PERFORMANCE EVALUATION OF SUB-SURFACE FLOW CONSTRUCTED WETLAND SYSTEMS UNDER VARIABLE HYDRAULIC LOADING RATES

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Abstract: Wastewater treatment has given an immense attention in the field of pollution control throughout the world. This has become a challenge in developing countries due to the limitations of resources and expertise. Constructed wetlands where water, plants and microorganisms interact to improve the quality of water have been proven to be an effective low-cost wastewater treatment technology in many parts of the world, which does not necessarily require skilled personnel to run the system. However, these systems are not yet widely spread in developing countries due to lack of information.

Constructed wetlands can be designed as surface flow or subsurface flow systems, depending on the level of the water column. This study compares the performance of vertical subsurface flow (VSSF) and horizontal subsurface flow (HSSF) constructed wetland systems at laboratory scale at tropical condition. This paper also evaluates the effects of Hydraulic Loading Rate (HLR) on treatment capacity of wastewater parameters such as Five day Biochemical Oxygen Demand (BOD_5), Total Suspended Solids (TSS), Nitrate Nitrogen (NO_3^-N), Phosphate (PO_4^{3-}), Ammonia Nitrogen (NH_4-N), Fecal Coliforms (FC) and Total Coliforms (TC).

Six wetland models of size 1.4 m x 0.5 m x 0.5 m (L x W x H) were constructed and arranged: 1) Two models as VSSF system with plants, 2) Two models as HSSF system with plants, 3) One model as a VSSF control without plants and 4) One model as a HSSF control without plants. An emergent macrophyte specie; cattail (*Typha angustifolia*), gravel media (size 10 – 20 mm) and synthetic wastewater with average concentrations of BOD_5 ; 29.51 ± 4.21 mg/L, NO_3^- - N ; 3.22 ± 1.25 mg/L, NH_3^- - N ; 15.14 ± 2.65 mg/L, PO_4^{3-} ; 6.78 ± 5.67 mg/L, Fecal Coliform $495.12 * 10^3 \pm 307.12 * 10^3$ counts/100 mL and Total Coliform $915.5 * 10^3 \pm 719.83 * 10^3$ counts/100 mL were used in this study. The HLR was increased from 2.5 – 25 cm/day at 12 days interval during two and a half months period. Sampling was carried out with each HLR from both influent and effluents of each wetland system after 12 days of constant flow rate, and wastewater quality parameters such as the BOD_5, TSS, NH_4-N, NO_3^--N, PO_4^{3-}, pH, Conductivity, FC and TC were measured in all samples. Results show that VSSF systems perform better than horizontal systems, but the treatment performance declines with the increasing HLR in all six wetland models.

Keywords: Wastewater treatment, Constructed wetlands, Vertical Subsurface Flow, Horizontal Subsurface Flow, tropics, variable Hydraulic loading rate, synthetic wastewater

1 Introduction

There is a growing demand for the development of appropriate and affordable wastewater management technologies particularly in developing countries like Sri Lanka to reduce the pollution of fresh water resources from unacceptable ways of wastewater discharges. Compared to conventional wastewater treatment technologies, constructed wetlands offer low cost, easy to operate, efficient and robust treatment [1] and have been used internationally with good results [2] mostly in temperate countries. The treatment performance of constructed wetlands is expected to be higher in tropical regions due to the higher temperatures and associated higher bacterial activities. Therefore, they are currently being studied as a wastewater treatment technology in tropical countries for many kinds of wastewaters including high strength wastewaters from agricultural fields, landfill leachate, mine drainage, sludge dewatering and municipal wastewaters from small communities [1]. However, the treatment performance of constructed wetlands depend on various factors like inflow pollutant characteristics, wetland design, Hydraulic and nutrient loading rates, climatic variations and essentially the required effluent characteristics [3]. In addition it has to be designed specifically to suit the local climatic conditions to take advantages of unique wetland properties to accomplish direct objectives [4].

