing water quality via the ecological remediation of existing urban water systems and the construction of blue and green spaces to capture and store rainwater. Conventional high-technology for rainwater treatment is not a suitable solution because it is not sustainable to install water treatment facilities which require guaranteed power supply, replaceable spare parts and a skilled labor for operation and maintenance. There are many techniques have been announced to treat the rainwater.

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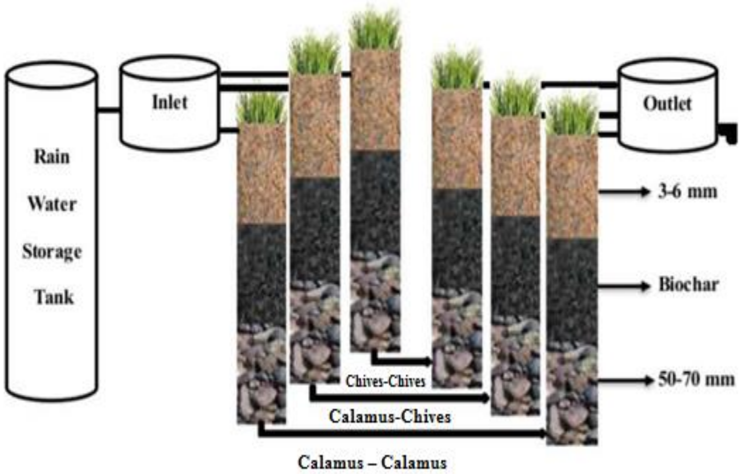

Fig. 1 Schematic diagram of the System

The use of membrane as an innovative technology for water treatment process is also available option (Teow Yeit Haan *et al.* 2017). Treatments by constructed wetlands can be efficient and low-cost technique. Recently, every country relies on some type of wetlands. There are many mechanisms involved in the wetlands such as Sedimentation, Adsorption, Plant uptake, Chemical precipitation, Infiltration, Oxidation, Volatilization, Bio-filtration, microbial decomposition, Matrix sorption, Denitrification, Aerobic microbial degradation, Anaerobic microbial degradation etc. BOD, COD, Nitrogen, Phosphorous are removed by those mechanisms involved in wetlands system (Shi-Kuan Jiang *et al.* 2017, Oluseyi Ewemoje and Abimbola Sangodoyin 2011, Zhang *et al.* 2009, Asit Biswas and Kris Hartley 2017, Avila *et al.* 2012, Gunes *et al.* 2012, Konnerup *et al.* 2009, Jairo *et al.* 2017, Vymazal 2005). Hence, it is proved that wetland system is enough well project to remove the pollutants. This study aims at developing a composite vertical flow constructed wetlands for rainwater treatment. This study aims to treat rainwater of Wuhan city through constructed wetlands. The project also evaluates the effectiveness of two types of plants and ACF prepared from luffa (Nshirirungu *et al.* 2018). The composite vertical flow constructed wetland, plants and ACF are innovatively combined and applied to the deep purification of rainwater to make efficient use of rainwater. Under the different hydraulic retention time (HRT), the removal effect of the composite vertical flow constructed wetland on COD, total nitrogen and total phosphorus in rainwater.

2. Materials and methods

2.1 Experimental set up

Experimental set up is mainly composed of a rainwater collecting unit (RC), a composite vertical flow constructed wetland unit, two types of plants, *calamus* and *Chives* and ACF (prepared from luffa). Study was started in March 2018 and Plants were grown well after Constructed Wetland was properly prepared, shown in Schematic diagram is shown in Fig. 1. The experiments were performed after successful acclimatization and establishment of the plants and microbial community. This study was conducted in School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan, China.

