WASTE MATERIALS AS SUBSTRATES IN VERTICAL FLOW CONSTRUCTED WETLANDS TREATING DOMESTIC WASTEWATER

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ABSTRACT

Vertical flow constructed wetlands (VFCW) are considered to be one of the most efficient type of wetlands and require a lesser footprint in comparison to other wetland types. Substrate is an important component of wetland. We used the common gravel (VFCW 1) and three waste materials: concrete (VFCW 2), slag concrete (VFCW 3) and coconut husk (VFCW 4) as substrates in experimental wetlands. All four experimental wetlands have been constructed in uPVC pipes, diameter and height of each VFCW was 89 mm and 1000 mm, respectively. A 15 mm diameter perforated pipe that penetrates to the wetland bottom was installed in each wetland for passive aeration. Canna indica, an ornamental plant was planted in all four wetlands. Pre-treated wastewater from a wastewater treatment plant was added manually to all VFCW. The maximum plant height observed was 78.7 cm in VFCW 1 while minimum plant height observed was 53.3 cm in VFCW 3. The four VFCW removed all monitored contaminants with good removal efficiencies during the 8 months monitoring period: suspended solids (79%, 74%, 74%, 54%); BOD (54%, 42%, 42%, 2%); COD (54%; 47%; 44%, 34%); ammonia-nitrogen (54%, 46%, 38%, 38%), ortho-phosphate (67%, 61%, 64%, 53%); and fecal coliforms (55%, 40%, 14%, 52%). DO levels increased for VFCW 1 and 4 and nitrate levels increased in all wetlands confirming the nitrification process. For the various waste materials used following were our observations: VFCW 2 performed the best for organic matter and ammonia-nitrogen removal while VFCW 3 outperformed others for phosphorus removal and VFCW 4 had the highest percentage of fecal coliforms removal.

Keywords: waste, substrate, vertical flow, constructed wetland, concrete, slag concrete, coconut husk, gravel, domestic wastewater.

1 INTRODUCTION

Constructed wetlands (CWs) are considered to be low cost and low energy wastewater treatment systems. Doody et al. [1] appraised and compared capital costs and O&M costs associated with constructed wetlands and the conventional electro-mechanical wastewater treatment plants. They found the former provided 50% and 90% savings in terms of capital costs and O&M costs, respectively. Constructed wetlands have the capability to treat various types of wastewaters including domestic and industrial wastewaters. They can be classified into two types with respect to the hydrology; free water surface (FWS) and subsurface flow (SSF) systems With respect to flow direction, SSF CWs can further be classified into two types; horizontal flow (HSSF) and vertical flow (VF) [2]. The important components of SSF systems are substrate, a basin with an impermeable layer and emergent plants. The wastewater enters at the inlet of the system flows horizontally or vertically through the substrate and exits the system from the outlet.

Decades of research has shown that vertical flow constructed wetlands require lesser area as compared to the HSSF wetland type [3]. They can successfully remove higher concentrations of organics, suspended solids and ammonia. The VF wetland can treat domestic wastewater, industrial wastewater and storm runoff as well. Substrate is an important component of wetland. They provide multiple benefits: growth of biofilms, support plant roots which in turn transfer oxygen and provide insulation to the wetland bed in colder

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climates. The substrates also remove various pollutants present in the wastewater through filtration, adsorption and precipitation processes [4], [5]. Vymazal [2] has listed substrate as an important and basic wetland component that should be taken into account while calculating overall cost of the constructed wetland system.

Vohla et al. [4] report that three types of substrates are commonly used in constructed wetlands. They include natural products like gravel, shale, zeolite; man-made products like light weight aggregates, light expanded clay aggregates, filtralite; and industrial by-products like scrap rubber filters. Based on the availability and economics, gravels are the most commonly used substrate material in wetland systems. But recently industrial by-products and waste products have also been used as a substrate material in wetland systems. The use of industrial by-products as alternative substrates has multiple benefits of cost savings, solid waste management and sustainable wastewater treatment. Few studies focusing on use of alternative substrate in wetlands have been conducted; waste rubber tire chips [5], sugarcane bagasse [6] and alum sludge [7].