Basically there are two types of constructed wetlands; sub-surface flow (SSF) wetlands which maintain the water level below the filter media and free water surface (FWS) wetlands which expose the water surface to the atmosphere. Distinctive advantages of SSF systems over FWS wetlands include, lack of odour problems, lack of mosquitoes and other insect vector problems and the minimal exposure of contact with wastewaters to general public [5]. SSF constructed wetlands can be further divided according to the flow direction as horizontal SSF and vertical SSF wetlands. VSSF systems have a much greater oxygen transfer capacity over the HSSF systems and hence VSSF can achieve very good results in removing organic material and to enhance the nitrification [6].

The wastewater flow into a constructed wetland can be fluctuated with the seasonal water consumption pattern. According to Brix et. al (2007) constructed wetlands can tolerate a high variability in loading rates and wastewater quality [1]. Wetland hydraulics, namely the hydraulic loading rate (HLR), and the hydraulic retention time (HRT) are directly affects the treatment performance of a constructed wetland [7]. Several studies reveal that by decreasing the HLR (ie. longer HRT) the pollutant removal efficiency in a constructed wetland system can be improved. The most effective HRT is ranged in between 4-15 days [8]. However, to incorporate a smaller hydraulic loading or longer retention time, the land area requirement for a constructed wetland is also become high. As there is a higher pollutant removal possibility by constructed wetlands in tropical regions, investigation of the treatment efficiencies with higher hydraulic loading rates or shorter retention times will lead for an optimum design to suit the local climate.

The objective of this study is to evaluate the pollutant removal performance under increasing hydraulic loading rates from sub-surface flow wetland systems (HSSF & VSSF systems) at tropical condition using cattail (*Typha angustifolia)* as the wetland vegetation and synthetic wastewater at laboratory scale. Cattail has been selected in this study as they are easily found in Sri Lanka and are very often a part of natural and constructed wetlands worldwide [9]. Also, cattail is a persistent plant, spreads rapidly and has a reproduction potential. In addition, cattail is capable in thriving and diverse environmental conditions [10]. Its biomass can be used as a valuable insulation material [9] or for weaving purposes.

2 Materials and Methods

2.1 Wetland Mesocosm Arrangement

In this study, Vertical Sub-surface Flow (VSSF) and Horizontal Sub-surface Flow constructed wetland systems were used. As illustrated in Figure 1 (a), Six wetland mesocosms of size 1.4 m x 0.5 m x 0.6 m were constructed with brick masonry and cement mortar and arranged as follows.

