Nanotechnology for Environmental Engineering (2019) 4:6
https://doi.org/10.1007/s41204-018-0053-z

ORIGINAL PAPER

Effect of hydraulic loading on bioremediation of municipal wastewater using constructed wetland planted with vetiver grass, Addis Ababa, Ethiopia

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Received: 18 October 2018 / Accepted: 17 December 2018 / Published online: 4 January 2019

Abstract

Gravel-based pilot horizontal subsurface flow constructed wetland planted with vetiver grass (*Vitiveria zinaniodes*) and unplanted operated at two hydraulic loading rates: 0.025 m/d and 0.05 m/d was carried out over a 3-year period. The aim of the study was to evaluate the effect of plant and hydraulic loading rate on the organic and nutrient removal performance of the constructed wetland system planted with vetiver grass (*Vitiveria zinaniodes*) in the removal of chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) from municipal wastewater. The removal efficiencies of COD, TN, and TP in the planted cell decreased from 95 to 90.8%, 95.2 to 86.8% and 95.2 to 88.5%, respectively, with an increase in HLR from 0.025 to 0.05 m/d. The estimated above-ground biomass of dry weights of vetiver harvested ranged from 10.1 to 10.3 kg DW/m^2, the nutrients uptake increased with plant age from 2.4 to 14.6 g N/kg DW and 0.8 to 8.5 g P/kg DW and above-ground biomass nutrient standing stock ranged from 147.5 to 150.4 g N/m^2 and 85.5 to 87.5 g P/m^2 in 16 months. The higher removal efficiency of COD, TN, and TP was achieved in HSSFCW planted with vetiver grass as compared to unplanted at both hydraulic loading rate operations. The results concluded that both applications of HLR are capable of removing organic matter and nutrients efficiently and vetiver grass can be used for remediation of pollutants in municipal wastewater in Addis Ababa.

Keywords Bioremediation · Constructed wetland · Hydraulic loading rate · Municipal wastewater · Vetiver grass

Introduction

Globally, constructed wetland technologies are utilized effectively for treating different types of wastewater [1–7] and the use of constructed wetlands is considered an effective secondary or tertiary treatment method [8]. Microorganisms contribute most to overall pollutant removal by decomposing complex organic matter and nutrients assimilated in constructed wetland system (CWs) [9]. The main characteristics of constructed wetlands that affect their removal efficiency are vegetation type, hydraulic residence time, and substrate [8, 10]. The performance of CWs improves with increasing age and is best during the growing season [11].

The factors that determine the treatment efficiency of wetland systems are the type of contaminants, the design of the wetland and interaction of microbes, and climatic conditions. Hydraulic loading rate (HLR) and corresponding hydraulic retention time (HRT) are considered the basic operational control parameters that influence the treatment performance of horizontal subsurface flow constructed wetland system

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[12]. The effect of hydraulic properties such as HLR on the performance of a constructed wetland system has been studied in different countries under various conditions [13]. The HLR is an important design parameter in CWs and significantly affects treatment performance [14]. There is, however, scarce information available regarding how the HLR affects the removal of organic matter and nutrients by horizontal subsurface flow constructed wetland (HSSFCW) planted with vetiver grass.

The practice of adopting constructed wetland technology from various localities can be incompatible with local requirements and conditions [15]. Therefore, it is necessary to conduct research on constructed wetlands as an alternative wastewater treatment system based on local conditions. The purpose of this study was to evaluate the effect of loading rate on performance of a horizontal subsurface flow constructed wetland planted with vetiver grass (*Vitiveria zinaniodes*) in the removal of chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) from primary effluent of municipal wastewater in Addis Ababa, Ethiopia.

Materials and methods

Experimental setup

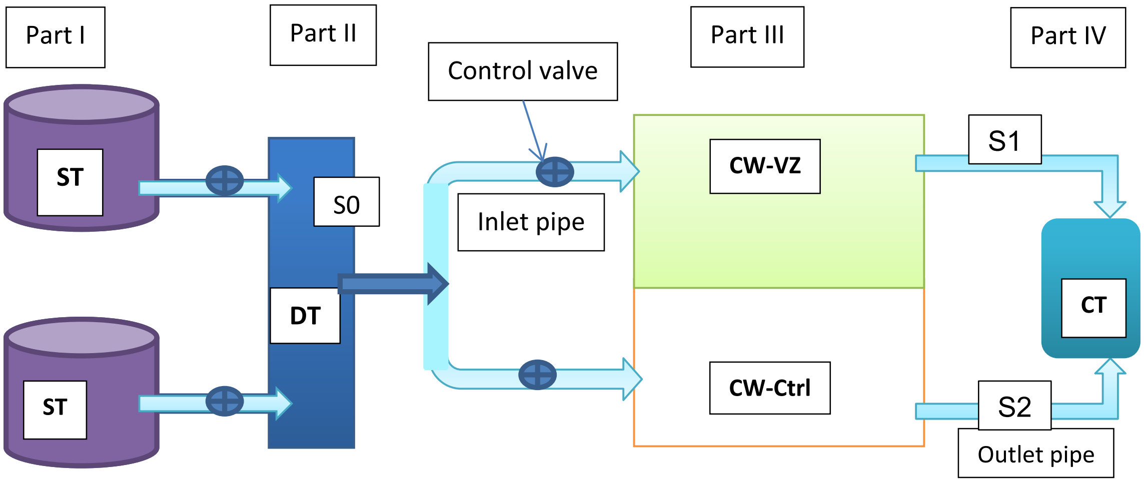
The study site is located on the premises of the wastewater treatment plant in Kaliti, at the southern periphery of Addis Ababa at an altitude of about 2200 m. The average annual temperature of the local tropical highland is 16 °C, rainfall 1400 mm, and relative humidity 60.7%. A pilot scale of HSSFCW with length, width, and depth of 3.5 m × 1 m × 0.6 m was constructed and covered with high-density polyethylene (geomembrane). The HSSFCW consists of two sedimentation tanks (1 m^3) and a distribution tank (0.75 m^3), two CW cells configured in parallel, and one common effluent collection tank constructed from concrete. The two cells of the CW were filled with gravel media, and one of the cells was planted with vetiver grass; the second cell was unplanted.

