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ORIGINAL ARTICLE

Organic Matter and Nutrient Removal Performance of Horizontal Subsurface Flow Constructed Wetlands Planted with *Phragmite karka* and *Vetiveria zizanioide* for Treating Municipal Wastewater

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Abstract Three pilot horizontal subsurface flow constructed wetlands (HSSFCWs) were constructed, covered with a geomembrane and filled with gravel media. The study compared the performance of the three pilot HSSFCWs, two planted with *Vetiveria zizanioide* and *Phragmite karka*, and one without plants, and all containing aeration facilities in treating municipal wastewater. HSSFCWs were loaded at a hydraulic loading rate of 0.025 m/d and a maximum organic loading rate of 6.16 g BOD/m^{2}d with a hydraulic retention time of 6 days. Results show that *V. zizanioide* had better removal efficiencies (TSS: 92.3%; BOD$_5$: 92.0%; PO_4^{3-}: 86.7%) than *P. karka* (TSS: 91.3%; BOD$_5$: 90.5%; PO_4^{3-}: 85.6%), whereas *P. karka*

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showed better removal efficiency of NH_4^+ (86%), NO_3^- (81.8%) and SO_4^{2-} (91.7%) than *V. zizanioide* (NH_4^+: 83.4%; NO_3^-: 81.3%; SO_4^{2-}: 90.5%). Removal rates in unplanted CWs were lower for all parameters: TSS (78%), BOD_5 (73%), NH_4^+ (61.0%), NO_3^- (55.5%), PO_4^{3-} (67.6%), SO_4^{2-} (78.1%). Higher removals of total coliform (3 log units) and *Escherichia coli* (2.4 log units) were obtained in the HSSFCW with plants compared to unplanted units (total coliform: 1.9 log units; *Escherichia coli*: 1.2 log units). Based on these findings, the treated water can be directly disposed into surface water bodies or used for irrigation as the concentrations of the pollutants are below the standard permissible limits of effluent discharge set by EEPA and WHO. Therefore, both *V. zizanioide* and *P. karka* are good candidates for remediation of wastewater by a constructed wetland system.

Keywords Aeration · Constructed wetland · Gravel media · Pollutant removal

1 Introduction

The direct discharge of municipal wastewater to water bodies presents considerable ecosystem and public health threats, causing eutrophication and propagation of water borne diseases (Chavan and Dhulap 2013). These problems occur in communities lacking adequate wastewater treatment plants and sanitation, and experiencing rapid urbanization and industrialization (Danh et al. 2009). Even though various wastewater treatment technologies have been developed (Arias and Brown 2009), the overall treatment capacity is still relatively low in developing countries due to their high cost (Wu et al. 2016).

In Addis Ababa and other Ethiopian cities, the sanitation and water pollution problems are severe. In 2015, 175,951 m^3 of wastewater were generated daily in the city of Addis Ababa. Because of insufficient sewage networks and limited capacity of wastewater treatment, many of Addis Ababa's residents are forced to defecate and dispose various domestic waste materials in open places (Abay 2010), causing dangerous health and other environmental problems (FFE 2010). Wastewater discharged from Addis Ababa municipality and the existing wastewater treatment plant does not meet environmental requirements. This has led to an increase in the concentration of various organic and inorganic water pollutants above WHO acceptable levels in the rivers flowing through Addis Ababa and several other Ethiopian towns (Beyene et al. 2008, 2009). Ethiopian municipalities are required to develop efficient wastewater treatment processes that meet environmental sustainability requirements, but these regulations are seldom enforced.

Constructed wetland (CW) technologies are being used worldwide, providing solutions to water quality issues and treating all types of wastewater (Abbasi et al. 2016). When constructed wetland technology is properly designed, it can remove pollutants from different wastewaters and can be a feasible solution for wastewater treatment, both economically and technically (Stefanakis et al. 2011). CWs can be used as alternative wastewater treatment systems to conventional treatment technologies (Gikas and Tsihrintzis 2014). Wetland technologies may be a sustainable solution for wastewater treatment (Chavan and Dhulap 2013).

Constructed wetlands are man-made treatment systems in which natural processes are carried out with the support of wetland plants, soil and microorganisms within a controlled environment (Vymazal 2005, 2010). The basic types of constructed wetlands are free-water surface flow and subsurface flow systems. Subsurface flow constructed wetlands are further classified into vertical (VSSFCW) and horizontal subsurface flow constructed wetlands

(HSSFCW), depending on the direction of wastewater flow (Choudhary et al. 2011; Baskar et al. 2014). HSSFCW types of constructed wetlands are designed for the treatment of municipal sewage. They have been examined extensively for organics, suspended solids, nitrogen, phosphorus and bacteria removal (Vymazal et al. 2009) and have been used for various types of wastewater treatment for more than four decades (Vymazal and Kropfelova 2009).

