Evaluating the performance of horizontal sub-surface flow constructed wetlands: A case study from southern India

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Abstract

Constructed wetlands are a nature-based engineering solution enabling polishing of septic tank effluents at low-cost. However to date, the influence of planting on treatment efficiency remains little understood. Here we report a case study evaluating the performance of two near-identical Horizontal Sub-Surface Flow Constructed Wetlands (HSSF-CW) deployed at a school in southern India. The HSSF-CWs were of similar size and construction with the exception that one system was planted (*Canna indica*) whilst the other was operated without plants. Both systems were operated at similar hydraulic loading rate (HLR) and hydraulic retention time (HRT) of 84 mm day^{-1} and 3.7 days, respectively to treat the effluent from septic tanks. The systems were monitored fortnightly for one year and the performance kinetics, nutrient and organics removal efficiencies were evaluated. Significant reduction in biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) ($p < 0.05$) were observed in both systems with BOD_5 removal efficiency of 67 % and 61 % in the planted and unplanted systems, respectively. Whilst the effluent from both systems met the environmental discharge standards set by Central Pollution Control Board (CPCB), India, the total phosphorus (TP) and total suspended solids (TSS) removal in the unplanted system were significantly greater than in the planted system. The first-order decay rate constants (K) obtained for TN (K_{TN}) and BOD_5 (K_{BOD_5}) in the planted system however (0.16 day^{-1} and 0.30 day^{-1}) were higher than in the unplanted system (0.09 day^{-1} and 0.27 day^{-1}).

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Greater R^2 values obtained for the planted system (~ 0.90) suggests applicability of a first-order decay model to assess contaminant degradation. Plants contributed to 7 % (0.3 gm/m^2/day) BOD_5, 18 % (1.9 gm/m^2/day) COD and 5 % (0.09 gm/m^2/day) TN load removal. Our data demonstrates that planting is effective in improving treatment efficiency in constructed wetlands, and whilst the improvement is marginal here, it is noted that a rust infection could have limited effectiveness of the plants in this case.

Keywords:

HSSF-CW, Wastewater, *Canna indica*, removal kinetics, load reduction, plant uptake

1. Introduction

The release of untreated domestic wastewater, agricultural runoff and industrial effluents results in the deterioration of surface water quality, loss of biodiversity and can cause serious risk to public health (Mayo and Mutamba, 2004). In 2014, the Government of India (GOI) launched the Swachh Bharat Mission (SBM) to eradicate open defecation and promote safe sanitation in all households across India. The SBM mission led to construction of 102 million new toilets across the country (Ministry of Urban Development, Government of India, 2017), and, by the end of July 2019, the GOI declared rural India as open defecation free. Since the mission was launched, numerous studies have been conducted to assess the impact of SBM on the aquatic environment (Bhallamudi et al., 2019; NIUA, 2017; Rohilla et al., 2017). A number of studies reported groundwater contamination of local aquifers as a result of black water disposal via soak pits (Bhallamudi et al., 2019; Kumpel et al., 2017; Olonga et al., 2015), a low-cost solution that allows leachate to percolate into the groundwater. To tackle this, septic tanks were suggested as a preferred treatment system for deployment at household and community level. However, given that septic tanks remove only 60 to 65 % of BOD_5, additional treatment units are required to meet effluent discharge standards set by the Central Pollution Control Board (CPCB) (DBT and CPCB, 2019). Low-cost decentralised treatment systems such as constructed wetland have the potential to polish the effluent from septic tanks to remove organics and nutrients, making effluent safe to discharge into the environment (Kivaisi, 2001; Mairi et al., 2012).

Various studies have been conducted on the potential of constructed wetland technologies for secondary/ tertiary treatment of wastewater in India (Juwarkar et al., 1995; Ramprasad and Philip, 2018; Srivastava et al., 2020; Suganya and Sebastian, 2017). The type of constructed wetlands used in India includes the PHYTORID systems (works on the principle of sub-surface flow technology), horizontal/ vertical sub-surface flow systems and hybrid reed bed systems, with different types of plantation (DBT and CPCB, 2019; Haritash et al., 2015; Sharma et al., 2014; Suganya and Sebastian, 2017). Constructed wetlands, by design, often support a dense growth of plants which are thought to be an important component of wetland systems with emergent macrophytes most commonly used in sub-surface constructed wetlands (Schierano et al., 2020; Wu et al., 2019).

