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Effectiveness of the Horizontal, Vertical and Hybrid Subsurface Flow Constructed Wetland Systems in Polishing Municipal Wastewater

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Abstract

This study aimed at comparing the performance of horizontal, vertical and hybrid subsurface flow system in polishing wastewater effluent from the maturation pond at Gusii wastewater treatment plant, Kenya. The treatments were monitored for six weeks duration for chemical oxygen demand, total suspended solids, total nitrogen and total phosphorous against Kenya's National Environmental Management Authority standards for effluent discharge. Among the systems planted with Vetiver grass, the hybrid subsurface flow system significantly removed the pollutants more efficiently than the single operated systems. The Vetiver planted hybrid subsurface flow wetland systems achieved the highest removal of COD, TN, TP and TSS at 82.4, 87.9, 65 and 94.6%, respectively as compared to other wetland systems. The planted vertical subsurface flow removed COD, TN and TP at 72.9, 75.7, and 50.7%, respectively more efficiently than the horizontal subsurface flow system that achieved removal of COD, TN and TP at 65.3, 70.0 and 43.8%, respectively. The planted horizontal subsurface flow wetland however showed better TSS removal at 89.9% compared to 83.2% achieved by vertical subsurface flow system. The unplanted systems exhibited a similar trend whereby the hybrid subsurface flow systems achieved better performance than the single systems though with significantly ($P \leq 0.05$) lower organics and nutrients removal efficiencies compared to the planted systems.

Keywords: Chemical oxygen demand, Constructed wetlands, Horizontal flow, Total nitrogen, Total phosphorous, Total suspended solids, Vertical flow, Vetiver grass

1. Introduction

Demand for fresh water resources is expected to rise with the growing global population yet this precious resource is under constant threat of pollution. Although there are natural causes, much of the eutrophication seen currently is a result of inadequate treated wastewater and agricultural run-off that end up in receiving water bodies (Hawkins et al., 2013). Adequate treatment of wastewater for reuse will therefore be a viable option in ameliorating the challenge of water scarcity and environmental degradation. Many industries in developing countries use conventional wastewater treatment systems to treat their wastewater before release into the environment (Konnerup et al., 2011; Zhang et al., 2014). However, these conventional treatment technologies have been found to be either ineffective, wasteful and costly (Nhapi, 2004). In Kenya, the National Environment Management Authority (NEMA) has set guidelines on the permissible effluent discharge limits into the environment and these standards are rarely met by the conventional treatment methods used. Adoption of low cost and effective technologies such as phyto-remediation will therefore be a suitable option for many industries and households involved in wastewater treatment.

Constructed wetlands are considered to be the best choice to treat wastewater since they are economical and effective in pollutants removal (William, 1999; Mthembu et al., 2013). Vegetation plays a critical role in the performance of constructed wetlands and hence selection of the most efficient vegetation type is important. The vegetation not only absorb pollutants from wastewater but their roots prevent wastewater from taking preferential paths in the substrate that can result to hydraulic short circuiting which would consequently reduce the retention time in the wetlands (Stottmeisteret al., 2003; Sehar et al., 2015). The roots also provide a large surface area for attachment of micro-organisms that degrade the organics in the wastewater (Wu et al., 2014; Yuan et al., 2016). The use of aquatic plants is thus becoming increasingly common in wastewater management as it integrates treatment, recycling and re-uses (Lishenga et al., 2015).

Vetiver grass (*Chrysopogon zizanioides)* for wastewater treatment has gained wider acceptance due to its ability to thrive in unfavourable environments. Vetiver grass can tolerate a wide range of pH, salinity, sodicity, acidity and heavy metals (Vimala & Kataria, 2005; Raude et al., 2009). In many cases, Vetiver grass has been used to clean up many kinds of pollutants including metals, pesticides, oils and organic contaminants from wastewater (Minh et al., 2015; Kamtekar & Verma, 2016). According to US EPA (2012), Vetiver grass eliminates several kinds of pollutants by completely destroying or converting them to carbon dioxide and water rather than simply immobilizing or storing them.

