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Evaluation of Sewage Treatment Efficiency of a Two-Stage Floating-Wetland System

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Abstract: Floating Treatment Wetlands (FTW) is a novel technology in wastewater treatment where emergent macrophytes are supported by a floating mat on the water surface. A small-scale two-stage FTW was designed and commissioned in April 2019 to treat sewage influent of the Kibendera Waste Stabilization Ponds (WSP), Ruiru, Kenya. The study evaluated the system's sewage treatment efficiency over a 6-month period (May-October 2019). The system operating under a constant inflow rate of $1.75m^3$/day was operated under aerobic (1^{st} stage) and anoxic conditions (2^{nd} stage). Highest mean monthly influent concentrations of 61.8mg/L, 544mg/L, 681mg/L, 72mg/L, 22.5mg/L and 0.12 mg/L were recorded for Total Phosphorus (TP), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), Ammonia, Nitrate and Nitrite respectively. Sedimentation, nitrification-denitrification, aerobic bacterial breakdown of organic matter, nutrients uptake by plants, entrapment of suspended solids by plant roots and adsorption onto filter media were responsible for wastewater treatment. Optimum treatment efficiencies of 69.9%, 84.3%, 94%, 80.1%, 91% and 80.3% for TP, COD, TSS, ammonia, nitrate and nitrite were recorded in August 2019. During this period, effluent TSS (27mg/L), ammonia (8mg/L), nitrate (0.6mg/L) and nitrite (0.012mg/L) concentrations conformed to NEMA's effluent guideline values. However, COD and TP concentrations of 85 mg/L and 11.6 mg/L respectively observed over the period failed to meet the local effluent standards. The study recommends further studies to investigate the adsorption capacities of other locally available materials for use as filter media to enhance organic matter and phosphorus removal. Based on the significant results reported, large-scale implementation of the technology in the WSP would realize a higher quality effluent.

Keywords: Floating Wetlands, Sewage Treatment Efficiency, Filter Media, Nitrification-Denitrification, Adsorption

1. Introduction

Wastewater management plays an important role in cushioning communities against water pollution effects like water-borne diseases and environmental degradation. Previous studies conducted in Kenya have revealed that where adequate wastewater treatment infrastructure is unavailable, most of the industrial, agricultural run-off and municipal wastewater is directly discharged into existing water bodies such as the Nairobi and Ngong rivers leading to elevated levels of chemical and biological oxygen demand, and turbidity [1, 2]. Based on a previous study, Kenya had a 17% national total sewerage coverage [3]. A later study in 2018 reported that sewage in Kenya was treated by 27 waste stabilization ponds (WSP), 10 constructed wetlands, 3 oxidation ditches, 6 activated sludge plants and 3 aerated lagoons [4].

The use of constructed wetland (CW) technology for both domestic and industrial wastewater treatment is gaining popularity due to its low-capital and maintenance costs. The technology is a system comprising of plants (macrophytes) planted in a porous media (sand or gravel). Pollutants removal in the wastewater is mainly by microbial action, plant uptake and adsorption/absorption by the media [5]. CWs are categorized as either Horizontal Subsurface Flow Constructed Wetlands (HSSF-CWs) or Vertical Subsurface Flow Constructed Wetlands (VSSF-CWs) based on the direction of flow of the wastewater through the media. Past research has indicated that Horizontal Subsurface Flow Constructed Wetlands (HSSF-CWs) are the most commonly used for wastewater treatment in Kenya [6-8].

Despite their gaining popularity and use, the rooted macrophytes in CWs can only tolerate relatively shallow water depths (commonly <0.5m over long periods) and short periods of total submergence [9]. This therefore renders the technology inappropriate in deep-wastewater environments. In addition, low nitrogen removal in HSSF-CWs has been observed [5, 8, 10]. To overcome the limited oxygen transfer in these systems, several researchers have combined HSSF-CWs with VSSF-CWs [11, 12]. This is because the latter provide better conditions for nitrification due to the oxidative conditions that occur within them [13, 14]. Moreover, quantifying the role played by the plants and filter media in the overall treatment process is difficult as both act as a unit. Developing improved CW systems that can treat deep wastewaters while clearly differentiating the wastewater treatment functions of the macrophytes and filter media is vital.