The ACF used in this work were obtained from material luffa. Material was produced by Henan Luohe Hua Hui Co LTD. It was prepared by proper way. Firstly, the luffa fiber was impregnated with a water-soluble phenolic resin for 24 hours, and taken out and drained at room temperature also placed in an aqueous sodium hydroxide solution and let it be soaked for 12-24h, remove and wash with distilled water until neutral, put into the oven (105 °C). After the immersed luffa fiber is baked in an oven (105 °C) for 1-2h, Into a high temperature resistance furnace for pre-oxidation, carbonization, activation treatment, high temperature resistance furnace, passing protective gas N2 (flow rate 0.6~0.8L/min), activation temperature is 550~850 °C. Finally, the obtained product was immersed in a 1 M hydrochloric acid solution for 2h to remove impurities such as ash from the product, wash it with deionized water until neutral, and dry. The product luffa activated carbon fiber is obtained.

Later it was characterized by different methods such as scanning electron microscope (SEM) (MIRA3, TESCAN) was used to measure surface morphology and also the micro metrics of the ACF. Fourier transform infrared spectrometer (Tensor27, Bruker Company, Germany) in the range 400–4000 cm−1 at a resolution of 2 cm−1 was applied for the qualitatively analysis for the functional groups. The ACF surface area was determined by using an ASAP-2020 surface area analyzer (Micromeritics Instrument Corporation, USA). Vario Elemental Analyzer (Elementar Company, Germany) was used to record the elemental analysis of the ACF. XRD pattern of the original luffa and sample 0 were determined. The microstructure of ACF is a series of indicators, such as the nitrogen adsorption desorption curve, specific surface area and average pore diameter obtained by BET detection.

Table 1 Influent water quality

Pollutants		CODcr (mg/L)	TN (mg/L)	TP (mg/L)	Ammonia nitrogen (mg/L)
Concentration range	Minimum	17.73	5.5	0.082	0.62
	Maximum	23.81	7.9	0.137	1.69
	Average	20.77	6.7	0.1095	1.155

2.2 Operational procedure and sampling

Studies have found that the rainwater in several cities i.e Beijing, Wuhan etc is polluted (Mulan *et al.* 2010, Xiao Wei and Zhang Si 2017). The rain water was piped into the cells for various complex physical, chemical and biological processes. Wetland X, Y and Z are prepared for the experimental study. In each wetland it has two cells connected to each other (with down-up flow) as a composite vertical flow constructed wetland system. Different wetland-plants are placed in each wetland, for example two cells with *Calamus* in Wetland X, two cells with *Calamus* and *Chives* in Wetland Y, and two cells with same plant *Chives* are put in Wetland Z. These are shown in fig 1. Three HRTs for five days were set according to the experiment, 6h, 9h, and 12h is individually. Samples are transported immediately from collection point to laboratory for analysing. Samples were measured for Chemical Oxygen Demand (COD), Total Phosphorus (TP), Amnonia Nitrogen and Total nitrogen, following the procedure of APHA (1999).

The total nitrogen is determined by potassium persulfate digestion spectrophotometry, the total phosphorus is determined by ammonium molybdate spectrophotometry, the ammonia nitrogen is determined by Nessler's reagent colorimetry, and the COD is determined by Suntech SN-200 COD rapid analyzer.

2.3 Influent water quality

Several studies have concluded that the rainwater in Wuhan City of China is highly polluted but the water quality is relatively good after half hour raining. The total phosphorus and COD can reach the water quality standards. In this study, the influent water was taken from the rainwater in 2018, in the frequent rains in Wuhan. The influent water quality is shown in Table 1.

3. Results and discussion

According to lab results, the removal effect of Chemical Oxygen Demand (COD), Total Phosphorus (TP), Amnonia Nitrogen and Total nitrogen under different HRT and in different wetlands (X, Y and Z) has shown different results (See table 2, Fig 2).