2. Material and Methods

2.1 Study Site Description

Gusii wastewater treatment plant is located in Kisii town; Suneka Division in Kisii County, Kenya at latitude 0° 39' 30” S and longitude 34° 42' 30” E. Kisii County is characterized by hilly topography and is endowed with several permanent rivers draining into Lake Victoria (Jaetzold et al., 2009; Wamalwa et al., 2016). Natural vegetation cover in the study area is low since 90% of the total area is under cultivation (GoK, 2009; Jaetzold et al., 2009).The area has a highland equatorial climate resulting into bimodal rainfall pattern with the long rains occurring between February and June, and short rains between September and December. The area receives a mean annual rainfall of 1500mm (Wamalwa et al., 2016). The month of January and July are generally dry and the maximum temperatures range between 21 to 30 ℃, while the minimum are between 15 to 20 ℃ (Jaetzold et al., 2009). Figure 1 shows the location of the study area.

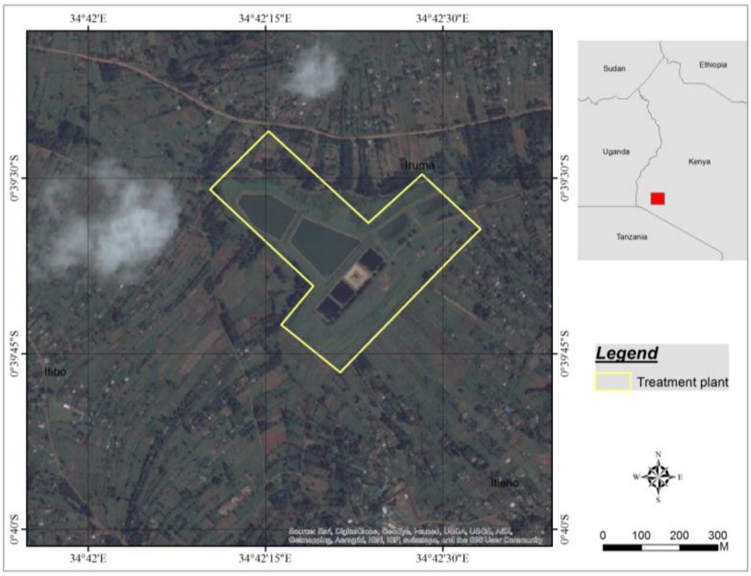

Figure 1. Location of the study area

2.2 Experimental Design and Layout

The treatments consisted of horizontal, vertical and hybrid subsurface flow wetland system either planted or not with Vetiver grass with each treatment replicated four times. Similar number of wetland systems were also set-up to act as controls (unplanted). The horizontal subsurface flow wetland had a length of 3.2m, width of 0.8m and depth of 0.3m. The vertical subsurface flow wetland had a length of 3.2m, width of 0.8m and depth of 0.4m. The first stage of the hybrid system consisted of vertical flow system having length of 3.2m, width of 0.8m and depth of 0.4m and the second stage was a horizontal flow system of length 3.2m, width of 0.8m and depth of 0.3m. The wetland units were lined with high density polythene 0.3mm thick filled with coarse river sand with a porosity of 34.3% and silt content of 9.9% as substrate. The constructed wetland units were planted with Vetiver grass at a spacing of 10cm within rows and 15cm between rows in all the wetland units. The horizontal subsurface system was operated on a continuous basis with wastewater flow rate of $0.036m^3d^{-1}$ while the vertical system was operated with two batches per day each constituting $0.018m^3$ of wastewater and evenly spread over the surface of the vertical subsurface flow wetland units through perforated pipes of 6mm in diameter spaced at 80mm. The flow rates at the inlets of the wetland systems were determined using a measuring cylinder and a stop watch as shown in Figure 2.