In constructed wetlands, the treatment of wastewater occurs through a combination of physical, chemical and biological processes (Sehar and Naz, 2016). Plants in constructed wetlands have been shown to stabilize hydraulic conductivity, prevent erosion, promote filtration, provide surface area for biofilms, uptake nutrients, release root exudates that are utilized by biofilms and introduce additional fungi species and symbiotic bacteria to the wetland ecosystem (Brix, 1997; Jason, 2007; Kadlec and Wallace, 2008; Stottmeister et al., 2003). Planted constructed wetlands are reported to remove 70-95 % of organic matter and nutrients from the wastewater (Albalawneh et al., 2016; Haritash et al., 2015; Ramprasad and Philip, 2018). *Canna indica* is widely used wetland plant species that is very effective in removing nutrients from wastewater (Liang et al., 2017). *Canna indica* exhibits rapid growth rate and high biomass production which provides surface area for the growth of biofilms, and, the fibrous root system and root oxygen release enhances microbial activity (Lekshmi et al., 2020; Li et al., 2013). *Canna indica* also acts as a good phyto-accumulator for reducing contaminant load (Suganya and Sebastian, 2017). Climatic conditions in India favors the growth of *Canna indica* making it suitable for wetland vegetation in rural communities (Haritash et al., 2015). Harvesting plants at regular intervals is important to sustain the contaminant removal efficiency of the constructed wetlands (Wallace, 2015). Regular harvesting however adds to the extra operational cost of constructed wetlands (Dotro et al., 2017), which is one of the key barriers towards adoption and scaling up of planted constructed wetlands (Kivaisi, 2001). A growing number of studies however report that microbial degradation, as compared to vegetation uptake processes, acts as the major contributor to contaminant removal in constructed wetlands (da Costa et al., 2015, 2013; Ebrahimi et al., 2013; Iasur-Kruh et al., 2010). In unplanted constructed wetlands systems, various processes contribute to treatment including physical filtration and sedimentation remove suspended matter; chemical formation of complexes can remove phosphorus; chemical precipitation can promote removal of iron and heavy metals; and microbiological degradation in the biofilm promotes removal of dissolved organic and inorganic matter (de Matos et al., 2018).

For effective deployment of constructed wetlands (with plants or without plants), confidence in the translation of design principles to the field is essential. Presently, constructed wetlands design and deployment for use in sanitation systems lacks design principles, and, understanding of the removal kinetics of contaminants in field conditions remains limited (Davis, 1995; Mairi et al., 2012; Rohilla et al., 2017). Here we present a case study based on field data describing the operation and performance of two near identical wetland systems deployed in rural India. The objective of the study is to a) assess and compare the performance of planted and unplanted horizontal subsurface flow constructed wetland (HSSF-CW) systems b) estimate the contaminant removal kinetics in the planted and unplanted HSSF-CW systems and c) assess the contribution of vegetation to contaminant load removal.

2. Methodology

2.1 Description of constructed wetlands

The HSSF-CW systems studied are one of a number of technologies deployed to provide a complete, closed-loop decentralised wastewater treatment and recycling system at Berambadi Government Primary School ($11^0 45' 44'' \ N; 76^0 34' 03'' \ E$) located in Berambadi village, Chamarajanagar district, Karnataka (Subramanian et al., 2020). The area receives an annual rainfall of 915 mm and has an average annual temperature of 22.9 ºC (Sekhar, 2016). Berambadi Primary School serves around 180 students and 5 teachers. The HSSF-CW systems reported in this study were deployed to provide secondary treatment to the effluent from two anaerobic systems (septic tanks) that serve as primary treatment for the black water and greywater (hand wash facility provided in the toilet block) generated at the school's toilet block. The planted HSSF-CW is connected to a plug-flow septic tank and the unplanted HSSF-CW to a conventional septic tank, both of which generate effluents of similar quality. The gravel bed of each HSSF-CW has dimension 4.4 m×1.0 m× 0.9 m (length×width×height) with sampling ports (locations of sampling pipes numbered 1-10) distributed along the length (Fig 1). The base of each wetland slopes towards the outlet with a 1% gradient. The outflow from each HSSF-CW is collected through an outflow pipe located at the bottom of the CWs. A riser pipe is used to maintain the water depth (0.8 m) in each of the HSSF-CW systems. For discharge monitoring, outflow from each system was collected separately in two graduated circular tanks. The overflow from the tanks was finally discharged into an open storm water drain.