Experimental design

The pilot-scale design of the HSSFCW cells was based on maximum areal loading rate of BOD as described in the general design of a constructed wetland system treating municipal wastewater [16] and described by Angassa et al. [17]. The schematic diagram of the experiment is shown in Fig. 1.

Vetiver grass

Vetiver clumps were obtained from a nursery in Welisso Town, Oromiya Region, Ethiopia. The clumps were split into tillers by hand. The roots of the tillers were washed carefully with tap water to remove adhering soil and sediment before planting. The shoots and roots of the vetiver tillers were trimmed to 10 cm and 5 cm, respectively. The vetiver tillers were planted at a spacing of 25 cm and 20 cm between rows in the first HSSFCW cell at a density of 20 plants per square meter on March 7, 2015, as shown in Fig. 2a.



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

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

CW-Ctrl= Constructed wetland unplanted

Fig. 1 Schematic diagram of the experiment

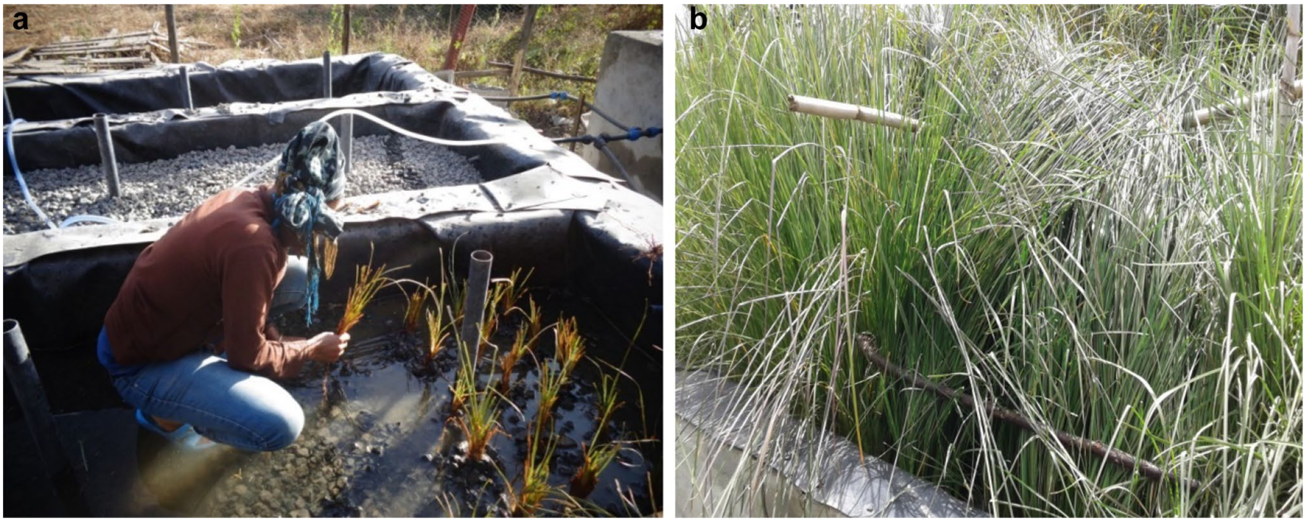


Fig. 2 Plantation of vetiver at start time (**a**) vetiver fully grown after one and half years (**b**)

After planting, tap water was introduced into the system twice a week for 1 month until the new shoots started to grow. Before the beginning of the full operation, the HSSFCWs received a serial municipal wastewater concentration of 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 75%, 100% over 3 months. The purpose of wastewater dilution was to avoid possible shock or stress to the plants caused by high concentrations of pollutants in the wastewater during acclimatization [16]. All shoots of vetiver tillers survived and grew rapidly after a few weeks. The vetiver grass established well on the gravel-based HSSFCW cell loaded with primary effluent of municipal wastewater (Fig. 2b).

Fig. 3 Measuring flow rate of influent for HSSFCW cells

Operation of HSSFCW

The pre-screened wastewater was collected manually from an inlet of the Kaliti wastewater treatment plant and filled into the sedimentation tank for primary treatment. The continuous flow of primary-treated wastewater was fed into the HSSFCW cells through the distribution tank and controlled by a gate valve with two operational modes of the hydraulic loading rate. The actual hydraulic loading rate was measured and adjusted daily. The average flow rates of the inlet and outlet were measured for the HSSFCW cells using a measuring cylinder, stopwatch, and plastic collecting bottle (Fig. 3) to calculate the hydraulic loading rate.

The study was conducted in two phases at different operational modes of the hydraulic loading rate (phase I and phase II experiments). The phase I experiment was conducted by continuous feeding of wastewater to the HSSFCW cells with an average flow rate of 0.088 m^3/d at a hydraulic loading rate of 0.025 m/d, with corresponding hydraulic retention time of 6 days for 15 months, between May 2015 and October 2016. After the phase I experiment, the above-ground vetiver shoots were harvested. In the phase II experiment, the HSSFCW was allowed to acclimatize to the new hydraulic loading rate for 3 months and until the vetiver grass was regrown, with continuous feeding of wastewater at an average flow rate of 0.177 m^3/d and a hydraulic loading rate of 0.05 m/d (October to December 2016) before the treatment performance data were collected. After the 3-month acclimatization period, performance tests were started to examine the effect of the hydraulic loading rate on HSSFCW cells on COD, TN, and TP from municipal wastewater treatment for the 10 months from January 2017 to October 2017; this was done by feeding the wastewater at a hydraulic loading rate of 0.05 m/d with a corresponding hydraulic retention time of 3 days.

The overall activities of the HSSFCW cells with vetiver grass and the control were conducted for a period of 3 years through monthly monitoring of the influent and effluent quality between March 2015 and October 2017.