Construction and combinations of different types of CW systems have been reported by Avila et al. (2015) and Button et al. (2015). The use of different plant species has been reported by Dyamanagowdru and Lokeshappa (2015). The ability of macrophytes to uptake and remove nutrients in CWs has resulted in the use of CWs for a variety of wastewater treatment. The capacity to assimilate nitrogen, which is a vital nutrient for plant growth, is different among macrophyte types (Jampeetong et al. 2012). Selection of suitable plant species for different wastewater treatments is an important component of CWs design. The performance of constructed wetland technologies varies considerably from system to system as well as within the same system due to complex processes and their component interactions in the system (Stottmeister et al. 2003). The comparative efficiency of wetland technologies depend on the species of plants, their known potential to treat wastewater, their growth rate, biomass and costs (Brisson and Chazarenc 2009).

The treatment performance of subsurface flow CWs with plants and without plants varies significantly in the removal of pollutants (Tanner 2001; Brisson and Chazarenc 2009; Vymazal 2009, 2011). This variation is partly attributed to differences in the types of plant species used in wastewater treatment (Jampeetong et al. 2012). *Vetiveria zizanioide* and *Phragmite karka* are commonly used wetland plants for wastewater treatment purpose (Kenatu 2011; Tadesse et al. 2016). *V. zizanioide* is a perennial grass characterised as a hardy plant that has short rhizomes with a massive, finely structured root system that grows fast (Edelstein et al. 2009).The typical characteristics of *V. zizanioide* are suited for wastewater treatment (Akbarzadeh et al. 2015) and remediation (Chen et al. 2004; Danh et al. 2009). It has been reported to grow to a depth up to 4 m in the first year of growth (Edelstein et al. 2009). The deep root system of *V. zizanioide* can tolerate droughts and floods (Truong and Danh 2015). *V. zizanioide* is commonly used to reduce soil erosion and for water conservation in Ethiopia (Kebede and Yaekob 2009).

The treatment performance of *V. zizanioide* varies with the type and concentration of wastewater to be treated as well as climate conditions (Dyamanagowdru and Lokeshappa 2015). However, no studies have been carried out on constructed wetland systems planted with *V. zizanioide* for treating wastewater in Ethiopia. *Phragmite karka* is well adapted to different environments, growing in tropical and subtropical regions in fresh water and brackish, marshy or seasonally flooded soils and moist locations, such as river banks and lake shores. It is a promising emergent macrophyte for sustainable use in wastewater treatment due to its rapid growth. *Phragmite karka* is a robust, erect, strongly tufted, perennial grass with an extensive, creeping, branching rhizome or stolon up to 20 m long, stems (culm) 2–8 m tall and 1.5 cm in diameter (Phillips 1995). *Phragmite karka* is is one of several wetland plants commonly used for the treatment of different wastewaters in constructed wetland systems in Ethiopia (Kenatu 2011; Kassa and Mengistu 2014; Tadesse et al. 2016).

Constructed wetlands have been thoroughly investigated and proposed for their potential to mitigate environmental pressures associated with wastewater loaded with nutrients and organic matter (Meers et al. 2008) as well as other pollutants found in domestic wastewater (Lesage et al. 2007; Van de Moortel et al. 2010). Nonetheless, these studies also suggest that local parameters such as types of plant species and climate, particularly temperature, influence overall performance. The benefits of the presence of plants have been repeatedly demonstrated. However, it is not known whether there are significant differences in removal efficiency among plant species. There are a growing number of published scientific papers that compare the effect of two or more plant species on pollutant removal, but findings across studies have not been synthesized. Even for the most tested plant species, the relative performance varied according to the pollutant considered, experimental design, type of wastewater, climate, etc. As a result, different conclusions were sometimes drawn for studies comparing the same pair of species (Brisson and Chazarenc 2009).

Because of this situation, constructed wetland performance cannot be simply extrapolated to implement a given system but requires local pilot investigations to assess the performance of HSSFCWs planted with different plant species grown in a certain area. *P. karka* and *V. zinaioide* have different growth rates and root structures, and these make for interesting comparisons of the performance of these two plant species in HSSFCWs. Considering the low pollutant removal efficiency in conventional CWs and limited oxygen transfer capability, we developed a novel HSSFCW system with aeration, which uses locally grown plant species for the removal of organics and nutrients from municipal wastewater. This study evaluates the organic and nutrient removal performance of *P. karka* and *V. zinzanioide* grown in gravel media under similar hydraulic loading rates (HLR) in aerated HSSFCWs for municipal wastewater treatment in Addis Ababa, Ethiopia.

2 Methodology

2.1 Experimental Location

A horizontal subsurface flow constructed wetland (HSSFCW) pilot plant was built on the premises of Akaky Kaliti wastewater treatment plant in Addis Ababa, Ethiopia, located at 8°91’85″N, 38°75’58″E and at an elevation of about 2200 m a.s.l., an area with an annual rainfall of 1400 mm and an annual mean temperature of 16 °C (EDHS 2011).