Emergent macrophyte Floating Treatment Wetlands (FTWs) is a novel treatment technology that provides unobstructed environment for elongation of plant roots [15]. The difference between the technology and conventional CWs is that macrophytes grow in a floating mat on the surface of the water rather than in media at the base of the wetland [16]. Roots in FTWs hang beneath the floating mat to provide an extensive surface area for attached biofilm growth and entrapment of fine suspended particulates [17]. In addition, roots are forced to acquire their nutrition directly from the water column hence enhanced rates of nutrient and element uptake into biomass [9].

Despite these potential advantages, studies investigating the potential efficiency of these systems in treating both domestic and industrial sewage in Kenya are limited and not scientifically documented. In view of this, a FTW-based two-stage system was designed incorporating two separate sub-systems: plant sub-system and filter media subsystem. Considering the low sewerage coverage in Kenya, the sewage treatment performance of the FTW system would provide a basis for possible largescale adoption of the technology. This would serve as an affordable decentralized sewage treatment option for households not connected to existing sewerage infrastructure.

This study aimed at evaluating the 6-month (May-October 2019) sewage treatment efficiency of a designed, small-scale two-stage floating-wetland system, treating sewage influent of the Kibendera waste stabilization ponds, in Ruiru, Kenya.

2. Materials and Methods

2.1. System Description

The system was installed at the intake works of the Kibendera Waste Stabilization Ponds (0.5^0N latitude and 37^0E longitude) in April 2019 and sewage allowed to flow through it for one acclimatization month before sampling began. A schematic of the system is shown in Figure 1. A $0.5m^3$ sedimentation tank received the influent through a submersible solar-powered water pump at an average flow rate of $1.75m^3$/day. Two-stage configuration was achieved by two $0.25m^3$ plastic reactors (*Tank 1* and *Tank 2*) connected using a 1-inch diameter PVC pipe. Whereas the solar-powered air compressor in *Tank 1* provided aerobic conditions, no external air supply was provided in *Tank 2* hence maintaining anoxic conditions. Young cattail plants (*Typha latifolia*) with an average stem and rhizome length of 25cm collected from the surrounding natural marshes were transplanted, washed properly for the removal of soil and debris attached to them, and finally planted (plant density of 20 cattails/m^2) in the prefabricated substrate-free columns on the same day (Figure 2a). Flooding of the beds with wastewater for acclimatization purposes then followed. The soil-free tubular blocks provided an environment for hydroponic and unobstructed elongation of the roots, hence increasing the root surface area for biofilm formation hence enhanced microbial degradation. 20 kg of ballast (size of 8-16mm) and 20 kg of river sand (size of 0.1-0.4mm) were placed in the inner columns of the tanks to act as filter media. The ballast column (with a height of 0.4m) was placed at the base followed by an overlying sand column with a height of 0.4 m.