1. One mesocosm as HSSF without vegetation
2. Two mesocosms as HSSF with vegetation [Figure 1(b)]

3. One mesocosm as VSSF without vegetation
4. Two mesocosm as VSSF with vegetation [Figure 1 (c)]

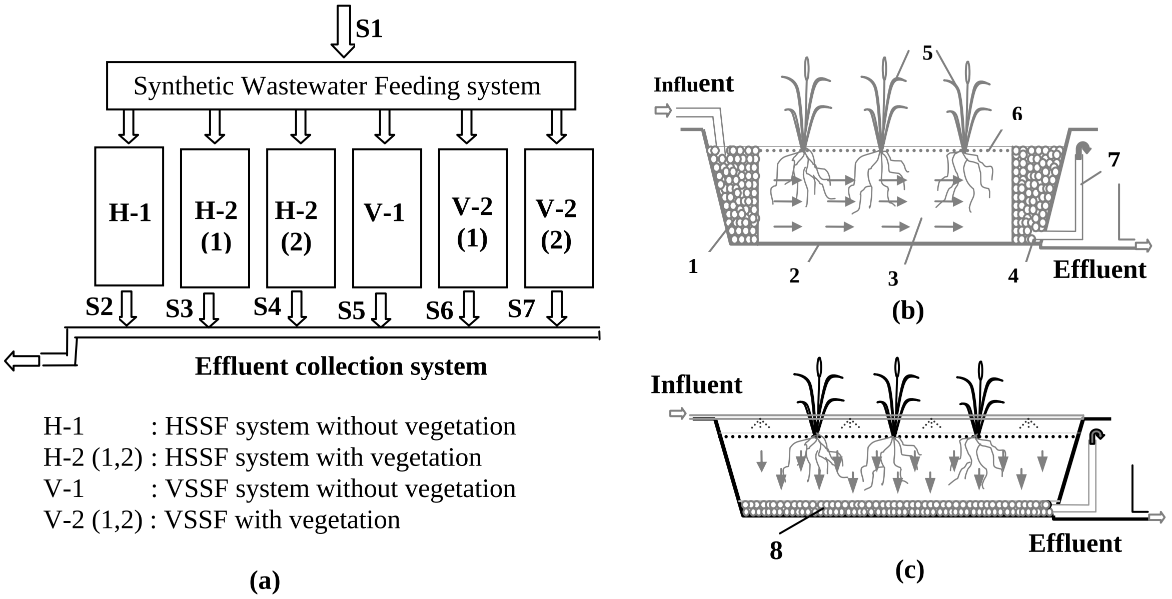


Figure 1. (a). Arrangement of wetland mesocosms [S 1 – S 7 are sampling points], (b). Schematic diagram of a HSSF wetland system with vegetation and (c). Schematic diagram of a VSSF wetland system with vegetation ; 1. Inlet zone, 2. Impermeable barrier, 3. Wetland media, 4. Outlet zone, 5. Wetland Vegetation, 6. Water level, 7. Swivel pipe, 8. Drain field.

To facilitate easy distribution and/or collection of wastewaters, the drain field of VSSF systems and the inlet and outlet zones of HSSF systems, were filled with 30 – 50 cm size gravel. However, in all the systems10 – 20 mm gravel was used as the wetland media. In addition, each system comprises with a surface layer of 10 cm deep soil (< 5 mm particle size) specially to support the vegetation. A nylon mesh was inserted in between soil and gravel layers to prevent soil sinking into the gravel layer. A locally available emergent macrophyte, *typha angustifolia* (cattail), found from a sludge lagoon of a municipal water treatment plant was used as the vegetation in vegetated beds.

2.2 Synthetic wastewater preparation

Wastewater preparation was done artificially by using 6 g of Urea, 20 g of Sugar, 1 g of Ammonium Chloride, 10 mg of Potassium Hydrogen Phosphate, 100 mL of Fertilizer solution and 650 mL of sludge in 250 L of tap water. The sludge was collected from municipal gulley suckers used to empty septic tanks from individual houses to large business establishments, and stored in a refrigerator below 4^0C. After adding all the ingredients in 250 L tap water, it was mixed thoroughly and pumped into an overhead tank. Each mesocosm was supplied wastewater from this tank evenly through a distribution system.

2.3 Operational procedure

To investigate the effect of hydraulic loading rate (HLR) on treatment efficiency, the HLR was increased in each mesocosm from 2.5 cm/day – 25 cm/day by 2.5 cm/day. The corresponding flow rates were calculated using the surface area and it was controlled by using a control valve arrangement. The flow was changed to the next HLR level after a 12 days period and the adjusted flow rate was monitored daily to minimize errors. The Hydraulic Retention Time (HRT) was also calculated for each HLR, using the porosity of the wetland media. The selected HLRs and corresponding flow rates and HRTs in this study are shown in the Table 1.

Table 1 : Selected HLRs and corresponding flow rates

HLR (cm/day)	2.5	5	7.5	10	12.5	15	20	25
Flow rate (mL/min)	12.2	24.3	36.5	48.6	60.7	72.9	97.2	121.5
HRT (days)	8	4	2.7	2	1.6	1.3	1	20 hrs

2.4 Sampling and analysis of wastewater

Sample collection was done at 12 days intervals at the end of each HLR application. Influent and effluent samples were collected in 500 mL plastic bottles and immediately transferred into the environmental laboratory. Wastewater quality parameters such as pH, conductivity, Dissolved Oxygen (DO), BOD_5, FC counts, TC counts, TSS, ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), and phosphate phosphorus (PO_4-P) were measured in all samples following Standard Methods of water and wastewater analysis. Then the removal efficiency of each parameter was calculated by using equation (1).

$$\text{Removal efficiency} = \frac{C_i - C_o}{C_i} \times 100\% \qquad (1)$$

Where, C_i = concentration of wastewater parameters at the influent and C_o = concentrations of wastewater parameters at the effluent. Then statistical analysis was carried out to test the significant treatment differences between each system.