Water sample collection and analysis

Water samples were collected from inlet and outlet points in the HSSFCW cells. These points are S_0 at the distribution tank, S_1 CW-Vz, and S_2 from the control as shown in Fig. 1. S_1 and S_2 represented sampling points for the treated effluent coming out of the HSSFCW cells with vetiver grass and the control, and S_0 represented a sampling point for the influent wastewater into the system. Three water samples (1 L each) were collected at each sampling period from the inlet and outlet points of the HSSFCW cells. All water samples were collected between 10 and 11 o'clock in the morning and taken immediately to the Addis Ababa Water and Sewage Authority laboratory for analysis using sterile plastic bottles (1 L).

For the phase I experiment, 10 replicas of water samples were collected every month at each sampling point on the HSSFCW cells (inlet and outlet) between January and October 2016. For the phase II experiment, 10 replicas of water samples were collected every month per sampling point on the HSSFCW cells from January to October 2017. All collected samples were analyzed for water quality parameters: temperature, pH and dissolved oxygen (DO), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). Temperature (by thermometer), pH (by pH meter) and DO (by DO meter) were measured on site immediately after sampling. COD (Method 8000-Reactor Digestion Method), TN (Method 10072-Persulfate Digestion Method Test N Tube Vials) and TP (Method 8190-Acid Persulfate Digestion Method) were measured by spectrophotometer according to HACH instructions.

Plant sample collection and monitoring

Vetiver shoot (tillers) counts and vetiver shoot height measurement were made monthly during the experimental period. The shoot heights and the number of vetiver tillers were measured from nine randomly selected clumps from inlet, middle, and outlet from June 2015 to September 2016. Each plant was given a code number. Plants were visually inspected on a weekly basis. Plants were harvested at operation day 500 (September 20, 2016), after three growing seasons. At the time of harvesting, vetiver shoots were cropped approximately 10 cm from the gravel surface. One day prior to harvesting, representative samples were collected from the HSSFCW and analyzed for dry weight and nutrient contents.

During the phase I experiment, from June 2015 to September 2016, a total of six plant samples were collected once every 3 months for nutrient (TN and TP) determination. For above-ground biomass determination, the plant samples were collected at the end of the experimental period. The plant samples were washed with distilled water and collected for dry weight biomass and nutrient determination. Dry matter of the above-ground biomass of vetiver grass was determined gravimetrically oven-dried at 105 °C until constant weight was obtained. All dried plant samples were grounded separately and passed through a 0.25 mm mesh screen, digested, and analyzed for total nitrogen by the Kjeldahl method and total phosphorus by the spectrophotometric vanadium phosphomolybdate method for above-ground biomass.

Data analyses

Data analysis was performed using Microsoft Excel and the SPSS package Version 24.0. The paired-sample *t*-test was used with 95% confidence interval between the two hydraulic loading rates of 0.025 m/d and 0.05 m/d as well as planted and unplanted HSSFCW cells for the removal of COD, TN, and TP in order to test for statistically significant differences ($p < 0.05$). The results of the analysis of the sample data for percentage removal of COD, TN, and TP measured from influent and effluent of the HSSFCW cells on a monthly basis during the study period were presented as descriptive statistics and in graphs. The quantitative linear relationship of loading versus removal was also analyzed. Treatment efficiency, measured as the percentage of removal for COD, TN, and TP, was calculated from Eq. (1). Pollutant mass loading rate (MLR) is the pollutant mass per unit of surface area of the HSSFCW per daily input and was calculated using Eq. (2). Pollutant mass removal rate (MRR) is pollutant mass removal rate per unit of surface area of HSSFCW per day and was calculated from Eq. (3). The HSSFCW performance was determined based on the concentrations for inlet and outlet water sample pairs. The average values reported for the HSSFCW performance were calculated based on the mean removal efficiencies over the specified experimental period. The amount of nutrient uptake accomplished by the above-ground biomass was calculated according to Eq. (4).

$$\% R = \left(\frac{C_{\mathrm{i}} - C_{\mathrm{e}}}{C_{\mathrm{i}}}\right) \times 100\% . \tag{1}$$

$$\mathrm{MLR} = \frac{Q * C_{\mathrm{i}}}{A_{\mathrm{s}}} \tag{2}$$

$$\mathrm{MRR} = \frac{Q * \left(C_{\mathrm{i}} - C_{\mathrm{e}}\right)}{A_{\mathrm{s}}} \tag{3}$$

$$N_{\mathrm{total}} = \left(\mathrm{DM}_{\mathrm{plant}} \times C_{\mathrm{plant}}\right) \tag{4}$$

where R = percent removal of pollutant in the HSSFCW, C_{i} = influent concentration of a pollutant in mg/L,

C_e = effluent concentration of pollutant in mg/L, Q = flow rate (L/day), A_s = surface area of wetland (m^2), DM = Values represent the total biomass of plant (kg/m^2), C = the average concentrations of N and P in the plants (g N/kg DW or g P/kg DW), N = the amount of nutrients uptake by the aboveground biomass of plants (g/m^2).

Results and discussion

Influent wastewater characterization

The characteristics of the municipal wastewater demonstrated variability during the experimental period. Data obtained from analyses of influent and effluent water samples collected every month during the study are summarized in Table 1. All data related to both the effect of plant and hydraulic loading rate on pollutant removal in influent and effluent water samples were subjected to statistical analysis. During the monitoring period, variations observed for the performance of the HSSFCWs were found to be affected by the applied hydraulic loads and the presence of plants.

