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Phosphorous Removal Potential of Vertical Constructed Wetlands Filled with Different Filter Materials

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Abstract

This investigation was carried out to observe the effects of filter materials on contaminant removal efficiencies of Vertical Constructed Wetland (VCW) units. Nine real scale VCW units were operated for a period of 12 months (Jan - Dec 2016) for treating dairy wastewater. All nine VCW units were filled with different sized filter materials (gravels and sand) and were planted with *Arundo donax* at surface. The hydraulic retention time (HRT) for all the units was fixed as 24 h. The major water parameter focused in the present study was total phosphorous (TP). The findings of this study revealed that all the three filter media (10 mm & 20 mm gravels and sand) were efficient in removing phosphorus from dairy wastewater. The average concentration of TP in the dairy influent was recorded as 39.3 ± 9.8 mg L^{-1}. Average TP concentration in gravel filters (CW-1 to CW-6) were recorded in the range of 16.9 to 18.1 mg L^{-1} while in sand filters (CW-7 to CW-9), it ranged between 2.2 to 3.9 mg L^{-1}. The reduction of TP in the effluent was more in case of sand filters (2.2 ± 2.6 mg L^{-1}). The removal rate in sand filters showed noticeable reduction as compared to gravel filters. Maximum removal rate of 94.1% was also observed in sand filled units while minimum removal was seen in gravel beds (54.7 to 58.1%). Hence, the results of this investigation recommends the use of sand as the better option for TP removal and a good alternate for designing VCW in future wetland construction.

Keywords- Filter materials, Vertical Flow Constructed Wetland (VCW) Units, Phosphorous, Dairy Influent, Hydraulic Retention Time (HRT)

1. Introduction

At current scenario, water pollution is a challenging problem all over the world and supply of clean water is a major priority for many countries (Marin-Muniz et al., 2018). Waste water has proved to be harmful to humans, animals as well as environments and should be treated prior to their disposal. Vertical flow Constructed Wetlands (VCWs) have been considered as alternatives for wastewater treatment as compared to commercial wastewater treatment techniques. These systems are highly efficient and remove contaminants, provides high quality effluent and lessens the requirement of chemicals (Arias and Brix, 2003; Garcia and Hernandez, 2008). These systems are a good option for treatment because of good environmental values, low cost as well as efficient pollutant removal mechanisms (Arias and Brix, 2003). There are various designs and operational parameters taken into consideration during construction phases of VCW system. These parameters include surface area, bed depth, filter medium, dosing pattern, surface vegetation types, hydraulic loading rates, retention time (Bohorquez et al., 2016) etc. In a Constructed Wetland system, vegetation plays a major role in pollutant removal but the size and nature of filter media allows the development of supplementary sites for adsorption of contaminants and formation of biofilm (Priya et al., 2013).

Another most important factor is the hydraulic conductivity of media substrate because the HRT in CW system is greatly dependent on the hydraulic conductivity. Therefore, it is very important to maintain hydraulic conductivity in a CW system (Sundaravadivel and Vigneswaran, 2001). The major parameter affecting hydraulic conductivity is the grain size of the media (Stottmeister et al., 2003). In previous studies (Sundaravadivel and Vigneswaran, 2001), it was concluded that in CW systems, fine soil substrates have low hydraulic conductivity, while coarse sand and gravel medium have higher conductivity. Filter medium is the most important design parameter in constructing VCW system. It serves as a platform for the growth of variety of microbes and promotes sedimentation and filtration of pollutants (Li et al., 2010) and also acts as a determinant of hydraulic conductivity, retention time, pH and microbial communities (Li et al., 2010; Schwager and Boller, 1997; Huang et al., 2013). Many CW systems are filled with expensive materials like zeolite (Rios et al., 2007; Shuib et al., 2011). In developing countries including India, most regions are rural and reside in harsh conditions; thus, use of local filter materials is an affordable and sound alternative for such areas (Marin-Muniz et al., 2018).