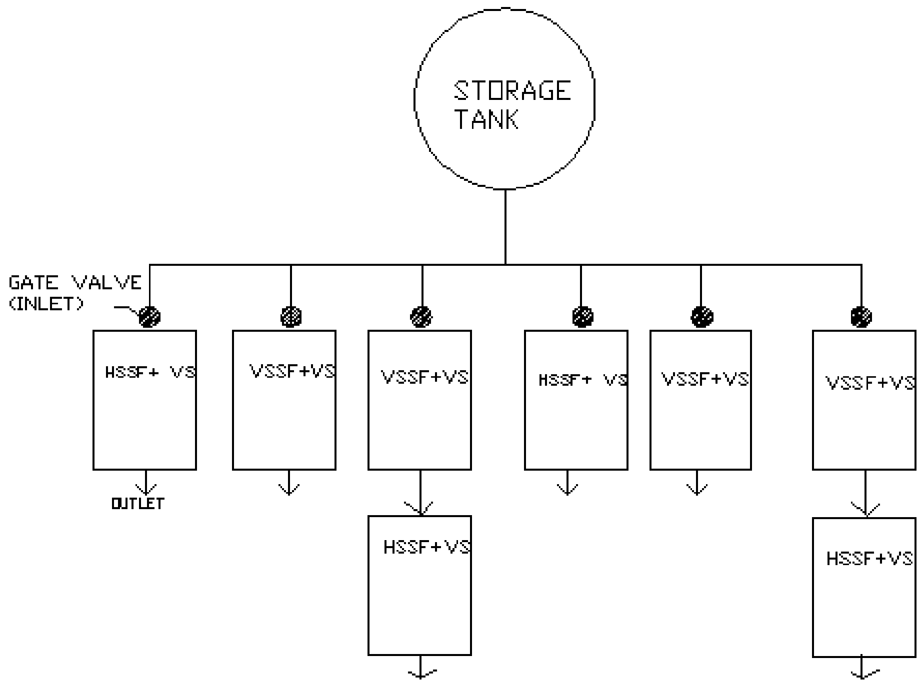

Figure 2. Layout of the experimental units

Legend: HSSF=Horizontal subsurface flow system, VSSF=Vertical subsurface flow system, VS= Vetiver grass

2.3 Planting and Establishment of the Vetiver Grass

The Vetiver grass slips of height 300mm were obtained from Kenya Agricultural and

Livestock Research Organization (KALRO) in Kisii and planted 100 mm within and 150 mm between rows in the substrate of the Horizontal, Vertical and Hybrid subsurface flow wetland systems. DAP fertilizer was used to enable root establishment since the substrate had low Nitrogen and Phosphorous content of 1200 and 19 mg/kg, respectively. For a period of one month since planting, they were watered with fresh water and subsequently in the 2nd and 3rd month with wastewater from the maturation pond. The Vetiver grass in all the wetland units began to continuously receive wastewater based on the experimental flow rate of $0.036m^3d^{-1}$ at the beginning of the fourth month for a period of 8 weeks into the Horizontal subsurface flow system. In the Vertical subsurface systems, it was intermittently fed with two batches daily with each batch having 0.018 m^3. Figure 3 and 4 shows the vetiver grass at planting and at three months respectively.

Figure 3. Planting vetiver grass

Figure 4. Vetiver grass at three months

2.4 Water Sampling and Quality Analysis

The water samples were collected at the inlet and outlets of the constructed wetland treatment systems planted with Vetiver grass and from the controls (unplanted) using one liter clean plastic bottles. Bi-weekly sampling for each treatment for duration of 6 weeks from 7th April to 19th May 2016 was done in duplicates. The samples were transported to the laboratory in cool boxes filled with ice cubes to prevent deterioration and /or transformation of parameters. Water quality parameters i.e. COD, TSS, TN and TP were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA, 2012).

2.5 Determination of Pollutants Removal Efficiencies

Removal efficiencies of pollutants from the wetland systems were calculated as shown in Equation: 1.

$$\text{Removal Efficiency}\ (\%) = \frac{Ci - Ce}{Ci} \times 100\% \quad \text{.......................................}(1)$$

Where:

Ci = Influent Concentration

Ce = Effluent Concentration

2.6 Statistical Analysis

Data obtained for COD, TSS, TN and TP from the treatment systems were subjected to analysis of variance (ANOVA) at 5% level of significance using SPSS statistical software version 21.Means were separated using LSD test to determine if there were significant differences between treatment pairs.

3. Results and Discussions

3.1 COD Removal

Effluent and influent COD concentrations for all the wetland units analyzed during the monitoring period are presented in Figure 5.

