Impact of hydraulic loading rate on performance of constructed wetlands for wastewater treatment

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Abstract— *Wastewater generation is increasing at an exponential rate as a result of rapid population growth and urbanization. Sri Lanka in its way forward to become a hub in Asia will have to give an immense attention for treatment of wastewater in the field of pollution control, which is a challenge in developing countries like Sri Lanka, due to the limitations of resources and expertise. Constructed wetlands where water, plants and microorganisms interact to improve the quality of water are growing popular as an effective, low-cost wastewater treatment technology, which does not necessarily require skilled personnel to run the system. However, these systems are not yet widely spread in Sri Lanka due to lack of information.*

This study investigated the performance of laboratory scale vertical subsurface flow (VSSF) and horizontal subsurface flow (HSSF) constructed wetland systems subjected to varying hydraulic loading rates (HLRs) at tropical condition. Four wetland beds of size 1.4 m x 0.5 m x 0.6 m (Length x Width x Height) were constructed and arranged - two beds as VSSF systems and the remaining two beds as HSSF systems. All four beds were filled with 10 – 20 mm gravel as the wetland media and planted with locally available emergent macrophyte, narrow-leaf cattail (Typha angustifolia). Each wetland system was supplied continuously with synthetic wastewater at different HLRs of 2.5, 3.5, 5, 7.5, 10, 12.5, 15, 20 and 30 cm/day at 12 days cycles over a period of four months. Samples were collected at the end of each HLR application and analysed for five day biochemical oxygen demand (BOD_5), total suspended solids (TSS), fecal coliform (FC) and Total coliform (TC). Results showed a decrease of removal efficiencies of BOD_5, TSS, FC and TC when increasing the HLR. However it was observed over 80% of BOD_5, 40% of TSS, 86% of FC, 90% of TC removal efficiencies in HSSF wetland systems and over 85% of BOD_5, 29% of TSS, 89% of FC, 88% of TC removal efficiencies in VSSF systems respectively from 2.5 – 30 cm/day HLRs. Results of this study can be used in field applications of CWs where frequent water flow fluctuations occur.

Keywords— **Constructed wetlands, variable Hydraulic loading rate, synthetic wastewater**

I. INTRODUCTION

The wastewater generation is increasing exponentially with the rapid increase in population and subsequent increase in urbanization, agricultural development, industrialization etc., and hence proper disposal of these wastewaters are essential in preventing public health hazards as well as mitigating the damage cause to the whole ecological system. However, due to economic constrains and lack of expertise, wastewater treatment is not always satisfactory at many locations in developing countries (Trang et al., 2010). Therefore, there is a growing demand for the development of appropriate and affordable wastewater treatment technologies particularly in developing countries like Sri Lanka to reduce the pollution of fresh water resources from unacceptable wastewater discharges.

Compared to conventional wastewater treatment technologies, constructed wetlands (CWs) offer low cost, easy to operate, efficient and robust treatment (Trang et al., 2010) with ecological values (Islam et al., 2009), which does not necessarily require skilled personnel to run the system and have been proven as an sustainable alternative with good results in many parts of the world. Also, the treatment performance of CWs is expected to be higher in tropical regions due to higher temperatures and associated higher bacterial activities. Therefore, they are currently being studied as a wastewater treatment option in tropical countries for many kinds of wastewaters including domestic and industrial wastewaters, landfill leachate, agricultural runoff, mine drainage, septage treatment and sludge dewatering (Trang et al., 2010). Contaminated water flowing through CWs is cleansed by physical, chemical and biological activities (Surrency et al., 2003). However, the treatment performance in CWs depend on various factors such as inflow pollutant characteristics, wetland design, hydraulic and nutrient loading rates, climatic variations and essentially required effluent quality (Tanaka et al., 2006). 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 (Gillepse et al., 1999).

Based on the level of the water column CWs can be divided into two basic types as sub-surface flow (SSF) wetlands which maintain the water level below the surface and free water surface (FWS) wetlands which expose the water surface to the atmosphere. Distinctive advantages of SSF systems over FWS systems include, lack of odour problems, lack of mosquito breeding and other insect vector problems and the minimal exposure of contact with wastewaters to general public (EPA, 1993). SSF wetlands can be further divided according to the flow direction as horizontal SSF (HSSF) and vertical SSF (VSSF) wetlands. It is expected to have a much greater oxygen transfer capacity in VSSF systems over the HSSF systems and hence VSSF can achieve very good results in removing organic material (Ghosh and Gopal, 2010).