Phosphorous (P) is one of the major water pollutant which should be necessarily removal for proper functioning of the ecosystems. It is also the main cause of eutrophication in the water bodies. Therefore, prior to discharge of the phosphorous rich wastewater into the nearby areas, it should be to properly treated for reducing phosphorous concentration at the outlets (Sharply and Tunney, 2000). P removal in sub-surface CWs is associated with physico-chemical and biological processes as well as hydrological properties of filter substrates as it is adsorbed and precipitated on the filter media surface (Grunebreg and Kern, 2000; Vohla et al., 2011). The search for an efficient and log-lasting filter media has been a matter of concern among the researchers for the last few decades and is still under concern. The major issue is of the sorption capacity of phosphorous (Johansson Westholm, 2006). Besides, good hydraulic conductivity, chemical composition of the substrate is also an important factor in designing a CW system. Since, P removal occurs by adsorption and precipitation, elements such as Ca, Fe and Al are key substances responsible for P removal. Hence, selection of filter media should be done very carefully because any filter media can get saturated after years of operation (10-15 years) even after having high P-binding capacity (Arias et al., 2001; Brix et al., 2001). In that case, there should be a separate filter unit consisting of replaceable material

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with high P-binding capacity. This may impart long-lasting properties of the CW systems (Hedstrom, 2006). The aim of the present study is to investigate the efficiency of vertical constructed wetland units filled with filter materials of different size (gravels and sand) in removing total phosphorous (TP) from dairy farm wastewater.

2. Methodology

2.1 Study Site Description

The design selected in the present study was Vertical flow Constructed wetlands as it has various advantages over other CW designs. As per previous literatures, VCW have been up-graded over the last few years and shown to attain good contaminant removal. These systems have provided better options for treating wastewater from villages, small group of houses, single houses, hotels, landfill sites, etc. The size of the VCW units was selected as per the recommendations of Cooper (2005).

The experimental site for the study consists of nine VCW units with a total area of 4 m^2 (first bed: 2.5 m^2 & second bed:1.5 m^2) and depth of each bed of 70 cm. The site is situated near Graphic Era, Clement town, Dehradun. The nine vertical flow units have been filled with different sized filter materials such as 20 mm gravels, 10 mm gravels and sand (easily available and cost effective). All the nine VCW units have surface vegetation of *Arundo donax* (Giant reed) (Figure 1 and Figure 2). CW-1, CW-2 and CW-3 was filled with 10 mm gravels, CW-4, CW-5 and CW-6 was filled with 20 mm gravels while CW-7, CW-8 and CW-9 was filled with sand. The gravel beds were covered with a 10 cm layer of crushed bricks in order to prevent excessive heating of the gravel surface during summer seasons.