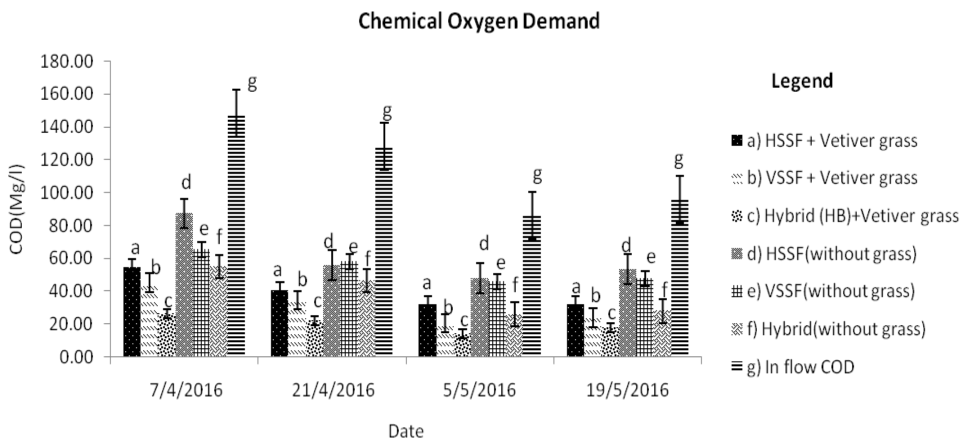

Figure 5. Effluent and influent COD for all the wetland units during the monitoring period

Among the subsurface flow wetland systems planted with Vetiver grass, the hybrid system achieved significantly ($p \le 0.05$) the lowest mean effluent COD of 20.19 mg/L followed by the vertical system at 31.06 mg/L. The horizontal system was at 39.75 mg/L. The more efficient polishing by the hybrid system could be attributed to the longer wastewater retention in the coarse sand media at a length of 6.4 m compared to 3.2 m length in the horizontal and vertical subsurface flow systems, thus hybrid system allowed microorganism's ample time to degrade organics. Deblina & Brij (2010) similarly observed that the higher retention time of 4 days helped achieve maximum removal of COD at 85% compared to 45% at 1 day retention time. Ewemoje et al. (2015) also observed that removal efficiency of COD increased with retention time. The authors obtained 84, 92.4 and 95.3% COD removal at 3, 5 and 7 days retention time, respectively and attributed it to better contact time for microbial degradation of organic matter.

However the significantly ($p \le 0.05$) better performance of the vertical than the horizontal subsurface flow systems planted with Vetiver grass could be due to the intermittent feeding of wastewater in the vertical system that created better aeration as opposed to the horizontal system that is fed continuously and hence always saturated. This increased the oxygen content in the wastewater required by microorganisms to degrade the organics thereby lowering amount of oxygen required to chemically oxidize organic matter in the effluent. The significance of oxygen in wetland performance is further demonstrated by Ong et al. (2011) in a study on treatment of textile wastewater in aerated and non aerated wetland reactors who observed a COD removal of 95 and 62%, respectively. The authors observed that aerobic conditions facilitated the growth and proliferation of aerobic microbes which enhanced the biodegradation of organic matters. Studies by Boonsong & Chansiri (2008) further support the importance of oxygen. They observed that dissolved oxygen in the effluent from the system fed with highly concentrated wastewater was lower at 0.96 mg/l compared to 1.45mg/l in the low concentrated wastewater. This was attributed to the consumption of oxygen in aerobic decomposition of organic matter by microorganisms.

The planted systems achieved significantly ($p \leq 0.05$) lower mean effluent COD compared to the unplanted systems with the planted hybrid system being the best in COD removal. This is an indication that Vetiver grass played a significant role in utilizing nutrients such Nitrogen and Phosphorous from wastewater. Lin et al. (2008) observed that the total biomass of Vetiver grass planted on gravel media significantly increased from 26±0 g at the start of the experiment to 352±33g after 35 days and attributed it to nutrient uptake to meet high biomass yield. The better performance of the planted systems could also be attributed to the massive rooting system from the vetiver providing a larger surface area for microbial attachment, which consequently degraded the organic matter. Gagnon et al. (2007) observed a bacterial density ratio of 10.3 between planted and unplanted wetlands. They attributed this to micro aerobic environment in the rhizosphere of plants that is suitable for microbial species growth and diversity that digests organic matter. The good performance of the unplanted hybrid system however shows that the coarse sand media could have also contributed to COD reduction by providing good environmental conditions for microorganisms to proliferate and degrade organics in wastewater.