The average temperature of the influent wastewater was 24.2 °C. Operating at HLR of 0.025 m/d and 0.05 m/d, the average pH of influent was 7, whereas the effluent from the planted cell and the control for both operations varied between 6.8 and 8.4. The pH values in the effluent for both operations in the planted HSSFCW increased over time. Another study reported that the pH level of domestic effluent of CW decreased from 7.02 to 6.04 after being treated with vetiver grass for 70 days [18]. The main parameters that impact the removal mechanisms for nitrogen and organic matter in constructed wetlands are pH, temperature, and dissolved oxygen (DO). This is because organisms present in biological wastewater treatments are sensitive to these parameters. During the experiment, the observed average temperature was 24.0 ± 1.5 °C, which was favorable for nitrification (16.5–32.0 °C) and denitrification (20.0–25.0 °C) processes.

DO increased in both operations in the planted HSSFCW; it increased an average of 8.3 mg/L for HLR of 0.025 m/d and an average of 7.9 for HLR of 0.05 m/d. DO also increased in the control cell; it increased an average of 3.8 mg/L for HLR of 0.025 m/d and 4.5 mg/L for HLR of 0.05 m/d. Evaluation of effluent water performed for treatments with two hydraulic loading rates showed that the lowest concentration of all pollutant parameters was in water samples obtained with the lowest HLR (0.025 m/d) with a corresponding hydraulic retention time (HRT) of 6 days (Table 1). DO in the CWs planted with vetiver increased significantly even when HRT was decreased from 6 to 3 days. This may be due to the release of oxygen by the roots into the root zone area where the root growth increased with plant age. The study results show that the vetiver grass grew fast and produced a large biomass, which influences transporting of oxygen into the wetland through large massive root hairs, resulting in more aeration.

In both operations, the HSSFCW received influent wastewater with a range of 432–510 mg/L of COD, 58–98 mg/L of TN, and 24–49.5 mg/L of TP. In the study, municipal wastewater characterized with physicochemical parameters showed that high range; this may be due to different sources of wastewater on a daily basis in the different season [19]. For the operation at a hydraulic loading rate (HLR) of 0.025 m/d, the HSSCW cells were subjected to COD, TN, and TP loading rates of 10.9–12.7 g/m^2 d, 1.9–2.5 g/m^2 d, and 0.9–1.25 g/m^2 d, respectively, and at a hydraulic loading rate (HLR) of 0.05 m/d, COD, TN, and TP loading rates were 22.5–25.8 g/m^2 d, 3.8–5 g/m^2 d, and 2–2.5 g/m^2 d, respectively. Higher mass removal of COD, TN, and TP in the HSSFCW with vetiver grass than in the control was recorded for both at operation HLR of 0.025 m/d and

Table 1 Organic matter and nutrient mean concentrations (mg/L) and range of influent and effluents in HSSFCW

HLR	Parameter	Influent			Effluent from CW_vetiver			Effluent from control		
		Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
0.025 m/d	COD	467 ± 25	432	504	23.5 ± 11	9.5	43.4	110 ± 8.5	95.7	120.3
	TN	84 ± 12	58.3	98.1	4.2 ± 1.9	1.9	7.2	26.8 ± 5	15.4	30.6
	TP	41 ± 6.6	24.3	48.6	2 ± 1.1	0.7	4.5	10.3 ± 1.3	7.5	12.2
	T	24.2 ± 1.4	22.2	25.8	24.1 ± 1.5	21.5	25.9	24.3 ± 1.9	21.1	26.6
	pH	7 ± 0.2	6.7	7.4	7.7 ± 0.3	7.3	8.1	7.5 ± 0.3	7.1	7.9
	DO	0.34 ± 0.07	0.24	0.43	8.3 ± 0.9	7.4	10.5	3.8 ± 0.8	3.1	5.9
0.05 m/d	COD	480 ± 20	445	510	44.4 ± 16	26	74.4	122 ± 10	104	138.4
	TN	88 ± 7.7	75.5	98	12 ± 6	6.2	23.3	30.6 ± 8	22	45
	TP	44 ± 3	38.6	49.5	5.1 ± 2.3	2.7	11.2	12.8 ± 2	10.8	16
	T	24.1 ± 1.1	22.6	25.6	23.7 ± 1.9	20.4	25.7	23.6 ± 1.9	20.4	25.7
	pH	7 ± 0.3	6.4	7.3	7.8 ± 0.3	7.4	8.4	7.2 ± 0.2	6.8	7.5
	DO	0.35 ± 0.09	0.24	0.48	7.9 ± 0.9	6.3	9.1	4.5 ± 0.5	3.4	5.1

0.05 m/d. The values of COD, TN, and TP for influent wastewater in this study are higher than the results recorded in a study by Konnerup et al. [20].

Removal efficiency

The overall organic matter and nutrients removal efficiency of the planted HSSFCW and the control with both operations at HLR of 0.025 m/d and 0.05 m/d are presented in Fig. 4. The removal of pollutants in CWs also depends on the inter- and intra-specific variabilities of plant species and/or microorganisms [21], climate conditions, and other factors such as construction type, wastewater quality, and operating conditions [22].

COD removal

In the study, the HSSFCW planted with vetiver grass and the control received municipal wastewater for 3 years using two different HLRs, 0.025 m/d and 0.05 m/d. For the HLR of 0.025 m/d, the maximum removal efficiency of COD was 97.9% for an average inflow concentration of 467 mg/L; for the HLR of 0.05 m/d, the maximum removal efficiency of COD was 94.5% for an average inflow concentration of 480 mg/L. Removal of COD from the HSSFCW system was assessed on the basis of influent and effluent mean concentrations of wastewater. The HSSFCW system removed the organics steadily along the course of the study in proportion to the influent composition in terms of COD removal (Table 1 and Fig. 4). Paired-sample *t*-tests were conducted to evaluate the effect of HLR on COD removal efficiency of the HSSFCW planted with vetiver grass.

COD removal was significantly lower at HLR from 0.05 m/d than at 0.025 m/d (Fig. 4). At HLR of 0.025 m/d, COD loading rate of the HSSFCW ranged from 11 to 12.7 g/m^2 d and the mass removal rate ranged from 10.4 to 11.9 g/m^2 d, whereas at HLR of 0.05 m/d, the COD organic loading rate ranged from 22.5 to 25.8 g/m^2 d and its mass removal ranged from 19.8 to 23.5 g/m^2 d (Table 2). An increase in the hydraulic loading rate increased the organic and nutrient load that passed through the system. The efficiency of the HSSFCW's application to the different hydraulic loading rate conditions was studied throughout their operations monthly over a 10-month period (Fig. 5).