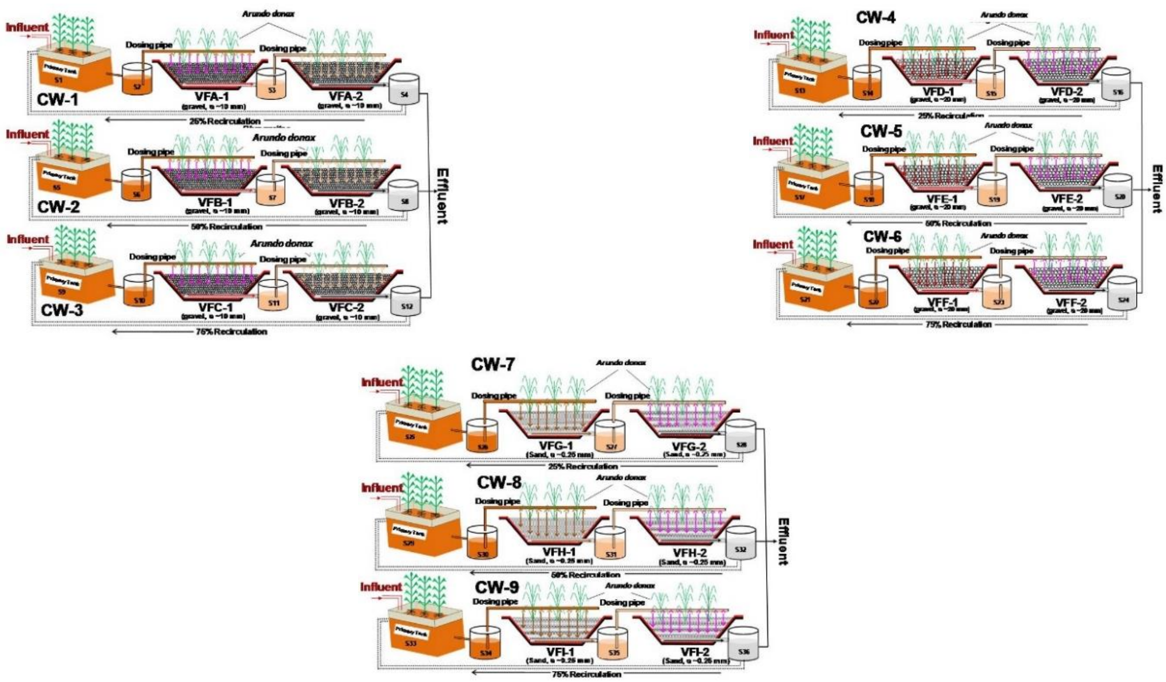

Figure 1. Design of nine vertical sub-surface flow constructed wetland units

All the nine beds (CW-1 to CW-9) were intermittently loaded with 220 liters of pre-treated dairy wastewater every day and allowed to retain inside the vertical beds for HRT of 24 hrs. Treated samples were collected in 1 L plastic bottles. Further treated water from the collecting tanks was recirculated back to their respective recirculation tanks. Soybean floating beds, prepared using bamboo stick and PVC pipes, were put in to the recirculation tanks. Recirculation pattern followed was 25% in CW-1, CW-4 and CW-7; 50% in CW-2, CW-5and CW-8while 75% in CW-3, CW-6 and CW-9 respectively (Figure 1). All the nine CW units were loaded with wastewater by same dosing pattern and sampling was done from outlets in 1 L plastic bottles (Figure 2).

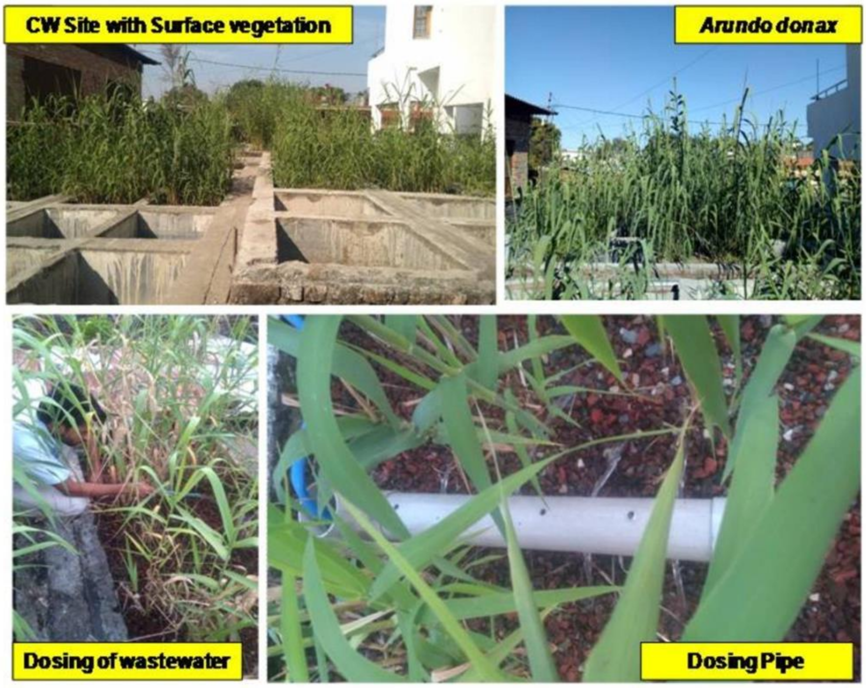

Figure 2. Pictures from the CW site Graphic Era dairy farm

2.2 Experiments

All the physical parameters were analyzed at the field during sampling. For analysis of total Phosphorous (TP), samples were brought to the laboratory and stored at 4°C and analysis was done according to the standard methods of examination of water and wastewater (APHA, 2005) and Hach manual (Table 1).