3.2 Nitrogen Removal

Figure 6 presents the total nitrogen (TN) concentrations in effluent and influent for all the units during the monitoring period.

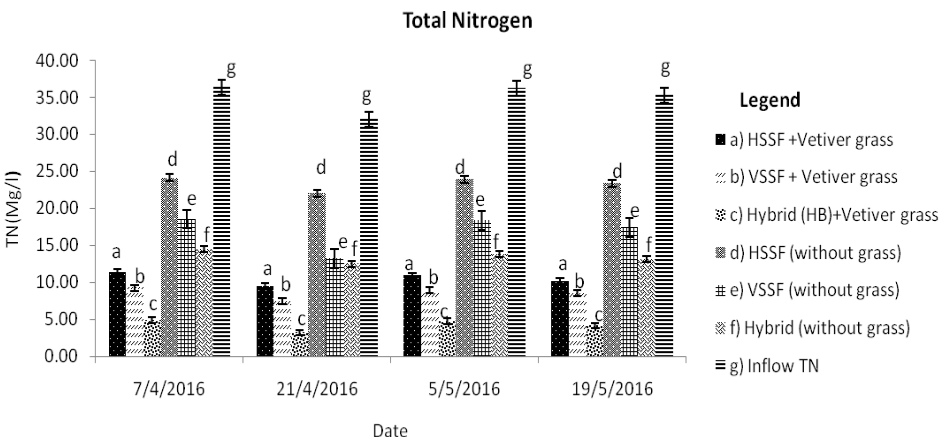

Figure 6. Effluent and influent Total Nitrogen for all the wetland units during the monitoring period

Among the subsurface flow wetland systems planted with Vetiver grass, the hybrid system achieved significantly ($p \leq 0.05$) the lowest mean effluent of TN at 4.23 mg/L followed by the vertical system at 8.51 mg/L. The TN in horizontal system was at 10.48 mg/L. The first stage of the hybrid system consists of the vertical subsurface flow system which is aerated due to intermittent feeding of wastewater. This promotes the conversion of ammonium in wastewater to nitrates by Nitosomonas bacteria (Fan et al., 2013; Yan et al., 2016) and the nitrates formed are easily taken up by Vetiver grass (Billore et al., 2002; Njau & Mlay, 2003). As wastewater flowed to the next stage of the hybrid system which consist of horizontal subsurface flow system, anaerobic conditions dominates since it is always saturated with wastewater. This in turn promotes reduction of the nitrates by chemo-autotrophic bacteria to gaseous forms of nitrogen (nitric oxide, nitrous oxide and dinitrogen) (Saeed & Sun, 2012; Vymazal, 2007,) which greatly reduced the effluent TN levels. Zhang et al. (2015) observed that hybrid system achieved 75.4% TN removal compared to vertical and horizontal system at 53.35% and 50.3%, respectively. The authors attributed the better performance of the hybrid system to its ability to provide both aerobic and anaerobic conditions simultaneously for multipurpose microorganisms which is suitable for nitrogen removal in wetlands. Similarly Vymazal (2007) observed that hybrid constructed wetlands are primarily used for enhanced TN removal because the various types of wetland environments provide different redox conditions which are suitable for nitrification and denitrification processes. The significantly ($p \leq 0.05$) better performance of the vertical subsurface flow system planted with Vetiver grass as compared to horizontal subsurface flow system planted with Vetiver grass could also be attributed to better aeration which enhanced nitrification process and consequently the nitrates formed are easily utilized by the plants.