Concrete is a composite material that comprises admixtures, fine and coarse aggregates, cement and water. Quantity wise, it is considered to be one of the largest materials made by humans. Concrete waste has problems with regard to its disposal. In the realm of construction engineering various researchers have investigated reusing concrete in road beds, wall panels, precast elements, etc. However, in the realm of wastewater engineering very few studies have focused on using alternative substrate materials. Therefore, the main aim of this study is to assess the potential of using locally available waste materials including concrete and slag concrete – university laboratory waste product and coconut waste by product as substrates in vertical flow wetlands treating domestic wastewater.

2 MATERIALS AND METHODS

2.1 Experimental setup

A rig consisting of four (4) experimental wetlands was erected just outside the Department of Environmental Engineering, NED University. The experimental wetlands consisted of vertical flow constructed wetlands (VFCW 1 to 4) and were made in uPVC pipes. Each VFCW pipe has a diameter of 89 mm and a height of 1000 mm. All four pipes have been supported with the help of an iron frame especially manufactured for the study. All pipes have effluent tubes at the bottom of pipe with ball valves for sample collection. A 15 mm diameter perforated pipe has been provided to each VFCW for providing aeration. Its purpose is to efficiently transfer air throughout the wetland in a passive manner. The aeration pipe is as tall as the wetland pipe but is elevated at a height of 100 mm from the bottom and its upper end can be seen coming out of the wetland inlet.

Various substrates, the commonly used gravel and waste products including concrete, slag concrete and coconut husk were used in the experimental wetlands. Cubes of concrete and slag concrete were collected from the Material Testing Laboratory of Civil Engineering Department, NEDUET. They were manually crushed into pieces of sizes in the range of 25 to 38 mm. Coconut husk was obtained from from a nearby market where vendors sell coconut and its water All substrate materials were filled to a depth of 800 mm. VFCW 1 contained the common gravel or aggregate while VFCW 2 contained concrete, VFCW 3 contained slag concrete and VFCW 4 was filled with coconut husk. All wetlands were planted with ornamental plants *Canna indica* which were purchased from a nearby plant nursery. Two plants were placed in each VFCW and each wetland was fed with freshwater from the tap in order to allow the plants to establish in the experimental wetlands. In order to overcome the evapotranspiration losses, fresh water was added for three continuous weeks. After three weeks of establishment period, small volume of wastewater was added to the wetlands for acclimatization. During and after the acclimatization period plant growth was monitored continuously. After three weeks of acclimatization period domestic wastewater were applied manually to all four VFCW. Pre-treated wastewater from the university's wastewater treatment plant were collected in PVC containers and added to each VFCW manually. The experimental wetlands were operated as a pulse load system. Experiments were conducted in weather condition where summers (38°C) are warm and humid while winters (10°C) are not very cold.

2.2 Water quality monitoring

Influent and VFCW effluent samples were collected and tested for various water quality parameters. The physical parameters included dissolved oxygen (DO), total dissolved solids (TDS), total suspended solids (TSS), electrical conductivity (EC) while chemical parameters monitored included pH, biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N), orthophosphate (PO_4-P) and sulphate (SO_4). Total coliforms (TC) and fecal coliforms (FC) were also monitored to cover microbiological analysis. Water quality testing was carried out in the Water Quality Laboratory of Department of Environmental Engineering NED University of Engineering and Technology. American Public Health Association (APHA) standard methods were used for testing of all parameters. The system was monitored for eight months.

3 RESULTS AND DISCUSSION

Table 1 represents the average influent and effluent concentrations with removal efficiencies in brackets for the four experimental wetlands with different substrate materials. The pre-treated wastewater that was added to each of the four VFCW was monitored for various physico-chemical parameters including pH, DO, electrical conductivity, suspended solids, chemical oxygen demand, biochemical oxygen demand, ammonia-nitrogen, nitrate-nitrogen and orthophosphate. Their respective mean values were 8.1, 181 NTU, 283 mg/L, 1146 mg/L, 746 mg/L, 328 mg/l, 164 mg/L, 34.1 mg/L, 6.7 mg/L and 1.7 mg/L, respectively. The microbiological parameter fecal coliforms were also monitored and their mean influent value was 80 MPN/100 mL.

(a) (b)

Figure 1: Vertical Flow Constructed Wetlands VFCW. (a) During acclimatization period; (b) Three months after acclimatization period.

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Table 1: Mean influent and effluent concentrations (removal efficiency %) for four experimental wetlands with different substrate materials.