The HSSFCWs with and without vetiver grass were compared for their removal efficiencies. For the HSSFCW with vetiver grass, average removals of COD up to 95% and 92% were obtained at HLR of 0.025 m/d and 0.05 m/d, respectively. Similarly, average removals of COD up to 76% and 74.7% were recorded for the control operation at 0.025 m/d and 0.05 m/d, respectively. In terms of organic matter, the COD removal efficiency of the HSSFCW with vetiver grass varied from 90.6 to 97.9% at HLR of 0.025 m/d and from 84 to 94.5% at HLR of 0.05 m/d; this compared to 72.7 to 80% and 70 to 78%, respectively, for the control. There

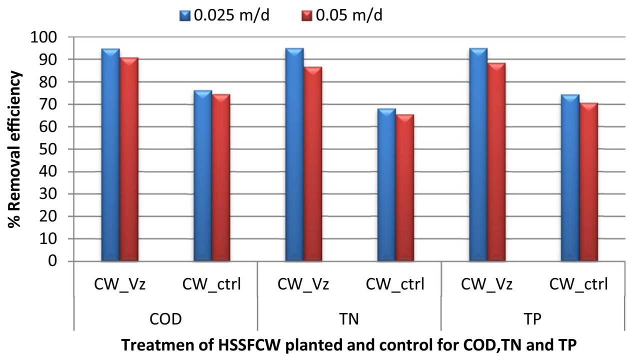


Fig. 4 Organic and nutrient removal efficiency of HSSCWs

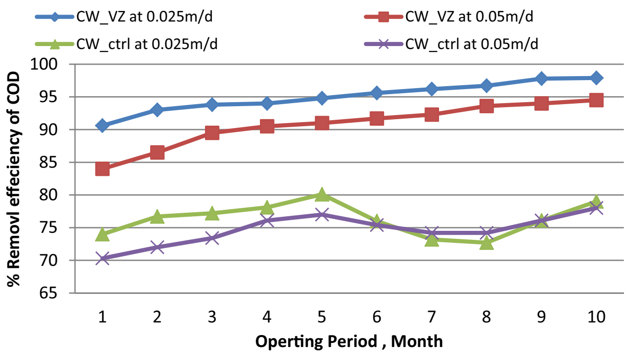


Fig. 5 COD removal efficiency of HSSCW over time

Table 2 Mean and range values of organic and nutrient mass loaded and removed of HSSFCW

HLR	Parameter	Influent MLR (g/m^2 d)		CW_Vz MRR (g/m^2 d)		CW_Ctrl MRR (g/m^2 d)	
		Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
0.025 m/d	COD	11.8 ± 0.6	10.9–12.7	11 ± 0.6	10.4–11.9	8.9 ± 0.7	7.9–10
	TN	2.2 ± 0.2	1.9–2.5	2 ± 0.2	1.8–2.3	1.5 ± 0.1	1.3–1.7
	TP	1.1 ± 0.1	0.9–1.25	1 ± 0.1	0.8–1.2	0.8 ± 0.1	0.63–0.96
0.05 m/d	COD	24.3 ± 1	22.5–25.8	22.2 ± 0.6	19.8–23.5	18.3 ± 0.6	16.5–19.7
	TN	4.5 ± 0.4	3.8–5	3.9 ± 0.3	3.5–4.2	2.9 ± 0.1	2.5–3.4
	TP	2.2 ± 0.2	2–2.5	2 ± 0.2	1.7–2.3	1.64 ± 0.1	1.4–2

were statistically significant differences for COD removal between the two HLRs ($p < 0.001$) in the HSSFCW with vetiver, whereas there were no significant differences in the control ($p > 0.05$).

Ghosh and Gopal [23] reported similar COD removal efficiencies of 46% and 71.8% at HLR of 0.15 and 0.1 m/d for municipal wastewater treatment in HFCWs. Konnerupa et al. [20] investigated CWs loaded with domestic wastewater using different HLRs ranging from 55 to 440 mm/d. The authors reported that the COD mass removal rate varied depending on the mass loading rate. Statistical evaluation of the data obtained for removal efficiencies related to COD showed that hydraulic loading rate (HLR) had a significant effect ($p < 0.001$) on the treatment of the municipal wastewater. The efficiency of CWs depends on influent concentrations, temperature, pH, hydraulic loading, and the presence or absence of macrophyte/microorganisms [24]. Ewemoje et al. [25] obtained 84, 92.4, and 95.3% COD removal at 3, 5, and 7 days retention, respectively. This may be due to longer contact time permitting greater microbial degradation of organic matter.

In the present study, the removal efficiency of COD obtained in operations at both 0.025 m/d and 0.05 m/d showed high removal performance. This could be due to a climatic condition, the presence of vetiver grass, and the addition of aeration by inserting pipes into the CWs. But higher removal efficiency was observed at the lower HLR of 0.025 m/d with HRT of 6 days than at HLR of 0.05 m/d with HRT of 3 days. At longer HRTs, an appropriate microbial community may be established in CWs that provides sufficient contact time to remove contaminants [26]. Shuib and Baskaran [27] reported that COD removal efficiency decreased from 93 to 78% when the HRT was increased from 3 to 4 days, which contradicts the finding of the present study. The results of this study also revealed that the COD mass removal rates of the system were closely dependent on the applied hydraulic loading levels ($R^2 = 0.98$) for the planted HSSFCW and the control.