3.1 Total Nitrogen

The mechanisms (volatilization, nitrification / denitrification, ammonification, plant uptake, and matrix adsorption) play vital role in the nitrogen removal in CWs (Shi-Kuan Jiang *et al.* 2017, Vyamzal 2006). Moreover several studies also have documented that ACF significantly affect to retain nitrogen (Ding *et al.* 2010). In this study, effect of vegetation was observed on nutrient removal among all the three wetlands (X, Y and Z), Wetland X containing *Calamus* plant has removed higher percentage of TN of 88.44%, which was significantly greater than those of wetlands Y (80.195%) and Z (75.48%) (See Fig 2). Moreover, microbial degradation process is also responsible for removal mechanisms, which also requires microbial activity and longer retention time. Furthermore, there were significant differences in total nitrogen removal rates under different HRT. For total nitrogen, the Unit containing plant *Calamus* has shown better results than the plant *Chives* at 12 h HRT (see fig 2 and table 3).

Table 2 Overall Statistics of Influent and Effluent Concentrations in Each Unit

	Influent Concentration(mg/L)	Effluent Concentration (mg/L)		
		Wetland X	Wetland Y	Wetland Z
Total nitrogen				
Mean	6.7	1.4	1.6	1.9
Minimum	5.5	0.8	1.0	1.3
Maximum	7.9	2.0	2.2	2.5
Ammonia nitrogen				
Mean	1.155	0.51	0.515	0.555
Minimum	0.62	0.28	0.30	0.34
Maximum	1.69	0.74	0.73	0.77
Total phosphorus				
Mean	0.1095	0.056	0.059	0.061
Minimum	0.082	0.041	0.043	0.046
Maximum	0.137	0.071	0.075	0.076
COD (cr)				
Mean	20.77	14.415	14.925	15.295
Minimum	17.73	11.37	11.87	12.30
Maximum	23.81	17.46	17.98	18.29

3.2 Ammonia nitrogen

In CWs, mechanism of ammonia nitrogen removal is comprised on biochemical (biochemical effects include plant uptake, ammonia fixation, ammonia volatilization, nitrification/denitrification) and physical (physical effects include sedimentation adsorption, and filtration) (Vyamzal 2006). The adsorption of ammonia on to ACF is well known (Spokas *et al.* 2012). Combine effect of adsorption, nitrification-denitrification, and volatilization can be the best for ammonia removal. The Plant *Calamus* containing wetland demonstrated 64.47% ammonia removal as compared to 59.12% in wetland Z, which contains plant *Chives* While Wetland Y has given good results than Wetland Z because it has both Plants, i.e *Chives* and *Calamus* (see fig 2 and table 3). In addition, several studies

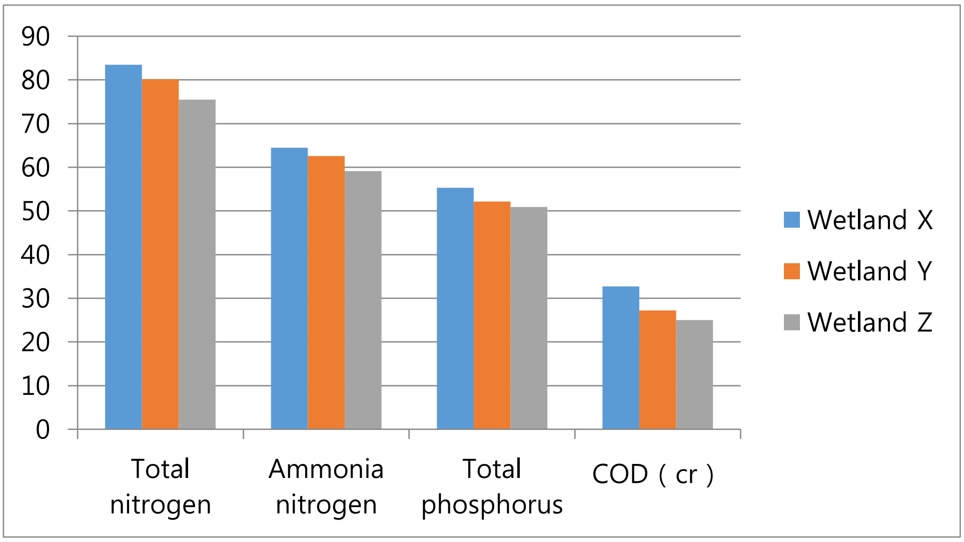

Fig. 2 Average percentage removal of pollutant among all wetland units

demonstrated the role of plant in the removal of ammonia; plants can play role for increasing the activity of microorganisms, divert water flow and transport oxygen (Hu *et al.* 2016). In this study, significant results were obtained between the different planted units.