2.2 Design and Experimental Setup

The pilot scale HSSFCW was designed based on the existing loading rates as described in the general guidelines for proper design of a constructed wetland system treating municipal wastewater (USEPA 2000). To achieve the outflow BOD concentration of 30 mg/L, the USEPA recommends area loads of BOD 6 g/m^2d. The size of the pilot HSSFCW was determined by Eq. (1), using the recommended area loading rate for BOD (6 g/m^2d), influent BOD concentration (240 g/m^3) and the flow rate of wastewater (0.088 m^3/d). The size of HSSFCWs was also designed using “rule of thumb” set at 5 m^2/PE (Ewemoje and Sangodoyin 2011). The size of each pilot scale HSSFCW unit in this study is equivalent to 3.5 m^2/PE. The effective aspect ratio (L/W) pilot design was 3.5:1, which is in the range of recommended values between 2:1 and 5:1 (Kadlec and Wallace 2009). The theoretical HRT was 6 days, which is estimated by Eq. (2) using the average flow through the system (0.088 m^3/d), the system dimensions (3.5 m × 1.0 m), the operating water level (0.4 m), and the initial (clean) porosity of the media (0.38), which was experimentally determined. The hydraulic loading rate (HLR) (m/d) is the volume of wastewater loaded per unit surface area of CW, calculated by Eq. (3):

$$A_s = \frac{Q\,C_o}{ALR} \tag{1}$$

$$\mathrm{HRT} = \frac{\mathrm{L\ W\ Dw\ n}}{\mathrm{Q_{ave}}} \tag{2}$$

$$HLR = \frac{Q}{A_s} \tag{3}$$

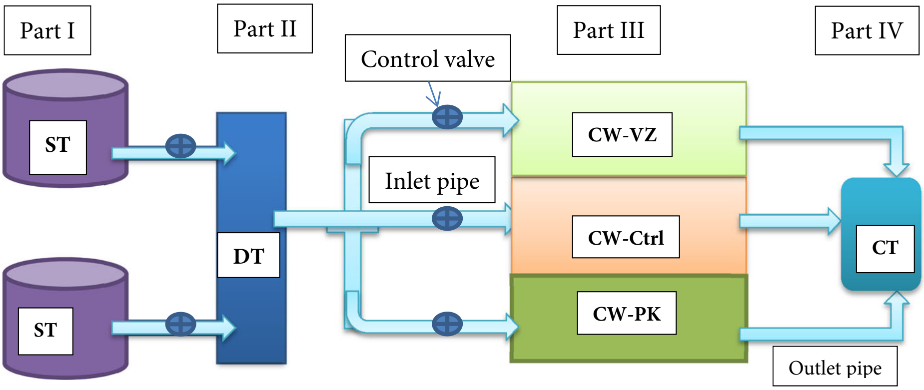
where

L	length of wetland, m
W	width of wetland, m
Dw	depth of water, m
Q_{ave}	average flow rate = $(\mathrm{flow_{in}} + \mathrm{flow_{out}})\ /2$, m^3/d
A_s	surface area of wetland, m^2
n	media porosity, unitless

2.3 Experimental Setup Description and Construction

The experimental setup is shown in (Fig. 1) which consists of four parts: sedimentation tank (part I), distribution tank (part II), HSSFCWs (part III) and collection tank (Part IV). The sedimentation tanks, distribution tank and the three HSSFCWs were connected by a PVC pipe with a control valve. Two sedimentation tanks of 500 L volume were used as storage tanks and for primary treatment. The distribution tank had a volume of 0.75 m^3 and dimensions of 1.5 m × 1.0 m × 0.5 m (L × W × D). The three equally sized wetland cells had L × W × D dimensions of 3.5 m × 1.0 m × 0.6 m. Slotted and perforated PVC pipes were installed along the width of the inlet. The outlet pipe was installed 5 cm above the floor inside the HSSFCW and was connected outside the HSSFCW with a 35 cm high L-shape pipe. The constructed wetlands were covered with black geomembrane and filled with gravel media to the level of 0.5 m. For aeration purposes, three perforated PVC pipes with 80 cm height and 80 cm length were inserted vertically in each HSSFCW cell. The advantage of these inserted perforated pipes was to transfer oxygen into the substrate of the HSSFCWs where oxygen is inadequate.

Healthy young *V. zizanioide* plants were collected from a nursery in Weliso town in West Shoa Zone. The *V. zizanioide* was uprooted from the soil and washed with water. Then, the tops and roots of the *V. zizanioide* shoots were trimmed to 10 cm and 5 cm, respectively. The *V. zizanioide* shoots were planted on March 7, 2015 in the first constructed wetland at a density of 15 plants per square meter. The stems *P. karka* were collected from Selaydengaye village in North Shoa Zone and their stems were planted into the second constructed wetland on April 7, 2015, as shown on the left side (photo a) in Fig. 2. The third constructed wetland was left unplanted and was used as control. After planting, tap water was introduced into the system twice a week for 1 month, until the plants were fully grown. After the plants were grown the wastewater was introduced starting on May 7, 2015, by increasing concentrations of 5%, 10%,



Where; ST= Sedimentation Tank; DT = Distribution Tank; CT= Collection Tank

CW-VZ = Constructed wetland planted with *Vetiveria zizanioide*

CW-Ctrl= Constructed wetland unplanted

CW-PK= Constructed wetland planted with *Phragmite karka*

Fig. 1 Schematic diagram of the experimental setup of the horizontal subsurface flow constructed wetland

15%, 20%, 25%, 30%, 40%, 50%, 75%, 100% for acclimatization until the end of June 2015 to avoid possible shock or stress to the plants caused by high concentrations of pollutants in the wastewater (USEPA 2000). The fully grown constructed wetlands are shown on the right side of Photo b in Fig. 2.