3 Results and Discussion

The characteristics of synthetic wastewater fed to the wetland mesocosms have been varied during the study period (Table 2). From the table it can be seen that even though the wastewater quality parameters such as pH, BOD_5, NH_3^-- N and conductivity has not varied significantly DO, TSS, PO_4-P, NO_3^- -N, FC and TC has varied significantly. However, the most remarkable variation has been observed in FC and TC counts. This variation of wastewater characteristics might be due to the fast growing rate of micro-organisms and the type of sludge used to prepare the synthetic wastewater during the study period.

Table 2 : Influent synthetic wastewater characteristics range throughout the study period

Parameter	Quality range
pH	6.99 ± 0.21
Conductivity (µs / cm)	268.44 ± 52.23
DO (mg/L)	4.48 ± 2.18
BOD_5 (mg/L)	30.12 ± 4.34
TC (count/100 mL)	$888 \times 10^3 \pm 678 \times 10^3$
FC (count/100 mL)	$514 \times 10^3 \pm 293 \times 10^3$
NO_3^- - N (mg/L)	3.31 ± 1.20
NH_3^-- N (mg/L)	15.68 ± 2.96
PO_4^{3-} (mg/L)	2.69 ± 1.11
TSS (mg/L)	171.78 ± 59.02

A constructed wetland should improve the quality of effluent water and this reduction of pollutants at the effluent can be caused by sedimentation, sorption, plant uptake and microbial activities. Different water parameters such as BOD_5, TSS, pH, Nitrogen, and coliform concentration are affected by microbial activities including nitrification-denitrification, utilization and predation. A well developed biofilm is essential for the effectiveness of the wetland system [12].

3.1 Effect of HLR in pollutant removal

Average water quality parameters at different hydraulic loading rates in both influent and effluents and the percentage removal efficiencies in different types of wetland mesocosms used in this study are shown in table 3. Sampling was done for about four month period at a 12 days interval from August to November 2010. Results show that even though there is some differences in removal efficiencies among the systems, all wetland types show a significant increase in water quality even at higher hydraulic loading rates. The V-2 system, that is VSSF system with plants, shows the best overall performance in pollutant removal.

Table 3 : Average water quality parameters of influent and effluent at different HLR and the percentage removal efficiencies if each parameter