3.3 Total phosphorus

The physiochemical and hydrological properties of the filter material are associated with removal of phosphorus, whereas phosphate is mainly precipitated or adsorbed in filter media. In broad meaning, the removal of phosphorus depends on the physical adsorption of the matrix, the chemical deposition, microbial degradation and plant adsorption. (Shi-Kuan Jiang *et al.* 2017, Sun *et al.* 2014, Braskerud 2002). In addition, ACF can play a vital role for phosphorus removal, the ACF surface is expected to be positively charged in most natural aqueous conditions and electrostatically attract the negatively charged phosphate species. The assimilation by microorganisms and plants mainly supports the phosphorus removal in CWs (Huett *et al.* 2005). Moreover, in this study, the vegetation played an important role as they provide temporary storage of phosphorus. The Plant *Calamus* containing wetland demonstrated 55.325% Phosphorus removal in wetland X as compared to 50.875% in wetland Z, which contains plant *Chives*. According the results (see fig 2 and table 3), the *Calamus* containing wetland has better results than others. Contact area between plants and influent water is increased by the developed root system of *Calamus* and also it brings aerobic, anoxic and anaerobic conditions in the wetland bed, plant roots and surrounding environment. It provides attachment sites for microorganisms. Under aerobic conditions, phosphate is taken up from water because microorganisms use oxygen as an electron acceptor to generate energy by PHB decomposition.

3.4 Chemical Oxygen Demand (COD)

The removal of COD mainly depends on the adsorption and filtration of the matrix and the interception of plant roots and the degradation of microorganisms in the wetland system (Shi-Kuan Jiang *et al.* 2017, Shibao Lu *et al.* 2015, Qaisar M *et al.* 2013, Abdulkadir S 2015). The removal rate of COD was relatively low in all wetland X, Y and Z 32.68, 27.19 and 25 respectively (see fig 2 and table 3). It is possibly because of vegetation or photosynthesis. The removal of Chemical Oxygen Demand (COD) needs many processes. It is removed mainly through photosynthesis and absorption assimilation. Plants in wetlands directly absorb and utilize small molecular organic compounds in sewage to reduce COD in sewage. In the surrounding matrix, the oxygen is added to the wetland by the help of plants, which can further promote the aerobic microorganisms to decompose the organic matter. When the dissolved oxygen in the water body decreases, the anaerobic bacteria multiply and the organic matter is anaerobically decomposed, thereby reducing the COD in the water. In this study, lower COD removal reason could be the HRT, because the COD concentration was observed to reduce higher at 12 h HRT, it can be increased.

3.5 Biomass growth studies

The macrophytes growing in constructed treatment wetlands have several properties in relation to the treatment processes that make them an essential component of the design (Calheiros *et al.* 2007). All the planted wetlands (X, Y and Z) showed positive growth, without any obvious symptoms of toxicity or nutrient deficiency. After a period of 3 months, mean plant height increased. Root and rhizome growth accounted to be grown. The biomass growth was varied among the wetland units and no significant effect was observed with respect to ACF addition on plant growth.

3.6 Effect of HRT on nutrient removal

The effect of Hydraulic Retention time (HRT) was studied at interval of 6, 9 and 12 hours up to 5 days. The effect of HRT variation was observed on nutrient removal among all the three wetlands (X, Y and Z). A significant Total nitrogen and Ammonia nitrogen removal was achieved at HRT 12 hours (Figure 3 & 4).