In this study, the age of vetiver plants had a positive effect on performance as the concentration of COD decreased during the study period (Fig. 5). This was associated mostly with the biomass increase within the wetland system, also reported by Paing et al. [28]. The removal of COD in CWs primarily depends on the amount of oxygen in wastewater [29]. The significance of oxygen on CW efficiency was studied in aerated and non-aerated wetland reactors for the treatment of textile wastewater, revealing COD removal of 95 and 62%, respectively [30]. Organic matter is aerobically and anaerobically decomposed by the microorganisms attached to the plant roots and the media surface [31].

The findings confirm that a high COD removal efficiency was obtained with the growth of vetiver, mostly due to a well-developed root system. Also, a major part of the degradation of COD in the wastewater could be attributed to microorganisms developing a symbiotic relationship with the plants. The higher efficiency of the planted CW could also be attributed to the massive rooting system from the vetiver providing a larger surface area for microbial attachment, which consequently decomposes the organic matter [32]. The results indicate that a HSSFCW with vetiver grass is a very effective method of treating wastewater containing high COD. Vymazal [6] also reported that HSSFCW systems usually achieve high removal of organic matter.

Nitrogen removal

The efficiency of the HSSFCW systems for TN removal at HLR 0.025 m/d was 95.2%, for an average inlet concentration of 84 ± 12 mg/L; at 0.05 m/d HLR, TN removal was 86.8% for an average inlet concentration of 88 ± 7.7 mg/L (Table 1 and Fig. 4). Nutrient removal in the HSSFCWs was found to be above the range reported by Vymazal [6] for domestic wastewater. For removal of TN, efficiency varied from 91.9 to 97.4% for the operation at HLR 0.025 m/d; at HLR of 0.05 m/d, TN removal efficiency of the HSSFCW with planted vetiver grass varied from 75.5 to 93.1% (Fig. 6a).

A paired-sample *t*-test was conducted to evaluate the effect of HLR on TN removal efficiency of the HSSFCW planted with vetiver grass. A statistically significant decrease in TN removal was found by increasing HLR from 0.025 to 0.05 m/d (Fig. 4). There were statistically significant TN differences in the HSSFCW planted with vetiver with the operation of the two HLRs ($p < 0.001$), whereas there was no statistically significant difference for the control ($p > 0.05$). According to Vymazal [6], nutrient removal is usually low in CWs and does not exceed 50% in municipal sewage. However, in this study at both HLRs, the average removal efficiency of TN was 75.5–97.4%.

The high removal of nutrients in this study may be due to the high biomass of vetiver and the tropical climatic condition. Higher macrophyte nutrient uptake rates have been reported for tropical CWs receiving wastewater [33]. Both plant species and HLR influence the removal of total nitrogen in CWs [20]. The processes of nitrogen removal in constructed wetland systems are affected by the process of mineralization (ammonification), nitrogen fixation, volatilization, nitrification, denitrification, plant and microbial uptake, nitrate-ammonification, and anaerobic ammonia oxidation. The results of the study revealed that the TN mass removal rates of the system depended on the applied hydraulic loading levels ($R^2 = 0.96$) for the planted HSSFCW and the control ($R^2 = 0.90$).

The HSSFCW planted with vetiver grass achieved a significantly lower mean effluent TN of 12 mg/L compared to the control at 30.6 mg/L. This may be attributed to the

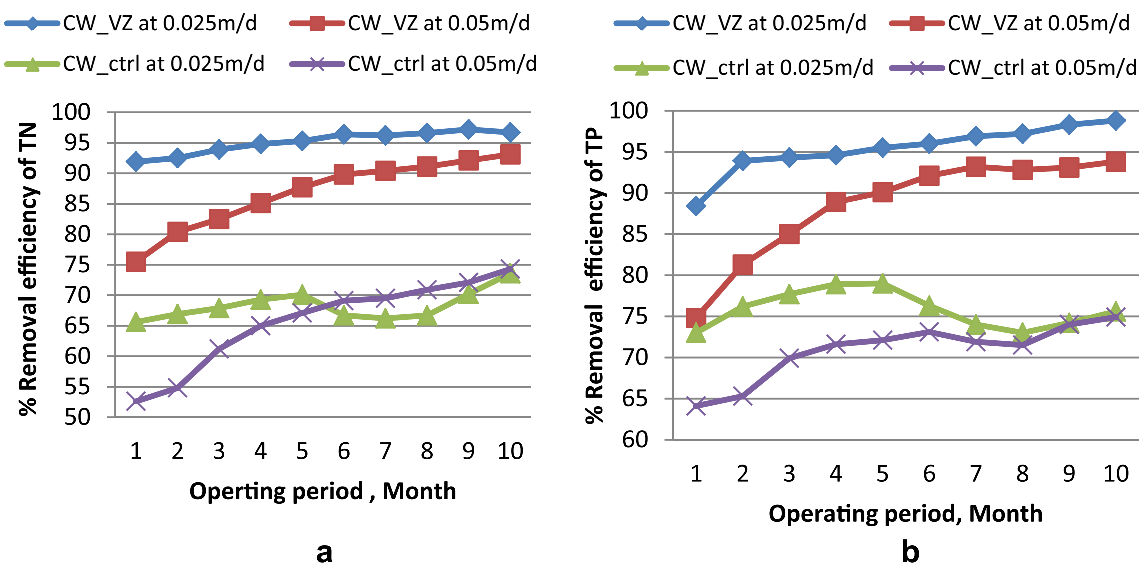


Fig. 6 Removal efficiency of the HSSCWs over time for TN (**a**) and TP (**b**)

uptake of nutrients from wastewater by plant roots and by microorganisms. In the present study, higher nitrogen removal efficiency was recorded at 6 days than at 3 days HRT in both planted and control HSSFCWs. The lower nutrient removal at the shorter HRT in CWs may be associated with incomplete denitrification of wastewater because nitrogen removal requires a longer HRT compared with that required for removal of organics [34]. In addition, the effect of HRT may differ among CWs due to differences in temperature and dominant plant species; these factors can affect the efficiency of wetlands.