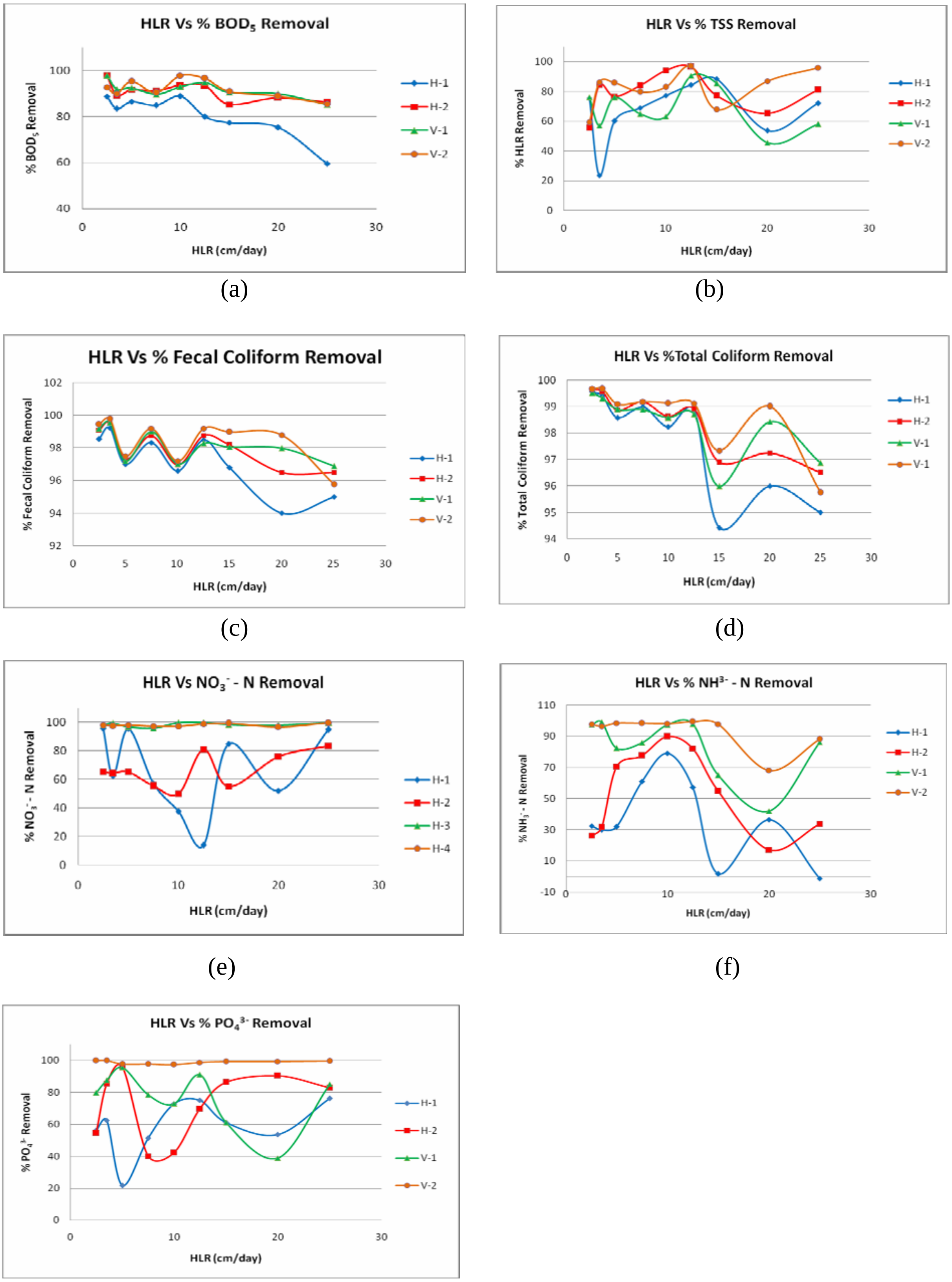
HLR (cm/day)	Influent	Effluent H-1	Removal H-1 (%)	Effluent H-2	Removal H-2 (%)	Effluent V-1	Removal V-1 (%)	Effluent V-2	Removal V-2 (%)
BOD$_5$ (mg/L)									
2.5	29.7	3.35	88.72	2.64 ± .09	97.86	1.64	94.45	1.16 ± 2.79	92.73
3.5	28.9	4.80	83.40	3.12 ± 0.54	89.21	2.33	91.94	2.91± 0.4	89.93
5.0	28.3	3.80	86.57	2.35 ± 1.1	91.70	2.15	92.40	1.33 ± 0.06	95.32
7.5	23.5	3.54	84.94	2.06 ± 0.76	91.23	2.43	89.66	2.27 ± 0.47	90.36
10.0	30.0	3.33	88.89	1.9 ± 0.35	93.66	2.12	92.93	0.64 ± 0.32	97.88
12.5	26.6	5.32	79.98	1.73 ± 0.24	93.49	1.39	94.77	0.91 ± 0.52	96.60
15.0	31.0	7.03	77.29	4.56 ± 1.32	85.27	2.94	90.50	2.84 ± 1.03	90.84
20.0	38.2	9.44	75.28	4.52 ± 0.02	88.17	3.83	89.97	4.26 ± 0.4	88.84
25.0	29.5	11.95	59.49	4.3 ± 0.75	86.1	4.38	85.15	4.28 ± 0.8	85.49
TSS (mg/L)									
2.5	139	34	75.54	62 ± 42.43	55.40	33	76.26	57 ± 1.41	58.99
3.5	128	98	23.44	20 ± 0	84.38	55	57.03	17.5 ± 3.54	86.33
5.0	158	63	60.13	37 ± 5.66	76.58	38	75.95	22.5 ± 0.71	85.76
7.5	296	92	68.92	47.5 ± 9.19	83.95	104	64.86	60.5 ± 4.95	79.56
10.0	228	52	77.19	13 ± 4.24	94.30	84	63.16	39 ± 9.9	82.89
12.5	190	30	84.21	6.5 ± 2.12	96.58	18	90.53	6 ± 2.83	96.84
15.0	170	20	88.24	39 ± 24.04	77.06	25	85.29	54 ± 49.5	67.65
20.0	112	52	53.57	39 ± 12.73	65.18	61	45.54	14.5 ± 0.71	87.05