Parameter	Unit	Influent	Effluent			
			VFCW 1	VFCW 2	VFCW 3	VFCW 4
pH	–	7.95	7.0	6.88	7.24	6.90
DO	mg/L	2.8	3.60	2.91	2.98	3.14
EC	μS/cm	1753.4	2629.54	2269.80	2853.00	2115.77
TSS	mg/L	125	26.29 (79)	33.10 (74)	32.86 (74)	56.57 (55)
BOD	mg/L	88	40.10 (54)	50.92 (42)	50.98 (42)	85.50 (2.3)
COD	mg/L	170	111.8 (47)	97.17 (54)	118.83 (44)	138.67 (34)
NH_4-N	mg/L	5.35	1.15 (54)	1.33 (46)	1.53 (38)	1.55 (37)
NO_3-N	mg/L	2.46	11.71 (-119)	12.46 (-133)	16.37 (-206)	17.64 (-230)
PO_4-P	mg/L	5.6	1.86 (67)	2.19 (61)	2.04 (64)	2.65 (53)
Fecal coliforms	MPN/ 100 mL	80	36 (55)	48 (40)	69 (14)	38.8 (52)

3.1 General water quality

Table 1 clearly shows the water quality improvements provided by the experimental wetlands. The influent pH was slightly above neutral while average pH effluent values for VFCW 1, VFCW 2, VFCW 3 and VFCW 4 were 7, 6.8, 7.2 and 6.9, respectively. The results indicate that effluent pH is above or very close to neutral. In VFCW 2 and VFCW the pH decreased slightly and this may be due to the substrates, concrete and coconut husk used in the above wetlands [9]. The DO concentrations increased in the all four VFCW. However, VFCW 1 and 4 had higher DO concentrations than VFCW 2 and 3. This difference may be due to difference in porosity of the different substrates. The dissolved oxygen is an important parameter as it supports aerobic decomposition of organic matter and also nitrification. The influent EC was 1753.4 μS/cm while effluent EC values were 2629.54 μS/cm, 2269.8 μS/cm, 2853 μS/cm and 2115.77 μS/cm for VFCW 1, VFCW 2, VFCW 3 and VFCW 4, respectively. The EC in all four VFCW increased and this increase may be due to the liberation of ionic compounds during chemical reactions.

3.2 Suspended solids removal

The mean influent suspended solids concentration was 125 mg/L while the effluent values for VFCW 1, VFCW 2, VFCW 3 and VFCW 4 were 26.29 mg/L, 33.10 mg/L, 32.86 mg/L and 56.57 (Fig. 2) with removal efficiencies of 79%, 74%, 74% and 55%, respectively. The wetland filled with conventional aggregate material provided the highest suspended solids removal. With regard to waste materials concrete and slag concrete had the same removal efficiencies and coconut husk showed the lowest removal efficiency for solids removal. In VFCW, interception and settling are considered formula to be the main mechanisms for removal of incoming suspended matter [9]. The size of the substrate used in the wetland also has an influence on the removal of solids. The lowest removal efficiency for coconut husk is suspected to be because of solids generation by the organic substrate.

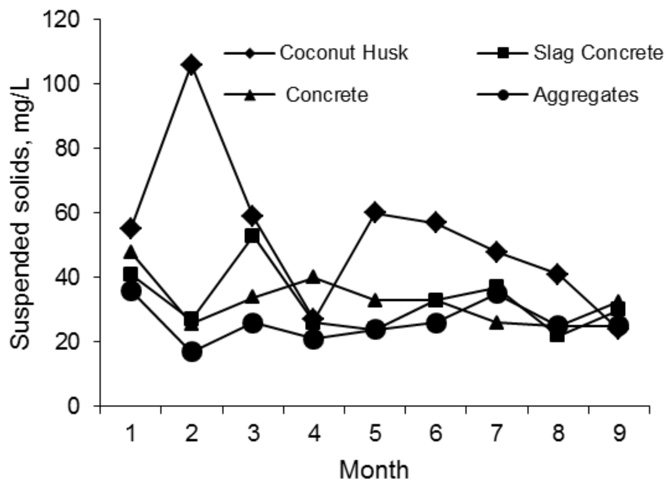

Figure 2: Effluent suspended solids concentrations for the four vertical flow constructed wetlands during the monitoring period.