Fig. 2 The pilot HSSFCWs planted with *V. zizanioide* and *P. karka* at the start of the operation (Photo a) and fully grown plants 1 year after plantation (Photo b)

2.4 Operation of the HSSFCWs

The operation of the HSSFCW commenced in May 2015 and the performance study was monitored for 15 months, between July 2015 and September 2016. After preliminary treatment (through bar screen and grit chamber), the municipal wastewater was collected and the sedimentation tank filled. The constructed wetlands were continuously fed with primarily treated wastewater from the distribution tank, controlled with the help of a gate valve. The desired flow rate of the influent wastewater was manually maintained at 88 L/d by regulating the gate valve and using a stopwatch and a measuring cylinder at the inlet of the constructed wetlands. The water depth was maintained at 0.4 m within the wetland with the aid of fixed outlet pipes. The study was conducted at a hydraulic loading rate 0.025 m/d, with a corresponding hydraulic retention time of 6 days.

2.5 Sampling and Sample Analysis

Eight replicates of samples were collected every 2 months per sampling point in the HSSFCWs during the 18-month experimental period. Water samples were collected between 10 and 11 o'clock in the morning for each experiment and were taken immediately to the Addis Ababa water and sewage Authority laboratory for analysis using 1000 mL sterile plastic bottle and 500 mL glass bottle. All collected water samples were analysed for the selected physicochemical and bacteriological wastewater quality parameters of biological oxygen demand (BOD_5), nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4^+-N), orthophosphate (PO_4^{3-}), sulphate (SO_4^{2-}), total suspended solids (TSS), electrical conductivity (EC), dissolved oxygen (DO), pH, temperature (T^o), total coliform bacteria (TC), and *Escherichia coli* bacteria.

DO, EC, pH and temperature were measured on-site during sampling times using the portable DO-meter, EC-meter (CC-401, ELMETRON), pH-meter (HI 9024 HANNA) and a thermometer, respectively. Nitrate nitrogen, ammonium nitrogen, orthophosphate, sulfate and TSS were measured by a spectrophotometer (DR/2010 HACH, Loveland, USA) according to HACH instructions and APHA (1999). BOD_5 was determined by Oxitop measurement using standard methods of APHA (1999). The bacteriological quality indicators, total coliform (TC) and *E. coli* were determined using Membrane Lauryl Sulphate Broth with membrane filter (MF) procedures according to standard methods for the examination of water and wastewater (APHA 1999).

2.6 Statistical Data Analysis

Data analysis was performed using Microsoft Excel XP version 2010 and SPSS package Version 20.0. One way analysis of variance (ANOVA) was used to compare the significance of mean differences of pollutant removal efficiency between the three horizontal subsurface flow constructed wetlands planted with *V. zizanioide*, *Phragmite karka* and the control, in regard to removal of organic matter, nutrients and bacteria in order to test for statistically significant differences ($P < 0.05$). The pollutant removal performance of constructed wetlands was calculated from Eq. (4).

$$\%R = \left(\frac{C_i - C_e}{C_i}\right) x\ 100\% \qquad (4)$$

where R = percent removal of pollutant in the constructed wetlands (%); C_i = influent concentration of a pollutant in mg/L; C_e = effluent concentration of pollutant in mg/L.

3 Results and Discussion

3.1 Characterization of Influent and Effluent Wastewater

In order to evaluate the pollutant removal efficiency of the three HSSFCWs, 8 water samples from each sampling points were collected from July 2015 until September 2016 (every 2 months). Table 1 shows the mean characteristics of wastewater concentrations and standard deviations of quality parameters before and after treatment by the HSSFCW system. The variability in time of influent and effluent concentrations of TSS, BOD_5, NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} in the three HSSFCWs is presented in Fig. 3. The organic loading rate of BOD_5 ranged between 5.5 g/m^{2}d and 6.16 g /m^{2}d and TSS ranged between 7.24 g/m^{2}d and 9.86 g/m^{2}d which were below the maximum recommended loading rate values for HSSFCW (USEPA 2000). The HRT was 6 days.

Analysis of 8 samples of influent wastewater to HSSFCWs indicated that the concentration of organic matter (BOD_5 and TSS) and nutrients varied during the study period (Table 1; Fig. 3). The organic matter and nutrient concentrations of the wastewater in the three HSSFCWs decreased with time, showing that organic matter and nutrient removal was achieved. In this study, slight increases in pH were observed at the effluent from all three wetland cells, ranging from 7.1 to 8.2; there was a significant difference between influent and effluent pH of the three constructed wetland cells ($P < 0.05$). The effluent temperatures of the three HSSFCWs ranged between 22.4 and 26.7 °C. These ranges are suitable for microbial activity as they are within the optimal values between 25 °C and 35 °C for temperatures and between 6.5 and 7.5 for pH (Kadlec and Reddy 2001; Metcalf and eddy 2003; Mairi et al. 2012). The level of dissolved oxygen (DO) measured in the effluent from the three wetland