Fecal Coliforms (FCU/100 mL)									
2.5	432000	6300	98.54	3950 ± 212	99.09	3600	99.17	2440 ± 509	99.44
3.5	864000	6800	99.21	4050 ±919	99.53	3800	99.56	2000 ± 282	99.77
5.0	320000	9600	97.00	8700 ± 424	97.28	9000	97.19	8000 ± 565	97.50
7.5	240000	4000	98.33	3000 ± 0	98.75	2400	99.00	1930 ± 99	99.20
10.0	255000	8700	96.59	7750 ± 495	96.96	7600	97.02	7150 ± 495	97.20
12.5	370000	5570	98.49	4600 ± 283	98.76	6400	98.27	3000 ± 283	99.19
15.0	400000	12800	96.80	7300 ± 2404	98.18	7800	98.05	4100 ± 283	98.98
20.0	1E+06	64800	94.00	37800 ± 7637	96.50	21800	97.98	13000 ± 283	98.80
25.0	665000	33250	95.00	23275 ± 4702	96.50	20750	96.88	28275 ± 16440	95.75
Total Coliforms (TCU/100 mL)									
2.5	992000	4500	99.55	3400 ± 283	99.66	4800	99.52	3500 ± 141	99.65
3.5	1E+06	7600	99.40	5350 ± 212	99.58	8800	99.30	4200 ± 849	99.67
5.0	434000	6160	98.58	4960 ± 57	98.86	4800	98.89	3920 ± 1018	99.10
7.5	430000	4400	98.98	3500 ± 424	99.19	4800	98.88	3500 ± 141	99.19
10.0	408000	7200	98.24	5650 ± 495	98.62	5800	98.58	3500 ± 141	99.14
12.5	480000	5430	98.87	5200 ± 283	98.92	6200	98.71	4200 ± 283	99.13
15.0	800000	44600	94.43	24900 ± 2970	96.89	32000	96.00	21300 ± 1556	97.34
20.0	3E+06	100800	96.00	69300 ± 8910	97.25	39600	98.43	25050 ± 778	99.01
25.0	665000	33250	95.00	23275 ± 4702	96.50	20750	96.88	28275 ± 16440	95.75