The wastewater flow into a CW can be fluctuated with the seasonal water consumption pattern. According to Brix et. al (2007) CWs can tolerate a high variability in loading rates and wastewater quality. Wetland hydraulics, namely the hydraulic loading rate (HLR), and the hydraulic retention time (HRT) are directly affects the treatment performance of a CW (Gosh and Gopal, 2010). Several studies reveal that by decreasing the HLR (ie. longer HRT) the pollutant removal efficiency in a CW system can be improved. Metcalf and Eddy (1991) stated that the most effective HRT is ranged between 4 - 15 days. However, to incorporate smaller hydraulic loading or longer hydraulic retention requires higher land area which is a major limiting factor for CW application. Hence, investigation of the treatment performance at different HLRs/HRTs will lead for an optimum design to suit the local climate, which in turn confirms the land area reduction capacity specially when frequent flow fluctuations occur.

The objective of this study is to evaluate the pollutant removal performance of laboratory scale HSSF and VSSF CW systems subjected to varying HLRs at tropical condition, in order to assess how much higher HLR can be applied to SSF wetland systems while maintaining sufficient buffer for an acceptable treatment.

II. MATERIAL AND METHODS

A. Wetland Mesocosm Arrangement

This study was conducted using four wetland units of size 1.4 m x 0.5 m x 0.6 m (Length x Width x Height), operated at the University of Peradeniya, Sri Lanka (80^0 35′ 59′′ E, 7^0 16′ 00″ N). Two of them were arranged as HSSF systems and the remaining two were arranged as VSSF systems. The experimental setup used is shown in the Figure 1 (a), and operated continuously for a period of four months from September to December 2010. Schematic diagrams of a HSSF system and a VSSF system are shown in Figure 1 (b) and Figure 1 (c) respectively. The four wetland units had 10 – 20 mm gravel as bed media, and 30 – 50 mm gravel for the inlet zone and outlet zone of the HSSF systems and the drain field of the VSSF systems. In addition, 10 cm deep soil layer (< 5 mm particle size) was laid on top of the wetland media to support the vegetation. A nylon mesh of size 1.5 mm x 1.5 mm was used between soil layer and bed media to minimize incidence of soil particles moving into the gravel layer. Then eight rhizomes (approximately 30 cm high and containing at least two nodes) of a local emergent macrophyte, *Typha angustifolia* (narrow leaf cattail) were planted in each wetland unit. After the planting, the wetland units were kept saturated with tap water for four weeks until the plants grew. Thereafter, they were fed with tap water for another two weeks to flush and rid the system of pollutants before being fed with synthetic wastewater. In this study data were collected after two months of wastewater application.

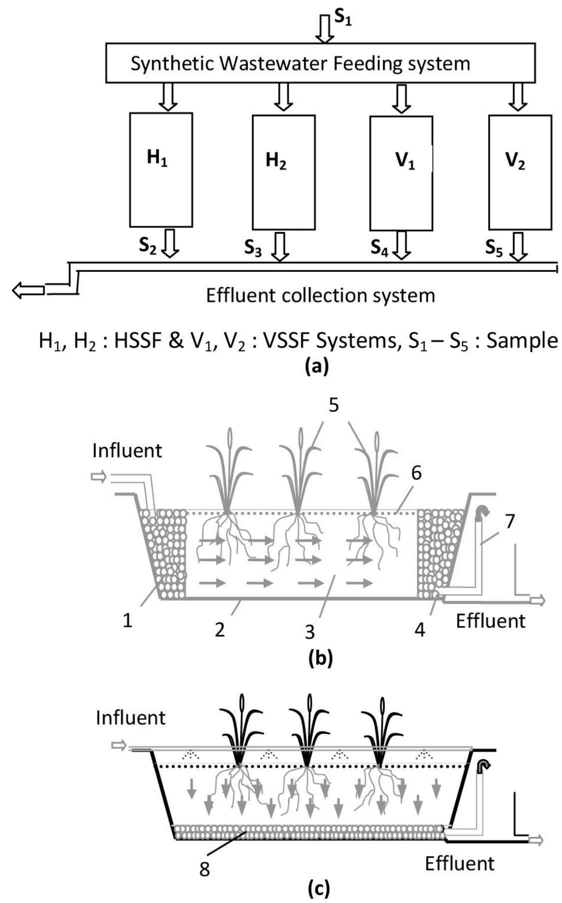

Fig 1. (a). Arrangement of wetland mesocosms, (b). Schematic diagram of a HSSF wetland system (c). Schematic diagram of a VSSF wetland system; 1. Inlet zone, 2. Impermeable barrier, 3. Wetland media, 4. Outlet zone, 5. Wetland Vegetation, 6. Water level, 7. Swivel pipe, 8. Drain field.