Nivala et al. [35] reported that plants may improve the availability of oxygen, exerting a strong promotion on the N paths and on nitrogen removal. Plants also can provide larger amounts of root surface for bacterial growth and for the release of organic carbon as an energy source for denitrifying bacteria [36]. In neutral condition, adsorption and volatilization are limited in constructed wetland systems [31].

Removal of TP

For TP, the removal efficiency varied from 88.4 to 98.8% for the operation at HLR of 0.025 m/d, whereas at HLR of 0.05 m TP removal efficiency of the HSSFCW planted with vetiver grass varied from 74.8 to 93.8%. A paired-samples *t*-test was conducted to evaluate the effect of HLR on the TP removal efficiency of the HSSFCW planted with vetiver grass and the control. A statistically significant decrease in TP removal was found with HLR increasing from 0.025 to 0.05 m/d (Fig. 4). There were also statistically significant differences in TP removal in the HSSFCW planted with vetiver grass between operations at the two HLRs ($p < 0.001$). The differences in TP removal efficiencies between the present study and other studies may be due to differences in the method of vetiver grass application, such as soil as a growing medium, hydroponic system with no supporting medium, and climatic conditions that affect plant growth [37]. Hydraulic loading rate (HLR) and hydraulic retention time (HRT) influence the performance of CWs [12].

The study results show high TP removal efficiency at HLRs of both 0.025 m/d and 0.05 m/d. They also show that increasing HLR leads to decreased removal rates of phosphorus in municipal wastewater. Vymazal [38] reported that in all types of constructed wetlands, the removal of phosphorus is low unless special substrates with high sorption capacity are used. In SSFCWs, the plant species, types of substrate, influent concentration, and climate play significant roles in phosphorous removal. The TP removal efficiency was influenced considerably by the phosphorus absorption capacity of the plants [38].

The finding of this study revealed that the HSSFCW planted with vetiver grass achieved higher TP removal than the control is similar to the finding by Lishenga et al. [39] that a soil-based vetiver system achieved 32.9% TP removal efficiency compared to 14.9% for the unplanted system. This may be due to the vetiver absorbing phosphate and its roots slowing down water velocity, thereby increasing TP removal through sedimentation as organic phosphorous. Albalawneh et al. [40] attributed high TP removal efficiency of CWs to the high affinity of vetiver for phosphorus for its root development.

The study concluded that the TP removal efficiency of HSSFCWs with the application of hydraulic loading rates of 0.025 m/d and 0.05 m/d increased over time as shown in

Fig. 6b. The results reveal that with increasing plant age, the TP removal rate increased for both operations of HLRs. This could be due to the fast-growing and massive root system of vetiver grass, which absorbs phosphorus for its growth. The result revealed that the TP mass removal rates of the system are positively and linearly associated with and closely dependent on the applied hydraulic loading levels ($R^2 = 0.95$) for the planted HSSFCW and the control.

Plant growth and biomass production

The vetiver grass became well established on the gravel-based HSSFCW system loaded with the primary effluent of municipal wastewater (Fig. 1). The growth response of vetiver was revealed by its ability to adapt, survive, and then generate new shoots. The shoots grew slowly during the first 3 months after planting. This period reflected the adaptation of vetiver to wastewater. There was a progressive increase in shoot length and number of shoot tillers with age of the plants. The number of vetiver tillers increased linearly with the growth of the plants. The vetiver grass grew vigorously, from approximately 2–3 tillers per clump to an average of 54–100 tillers per clump in 1 year (Fig. 7a) with a length up to 2.8 m, and formed a dense stand covering the wetland surface (Fig. 7b). The vetiver grass regenerated successfully after harvesting.

The difference in shoot length and a number of tillers of vetiver at the inlet, middle, and outlet zones of the HSSFCWs may be due to greater nutrient load at the inlet than the outlet of the system, making shoot length at inlet greater than in the outlet zone. At inlet, the shoots utilize more nutrients (nitrogen and phosphorus) than an outlet because the availability of nutrient is high in the inlet zone. This indicates that nutrient content was reduced along the length of the HSSFCW. In HSSFCWs, the progressive increase in vetiver shoot height during the monitoring period could be attributed to the increase in the uptake of nutrients with physiological age and biomass of vetiver. At the end of the phase I experiment, samples of above-ground biomass of vetiver from the HSSFCW were harvested and assessed. The dry weight (DW) of the harvested vetiver grass with about 9 tillers ranged from 63.5 to 65.2 g DW. The estimated above-ground biomass dry weight ranged from 10.1 to 10.3 kg DW/m^2 in the HSSFCW cell in 16 months.

Troung and Danh [41] reported that under tropical hot and wet conditions, vetiver grass grows very fast and its biomass is extremely high, more than 100 tons of dry matter per hectare per year, similar to the finding of the present study. This could be due to a fast and very high capability to absorb nutrients in wastewater, mainly nitrogen and phosphorus. From these results, the above-ground part of the vetiver showed that the uptake of nutrients increased with plant age, as shown in (Fig. 8). When plants grow rapidly, they absorb large amounts of nutrients [42]. Results also showed that for the above-ground biomass, nitrogen accumulation exceeded that of phosphorus.