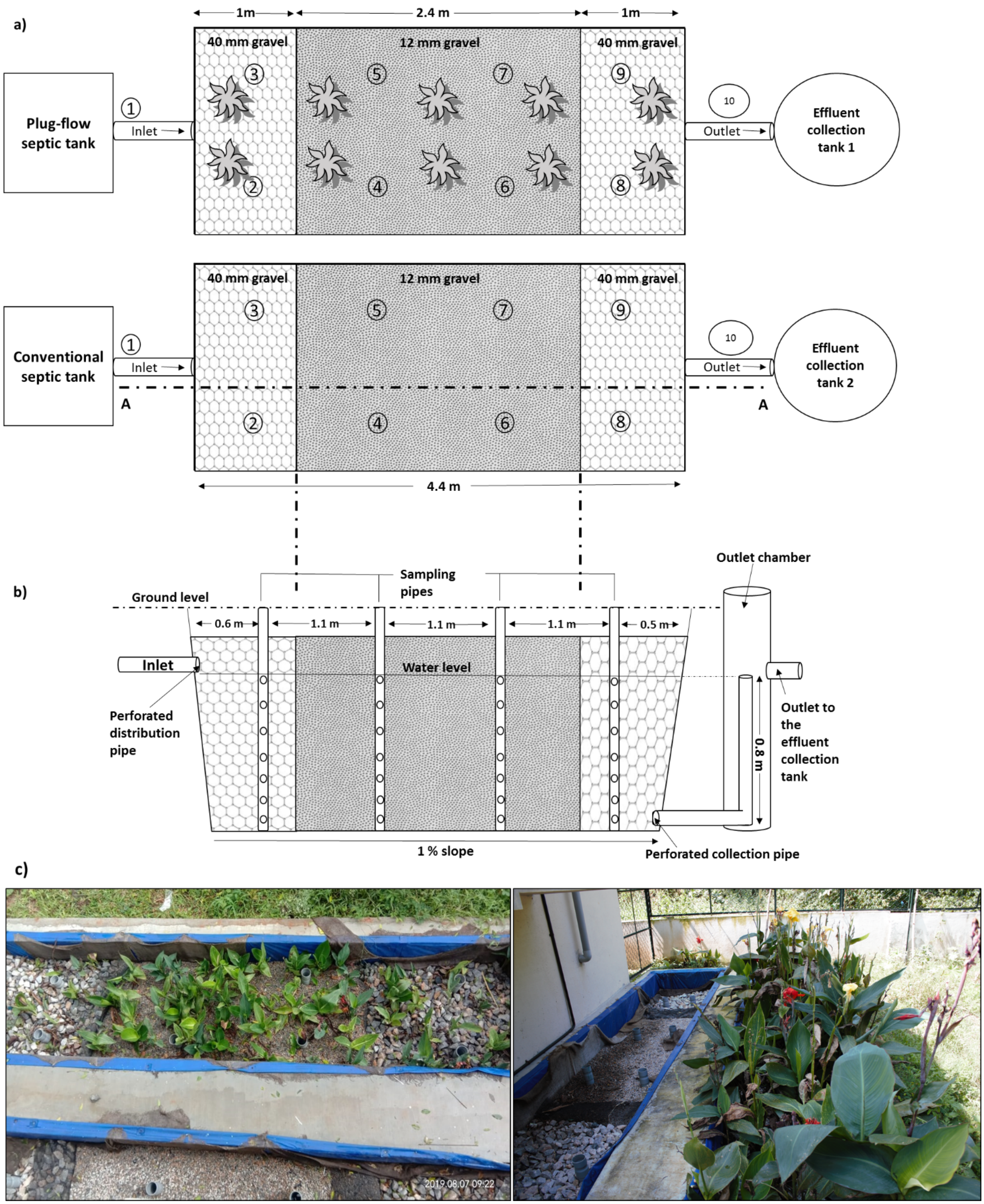


Fig 1: a) Flow diagram of the plan view, b) elevation view (section 'AA') and c) field image of the HSSF-CW systems.