Table 1 Mean concentrations with standard deviations of water quality parameters in HSSFCW ($N = 8$) (values are in mg/L except pH, temperature (°C), EC (mS/cm) & coliform (log10 units CFU/100 mL)

Parameter	Influent concentration (Mean ± SD)	Effluent concentration (Mean ± SD)			EEPA & WHO Irrigation WQS
		CW with *V. zizanioide*	CW with *P.karka*	Control	
T	23.8 ± 1.3	24.3 ± 1.2	24.3 ± 1.4	24.3 ± 1.6	–
pH	7 ± 0.3	7.8 ± 0.2	7.8 ± 0.3	7.5 ± 0.3	6–9
DO	0.33 ± 0.07	6.2 ± 2	6.4 ± 2.3	2.9 ± 0.8	–
EC	13.3 ± 1.1	2.5 ± 0.8	2.8 ± 0.8	4.3 ± 0.8	850
TSS	346.8 ± 38	27 ± 22	30.6 ± 25	76.4 ± 24	
BOD_5	233.8 ± 8	18.7 ± 15	22 ± 18.6	63 ± 17	200
NH_4^+	29 ± 3	4.9 ± 4	4.1 ± 3.4	11.4 ± 3.6	30
NO_3^-	3 ± 0.4	0.58 ± 0.5	0.56 ± 0.5	1.35 ± 0.3	10
PO_4^{3-}	12.2 ± 2.7	1.5 ± 1.4	1.7 ± 1.4	3.9 ± 1.6	5
SO_4^{2-}	29.5 ± 4.6	2.7 ± 2.8	2.3 ± 2.3	6.2 ± 2.7	250
TC	7.03 ± 0.03	3.98 ± 0.07	3.95 ± 0.08	5.07 ± 0.05	< 3
E.coli	5.94 ± 0.11	3.48 ± 0.29	3.53 ± 0.26	4.76 ± 0.28	< 3

E. coli, *Escherichia coli*; *EC*, electrical conductivity; *TC*, total coliforms; *WQS*, water quality standards

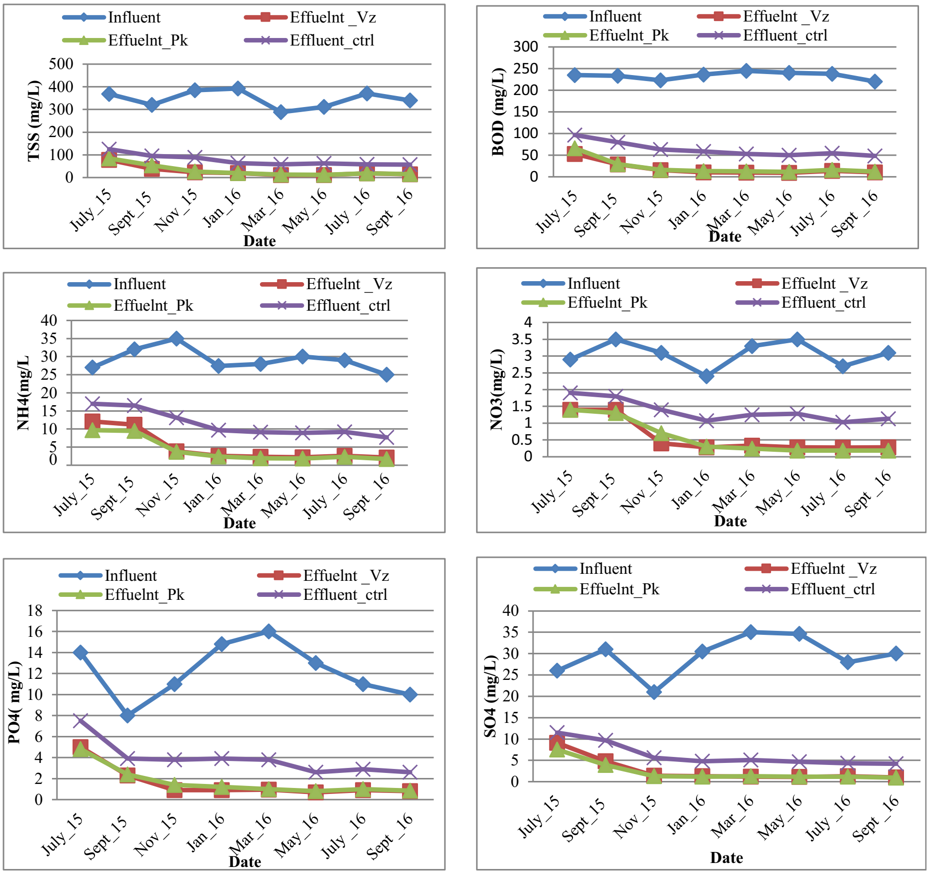


Fig. 3 Time variation graphs of pollutant influent and effluent concentrations in the three HSSFCWs

cells increased from that in influent wastewater, as shown in Table 1. The amount of DO was significantly different in the wetlands with *V. zizanioide* and the control ($P < 0.05$), and in the wetlands with *P. karka* and the control ($P < 0.05$). These results revealed that the presence of plants can increase the amount of oxygen transfer into the wetlands. The electrical conductivity (EC) was significantly higher in the influent than in the effluent in all three HSSFCWs ($P < 0.001$).