PO_4^{3-} (mg/L)									
2.5	3	1.32	56.00	1.37 ± 0.82	54.33	0.61	79.67	0.13 ± 0.04	99.77
3.5	2.4	0.9	62.50	0.35 ± 0.49	85.42	0.3	87.50	0.15 ± 0.15	99.82
5.0	5.1	4	21.57	0.22 ± 0.01	95.78	0.23	95.49	2.31 ± 2.4	97.59
7.5	1.66	0.81	51.20	1.0 ± 0.18	40.06	0.36	78.31	0.94 ± 0.51	97.65
10.0	2.57	0.7	72.76	1.49 ± 1.15	42.02	0.7	72.76	1.15 ± 0.78	97.28
12.5	2	0.5	75.00	0.61 ± 0.13	69.50	0.18	91.00	0.85 ± 0.06	98.78
15.0	2.1	0.82	60.95	0.29 ± 0.01	86.19	0.82	60.95	0.66 ± 0.04	99.23
20.0	1.7	0.79	53.53	0.17 ± 0.09	90.29	1.04	38.82	0.56 ± 0.49	99.39
25.0	3.7	0.88	76.22	0.64 ± 0.22	82.84	0.55	85.14	0.44 ± 0.52	99.47
NH_4^+- N (mg/L)									
2.5	12.3	8.3	32.52	9.05 ± 0.21	26.42	0.3	97.56	0.59 ± 0.16	97.77
3.5	11.7	8.2	29.91	8 ± 0.85	31.62	0.1	99.15	1.1 ± 0.14	96.52
5.0	14.1	9.6	31.91	4.15 ± 0.64	70.57	2.5	82.27	1.05 ± 0.49	98.51
7.5	14.9	5.8	61.07	3.35 ± 3.04	77.52	2.1	85.91	1.25 ± 1.34	98.39
10.0	18.2	3.8	79.12	1.85 ± 0.49	89.84	0.5	97.25	1.7 ± 0.42	98.11
12.5	13.8	5.9	57.25	2.45 ± 2.76	82.25	0.3	97.83	0.55 ± 0.35	99.33
15.0	18	17.7	1.67	8.15 ± 7.14	54.72	6.3	65.00	1.2 ± 0.85	97.81
20.0	18.1	11.5	36.46	15 ± 0.14	17.13	10.5	41.99	5.45 ± 0.21	68.18
25.0	20	20.25	-1.25	13.25 ± 11.31	33.75	2.75	86.25	4 ± 1.77	88.15
NO_3^-- N (mg/L)									
2.5	2.3	0.1	95.65	0.8 ± 0.28	65.22	1.2	98.16	1.25 ± 0.21	98.08
3.5	2.4	0.9	62.50	0.85 ± 0.49	64.58	0.4	99.38	1.55 ± 1.06	97.60
5.0	2.3	0.1	95.65	0.8 ± 0.28	65.22	2	96.93	1.25 ± 0.21	98.08
7.5	2.8	1.2	57.14	1.25 ± 0.35	55.36	2.2	96.03	1.45 ± 0.21	97.38
10.0	4	2.5	37.50	2 ± 1.41	50.00	0.1	99.80	1.35 ± 0.64	97.30
12.5	5	4.3	14.00	0.95 ± 0.35	81.00	0.1	99.88	0.9 ± 0.28	98.89
15.0	2	0.3	85.00	0.9 ± 0.28	55.00	0.8	98.55	0.45 ± 0.07	99.18
20.0	5	2.4	52.00	1.2 ± 1.56	76.00	1.5	98.03	2.4 ± 0.28	96.84
25.0	4	0.2	95.00	0.65 ± 0.49	83.75	0.1	99.88	0.2 ± 0.0	99.76