Table 1. Methods for analysis of Physical parameters (APHA, 2005 and Hach manual)

S. No.	Parameter	Type of parameter	Method of analysis
1.	pH	Physical	Multiparameter system (Hach SensION + MM150)
2.	Temperature	Physical	Multiparameter system (Hach SensION + MM150)
3.	ORP	Physical	Multiparameter system (Hach SensION + MM150)
4.	EC	Physical	Multiparameter system (Hach SensION + MM150)
5.	TDS	Physical	Multiparameter system (Hach SensION + MM150)
6.	Salinity	Physical	Multiparameter system (Hach SensION + MM150)
7.	Dissolved Oxygen (DO)	Physical	DO Meter and sensor (Hach SensION)
8.	Total Phosphorous (TP)	Chemical	Molybdovanadate method

The performance of each CW unit for each parameters was calculated using the following equations (Cui et al., 2010; Sharma et al., 2013):

$$Removal\ rate\ (\%) = (C_i - C_o) * 100/C_i \qquad (1)$$

$$Load\ (g\ m^{-2}\ day^{-1}) = [Volume\ of\ wastewater\ dosed\ (litre)*Conc.\ (mg\ L^{-1})/1000]/A\ (m^2) \qquad (2)$$

Where,
C_i = Inlet concentration (mg L^{-1}); C_o = Outlet concentration (mg L^{-1})
A= Area (m^2).

3. Results and Discussion

3.1 Effect of Filter Materials on Physical Parameters

Table 2. Characteristics of dairy farm influent and effluents in the three filter materials

		pH	EC (μ S cm^{-1})	TDS (mg L^{-1})	Salinity (mg L^{-1})	Temperature (°C)	DO (mg L^{-1})
Influent		7.9 ± 0.6	1141.1 ± 384.2	725.8 ± 232.2	565.3 ± 185.5	20.1 ± 4.6	1.7 ± 1.1
CW1	**10 mm Gravels**	8.1 ± 0.5	998.9 ± 362.0	642.5 ± 234.5	487.0 ± 178.2	21.3 ± 4.3	5.3 ± 1.6
CW2		8.1 ± 0.5	1000.2 ± 352.3	638.9 ± 229.3	482.7 ± 171.4	21.1 ± 4.5	5.6 ± 1.6
CW3		8.1 ± 0.5	1011.0 ± 345.9	647.8 ± 223.3	492.7 ± 168.2	20.9 ± 4.9	6.1 ± 1.4
CW4	**20 mm Gravels**	8.2 ± 0.6	991.1 ± 354.9	633.8 ± 225.6	486.1 ± 175.5	21.4 ± 4.5	5.6 ± 1.7
CW5		8.2 ± 0.5	976.3 ± 351.1	626.7 ± 228.5	475.8 ± 172.5	21.3 ± 4.6	5.8 ± 1.8
CW6		8.2 ± 0.5	956.1 ± 350.6	613.5 ± 225.3	461.2 ± 170.1	21.1 ± 4.6	6.0 ± 1.7
CW7	**Sand**	8.1 ± 0.4	1032.3 ± 456.8	644.1 ± 334.6	516.3 ± 262.1	20.0 ± 5.0	7.4 ± 1.0
CW8		8.1 ± 0.3	986.1 ± 463.8	601.8 ± 303.7	480.2 ± 228.3	20.2 ± 5.3	7.3 ± 1.1
CW9		8.1 ± 0.4	951.1 ± 414.9	577.9 ± 269.6	457.0 ± 201.3	20.2 ± 5.2	7.2 ± 1.1

The characteristics of dairy farm wastewater have been shown in the Table 2. All the filter medium (gravels and sand) showed good contaminant removal potential from dairy wastewater. The pH of the dairy influent varied from 6.7 to 8.6 during the experimental period. Dissolved Oxygen (DO) is the quantity of gaseous oxygen (O_2) dissolved in the water. This dissolved oxygen is utilized by the microbes for degradation of organic matter present in the wastewater. Dissolved oxygen showed an average value between 0.3 to 4.3 mg L^{-1}in the influent with an average of 1.7 mg L^{-1}. Average DO in the effluent was recorded between 5.3 to 7.4 mg L^{-1} during the study period (Table 2).