Of the unplanted subsurface flow systems, the hybrid system again achieved significantly ($p \leq 0.05$) lowest mean effluent TN load of 13.48 mg/L followed by vertical and horizontal system at 16.87 and 23.31 mg/L, respectively. The best performance of the hybrid system could be attributed to the longer wastewater retention in the coarse sand media at a length of 6.4 m compared to 3.2 m in the horizontal and vertical subsurface flow systems, which allowed microorganisms more time to degrade organics. Bioaloweic et al. (2011) observed that 59.5% of nitrogen removal occurred through microbiological processes in the gravel used as substrate while volatilization and plant uptake accounted for only 13 and 15%, respectively. Coarse sand thus acts as a habitat for microorganism communities who assist in effectively removing nitrogen from contaminated water for their physiological need. Significance of substrate in nitrogen removal is further demonstrated in a study by Kantawanichkul et al. (2013) who noted that altering the media from sand to gravel decreased nitrogen removal efficiency from 65 to 46.8%. The authors indicated that sand particles have a larger surface area to support microorganisms and provide a longer retention time for biological processes such as nitrification and denitrification.

However the significantly ($p \leq 0.05$) better performance of the vertical than the horizontal unplanted subsurface flow systems could be due to the influence of better aeration on nitrogen removal as explained in the planted systems. Jamieson et al. (2003) also observed that the introduction of aeration to a pilot scale constructed wetland model improved the mean ammonia-nitrogen removal efficiency from 50.5 to 93.3%, following a 2 week lag phase. Increased removal was primarily attributed to increased nitrification indicating continual aeration has great potential to enhance nitrification in constructed wetlands and NO_3 formed used as nutrients by the macrophytes thereby reducing TN level in wastewater.

The planted systems had significantly ($p\leq0.05$) lower mean effluent TN compared to the unplanted systems with the planted hybrid system being the best in TN removal. This is an indication that Vetiver grass played significant role through nutrient uptake from wastewater. Mairi et al. (2003) observed performance efficiency of nitrogenous chemical removal was greatly increased by macrophytes absorption as percent NO_3 removal averaged 58.1% for planted cells and 21.6% for unplanted cells in his study. Similar observations were made by Bioaloweic at al. (2011) whereby plant uptake accounted for 15% nitrogen removal in a vertical flow wetland. Chang et al. (2013) observed that plants enhance nitrate removal by plant assimilation which accounted for 2-10% of removal efficiency. Tanner et al. (2012) noted that vegetation increases aeration within the constructed wetland system hence assisting nitrification process and the nitrates released taken up by the vegetation.

3.3 Total Phosphorous Removal

Figure 7 presents the total phosphorous (TP) concentrations in effluent and influent analyzed in the wetland units during the monitoring period.

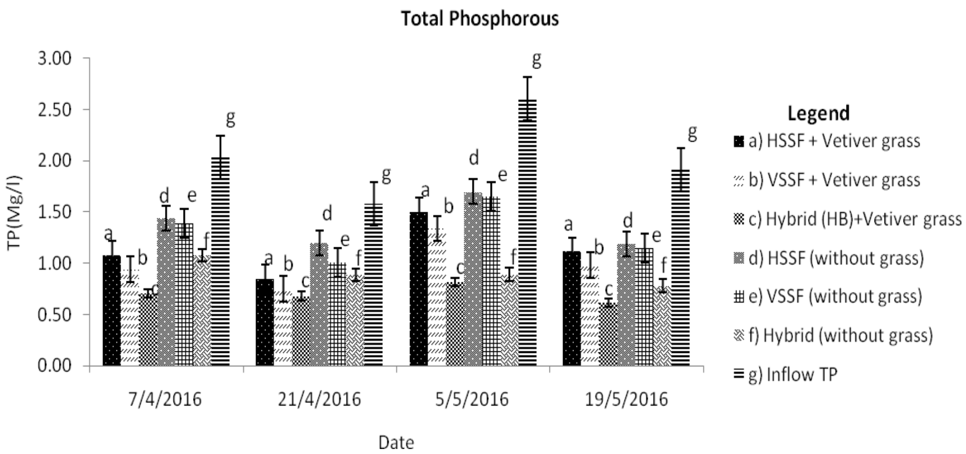

Figure 7. Total Phosphorous content in Effluent and influent in the wetland units during the monitoring period