Uptake of nutrients of the above-ground biomass of vetiver grass increased with plant age from 2.4 to 14.6 g N/kg DW and 0.8 to 8.5 g P/kg DW during phase I of the experimental period. At the end of the experiment, the above-ground nutrient standing stock of vetiver grass in the HSSFCW was 147.5 to 150.4 g N/m^2 and 85.5 to 87.5 g P/m^2. Vymazal and Kröpfelova [31] reported above-ground N standing stock in the range of 5.3–58.7 g N/m^2

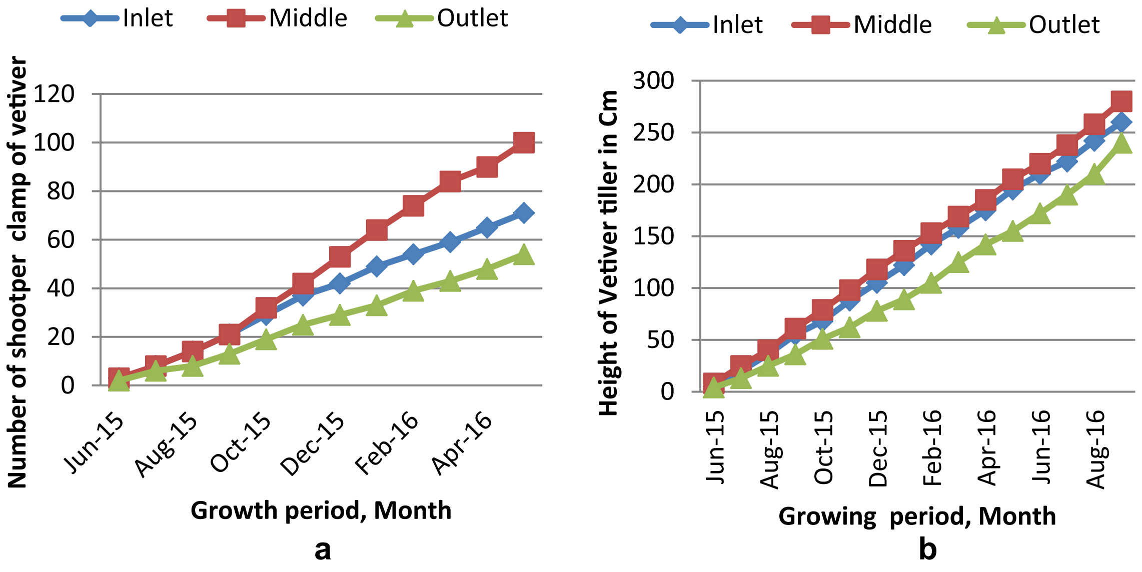


Fig. 7 Monthly development of vetiver shoot density (**a**) and vetiver grass height (**b**) during the experimental period

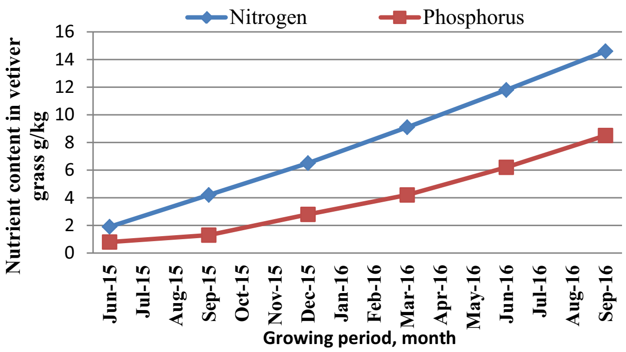


Fig. 8 Nutrient uptake of the above-ground vetiver grass during the experimental period

and the above-ground P standing stock within the range of 0.7–5.5 g P/m^2 for different plants species in HFCW systems. Nutrient uptake in the present study was higher than the reported results in the literature.

Wetland plants need nutrients for growth and reproduction. They take the nutrients up primarily through their root systems. As wetland plants are very productive, considerable amounts of nutrients can be stored in their biomass [43]. Studies indicated that the above-ground and below-ground parts of the plants in CWs increase microorganism diversity and provide large surface areas for the development of a biofilm, which is responsible for most of the microbial processes [44].

Conclusion

The pilot-scale HSSFCWs showed high pollutant removal efficiency and high effluent quality of municipal wastewater for COD, TN, and TP levels. The highest average pollutant removal efficiencies of COD, TN, and TP were obtained using HLR of 0.025 m/d with an HRT of 6 days in the HSSFCW planted with vetiver grass; efficiencies were 95%, 95.2%, and 95.2%, respectively. The second highest efficiencies were achieved at HLR of 0.05 m/d with an HRT of 3 days: 90.8%, 86.8%, and 88.5%, respectively. The *t*-test results showed that COD, TN, and TP removal were significantly higher in the HSSFCW planted with vetiver grass than in the unplanted plot ($p < 0.001$). The significantly higher mass removal rates of COD ($R^2 = 0.98$), TN ($R^2 = 0.96$), and TP ($R^2 = 0.95$) in the HSSFCW planted with vetiver grass were strongly dependent on the hydraulic loading rates for municipal wastewater treatment. The estimated above-ground biomass of dry weights of vetiver harvested ranged from 10.1 to 10.3 kg DW/m^2 in the HSSFCW cell during the 16-month study period. The uptake of nutrients of the above-ground biomass of vetiver grass increased with plant age, from 2.4 to 14.6 g N/kg DW and 0.8 to 8.5 g P/kg DW during the study period. At the end of the experiment, above-ground nutrient standing stock of vetiver grass in the HSSFCW ranged from 147.5 to 150.4 g N/m^2 and 85.5 to 87.5 g P/m^2. The study concluded that both applications of HLR are capable of removing organic matter and nutrients efficiently. Therefore, vetiver grass can be used for remediation of pollutants in municipal wastewater in Addis Ababa. An HSSFCW offers a simple and adaptable approach to treating municipal wastewater that needs to be validated for wider use in other towns with different wastewater characteristics and different climates.

Acknowledgements The authors thank Ethiopian Institute of Water Resources, Addis Ababa University (AAU) who supervised the financial support provided by the United States Agency for International Development (USAID) and Research Fund for International Young Scientists (Grant Agreement No: W/5799-1). The authors are also thankful to the Addis Ababa Water and Sewerage Authority for allowing developing the pilot-scale constructed wetland system in the premises of wastewater treatment plant and the laboratory facilities. The authors also acknowledge the University of Connecticut for the facility of access to electronic library and Ann Byers for editing the manuscript at short notice.

Author's contributions KA conducted experiments in the field and wrote up the manuscript. SL, WM, HK, EM supervised the experimental site and structured, read, edited, and approved the final manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the United States Agency for International Development (USAID) and Research Fund for International Young Scientists (Grant Agreement No: W/5799-1).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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