Electrical conductivity (EC) of wastewater refers to the capability of water sample to conduct electric current through it (Tchnobanoglous and Kreiti, 2002). EC of wastewater is due to the presence of ionic salts or solids. It affects the growth pattern of biological forms in the CW beds (Marin-Muniz et al., 2018). In this study, EC of the dairy influent varied between 625.0 to 1896.0 μ S cm^{-1} with average value of 1141.1 μ S cm^{-1} during the experimental period. Dairy effluent showed a decrease in the average values of EC (1032.3 to 951.1 μ S cm^{-1}) (Table 2).

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Total dissolved solids (TDS) can be defined as the amount of solid matter that remains as residue after evaporation. Solids in wastewater are generally organic or inorganic in nature. These solids may be present in dissolved or suspended form. Dissolved solids can be differentiated from suspended solids by filtration (Uwidia and Ademoroti, 2012). In the present study, the values of TDS in the influent showed fluctuation between 413.0 to 1201.0 mg L^{-1} having an average value of 725.0 mg L^{-1}. The TDS values decreased further in the effluents and recorded in the range of 648.0 to 578.0 mg L^{-1} (Table 2). All the filter (porous) media have better effects on pollutant removal and are important design parameters for future wetland constructions. The media used in the study are cost effective as compared to other porous media used in CWs such as zeolite ortezontle which has cost ranging between 100 to 300 dollars per m^3 (Marin-Muniz et al., 2016). Gravels and sand are naturally occurring, easily available and cheaper materials for use as porous medium.

3.2 Effect of Filter Materials on Removal of Total Phosphorous (TP) from Dairy Wastewater

In dairy farm influent, phosphorous (P) is present in the form of orthophosphates and discharged along with other substances in wastewater. Detergent washings also contribute to the increase of phosphorous amount in the wastewater. P removal from dairy wastewater includes various natural processes such as matrix adsorption, desorption, precipitation, plant uptake, microbial activities, fragmentation, leaching, and sedimentation (Vymazal, 2007). Among these, the major processes for P removal are precipitation and adsorption on filter media while biological assimilation and plant uptake has very minor role in P removal. Thus major role in removing P is played by filter materials (Dong Cheol Seo, 2005). Here, in the present study, the value of phosphorus in the influent was recorded to be 16.0 to 49.9 mg L^{-1} with average concentration being 39.3 ± 9.8 mg L^{-1}. There was notable decrease in the concentrations of P in all the subsequent VCW beds. In gravel filters (CW-1 to CW-6), the average concentrations ranged between 16.9 to 18.1 mg L^{-1} while the concentration showed further reduction in sand filters and values recorded were 3.9, 3.3 and 2.2 mg L^{-1} in CW-7, CW-8 and CW-9 respectively (Figure 3).