3.2 Performance of the HSSFCW

3.2.1 Temperature Effect on Pollutant Removal

The study site is located in a subtropical climate. The air temperature did not show any significant temporal variations during the experimental study (May 2015 to September 2016), and generally, ranged between 22.4 and 26.7 °C. Monthly variations in wastewater temperatures were insignificant for organic and nutrient removal. The temperature of wastewater affects the activity of microorganisms and plants in CWs. Changes in temperature alter dissolved oxygen (Maria et al. 2015). Some studies have indicated higher treatment efficiency of tropical CWs and attributed this to higher temperatures, which stimulate year-round vegetation growth and microbiological activity, and thus, result in higher nutrient uptake (Kivasi 2001; Mburu et al. 2013). Gikas et al. (2007) studied the influence of temperature on pollutant removal in CWs. The authors reported that for temperature values above 15 °C, with plants growing and bacteria function promoted, NH_4^+ and PO_4^{3-} removal was significantly higher than that of temperature values below 15 °C. In our study, the recorded temperature range was between 22.4 °C and 26.7 °C throughout the study period, which was favourable for nitrification and denitrification processes.

3.2.2 Removal of BOD and TSS

Both *P. karka* and *V. zizanioide* grew well in the gravel-based HSSFCWs when loaded with municipal wastewater and produced a plant cover with large biomass. The growth of the plants affects treatment processes in the system and contributes to the removal of organic and nutrients from wastewater. Removals of BOD_5 and TSS of the wetland planted with *V. zizanioide* ranged from 77.5% to 96.2% and 78.7% to 96.4%, respectively; corresponding values for *P.karka* ranged from 72% to 96% and 77% to 97%, and for the control unit from 59% to 79% and 66% to 84%, respectively. Both BOD_5 and TSS removal efficiencies were statistically significantly higher in the wetland with *V. zizanioide* and *P. karka* than in the control unit ($P < 0.05$). The removal mechanisms of organic matter in HSSFCWs are both aerobic and anaerobic microbial processes and also physical processes of filtration and sedimentation (Vymazal and Kropfelova 2009; Vymazal 2011). Dyamanagowdru and Lokeshappa (2015) reported 65% of TSS and 70% of BOD_5 removal performance in CWs planted with *V. zizaniode* with HRT of 6 days for domestic wastewater treatment. The better removal efficiency obtained in the present study may be due to the oxygen transfer and the massive root system of *V. zizaniode* which increased over time. Tadesse et al. (2016) also showed 90% of BOD_5 removal using anaerobic-SBR System integrated with CWs planted with *P. karka* with HRT of 5 days for the treatment of tannery wastewater in Ethiopia. In another study in Kenya, a pilot HSSFCW planted with *Cyperus papyrus*, treating municipal wastewater, showed 75% removal performance for TSS and 60.7% for BOD_5 (Mburu et al. 2013). A similar pilot HSSFCW, treating black and grey wastewater, showed a removal performance for TSS of 82.2% and for BOD_5 of 70.3% with 5 days HRT, and TSS of 89% and BOD_5 of 86.4% with 10 days HRT (Abdel-hefya et al. 2009). Compared with the above studies, we achieved a relatively better removal performance for BOD_5 and TSS for both plant species. The findings of the present study revealed that the HSSFCW planted with *V. zizaniode* removed more TSS (92.3%) and BOD_5 (92%) than *P. karka* (TSS 91.3%, BOD_5 90.5%) with HRT of 6 days (Fig. 4), however the difference was not statically significant ($P > 0.05$). The presence of plants and the selection of appropriate plant species have been shown to increase pollutant removal from CWs (Tanner 2001; Brisson and Chazarenc 2009). Akratos and Tsihrintzis (2007) reported 88.3% and 84.5% removal of BOD_5 obtained in HSSFCW planted with *Typha latifolia* and HSSFCW planted with *Phragmites australis*, which were less than in the present study. This difference may be due to the lower temperatures in northern Greece than in Addis Ababa.

The removal efficiency of BOD_5 of both plants increased over time and the removal increment was slightly higher for the wetland with *V. zizanioide* than *P. karka*, during the study period. The reason for higher removal of BOD_5 in the wetland with *V. zizanioide* may be due to its massive roots, which increase the surface area for microbial growth and biofilm

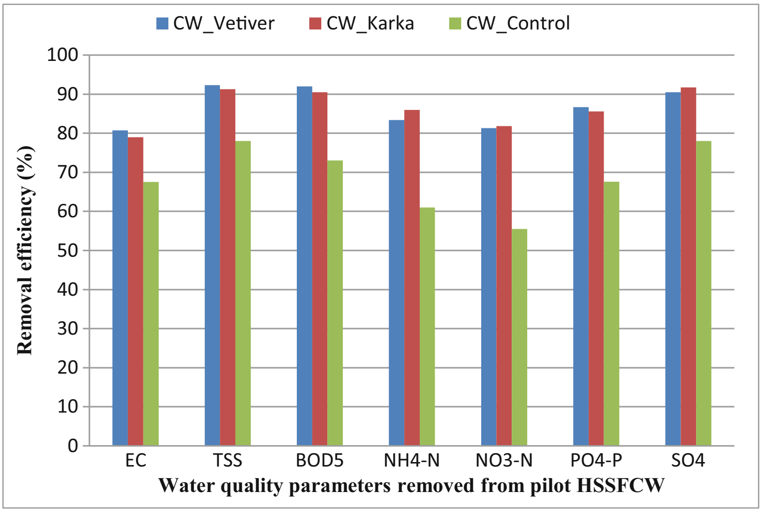


Fig. 4 The removal efficiency of water quality parameters in the three HSSFCW cells