2.2 Flow measurements and operating conditions

The volumetric flow rate to each of the HSSF-CWs was estimated using data collected on water consumption in the toilets. The water consumption was monitored via a float gauge connected to overhead tanks supplying water to the toilets. Samples for water quality analysis and water consumption data was collected simultaneously during the working hours. The average water consumption in the toilets was 740 L day^{-1} and the average outflow from each HSSF-CW was 350 L day^{-1}. The calculated hydraulic loading rate (HLR) and the hydraulic retention time (HRT) were 84 mm day^{-1} and 3.7 days respectively. The porosity of both HSSF-CW systems were calculated using equation 1 and was approximately 32 % (Conley et al., 1991).

$$Porosity\ (\%) = \frac{V_V}{V_T} \times 100 \qquad (1)$$

Where, V_V is the void volume determined at the beginning of the study by pouring a known amount of water into the wetland bed filled with aggregate material and V_T is the total volume of the bed.

Both systems were operational from January 2019 and the water quality monitoring was carried out fortnightly from January to December 2019. The systems were operating without plants until July 2019. To meet the objectives of the study, in July 2019 young *Canna indica* plants (with similar shoot length and dry biomass around 17.7 g/plant) propagated from rhizome cuttings were transplanted into one of the HSSF-CW systems at a planting density of 20 plants/m^2. The plants were allowed to acclimatize for one month and samples were collected for water quality analysis and efficiency evaluation/comparison of two systems(Mantovi et al., 2003).

2.3 Water Sampling and analytical methods

Water samples were collected from ten locations (perforated pipes) provided across each system (Fig 1, sample points 1 to 10). The inflow (outflow from the septic tanks) samples were collected from the sampling ports provided during the time of construction. Water samples were collected in sterile borosilicate glass bottles (100 ml) and plastic bottles (500 ml) (LDPE, medical-grade USP Class VI autoclavable) and were tested for physical, chemical and biological parameters. Samples were preserved at a pH < 2 for some parameters (*) using sulfuric acid to minimize precipitation and microbial degradation. Samples were stored at temperature < 4^o C during transportation to the Water and Soil Laboratory at the Ashoka Trust for Research in Ecology and Environment (ATREE). All water quality parameters were tested according to methods described in APHA Standard Methods for the Examination of Water and Wastewater (Federation and Association, 2005). Temperature, pH, electrical conductivity (EC) and dissolved oxygen (DO) were measured onsite using a YSI Pro 1030 and YSI Pro ODO sensors (YSI, Yellow springs, USA), and nitrate-N was measured onsite using a Hach Nitrate Pocket Colorimeter (Hach Company, Loveland, USA). Ammonium-N*, total nitrogen (TN)*, orthophosphate-P (ortho-P) and total phosphorus (TP)* were analyzed photometrically (Merck KGaA, Darmstadt, Germany). Biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD)* were analyzed by methods described in APHA standard methods, 2005. Faecal coliforms (FC) were detected and enumerated using Colilert 18 (IDEXX Laboratories, Westbrook, USA).

2.4 Data analysis

Statistical analysis of data was conducted using IBM SPSS Statistics 23.0 (Armonk, NY: IBM Corp.). Statistical difference between the influent and effluent quality of two systems were determined using an independent sample t-test. Linear regression graphs were plotted using Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA; USA).

2.5 Calculations

Contribution of plants to contaminant removal

The contribution of plants to contaminant removal was estimated as the difference (percentage) in load reduction between two systems. Mass loading of contaminants at the inlet and outlet of each were estimated using equation 2. The percentage reduction in the contaminant loads were estimated using equation 3.

$$Contaminant\ load\ (L)\ (mg.day^{-1}) = C \times Q \times 1000 \qquad (2)$$

Where C is the contaminant concentration (mg/L) and Q is the flow rate (L/day)

The contribution of plants to contaminant removal was estimated using equation 2

$$Contaminant\ load\ reduction\ (\%) = \frac{(L_i - L_o)}{L_i} X100 \qquad (3)$$

Where,

L_i is the contaminant load at the inlet and L_o is the contaminant load at the outlet.

Contaminant removal kinetics

The first-order plug-flow model was used to describe the removal of TN, TP, BOD_5 and COD. The removal rate constant K was calculated by linear regression using the integrated first-order plug-flow equation (4) (Sooknah and Wilkie, 2004):

$$\ln\left(\frac{C_i}{C_o}\right) = K_T t \qquad (4)$$

Where C_i is the influent contaminant concentration in mg/L and C_o is the effluent contaminant concentration.