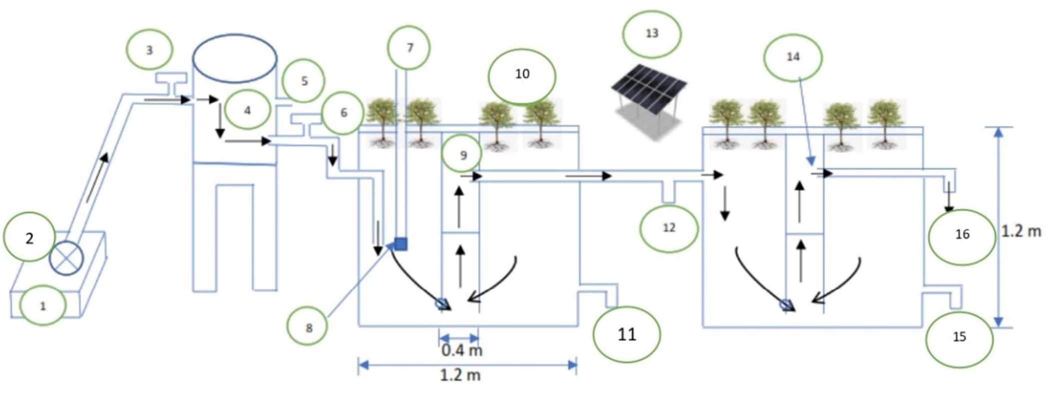

Figure 1. *The FTW System. (1) Inlet, S_1 (2) Submersible pump (3) Flow meter (4) Sedimentation Tank (5) Tank Overflow (6) Sedimentation tank's sampling point, S_2 (7) Aerator (8) Plant Tank 1 (9) Filter Column 1 (10) Cattails (11) Plant Tank 1 sampling point, S_3 (12) Filter Column sampling point, S_4 (13) Solar power system (14) Filter Column 2 (15) Plant Tank 2 Sampling point S_5 (16) Effluent's Sampling point, S_6.*

(a) (b) (c) (d)

Figure 2. *(a) Tank with prefabricated tubular blocks for plant support and filter column (b) Connected tanks before introduction of plants and filter (c) Typha latifolia planted in Tank 1 (d) Complete FTW system.*

2.2. Wastewater Sampling and Analysis

Triplicate wastewater samples were collected daily at 8.00 a.m, 12 noon and 4 pm in order to cater for daily load variations. The six (6) sampling points were the Inlet (S_1), Sedimentation tank (S_2), Plants Tank 1 (S_3), Filter Column 1 (S_4), Plants Tank 2 (S_5) and outlet of the system (S_6). Standard Methods for the Examination of Water and Wastewater procedures were used to analyze the concentrations for COD, total suspended solids (TSS), Inorganic Nitrogen (Ammonia, Nitrates and Nitrites) and Total Phosphorus [18]. Mean monthly data for the study was obtained from the daily data collected. Effluent concentrations were compared with the National Environmental Management Authority (NEMA) standards for compliance.

2.3. Flow Rates and Hydraulic Retention Time (HRT)

The sewage inflow rate (Q_{in}) and outflow rates (Q_{out}) of the FTW system were measured using flow rate meters. Table 1 summarizes the inflow and outflow rates as well as the computed hydraulic retention time (Equation 1):

$$HRT = \frac{V(S_t)+V(t_1)+V(t_2)}{Q_{in}} \quad (1)$$

Where HRT = Hydraulic Retention Time, hours
$V(S_t)$ = Volume of the sedimentation tank, m^3
$V(t_1)$ = Volume of Tank 1, m^3
$V(t_2)$ = Volume of Tank 2, m^3
Q_{in} = inflow rate, m^3/day

2.4. Determination of Treatment Efficiency

The overall system efficiency was obtained using Equation 2 calculated as:

$$System\ Treatment\ Efficiency\ (\%) = \frac{Influent(S_1)-Effluent(S_6)}{Influent(S_1)} \times 100 \quad (2)$$

Where;
Influent (S_1) = Influent concentration of the analyzed parameters.
Effluent (S_6) = Effluent concentration of the analyzed parameters.

3. Results and Discussion

3.1. Flow Rates and Hydraulic Retention Time

Table 1. *Flow Rates and Hydraulic Retention Time.*

Month	(Q_{in}) (m^3/day)	V (S_t) m^3	V (t_1) m^3	V (t_2) (m^3)	(Q_{out}) (m^3/day)	HRT (Hours)
May	1.75	0.5	0.25	0.25	1.72	13.7
June	1.75	0.5	0.25	0.25	1.70	13.7
July	1.75	0.5	0.25	0.25	1.68	13.7
August	1.75	0.5	0.25	0.25	1.56	13.7
September	1.75	0.5	0.25	0.25	1.52	13.7
October	1.75	0.5	0.25	0.25	1.50	13.7

Based on Equation 1, a HRT of 13.7 hours was maintained throughout the study period. A declining outflow rate was observed over the months as shown in the Table 1. This was attributed to consumptive water use by the plants vital for plant growth and evapotranspiration losses from the tanks. Table 2 summarizes the mean monthly weather data obtained from the Kenya Meteorological Department for a nearby station (Thika Agromet Station ID 9137048).