Table 3 Results for Removal of TN, Ammonia Nitrgen, TP and COD

		Total nitrogen			Ammonia nitrogen			Total phosphorus			COD（cr）		
Type	Residence time	Influent concentration	Effluent concentration	Removal rate%	Influent concentration	Effluent concentration	Removal rate%	Influent concentration	Effluent concentration	Removal rate%	Influent concentration	Effluent concentration	Removal rate%
Wetland X (*Calamus – Calamus*)		7.6	1.8	76.32	0.95	0.45	52.63	0.115	0.071	38.26	23.25	17.46	24.90
		5.9	1.4	76.27	0.84	0.41	51.19	0.106	0.062	41.51	23.26	16.45	29.28
	6H	6.8	1.8	73.53	1.28	0.67	47.66	0.113	0.061	46.02	21.62	16.70	22.76
		7.8	2.0	74.36	1.10	0.54	50.91	0.105	0.066	37.14	21.56	15.90	26.25
		6.4	1.6	75.00	0.70	0.36	48.57	0.090	0.055	38.89	22.51	17.23	23.46
		7.8	1.6	79.49	0.81	0.37	54.32	0.118	0.055	53.39	17.73	13.34	24.76
		7.3	1.5	79.45	0.62	0.28	54.84	0.137	0.058	57.66	20.86	14.35	31.21
	9H	5.6	1.1	80.36	1.41	0.61	56.74	0.115	0.051	55.65	23.81	14.87	37.55
		7.6	1.5	80.26	1.69	0.74	56.21	0.117	0.055	52.99	18.13	11.37	37.29
		6.4	1.4	78.13	1.34	0.58	56.72	0.128	0.060	53.13	23.63	15.41	34.79
		7.0	1.3	81.43	1.15	0.47	59.13	0.082	0.041	50.00	20.12	12.45	38.12
		7.9	1.4	82.28	1.27	0.51	59.84	0.111	0.055	50.45	20.79	13.77	33.77
	12H	5.5	0.8	85.45	1.68	0.51	69.64	0.093	0.050	46.24	18.61	13.54	27.24
		6.1	0.9	85.25	1.23	0.41	66.67	0.124	0.061	50.81	23.77	16.21	31.80
		6.3	1.0	84.13	1.59	0.48	69.81	0.128	0.066	48.44	21.76	15.45	29.00
Wetland Y (*Calamus – Chives*)		7.6	2.0	73.68	0.95	0.47	50.53	0.115	0.075	34.78	23.25	17.80	23.44
		5.9	1.5	74.58	0.84	0.43	48.81	0.106	0.066	37.74	23.26	16.87	27.47
	6H	6.8	2.1	69.12	1.28	0.69	46.09	0.113	0.063	44.25	21.62	17.24	20.26
		7.8	2.2	71.79	1.10	0.58	47.27	0.105	0.061	41.90	21.56	16.74	22.36