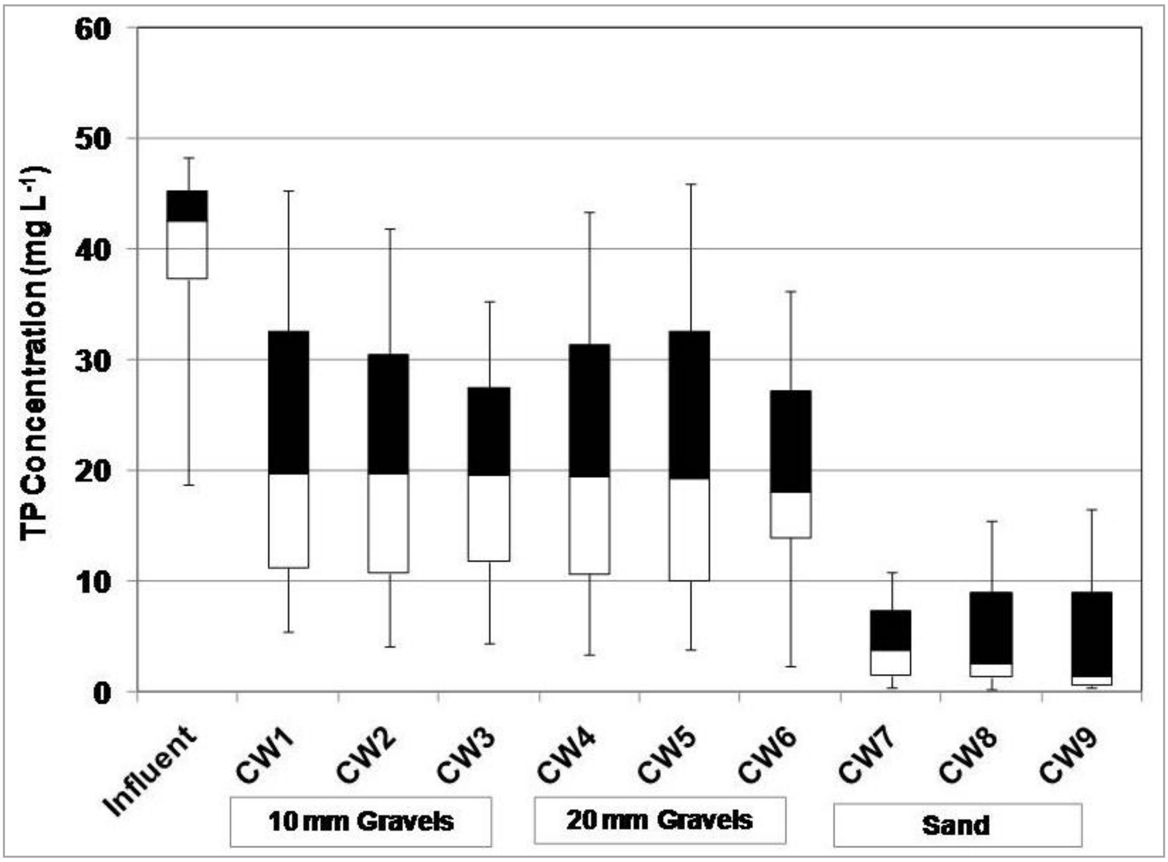

Figure 3. Box plot graphs representing average concentration of total phosphorous in dairy wastewater

Removal rates of TP also varied in the same pattern in gravel and sand filters. Sand filters showed maximum TP removal during the study period while TP removal in gravel filters was low. In gravel filled units (CW-1 to CW-6), the removal rate varied between 54.0 to 58.1% while in sand filters (CW-7, CW-8 and CW-9), the removal rate increased considerably to 90.0, 91.3 and 94.1% (Figure 4). This removal was the result of various processes of sedimentation, plant uptake, precipitation etc. In a similar work, the removal rate of 93.1% was observed in case of sand filters (Sharma et al., 2018). Some studies showed the removal efficiency of gravels filters (20 mm gravels) which was recorded in the range of 55.5 to 63% (Minakshi et al., 2018). Here, in this study, it was observed that sand filter material showed higher efficiency in removing phosphorous as it provided greater surface area for adsorption of phosphate ions as well as served as finer filtration material. Sand, due to its very fine pore size, prevented the passage of solid particles inside the bed and thus decreased the TP concentration in the treated effluent (Sharma et al., 2018). But if we further go for using more finer filter media, that can lead to clogging of the VCW beds. Some part of P is removed after dosing of wastewater on the VCW bed surface due to sedimentation of solid particles while some gets precipitated as calcium phosphates on the cations (Ca^{2+}, Al^{2+}, Fe^{2+}) attached on the filter media surface. Filter media such as sand and gravels have high binding capacity and are responsible for precipitation and attachment of phosphorous. This leads to reduction in the phosphorous concentration in the dairy wastewater. Plant uptake also plays role in TP removal by capturing nutrients and utilizing for their own growth. This phosphorous gets attached to the filter media surface, is absorbed by the roots of the plant (*Arundo donax*). This reed plant utilizes the absorbed phosphorus for its growth (Sharma et al., 2018).