B. Synthetic Wastewater Preparation

The synthetic wastewater was prepared using; 6 g of Urea, 20 g of normal granular Sugar, 1 g of Ammonium Chloride (NH_4Cl), 10 mg of Potassium Hydrogen Phosphate (K_2HPO_4), 100 mL of Fertilizer solution containing N, P, K, S, Mg, Cu, Fe and Mn and 650 mL of septage sludge added to 250 L of tap water. The septage sludge was collected from municipal gulley bowsers and stored below 4^0C until used. Synthetic wastewater was then pumped into an overhead tank from which it was channelled to each wetland unit at predetermined flow rates.

C. System Operation

The impact of HLR variation on treatment performance was investigated by changing HLR from 2.5 – 30 cm/day at 12 days interval. The flow rate corresponding to each HLR was calculated using the surface area of the wetland unit and flow then controlled using a valve arrangement. The flow rates once set were monitored daily to minimize fluctuations.

D. Sample Analysis

Influent and effluent water samples were collected [from sample points S_1 – S_5 as shown in Fig. 1(a)] at 12 days intervals (i.e. at the end of each HLR application) in 500 mL plastic bottles. pH, Electrical Conductivity (EC) and Dissolved Oxygen (DO) were measured immediately after collection using appropriate probes. Biochemical Oxygen Demand (BOD_5), Fecal Coliform (FC), Total Coliform (TC) and Total Suspended Solids (TSS) were measured in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Removal efficiencies of each wastewater parameter following each sampling occasion were calculated as the percentage change in concentration from influent to the effluent using Equation 1. The corresponding Mass Loading Rate (MLR) and Mass Removal Rate (MRR) for BOD_5, TSS, FC and TC were calculated using Equation 2 and Equation 3 respectively (Jing et al., 2002 and Chang et al., 2007).

$$\text{Removal Efficiency (RE)} = \frac{C_i - C_o}{C_i} \times 100\% \quad (1)$$

$$\text{Mass Loading Rate (MLR)} = C_i \times HLR \quad (2)$$

$$\text{Mass Removal Rate (MRR)} = (C_i - C_o) \times HLR \quad (3)$$

Where,

C_i = Influent wastewater concentration

C_o = Effluent wastewater concentration

E. Statistical Analysis

All statistical analyses were conducted by using 'MINITAB 16' statistical software. The significant treatment differences between wetland systems subjected to varying HLRs were tested by using 2-sample 't-test' for normally distributed data and Mann-Whitney test for non normal data. The correlation between MLRs and MRRs were identified by using linear regression test.

F. Plant growth

Shoot height and shoot density of plants in each wetland bed were monitored following each 12 days period throughout the study in order to ascertain the effect of plant growth in treatment performance.

III. RESULTS AND DISCUSSION

A. Wastewater Characteristics

The average wastewater concentrations of the influent and effluents, both in HSSF and VSSF wetland systems are shown in the Table 1. The coefficients of variations (CV) obtained for influent wastewater strength using MINITAB 16 statistical software showed values of 65%, 54%, 34% and 30% for TC, FC, TSS and BOD_5 respectively, indicating a significant quality fluctuation over the study period. This quality variation is graphically shown in the Figure 2. The significant variation in influent properties might be attributed to the differences in quality of septage sludge used in the preparation of synthetic wastewater. Furthermore, Figure 2 shows that the effluent quality was also influenced by these influent quality variations. However, the normality of the influent wastewater parameters were statistically tested using MINITAB 16 software performing the Anderson Darling, Ryan-Joiner and Kolmogorov-Smirinov tests, and found only BOD_5 and TSS values were normally distributed ($p > 0.05$) but the FC and TC were not ($p < 0.05$). The effluent wastewater parameters of both VSSF and HSSF wetland systems showed, only BOD_5 was normally distributed.