		6.4	1.8	71.88	0.70	0.41	41.43	0.090	0.060	33.33	22.51	17.98	20.12
		7.8	2.1	73.08	0.81	0.40	50.62	0.118	0.058	50.85	17.73	14.21	19.85
		7.3	1.8	75.34	0.62	0.30	51.61	0.137	0.062	54.74	20.86	15.13	27.47
	9H	5.6	1.3	76.79	1.41	0.62	56.03	0.115	0.055	52.17	23.81	16.21	31.92
		7.6	1.7	77.63	1.69	0.73	56.80	0.117	0.059	49.57	18.13	11.87	34.53
		6.4	1.6	75.00	1.34	0.61	54.48	0.128	0.063	50.78	23.63	16.24	31.27
		7.0	1.5	78.57	1.15	0.50	56.52	0.082	0.043	47.56	20.12	13.44	33.20
		7.9	1.6	79.75	1.27	0.50	60.63	0.111	0.059	46.85	20.79	14.48	30.35
	12H	5.5	1.0	81.82	1.68	0.54	67.86	0.093	0.054	41.94	18.61	14.21	23.64
		6.1	1.2	80.33	1.23	0.45	63.41	0.124	0.070	43.55	23.77	17.11	28.02
		6.3	1.3	79.37	1.59	0.50	68.55	0.128	0.071	44.53	21.76	16.22	25.46
Wetland Z (*Chives–Chives*)		7.6	2.4	68.42	0.95	0.50	47.37	0.115	0.076	33.91	23.25	18.10	22.15
		5.9	2.0	66.10	0.84	0.45	46.43	0.106	0.070	33.96	23.26	17.43	25.06
	6H	6.8	2.4	64.71	1.28	0.71	44.53	0.113	0.066	41.59	21.62	17.89	17.25
		7.8	2.5	67.95	1.10	0.62	43.64	0.105	0.064	39.05	21.56	17.14	20.50
		6.4	2.2	65.63	0.70	0.44	37.14	0.090	0.061	32.22	22.51	18.29	18.75
		7.8	2.3	70.51	0.81	0.42	48.15	0.118	0.061	48.31	17.73	14.12	20.36
		7.3	2.0	72.60	0.62	0.34	45.16	0.137	0.062	54.74	20.86	15.11	27.56
	9H	5.6	1.5	73.21	1.41	0.66	53.19	0.115	0.060	47.83	23.81	17.12	28.10
		7.6	2.0	73.68	1.69	0.77	54.44	0.117	0.062	47.01	18.13	12.30	32.16
		6.4	1.8	71.88	1.34	0.64	52.24	0.128	0.061	52.34	23.63	16.54	30.00
		7.0	1.7	75.71	1.15	0.55	52.17	0.082	0.046	43.90	20.12	13.57	32.55
		7.9	1.9	75.95	1.27	0.54	57.48	0.111	0.058	47.75	20.79	15.14	27.18
	12H	5.5	1.3	76.36	1.68	0.57	66.07	0.093	0.057	38.71	18.61	14.68	21.12
		6.1	1.5	75.41	1.23	0.50	59.35	0.124	0.072	41.94	23.77	17.68	25.62
		6.3	1.6	74.60	1.59	0.55	65.41	0.128	0.076	40.63	21.76	16.87	22.47