Among the subsurface flow wetland systems planted with Vetiver grass, the hybrid system achieved significantly ($p\leq0.05$) the lowest mean TP of 0.71 mg/L in the effluent followed by the vertical at 1.00 mg/L and finally at 1.14 mg/L in the horizontal system . The best performance of the hybrid system could be attributed to the longer wastewater retention in the substrate at a length of 6.4 m compared to 3.2 m in the horizontal and vertical subsurface flow systems, which allowed the coarse sand media to adsorb more phosphorous. Adsorption of phosphorous has been reported to be the major mechanism of its removal from wetlands. Njau et al. (2003) in a study on the potential of pumice as a substrate to adsorb P from wastewater observed that 39% of all dissolved P was removed via sorption to the pumice soil substrate. Ayoub et al. (2001) in a study on use of sands coated in iron aluminium hydroxide for low concentration phosphorous removal from wastewater observed that 70% of P was adsorbed to the coarse sand.

The significant ($p \leq 0.05$) better performance of the planted vertical subsurface flow system compared to planted horizontal system could be due to the saturated conditions in the horizontal system that inhibits microbial decomposition of organic matter containing phosphorous as opposed to well aerated conditions in the vertical system. Forbes et al. (2009) observed that the wetland that was intermittently fed with wastewater achieved the highest removal rate of phosphate phosphorous at 67% compared to the wetland that was operated on a continuous flow that achieved 58% removal rate. This suggests that the intermittent dosing improved dissolved P removal, perhaps by higher iron-P precipitation rates occurring under oxidized conditions. According to Tang et al. (2009) during the loading period in a vertical subsurface flow wetland, air is forced out of the soil and during the percolation phase , the surface soil dries out drawing air back into the soil pore spaces consequently providing alternating oxidizing/reducing conditions in the soil promoting phosphorous adsorption.

The planted systems achieved significantly ($p \leq 0.05$) lower mean effluent TP compared to the unplanted systems with the planted hybrid system being the best in TP removal. This could be attributed to the utilization of nutrients from wastewater by Vetiver grass in the wetland. Lishenga et al. (2015) observed that soil based vetiver system achieved 32.9% TP removal efficiency compared to the unplanted system that achieved 14.85%. This was because Vetiver grass could absorb phosphate-P and the Vetiver roots could slow water velocity thereby increasing TP removal through sedimentation of organic phosphorous. Mng'anya et al. (2001) observed that Vetiver grass contributed about 3% in phosphorous removal from the wetland through uptake. Yeboah et al. (2015) in a study on purification of industrial wastewater with Vetiver grass grown hydroponically on palm oil mill effluent observed that phosphate level was reduced from 10.5mg/l to 1.62mg/l corresponding to 84.57% reduction. This was attributed to Vetiver's high affinity for phosphate for its root development.

3.4 Total Suspended Solids Removal

Figure 8 presents the total suspended solids (TSS) concentrations in effluent and influent analyzed for wetland units during the monitoring period.

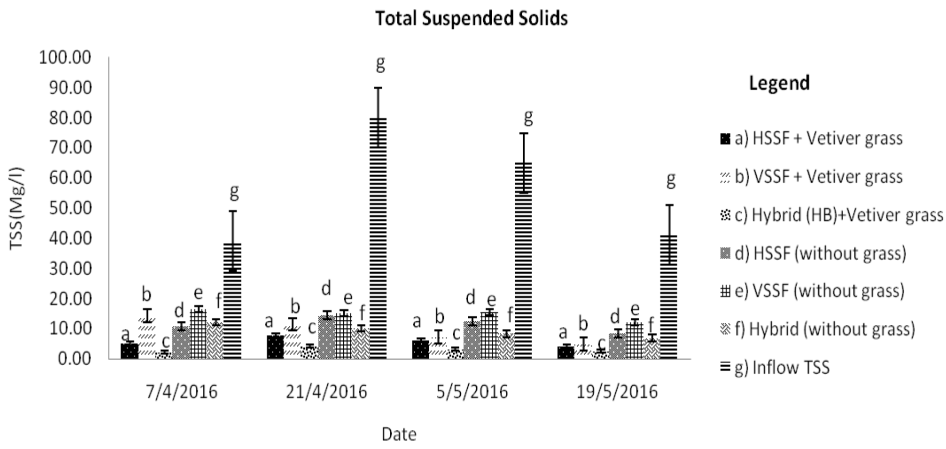

Figure 8. Total Suspended solids in Effluent and influent during the monitoring period