B. Pollutant Removal Efficiencies

Figure 3 illustrates BOD_5, FC, TC and TSS removal efficiencies in VSSF and HSSF wetland systems over the study period. Corresponding HLRs applied are also indicated in the same plot. Results showed both VSSF and HSSF wetland systems follow almost similar pollutant removal trend; a decrease of removal efficiency corresponding to increasing HLR. It is noted that the VSSF system had removed over 85% of BOD_5, 89% of FC, 88% of TC and 29% TSS while the HSSF system reduced over 81% of BOD_5, 86% of FC, 90% of TC and 40% of TSS respectively with varying HLRs from 2.5 – 30 cm/day.

However, statistical analysis carried out to identify treatment differences between two wetland systems by 2-sample-t test for normally distributed data and Mann-Whitney test for non-normal data (MINITAB 16 statistical software) showed there is no significant treatment difference between VSSF and HSSF wetland systems for all wastewater parameters ($p > 0.05$).

Primary mechanisms of BOD_5 removal in a wetland system include adsorption, sedimentation and microbial metabolism (Karanthasis, 2003). From Figure 3 (a) it is noted that BOD_5 removal in VSSF system has gradually decreased from 96% - 85% during 2.5 – 30 cm/day HLR levels while there was a decreasing but a zig-zag pattern was observed for HSSF system during the same HLR levels.

Parameter	Influent	CV	Effluents	
			VSSF	HSSF
BOD5 (mg/L)	29.8 ± 3.8	30%	2.7 ± 1.3	3.6 ± 2.3
TSS (mg/L)	178.5 ± 55.5	34%	54.8 ± 46.0	61.9 ± 35.2
FC (FCU/100 mL)	$5.0*10^5 \pm 2.8*10^5$	54%	$9.9*10^3 \pm 1.2*10^4$	$1.5*10^4 \pm 1.7*10^4$
TC (TCU/100 mL)	$9.0*10^5 \pm 6.3*10^5$	65%	$2.2*10^4 \pm 2.9*10^4$	$2.3*10^4 \pm 2.6*10^4$
DO (mg/L)	4.7 ± 1.7	40%	6.7 ± 1.5	6.3 ± 1.7
pH	7.0 ± 0.2	31%	6.9 ± 0.14	6.9 ± 0.17
EC (µs)	266.7 ± 49.5	31%	428.3 ± 77.2	350.6 ± 46.9
HLR (cm/day)	-	-	13.1 ± 9.4	13.1 ± 9.4

Table 1. Average wastewater characteristics in the influent and effluents of wetland units (n = 10)