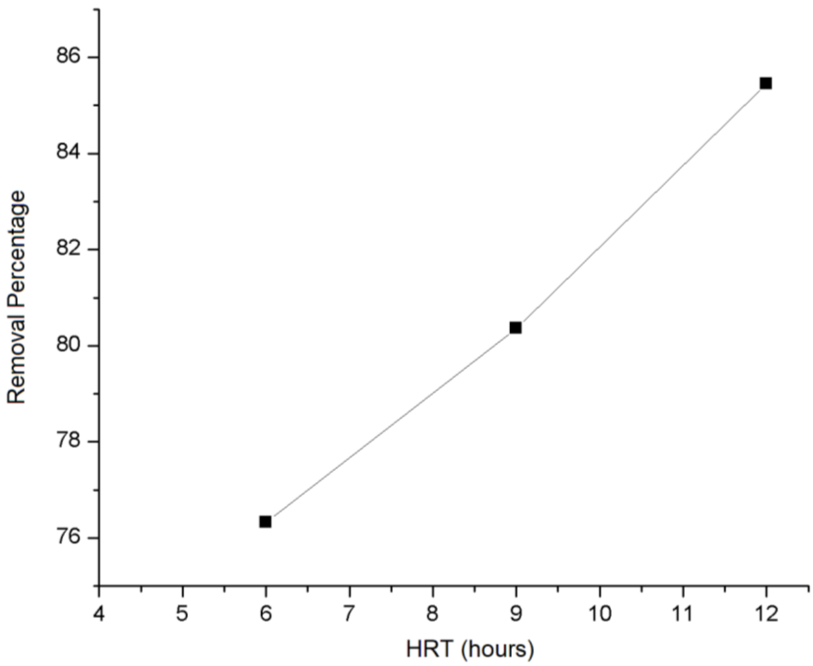

Fig. 3 Effect of Hydraulic Retention Time (HRT) on Total Nitrogen removal

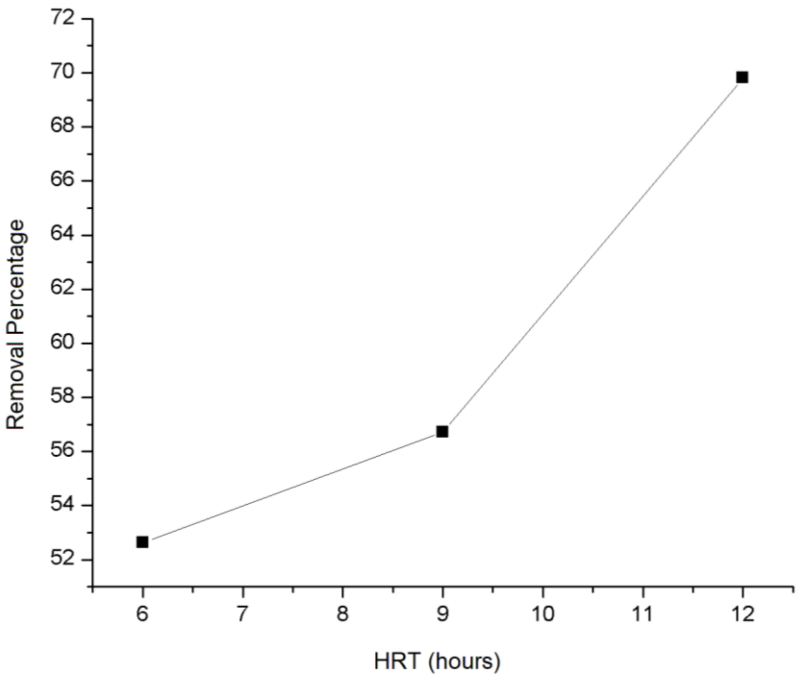

Fig. 4 Effect of Hydraulic Retention Time (HRT) on Ammonia Nitrogen

Moreover, Total nitrogen and Ammonia nitrogen removal was higher in wetland X than those observed in wetland Y and Z. In case of TP, the best TP removal wasachieved in wetland X at HRT 9h (Figure 5). However, the TP removal slowed down at 12h HRT, possibly suggesting that TP removal in wetland was relatively slower compared as compared to TN removal. The COD concentration was observed to reduce higher at 12h HRT (Figure 6) but overall COD removal was relatively low.

Table 4 Removal percentage

Type	Total nitrogen	Ammonia nitrogen	Total phosphorus	COD (cr)
Wetland X	83.44	64.47	55.325	32.68
Wetland Y	80.195	62.535	52.155	27.19
Wetland Z	75.48	59.12	50.875	25