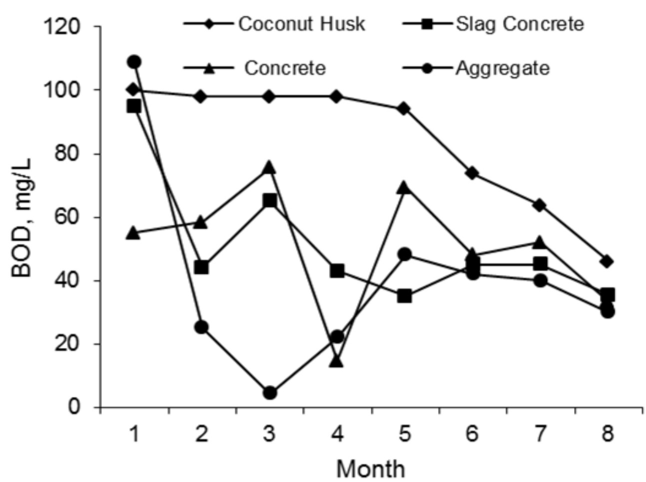

Figure 3: Effluent BOD concentrations for the four vertical flow constructed wetlands during the monitoring period.

3.3 Organic matter removal

The mean influent BOD concentration was 88 mg/L while the effluent values for VFCW 1, VFCW 2, VFCW 3 and VFCW 4 were 40.10 mg/L, 50.92 mg/L, 50.98 mg/L, 85.50 mg/L, respectively. Fig. 3 shows the variation of the organic pollutants in effluent of the four VFCW during the observing period. The average reduction in BOD concentrations over the monitoring period were 54%, 42%, 42% and 2.3% for VFCW 1, VFCW 2, VFCW 3 and VFCW 4, respectively. The VFCW with concrete and slag concrete substrates performed better that the VFCW with coconut husk substrate material. A study conducted by Saeed and Sun [10] reported leaching of carbon from organic substrates in wetlands. This is considered to be the main reason of poor organic matter removal in VFCW 4.

As seen from Table 1, the influent BOD_5/COD ratio is 0.51 and this ratio decreases for all VFCW effluents except for VFCW 4 that has a ratio of 0.61. This infers that organic matter likely to be degrading biologically was removed. However, for VFCW 4 the behaviour indicates discharge of carbon from the coconut husk substrate as mentioned above. Overall it can be seen in Fig. 3 that from sixth month of observation the removal of BOD has a stable downward trend.

3.4 Nutrient and pathogen removal

The mean influent NH_4-N concentration was 5.35 mg/L while the effluent values for VFCW 1, VFCW 2, VFCW 3 and VFCW 4 were 1.15 mg/L, 1.33 mg/L, 1.53 mg/L, 1.55 mg/L, respectively. Fig. 4 shows the variation of the ammonia nitrogen in effluent of the four VFCW during the observing period. The average reduction in concentrations over the monitoring period were 54%, 46%, 38% and 37% for VFCW 1, VFCW 2, VFCW 3 and VFCW 4, respectively. In terms of removal efficiency of wetlands containing waste materials as substrates, VFCW 2 presented the highest percentage removal of ammonia nitrogen while VFCW3 and VFCW 4 had almost the same performance.

In wetland systems nitrification is considered to be the one of important mechanisms to remove ammonia. Ammonia concentrations decreased in all four wetlands confirming the process of nitrification. By looking at the nitrate concentrations in Table 1 it is evident that there is nitrification process resulting in an increase in the levels of nitrates in all four VFCW. However, some systems have high and some have low removal rates. Hua et al. [11] conducted a study and found that there is a significant relationship between substrates used in constructed wetlands and their treatment efficiency. This discrepancy may be due to difference in porosity of media and also plant roots depth and their penetration.