development, and also filters the settleable organic matters by filtration and sedimentation (Sani and Dareini 2014). Plant roots and media surface in CWs stimulates microbial community density and activity by providing root surfaces for microbial growth (Tanner 2001; Vymazal 2005). In addition to the installed aeration facilities, the long roots of the *V. zizanioide* (Truong and Danh 2015) and *P. karka* (Vymazal 2005) plants caused aeration in the deeper layers of the system and increased the transfer of oxygen into the wetland for suitable aerobic microorganism activities. The findings of our study also corroborate those by Vymazal and Kropfelova (2009) on the removal performance of a HSSFCW system for BOD_5, which varied between 75% and 93%.

3.2.3 Nutrient Removal

The removal efficiencies of nutrients (in terms of NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-}) in the three HSSFCW cells are shown in Fig. 4. The average concentration of NH_4^+ and NO_3^- decreased from influent to effluent (Table 1). The removal efficiency range of NH_4^+ in the wetland planted with *V. zizanioide* was between 55.2 and 92.7%, for *P. karka* 64.1 to 94.0%, and for the control 37.0 to 70.3%; NO_3^- removal ranged from 51.7 to 92.0% for V. *zizanioide,* 51.7 to 94.9% for *P.karka*, and 34.5 to 63.6% for the control. Similarly, the rates of phosphate and sulphate removal ranged from 64 to 95% and 65 to 97% for *V. zizanioide*, 65.7 to 94.4% and 71 to 98% for *P. karka*, and 46 to 80% and 56 to 88% for the control, respectively. The average removal of NH_4^+, NO_3^- and SO_4^{2-} was slightly higher in the wetland with *P. karka* (86.0%, 81.8% and 91.7%) than with *V. zizanioide* (83.4%, 81.3% and 90.5%) and the unplanted bed (61%, 55.5% and 78.1%), respectively. But PO_4^{3-} removal in the wetland with *V. zizanioide* (86.7%) was higher than in the wetland with *P. karka* (85.6%) and the control (67.6%). The removal difference between the wetland with *V. zizanioide* and *P. karka* was not statistically significant for the parameters NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-}during the study ($P > 0.05$). However, NH_4^+, NO_3^-, PO_4^{3-} and SO_4^{2-} removal were statistically higher in the two planted wetlands than in the control ($P < 0.05$).

In this study, *P. karka* showed a better performance for NH_4^+ and NO_3^- removal than *V. zizanioide* but the difference was not statistically significant ($P > 0.05$). The major removal mechanism of nitrogen in HSSFCWs is nitrification/denitrification (Vymazal 2005). Nutrient removal performance of the three wetlands, increased with the age of the wetlands. This may be due to the growth of microorganisms. The capacity of plants to take up nutrients also gradually increased. These increases are also linked with the gradual growth of the plants and their biomass (Xia et al. 2004).

In HSSFCWs plant root morphology and development, substrates have an effect on the development of microbial communities (Stottmeister et al. 2003). Dhanya and Jaya (2013) reported a removal performance of 81.4% for NH_4^+ (55.5%) and NO_3^- in a wetland planted with *V. zizanioide*, which is lower than in the present study. The mechanisms involved in nitrogen removal in CWs are ammonification, denitrification, nitrification, adsorption, volatilization, plant uptake and microbial degradation (Vymazal 2011). NH_4^+ can be removed by volatilisation processes in HSSFCWs, however, this requires a pH higher than 11 (Tadesse et al. 2016). The measured pH in our study was between 7.1 and 8.2, precluding this mechanism.

In CWs, phosphorus removal can be achieved by adsorption, precipitation and plant uptake for plant growth. The estimated phosphorus removal ratio by plant growth of up to 10% is possible depending on the climate, plants, type of wastewater (Hoffmann et al. 2011). Dhanya and Jaya (2013) found 70.3% PO_4^{3-} removal efficiency in wetlands with vetiver grass in the treatment of raw sewage, which was less than in the present study. Different plant species have different nutrient treatment performances (Sehar et al. 2015). HSSFCWs with *V. zizanioide* showed higher removal efficiency of PO_4^{3-} compared to that of the HSSFCW planted with *P. karka*, which may be due to relatively better plant uptake of *V. zizanioide* (Dhanya and Jaya 2013), something attributed to the larger root system of the former plant that is responsible for the uptake of nutrients (Boonsong and Chansiri 2008). The microbial community is different among different plant species, which may be responsible for variations in nutrient removal in CWs (Yang et al. 2016). In the study of HSSFCW planted with *Typha latifolia* and *Phragmites australis* with a longer HRT of 6–20 days showed removal rates of 36.2% and 53.6% for NH_4^+, respectively (Akratos and Tsihrintzis 2007), which are lower than in the present study (mean removal of NH_4^+ was 83.4% for HSSFCW planted with *V. zizanioide* and 85.6% for HSSFCW planted with *P.karka*). The higher removal efficiency of NH_4^+ observed in the present study could be due to the potential nutrient uptake of the plant species, aeration of HSSFCW by inserting a perforated PVC pipe and higher temperature of the wastewater, which ranged between 22.4 and 26.7 °C throughout the year. The removal efficiency of planted HSSFCW cells was also influenced by the fast growing and large biomass of the two plant species during the experimental study.