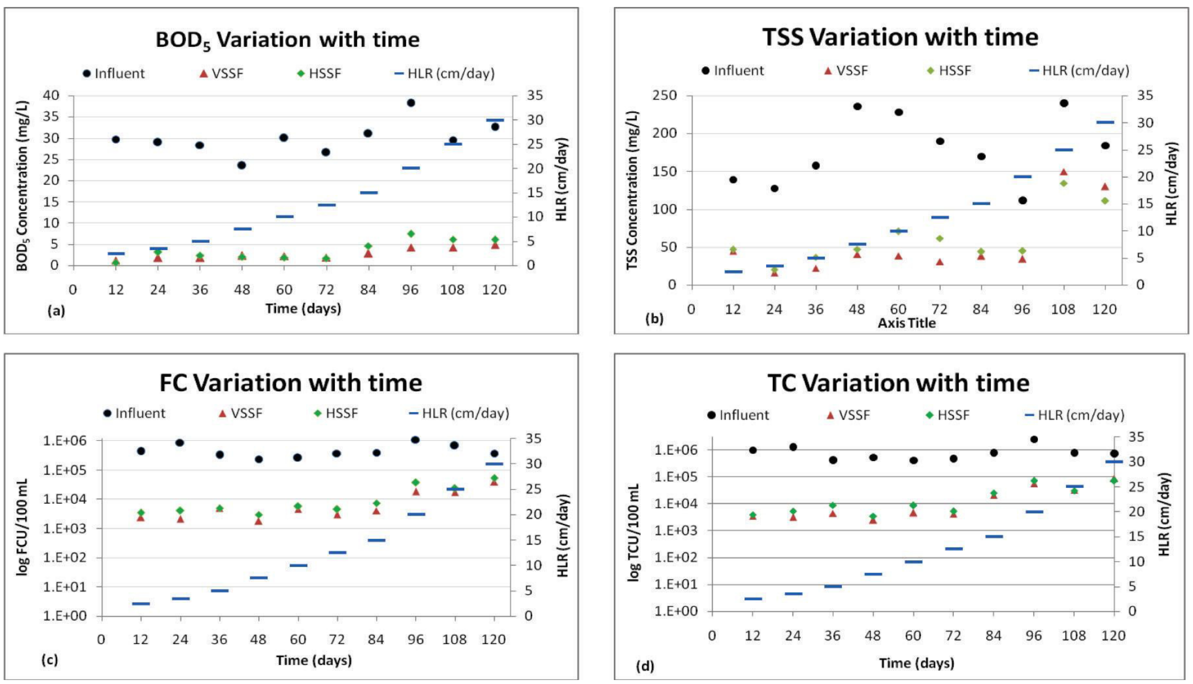

Fig 2. Variation of (a) BOD_5, (b) TSS, (c) FC and (d) TC concentrations at the influent and effluents of HSSF and VSSF wetland systems during the study period

Also, at initial and later stages VSSF system has showed a better BOD_5 removal than that in HSSF system. For better reduction of organic matter in a wetland system, there should be a well grown bio-film, sufficient DO and nutrients. Although, the development of the bio-film, the amount of nutrients present in the wastewater and the DO transmitted by wetland vegetation through the root zone could be similar in both wetland systems, the way of application of wastewater in VSSF system was by means of a sprinkler arrangement from the top and hence there is a possibility for contact and diffuse more oxygen to the wastewater. This could have enhanced the BOD_5 removal in VSSF system.

Coliform removal in a wetland system may involve several factors including extent of plant coverage, available HLR and settling of microorganisms (Perkins and Hunter, 2000). Alternation of any of these factors may results in variation of removal efficiencies. In addition processes involved in coliform removal in wetlands include natural die off, predation, sedimentation, filtration, adsorption and UV radiation. In this study, even though FC removal is not significantly different between VSSF and HSSF wetland systems, from Figure 3 (c) it is noted that in VSSF wetland system, FC removal was over 98% from 2.5 – 20 cm/day HLR levels, and there after FC removal has decreased to 97% at 25 cm/day HLR and a rapid drop to 89% at 30 cm/day HLR respectively while in HSSF system FC removal was over 98% only up to 15 cm/day HLR and then it has decreased to 96% up to 25 cm/day HLR and a sudden drop to 86% at 30 cm/day HLR. This implies that VSSF system is slightly better in FC removal even though it is not significant. On the other hand, Figure 4 (d) shows, TC removal in VSSF system was over 99% from 2.5 – 12.5 cm/day HLR levels and then TC removal has decreased to 96% up to 25 cm/ day HLR and further decreased with a sudden drop to