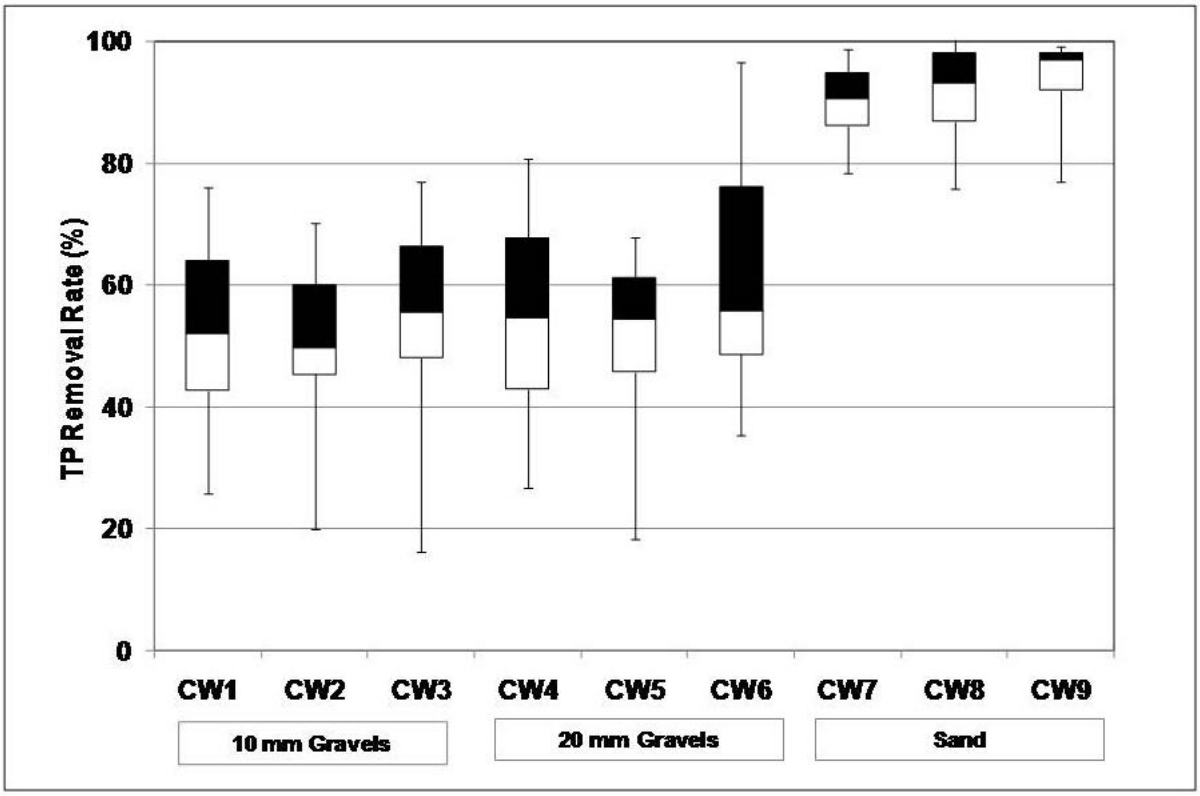

Figure 4. Box plot graphs showing average removal rate of total Phosphorus from dairy wastewater

The influent load in dairy wastewater ranged between 0.9 to 2.7 g m-2 d^{-1} with average being 2.2 ± 0.6 g m^{-2} d^{-1}. The average TP load in dairy effluent fluctuated between 0.1 to 1.0 g m^{-2} d^{-1}. Noticeable decrease in the phosphorous load was observed in the effluent in all the three filters. Minimum TP load of 0.2, 0.2 and 0.1 g m^{-2} d^{-1} was recorded in sand filters (CW-7, CW-8 and CW-9) respectively (Figure 5)

The results from all three filters showed good removal of phosphorous from dairy wastewater as the contents retained in the uppermost part of the media layers. In a previous study, it was stated that because of good growth of biological organisms in the upper layers of the filters and thus the contaminants are removed by the filter as the pore sizes fits (Knowles et al., 2011; Egemose, 2018). In sand and gravel filters, P remains bound to the media surface as a result of precipitation and adsorption with Ca^{2+}, Al^{2+} and Fe^{2+}. Removal of TP is also affected by change in pH levels. At high pH, a combination of adsorption to Al^{2+} and Fe^{2+} and precipitation as soluble calcium phosphate occurs while at low pH, precipitation takes place

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in the form of iron and aluminium phosphates. Hence, removal of TP by using different filter media is greatly dependent on presence of these minerals (Vohla et al., 2011).