K_T is the temperature-dependent first-order volumetric rate constant (day^{-1}), and t is the Hydraulic Retention Time (day).

3. Results and discussion

3.1 Performance of planted vs. unplanted constructed wetlands

The effluent quality of both systems met the discharge standards set by CPCB (MOEF & CC, 2017) with BOD_5 and COD less than 30 mg/L and 250 mg/L respectively (Table 2). Whilst the water quality characteristics of influent and effluent of each of the HSSF-CWs was observed to be variable (Table 2), this is common of systems deployed in the field under real-world operating conditions.

The DO levels at the inlet of both HSSF-CW systems were very low since the systems receive primary treated effluent from anaerobic systems. Despite this, a significant reduction ($p < 0.05$) in the effluent BOD_5 and COD was observed in each system and the planted HSSF-CW offered slightly higher removal of both BOD_5 and COD. This can be attributed to release of oxygen through the roots of *Canna indica* which facilitates the decomposition of organic matter by aerobic microbes (Gaballah et al., 2020). In addition, the exchange of oxygen through perforated stand pipes provided for sample collection might have contributed to the degradation of organic matter in both systems. An average of 67 %, 61 % reduction in BOD_5 and 53 %, 38 % reduction in COD was observed in planted and unplanted HSSF-CW respectively (Table 2). Removal efficiency here is lower than that reported by Haritash et al., 2015 who observed 70-96 % and 64-99 % reduction in BOD_3 (BOD measured after 3 days of incubation at 27 °C) and COD respectively in HSSF-CW planted with Canna lily (HRT ~ 24 hours). The contaminant removal efficiency depends on composition of contaminants/constituents present in the inflows to the constructed wetland system (D. Wang et al., 2014). The system reported in the study cited by Harish et al. 2015 was fed with synthetic wastewater containing readily degradable constituents such as glucose, potassium dihydrogen phosphate (KH_2PO_4), ammonium sulphate [$(NH_4)_2SO_4$], and potassium nitrate (KNO_3), whilst the systems reported here were fed with the effluent from septic tanks. Thus, whilst removal efficiencies are lower, both systems reported here may be qualitatively described as well functioning with respect BOD_5 and COD removal.

No significant difference ($p>0.05$) was observed in ammonium-N removal efficiencies between the two systems. Nitrate-N concentration was observed to increase significantly in the effluent of both the planted and unplanted HSSF-CW systems. This can be accounted to the low C/N ratio of the influent (2.0) which facilitates the colonization of nitrifying community and nitrification (Hu et al., 2009; Zhu et al., 2014). The net increase in nitrate-N concentration observed in the planted HSSF-CW was significantly lower indicating uptake/assimilation of nitrate-N by plants (Table 1). Some studies have reported 280 -500 % increase in nitrate-N concentration in both planted and unplanted constructed wetland, suggesting conversion of ammonium-N to nitrate through the nitrification process (Dornelas et al., 2009; Iasur-Kruh et al., 2010). Aeration through perforated pipes present in the systems of this study might have further facilitated the metabolism of nitrifying microbial community. No significant difference was observed in the average TN concentrations suggesting the major role of biofilms in nitrogen assimilation in both systems. Relative to the unplanted system, an increase of 5 % in ortho-P and 7 % in TP concentration were observed at the outlet of planted HSSF-CW. Many studies have reported the presence of more efficient and high concentration of inorganic P-solubilizing bacteria and organic P mineralizing bacteria in the rhizosphere soil than in the non-rhizosphere soil (Cao et al., 2018; Qian et al., 2010; Rodríguez and Fraga, 1999; Teng et al., 2019). Hence the increase in ortho-P concentration at the outlet of planted HSSF-CW could be accounted to increased solubilization of insoluble P in the system and the incompetency of Canna plants to assimilate ortho-P due to rust infection. Again, the relative increase of TP in the planted HSSF-CW could have arisen due to rust infections observed in *Canna indica* and subsequent release of phosphorus assimilated into the plant biomass back to the effluent due to necrosis (Iasur-Kruh et al., 2010; Garcia et al., 2010; Dotro et al., 2017; Wallace, 2015).