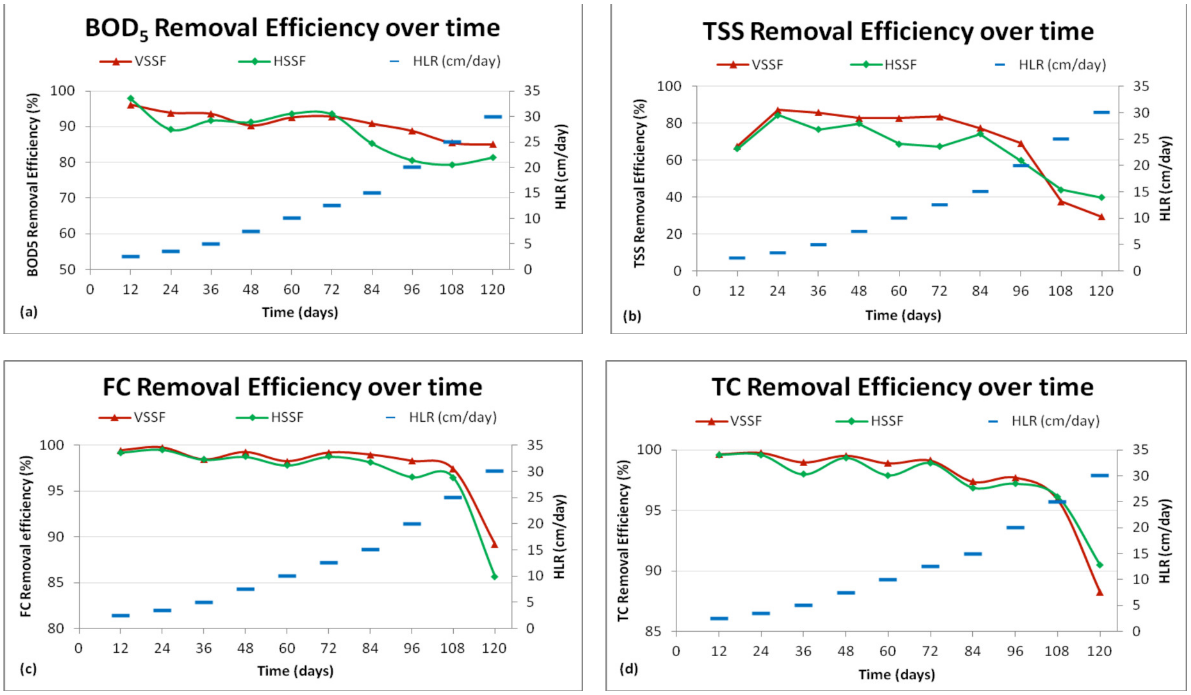

Fig 3. Variation of (a) BOD_5, (b) TSS, (c) FC and (d) TC Removal Efficiencies of HSSF and VSSF wetland systems during the study period

88% at 30 cm/day HLR while in HSSF wetland system TC removal was being varying between 99% and 98% from 2.5 – 12.5 cm/day HLR levels and then it has decreased to 96% up to 25 cm/day HLR level and further decreased with a significant drop to 90% at 30 cm/day HLR respectively, showing only a little difference between two systems satisfying the results of statistical analysis. From these results it is observed that subsurface flow CWs is more effective in coliform removal below 25 cm/day HLR at tropical condition. However, this 25 cm/day HLR needs further confirmation before reaching a firm decision.

TSS reduction in a wetland system is aided by physical processes such as filtration and sedimentation followed by aerobic and anaerobic microbial degradation inside the wetland media (Kadlec and Wallace, 2009 and Shubiau et al., 2011). From Figure 3 (b) it is observed that TSS removal was very low at 2.5 cm/day HLR (68% in VSSF system and 66% in HSSF system) and there was a sudden increase to 87% in VSSF system and to 84% in HSSF system respectively at 3.5 cm/day HLR. This initial lower removal could be due to higher pore spaces at initial stage. Then from 3.5 – 20 cm/day HLR, TSS removal has gradually decreased to 69% in VSSF system and to 60% in HSSF system respectively. Thereafter, there was a rapid reduction of TSS removal to 29% in VSSF system, while there was a gradual drop to 39% in HSSF system respectively at 30 cm/day HLR showing some contradictory results. This could be due to the higher chances of escaping solid material at higher HLRs and the short travel time in VSSF system compared to HSSF system.

C. Plant growth performance

Figure 4 illustrates the average shoot heights and average shoot densities in VSSF and HSSF systems during the study period. Shoot height in HSSF system showed a gradual increase with HLR increment while VSSF showed a rather rapid increase of height over the study period. However, plant heights in HSSF system were higher than that of VSSF system throughout the study. On the other hand, VSSF system showed a higher number of shoots during 10 – 25 cm/day HLR levels. This variation in shoot heights and shoot densities could be a result of the different wastewater application mechanism in VSSF and HSSF systems. However, results showed that there is no considerable impact of HLR increment on plant growth except rapid increase in shoot numbers in VSSF system from 10 cm/day HLR and in HSSF system from 25 cm/day HLR respectively.

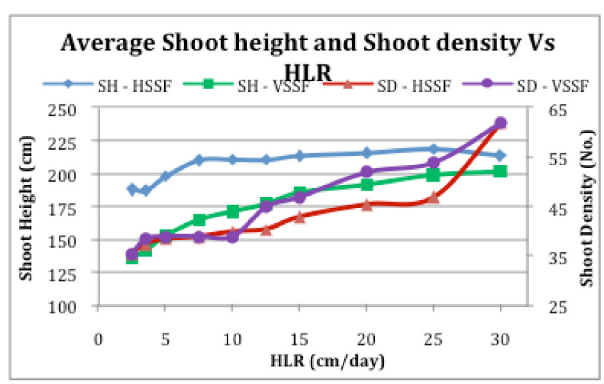

Fig 4. Variation of shoot heights and shoot densities of VSSF and HSSF wetland systems with respect to HLR