3.2.4 Pathogen Removal

Total Coliform and *E. coli* are the primary indicators for water contaminated with faecal matter due to their prevalence in the gut of warm-blooded animals and their excretion in large numbers in both human and animal feces (UN-Water 2015). The removal of pathogens from wastewater as a disease prevention method is receiving high priority by many environmental health programs (Wu et al. 2016). The main processes responsible for the removal of pathogen in CWs include filtration, sedimentation, natural die off and predation by other organisms (Kadlec and Wallace 2009). The average log removal values of TC and *E. coli* from the municipal wastewater treatment with HSSFCWs and the counts of TC and *E. coli* in influent and effluent are shown in Table 1. They show that higher removals of TC (3 log unit) and *E. coli* (2.4 log unit) were obtained in the HSSFCW with plants compared to the unplanted HSSFCW (1.9 log units for TC and 1.2 log units for *E. coli*) because vegetation is one of the factors that influence these removals (Wu et al. 2016).

The concentrations of TC and *E. coli* in the effluent from HSSFCWs with plants were generally significantly different ($P < 0.05$) from the unplanted HSSFCW. However, there is no statistically significant difference ($P > 0.05$) between the two HSSFCWs planted with *V. zizanioide* and *P. karka* for TC and *E. coli* removal. Avelar et al. (2014) observed greater removal of TC (3.41 log unit) and *E. coli* (3.46 log unit) for CWs planted with *P. australis* than CWs without plants (2.12 log unit for TC; 2.16 log units for *E. coli*) for sewage wastewater. The authors reported that planted CWs resulted in higher removal performance for TC and *E. coli* compared to unplanted CWs, corroborating the findings of the present study. This may be due to the root exudates released by plant species that contain bactericidal activity being toxic to pathogenic microorganisms and also change the physical and chemical environment (Tuncsiper et al. 2012). Final effluent concentrations of analysed parameters from the wetland complied with the Ethiopian Environmental protection Agency (EEPA) and WHO limits for some water reuse for irrigation and discharge to surface water for all parameters except for total coliform, which were higher than the standard limits (400 CFU/mL) set by WHO (2006).

3.2.5 Overall Performance

For all parameters under investigation, quality of the effluent was considerably superior to that of ingoing influent. Based on oxygen saturation of the wastewater and the reduced nutrient content, we can deduct that the eutrophication pressure that would otherwise be associated with discharge in local surface water, can be successfully mitigated by using the tested plant species in HSSFCWs. The removal of degradable organic matter (as expressed in BOD) resulted in a more healthy oxygen content in the water column of receiving waterways, thereby providing protection to waterborne biodiversity. The effective removal of gastro-intestinal microorganisms can also reduce the disease pressure for surrounding communities as these organisms have tendencies to include opportunistic pathogenic strains. Following these encouraging findings, further investigation of plant biomass and plant nutrient uptake potential may also turn towards the impact on and the fate of other contaminants which may be found in municipal wastewater.

4 Conclusions

To overcome oxygen transfer limitations in HSSFCWs, aeration was developed by inserting a perforated pipe which can increase the oxygenation capacity of HSSFCWs. A one and half year investigation of a HSSCW system with both V. *zizanioide* and *P. karka* integrated with aeration showed high performance of pollutant removal in all parameters analysed during the experimental study of municipal wastewater in the subtropical highland climate of Addis Ababa. The treatment performance of HSSFCWs in terms of organic pollutant, nutrients and microorganisms is greatly affected by the presence of plants. The utilization of aeration with appropriate plant species in constructed wetlands can increase the removal of phosphorus and nitrogen by plants with extensive root networks (*V. zizanioide)* and large biomass *(P. karka)*, respectively. These findings indicate that the treated water can be directly disposed into surface water bodies or used for irrigation as the concentrations of the pollutants are below the standard permissible limits of effluent discharge (pH = 6-9, EC = 850 mS/cm, BOD = 200 mg/L, NO_3^- = 10 mg/L, NH_4^+ = 30 mg/L) set by EEPA and WHO. Therefore, both *V. zizanioide* and *P. karka* are good candidates for remediation of wastewater using HSSFCWs integrated with aeration in countries with humid subtropical climates. Finally, the water quality improvements, reported in this paper can inform policy makers and water managers in making informed decisions concerning surface water quality improvement by mitigating wastewater pollution using CWs. Follow-up research may elucidate additional hydroponic and phytoremedial potentials of different plant species using aerated horizontal subsurface constructed wetlands.

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