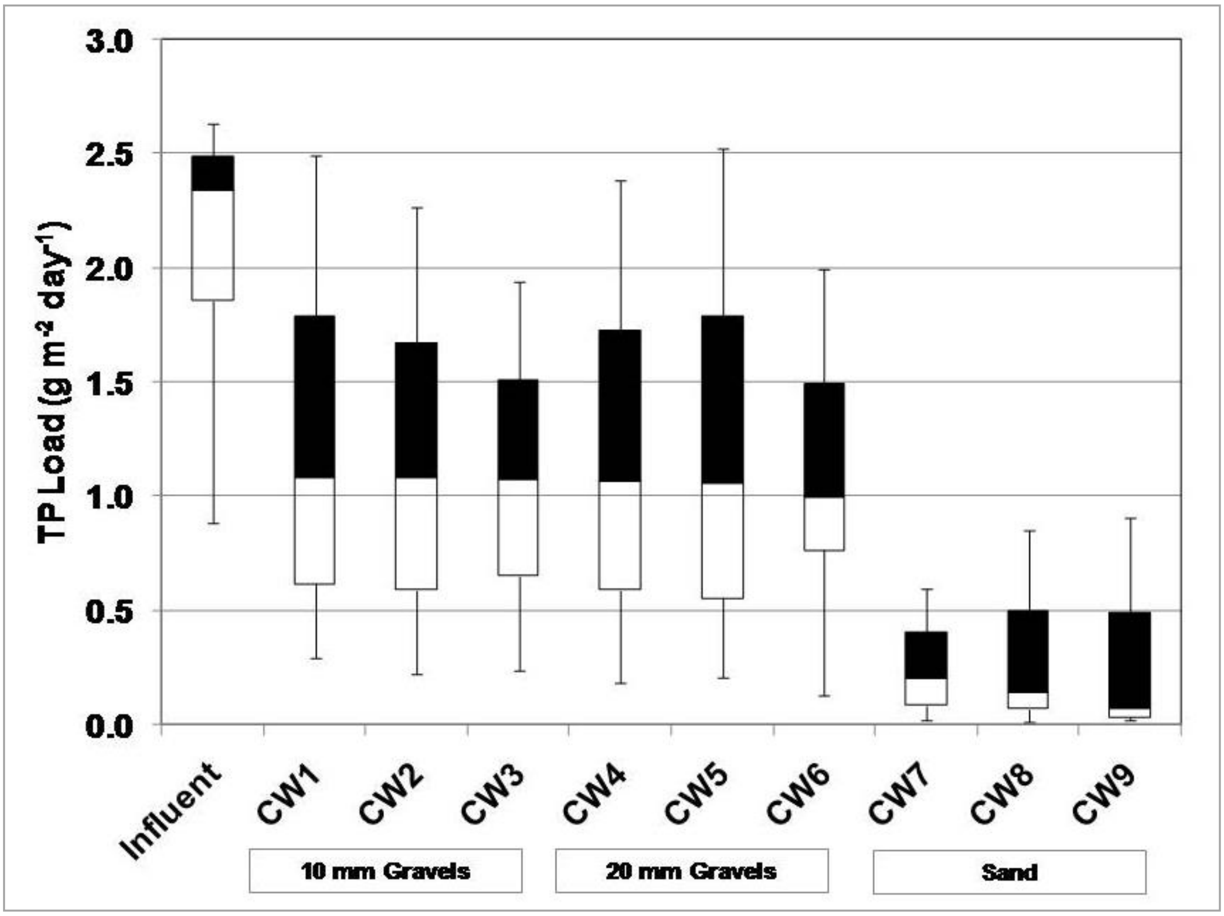

Figure 5. Box plot graphs showing average total Phosphorus load in dairy wastewater

4. Conclusion

All the VCW units showed good pollutant removal potential during the experimental period. There was a noticeable reduction in the average concentration of TP in all the CW units. The recorded average concentrations of TP in the influent was 39.3 ± 9.8 mg L^{-1}. Due to various phosphorous removal mechanisms (physical, chemical and biological) that occurs inside the VF beds, there was reduction in the levels of phosphorous in the treated dairy water. According to this study, it can be recommended that sand can serve to be the best filter media for P removal for constructing VCW units in future. The final effluent released from the VCW can be discharged without any risk into the water and land bodies as it contains no harmful contaminants. The treated effluent can also be reused in dairy premises for cattle bath, floor washings as well as for irrigation in horticulture and agricultural fields.

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