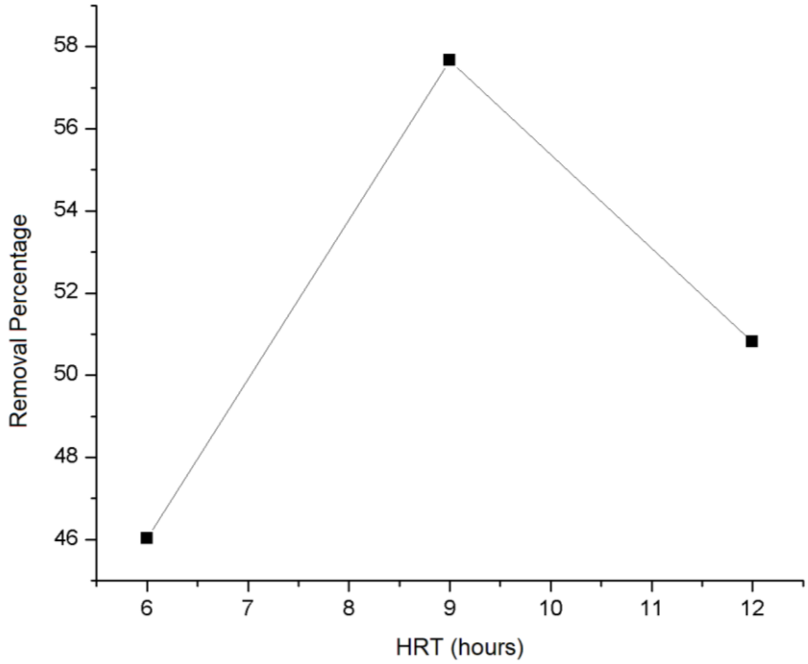

Fig. 5 Effect of Hydraulic Retention Time (HRT) on TP

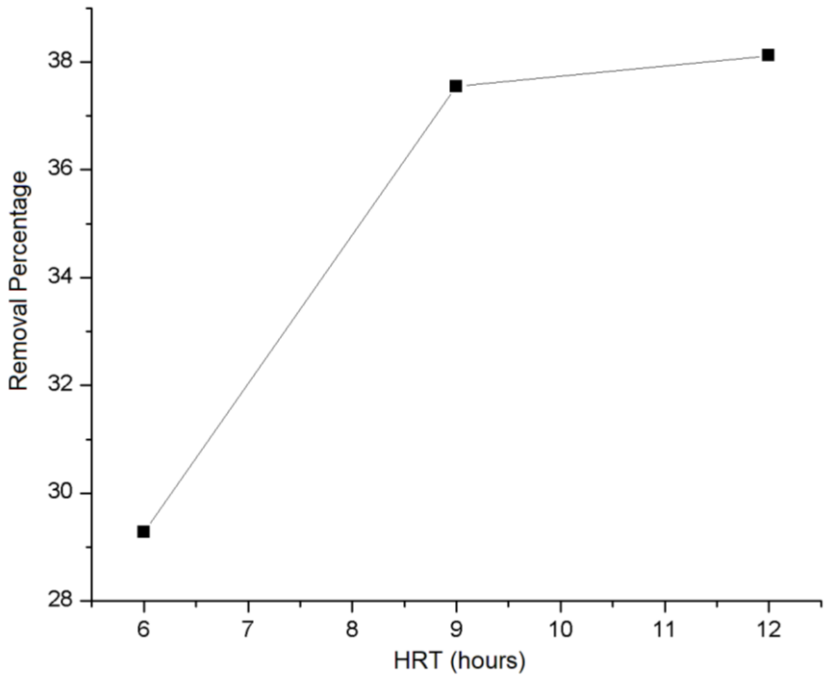

Fig. 6 Effect of Hydraulic Retention Time (HRT) on COD

4. Conclusions

It is concluded that based on the treatment of rainwater resources for miscellaneous water, this paper constructs a Composite Vertical Flow Constructed Wetlands for rainwater treatment has been found efficient. This study observed that wetlands with ACF and selected plants were more efficient as compared to the wetland with gravels alone in the removal of various organic and inorganic pollutants. Highest removal rate were achieved in wetland X containing plants *Calamus*. Results show that after the pretreatment of Wuhan City rainwater by a Composite Vertical Flow Constructed Wetlands unit, the content of total nitrogen, Ammonia nitrogen and total Phosphorus decreased significantly, while the removal rate of COD was relatively low. There were significant differences in removal of rates of total nitrogen, ammonia nitrogen, total phosphorus and COD under different HRT, 6h, 9h and 12h

Fig. 7 Images of project CVFCW, Wuhan University of Technology

respectively. So it is recommended that a Composite Vertical Flow Constructed Wetlands for rainwater treatment is a good idea to explore the effect of deep purification of rainwater in Wuhan, and provides strong support for its practical engineering application. In addition, weather also effect on the efficiency vegetation, especially cold weather is not very much suitable. However this study is preliminary, there is still gap; it is acknowledged that further studies with rigorous methodologies are needed before conclusions can be drawn. In general, plant *Calamus* is efficient and the use of ACF in wetlands is best choice.

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