Table 2. *Estimated Meteorological data for Ruiru (May-Oct 2019).*

Month	Mean Air Temp (°C)	Evaporation (mm)	Rainfall (mm)
May	21.7	3.6	27.8
June	19.6	3.1	60.1
July	17.0	2.8	3.2
August	18.6	3.1	31.9
September	20.4	4.1	17.3
October	21.8	5.23	312

3.2. Sewage Concentrations and Removal Efficiencies

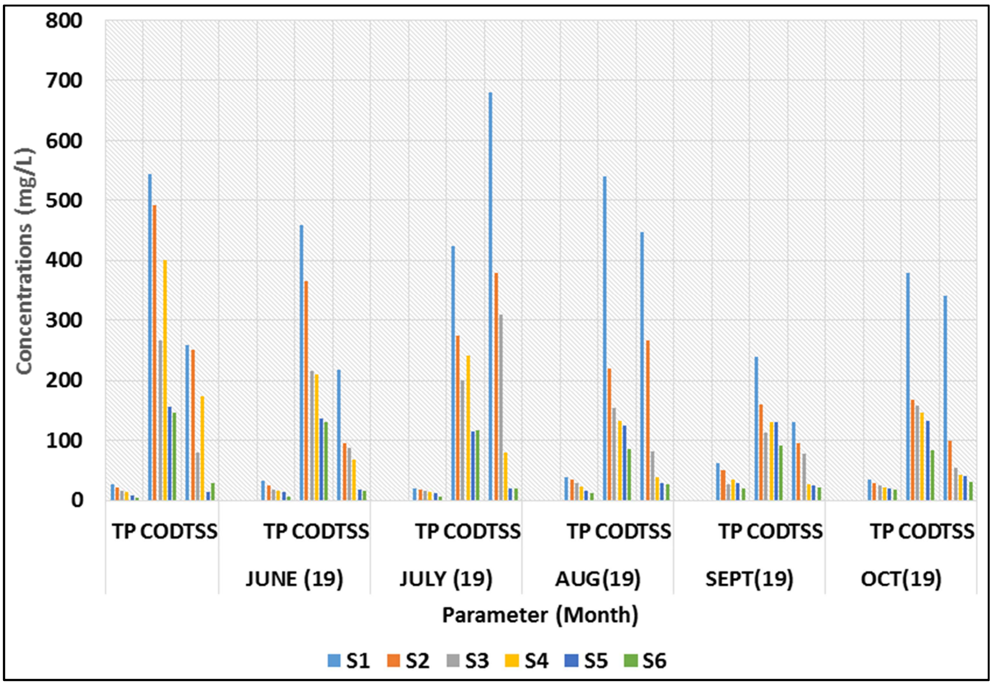

Figure 3. *COD, TSS and TP concentrations at various sampling sites.*

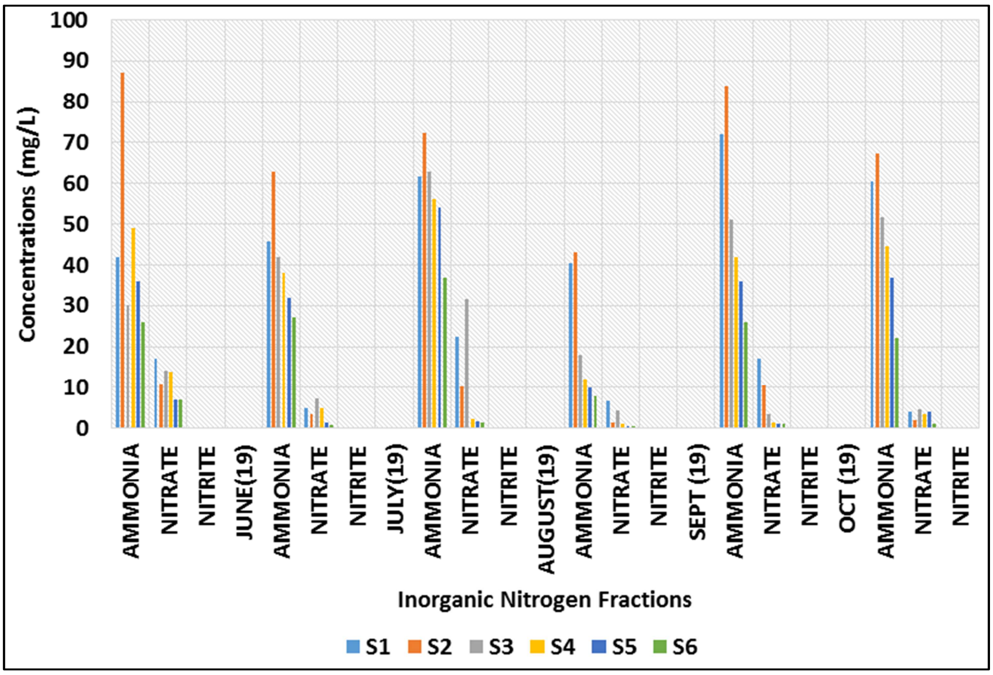

Figure 4. *Inorganic Nitrogen concentrations at various sampling sites.*

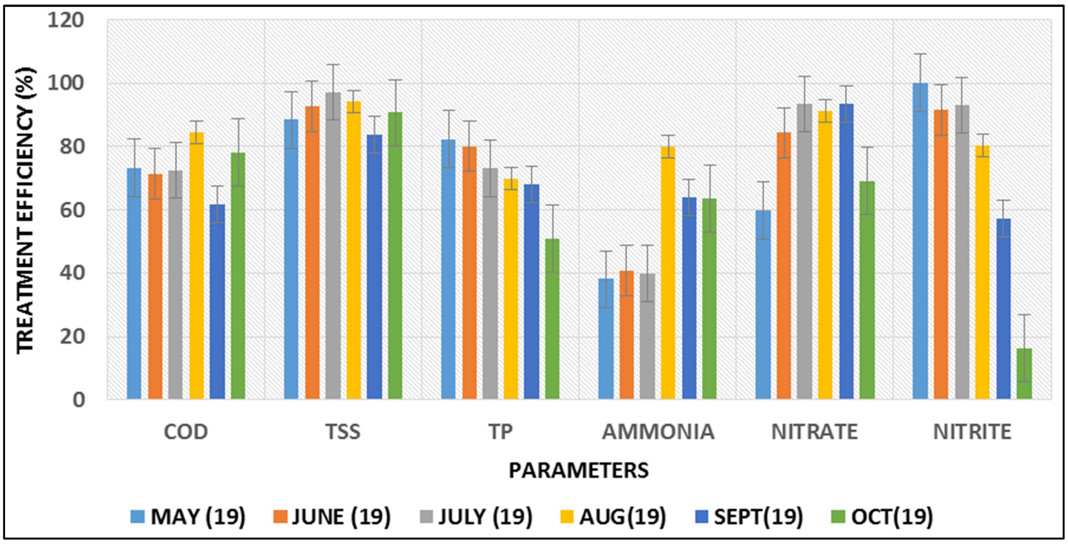

Figure 5. *System's Treatment Efficiencies.*

Based on Figure 3, highest mean monthly influent concentrations of 61.8mg/L (Sept 2019), 544mg/L (May 2019), 681mg/L (July 2019) for Total Phosphorus (TP), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS) were recorded. The corresponding Ammonia, Nitrate and Nitrite concentration values were 72mg/L (Sept 2019), 22.5mg/L (July 2019) and 0.12 mg/L (May 2019) respectively (Figure 4).

Least effluent concentrations of 16mg/L (June 2019), 83mg/L (October 2019), 4.7mg/L (May 2019) were observed for TP, COD and TSS respectively (Figure 3). The corresponding Ammonia, Nitrate and Nitrite concentration values were 8mg/L (Aug 2019), 22.5mg/L (Aug 2019) and 0 mg/L (May 2019) respectively (Figure 4). However, August 2019 realized optimum effluent concentrations for all parameters studied (Table 3).