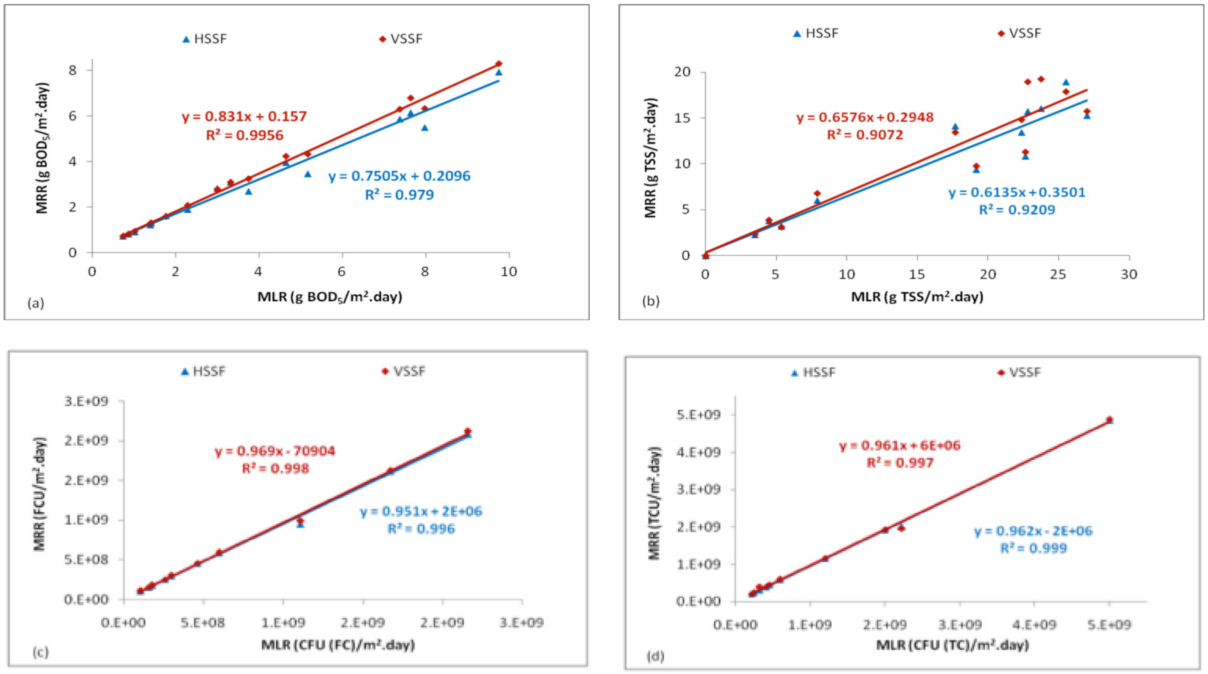

Fig 5. Relationship between Mass Loading Rates versus Mass Removal Rates of (a) BOD5, (b) TSS, (c) FC and (d) TC in VSSF and HSSF wetland systems during the study period

D. Mass loading rates verses mass removal rates

Figure 5 represents the relationship between applied mass loading rates (MLR) and mass removal rates of BOD_5, TSS, FC and TC in VSSF and HSSF wetland systems. It is observed that MRRs of BOD_5 and TSS in VSSF systems were marginally higher than that of HSSF systems while FC and TC removal is almost same in both systems. Also, a good linear correlation between the incoming mass loads and the mass removal rates were observed for all wastewater parameters in both wetland systems with higher R^2 values as shown in the Figure 5.

CONCLUSIONS

Experimental results show both HSSF and VSSF constructed wetland systems are capable in substantial pollutant removal from wastewater subjected to varying HLRs with a good buffering capacity at tropical regions even though there is a reduction of removal efficiencies with increasing HLRs. Both wetland systems were more effective in pollutant removal up to 25 cm/day HLR level with over 80%, 97%, 96% and 40% of BOD_5, FC, TC and TSS respectively. The graphical representations illustrate VSSF systems perform slightly better than the HSSF systems even though there is no significant treatment difference between two systems. However, the 25 cm/day HLR limit under varying hydraulic conditions needs further clarification before making a firm decision.

Results of this study are useful in application of CW technology at a place where frequent flow fluctuations occur.

ACKNOWLEDGEMENT

The authors like to acknowledge the CB project in Postgraduate Institute of Agriculture, University of Peradeniya for providing funds to carry out this study and to the staff of the Environmental Engineering Laboratory in the Department of Civil Engineering, the Department of Agricultural Engineering and the Postgraduate Institute of Agriculture of University of Peradeniya for the generous support extended throughout the study.

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