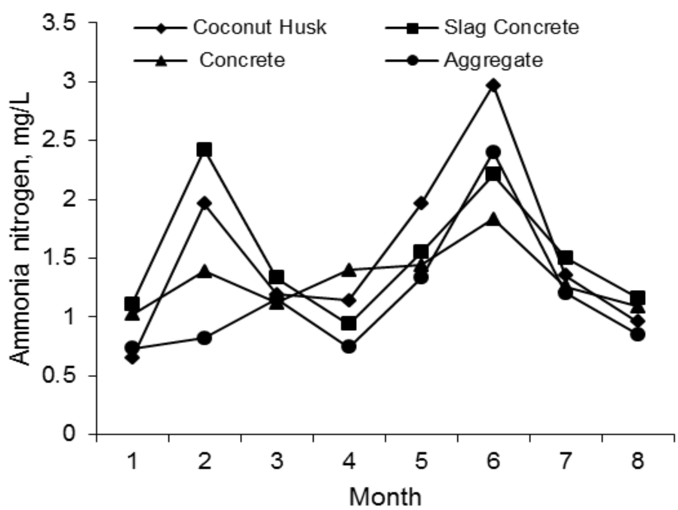

Figure 4: Effluent ammonia nitrogen concentrations for the four vertical flow constructed wetlands during the monitoring period.

The mean influent PO_4-P concentration was 5.6 mg/L while the effluent values for VFCW 1, VFCW 2, VFCW 3 and VFCW 4 were 1.86 mg/L, 2.19 mg/L, 2.04 mg/L, 2.65 mg/L, respectively. The average reduction in concentrations over the monitoring period were 67%, 61%, 64% and 53% for VFCW 1, VFCW 2, VFCW 3 and VFCW 4, respectively. In terms of removal efficiency of wetlands containing waste materials as substrates, VFCW 3 presented the highest percentage removal of orthophosphate while VFCW 2 had better performance than VFCW 4.

Major phosphorus removal in wetlands is through sorption on substrate material and plant uptake. VFCW 3 containing slag concrete substrate seems to have more sorption sites than VFCW 2 and VFCW 4 and hence greater removal of orthophosphate.

The influent fecal coliforms reported were 80 MPN/100 mL. Removal efficiencies of the four VFCW were 55%, 40%, 14% and 52% for VFCW 1, VFCW 2, VFCW 3 and VFCW 4, respectively. VFCW 4 containing coconut husk performed well and had the highest pathogen removal potential amongst the various substrates tested. Pathogen removal in wetlands is through predation, natural die-off and unreceptive conditions.

3.5 Plant growth

Plants grew well in all four VFCW. However, the growth pattern was different. Fig. 5 shows the plant height for the four vertical flow constructed wetlands during the monitoring period. In terms of plant height, following was the pattern: VFCW 1 (78.7 cm) > VFCW 4 (76.2 cm) >VFCW 2 (66.3 cm) > VFCW 3 (53.3 cm). In terms of leaves, VFCW 1 had the highest number of leaves (25) followed by VFCW 4 that had 24 leaves. VFCW 2 and VFCW 3 had 19 and 3 leaves, respectively. Flowers also blossomed in VFCW 1 and VFCW 4. Plants in constructed wetlands play an important role in transfer of oxygen through their roots and also nutrient uptake.

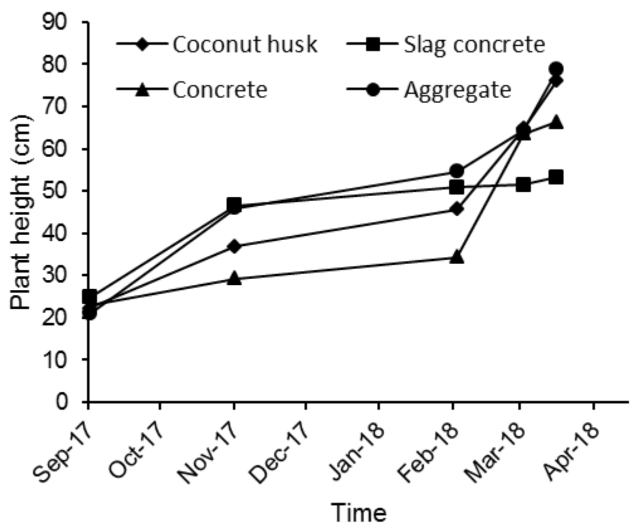

Figure 5: Plant height for the four vertical flow constructed wetlands during the monitoring period.

4 CONCLUSION

The studied vertical flow constructed wetlands containing various waste materials as substrates removed the monitored pollutants from domestic wastewater. For removal of organic matter concrete and slag concrete both can be used as substrates. For ammonia removal concrete material as a substrate showed the best performance while for phosphorus removal concrete and slag concrete both showed good removal. For pathogen removal coconut husk showed the best performance. Waste materials can be used as substitute substrates in constructed wetlands for pollutant removal.

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