Highest treatment efficiencies of 84.3% (Aug 2019), 97.1% (July 2019), 82.3% (May 2019), 80.1% (Aug 2019), 93.5% (Sept 2019) and 100% (May 2019) were recorded for COD, TSS, TP, Ammonia, Nitrate and Nitrite respectively (Figure 5). Previous studies in different FTW systems have reported treatment efficiencies of 53-90% for COD, 22-78% for TSS, 20-37% for TP [19-22]. The high treatment efficiency for TP (80.1%) in this study is attributed to presence of filter media that provided adsorption sites for TP removal [23-25]. The results for nitrate and ammonia reported in this study were consistent with those from previous studies, which reported treatment efficiencies of 34.6-96.8% for nitrate and 16.7-70% for ammonia [19, 21, 26].

Table 3. *Optimum effluent concentrations in August 2019.*

Parameter	Effluent Concentration (mg/L)	NEMA Guideline Value (mg/L)
COD	85	50
Inorganic Nitrogen	8.61*	100
TP	11.6	2
TSS	27	30

* Nitrate (0.6) +Nitrite (0.01) +Ammonia (8)

The effluent concentrations from the system were compared with the NEMA guideline values for compliance. Based on the study, highest effluent quality was observed in August 2019. Table 3 summarizes the various effluent concentrations recorded during the period. Failure of the system to realize NEMA-compliant COD and TP effluent was attributed to low adsorption capacities of the filter media used and relatively shorter HRT. In addition, continuous pollutant loading on the filter media may result in pollutant-saturated sites hence reduced phosphorus adsorption/removal over time [23-25].

3.3. System's Treatment Mechanisms

3.3.1. Sedimentation

Sedimentation in the sedimentation tank contributed to significant reduction of TSS (2.7-70.7%), TP (8.8-19.9%) and COD (18.6-40.8%). The presence of particulate phosphorus that settled down with the suspended solids may have contributed to reduced TP concentrations [25]. The presence of particulate COD in suspended solids in wastewater has also been reported [26]. TSS, TP and COD concentrations reduction observed in the sedimentation tank through settling of solids was obvious [27]. Low water velocity in the tanks enhanced settling of solids hence reduced TSS load [28]. Although this observation was not made in this study, TSS production may occur in the wetland due to the death of microbes, fragmentation, detritus from plants, and formation of chemical precipitates [29]. Biological oxygen demand (BOD) removal in wetlands is due to physical and biological processes that involve sedimentation and microbial degradation, principally by aerobic bacteria attached to plant roots.

3.3.2. Nitrification-Denitrification

The presence of anaerobic, aerobic and anoxic conditions in the sedimentation tank, aerobic tank and anoxic tank respectively contributed to ammonia, nitrate and nitrite removal. Increase in ammonia concentrations (6.7-94.93%) and reduction in nitrate concentrations (29.4-51.2%) and nitrite concentrations (16.7-46.5%) in the sedimentation tank was primarily due to transformation of nitrite/nitrate to ammonia due to anaerobic conditions. However in Tank 1, aerobic conditions favored the nitrification process hence reduced ammonia concentrations but increase in nitrate concentrations. The anoxic conditions provided in Tank 2 favored the denitrification process hence the reduced ammonia, nitrate and nitrite concentrations in the effluent. *Nitrosomanas* and *Nitrobacter* bacteria were responsible in converting ammonia to nitrate (nitrification) as summarized by the chemical reaction represented by Equation 3. On the other hand, denitrification represented by Equation 4 was responsible for nitrate and nitrite removal [30, 31].

$$NH_4 + 2O_2 \rightarrow NO_3 + 2H + H_2O \quad (3)$$

$$2NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O \quad (4)$$

More than half of the nitrogen content of municipal wastewater is found to be in the form of ammonia and organic nitrogen. The conversion of organic nitrogen to ammonia in the wetland by the process of decomposition and mineralization precedes biological nitrification-denitrification in wetlands [32].