The efficiency of BOD_5 removal at the effluent in all wetland cells has reduced significantly with the increase of HLR beyond 10 cm/day. Compared to all other systems horizontal unplanted (H-1) system has more deviation in effluent quality with the HLR increment (Figure 2 (a)). Also, it is evident that the BOD_5 removal in planted systems (H-2, V-2) is higher than that of corresponding unplanted systems (H-1, V-1). However, there is no significant difference of effluent qualities in vertical systems beyond 7.5 cm/day HLR. This might be due to the better oxygen transfer capacity in VSSF system. Vertical systems and planted horizontal system have given nearly 86% of BOD removal at the highest HLR (25 cm/day) in this study. But unplanted horizontal system has given a poor removal of 60% at the highest HLR.

From the graphical representation shown in Figure 2 (b) and Table 2, it can be seen that there is a greater fluctuation in removal efficiency of TSS with the increase of HLR. Though it is expected to have a decreasing trend in TSS removal, there is a quick increase at the highest HLR application in this study. This might be due to the dilution occurred with the rainfall which has not thoroughly analyzed in this paper. However, even though the removal pattern is not very clear among different wetland types, the higher removal efficiency has varied between vertical and horizontal planted systems within 60 – 97% range during the study. Also, it was observed that the vertical systems (V-1, V-2) and horizontal systems (H-1 and H-2) follow almost similar removal pattern throughout the study.

According to the Figure 2 (c) and (d), it can be seen that both Fecal and Total coliform removal patterns of all the wetland systems follow the same until 12.5 cm/day HLR. Within this period, the removal efficiency varies between 96.4 – 99.8% in all the systems. Beyond this limit until the highest HLR, the removal efficiencies in V-1, V-2 and H-2 systems does not show much difference. It varies only between 95.75 – 99.2% in these systems. However, only the H-1 system shows a little deviation from others varying the removal efficiency from 94-98%. This is also not much significant. All the systems were able to achieve two log removal until 12.5 cm/day HLR and then one log removal until 25 cm/day HLR.



(a) (b)

(c) (d)

(e) (f)

(g)

Figure 2 : Variations of percentage BOD_5, TSS, FC, TC, NO_3^--N, NH_4^+-N and PO_4^{3-} removal in different wetlands systems with hydraulic loading rate.

Figure 2 (e) shows the NO_3^-- N removal efficiency in all vertical wetland systems (V-1 and V-2) is almost same throughout the study period giving 98 – 99.8% removal range. This might be due to the enhance nitrification within the vertical system. However, the horizontal systems (H-1 and H-2) give a less removal with a wide variation during the study period. It also shows that the planted system performs better than the unplanted system. Figure 2 (f) shows the NH_4^+-N removal efficiencies in different wetland system. It shows the best removal efficiency has achieved by the vertical planted system (V-2). Horizontal systems, both planted and unplanted, show poor NH_4^+-N removal efficiency with a wide variation throughout the study. A very good PO_4^{3-} removal efficiency has achieved in vertical planted system (Figure 2 (g)). In contrast other three systems show a greater variation in PO_4^{3-} removal. However, from unvegetated systems vertical system show a better performance than the horizontal system for removal of nutrients.

4 Conclusions

The experimental results show that the constructed wetland systems provide a promising technology for wastewater treatment in tropical regions. Even though more long-term data are required, the results generated so far indicated that vegetated VSSF constructed wetland system (V-2) provide better treatment performance over the other systems in the study; viz. vegetated HSSF system and unvegetated VSSF & HSSF systems (H-2, H-1 & H-2) under increasing HLRs up to 25 cm/day. However, at lower HLRs up to 10 cm/day (corresponding HRT = 2 days in this study) BOD_5, TSS, FC and TC removal efficiencies in vegetated systems (H-2 & V-2) does not show a significant variation. But unvegetated systems show a little deviation of performance specially in BOD_5 and TSS reduction. In contrast, coliform removal has not affected by the type of the wetland system up to 12.5 cm/day HLR. However there is a little deviation of removal efficiencies beyond that limit. On the other hand, NO_3^--N, NH_4^+-N and PO_4^{3-} removal efficiencies in the V-2 system has given a very good performance throughout the study period where other systems show a significant decrease of pollutant removal with the HLR increment. Therefore, it can be concluded that, vegetated VSSF systems give better results in pollutant removal than vegetated HSSF systems or unvegetated HSSF and VSSF systems. In addition when comparing wetland types separately, vegetated systems perform better than unvegetated systems, and vertical systems perform better than horizontal systems under variable HLRs.

As removal patterns of some pollutants are observed to be complex this study can be continued to gather more data to find out the most favorable HLR for optimum pollutant reduction in tropical countries.

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