Among the subsurface flow wetland systems planted with Vetiver grass, hybrid system achieved significantly ($p \leq 0.05$) lowest mean TSS of 3.04 mg/L in effluent followed by the horizontal at 5.71 mg/L and finally 9.44 mg/L for the vertical system. The best performance of the hybrid system could be attributed to the longer wastewater retention in the substrate at a length of 6.4 m compared to 3.2 m in the horizontal and vertical subsurface flow systems, which allowed the substrate to filter much of the suspended solids from the wastewater. Shruthi & Lokeshappa (2015) using Vetiver grass observed better removal efficiencies of TSS at 60 and 66% were achieved at 4 and 6 days retention time, respectively compared to 58% achieved at 2 days . Ewemoje et al. (2015) in a study on the effect of hydraulic retention time on pollutant removal in a wetland planted with *Coix lacryma jobi*, observed TSS removal was 26.1, 41.9 and 47.8% at 3, 5 and 7 days retention time, respectively. Of the vetiver grassed plots, significantly ($p \leq 0.05$) better performance of the horizontal subsurface flow system compared to vertical could be attributed to the uniform flow in the horizontal system due to consistent and continuous feeding of wastewater. This could have reduced disturbance on the particles that have been trapped in the system. However in the vertical system, the batch feeding led to turbulence as wastewater flow downwards under gravity thereby disturbing the sediments bound to the media in the constructed wetland. The particles are consequently dislodged from the wetland and contribute to the high TSS level in the effluent.

The planted systems achieved significantly ($p \leq 0.05$) lower mean effluent TSS compared to the unplanted systems with the planted hybrid system being the best in TSS removal. The difference in performance could be attributed to the trapping of the solids by the fibrous rooting system of the Vetiver grass. Barakati et al. (2011) in a study on use of Vetiver grass instead of reed in municipal wastewater treatment reported 82% and 96.5% TSS removal for reed and Vetiver grass, respectively. They attributed it to long, branched and bulky rooting system of Vetiver grass that like a powerful filter traps the coarse sediments in wastewater. Abolfazl et al. (2014) also in a study on treatment of hospital wastewater by Vetiver and typical reed plants in a horizontal flow wetland observed that the removal value for TSS for Vetiver grass had a better increasing trend than reed during a period of 3 months. However, no meaningful difference was observed based ($p \geq 0.05$). The authors attributed it to the massive and bulky rooting system of Vetiver grass that traps sediments effectively. Mburu et al. (2013) observed that vegetated cells with *cyperus papyrus* achieved 50% TSS removal compared to 18.4% in the unplanted cells. The authors explained that at constant hydraulic loads, roots and rhizome contribute to stabilise the wetland beds and increase the interception and sedimentation. The roots of Vetiver grass are likely to have slowed down the velocity of wastewater through the coarse sand media thereby increasing the retention time which consequently improved filtration level. Karathanasis et al. (2003) observed that the vegetated systems with cattails (*Typha latifolia*) showed significantly greater ($p \leq 0.05$) removal efficiencies for TSS at 88% compared to the unplanted systems at 46%. They attributed it to rooting biomass of the vegetated systems which provides more effective filtration of the TSS load as well as contributing complimentary treatment of the organic portion of the TSS load through microbial decomposition by offering extensive surface area for microbial attachment.

4. Conclusions

Constructed wetlands are effective in pollutants removal from municipal wastewater. Among the subsurface flow wetland systems planted with Vetiver grass, the Hybrid systems achieved significantly ($p \leq 0.05$) the highest pollutants (COD TSS, TN and TP) removal, compared to the horizontal and vertical subsurface flow systems. The vertical subsurface flow system also performed significantly ($p \leq 0.05$) better in COD, TN and TP removal compared to Horizontal system except in TSS removal. Similar trend was exhibited in the unplanted systems. Overally, the planted systems performed significantly ($p \leq 0.05$) better than the unplanted systems in pollutants removal with the hybrid system planted with Vetiver grass being the best in polishing municipal wastewater.

Acknowledgements

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