Nitrification rate is the limiting factor controlling nitrogen removal via the nitrification and denitrification processes [33]. Nitrifying bacteria, which are slow growing and have a high oxygen requirement, develop in the aerobic zones and convert ammonium to nitrate. On the other hand, the role of the denitrifying bacteria was to convert nitrate to nitrogen gas [34, 35]. In addition, low oxygen and high carbon concentrations derived from the influent sewage limits the nitrification process hence poor nitrogen removal.

3.3.3. Mechanical Entrapment of Suspended Solids by the Roots

The growing root sub-system in both stages acted as a physical filter for total suspended solids (TSS) as has been found out in research involving the use of FTW [9, 36]. The unobstructed root growth in the system provided higher surface area for the entrapment of suspended solids hence the high TSS removal efficiencies recorded [17].

3.3.4. Role of Plants in Nutrients Uptake and Translocation of Oxygen

The aerobic zones around the plant roots provided sites for microbial degradation and uptake of the pollutants by the plants. Nitrogen, ammonia-N and phosphorus removal through plant uptake has been reported [9, 37, 38]. In addition, the large root surface area has been associated with high microbial activity in organic matter degradation [19]. Studies comparing the performance of CW cells and non-planted cells have reported better results for cells planted with *Typha latifolia* [39, 40]. Other studies have also confirmed that vegetated CW demonstrate high BOD_5 reduction efficiency in comparison to non-vegetated ones [41-43]. The role of the CW plants in the translocation of oxygen from the upper parts of the plants to the roots was also observed in these studies.

3.3.5. Adsorption onto Filter Media

Several studies have reported significant phosphorus removal by various substrates [23, 24]. In this study, highest TP removal was observed in May 2019 (82.3%). However, the removal efficiency progressively declined over time to realize the least efficiency (50.9%) in October 2019 (Figure 4). The declining phosphorus removal was attributed to the fact that the filter media played a role as the main sink for phosphorus [44, 45] as well as high phosphorus levels (19.3-61.8 mg/L) in the influent [46]. Formation of biofilm over the filter media also supported the removal of TSS through adsorption of colloidal and soluble compounds [31, 47]. Several studies involving the use of sand and gravel as the filter media reported a weak phosphorus removal potential of 20-30% in the long term [48-51]. Although the phosphorus sorption efficiency was not investigated in this study, previous studies revealed sand sorption efficiency ranging from 0.13 g kg^{-1} to 0.44 g kg^{-1} [25, 52, 53]. The sorption efficiency of gravel ranged between 0.03 g kg^{-1} to 0.05 g kg^{-1} [25, 54].

4. Conclusion

The 6-month (May-October 2019) sewage treatment efficiency of a small scale two-stage FTW system was evaluated. The system operating under a constant flow rate of 1.75 m^3/day realized optimum removal efficiencies of 69.9%, 84.3%, 94%, 80.1%, 91% and 80.3% for TP, COD, TSS, ammonia, nitrate and nitrite respectively in August 2019. Highest quality effluent obtained during this period conformed to NEMA effluent guideline values for ammonia (8 mg/L), nitrate (0.6 mg/L), nitrite (0.012 mg/L) and TSS (27 mg/L). However, the effluent COD (85 mg/L) and TP (11.6 mg/L) during this period failed to meet the NEMA standards. Considering the NEMA guideline values of 100 mg/L and 30 mg/L for inorganic nitrogen and TSS respectively, the effluent concentrations for these parameters remained NEMA-compliant throughout the study period. The non-compliance of COD and TP effluent concentrations was attributed to low adsorption capacity of the filter media and relatively short HRT. Studies aimed at obtaining optimum HRT for locally available and industrial high-adsorption filter media are recommended. Large-scale adoption of the technology in the WSP would combine the processes of sedimentation, nitrification-denitrification, plant-algal uptake of nutrients, entrapment of suspended solids by the plant roots to realize NEMA-compliant effluent.

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