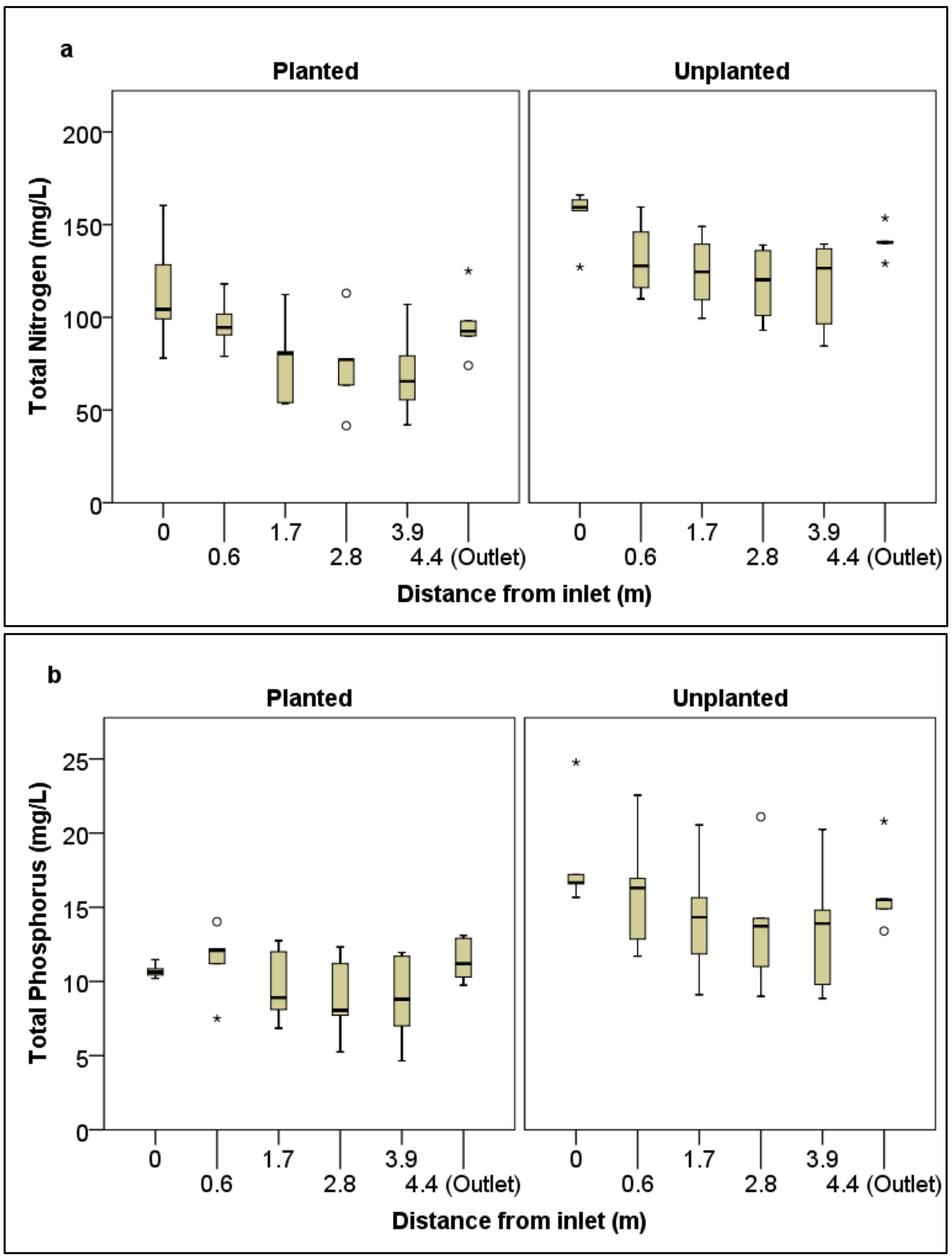
Lower TSS removal was observed in planted HSSF-CW as compared to the unplanted HSSF-CW. This was unexpected as vegetation is thought to promote TSS removal via settling, interception and filtration by vegetation. Again, this may have been influenced by the onset of rust infections in the Canna plants. The appearance of yellow pustules in the foliage of Canna plants were observed after a few days of planting and resultant immature leaf drying and dropping as a result of the infections in *Canna indica* can contribute to lower TSS removal in planted HSSF-CWs (Kadlec and Wallace, 2008). One log order reduction in the faecal coliform (FC) levels was observed across each of the two systems. Similar FC removal rate were observed for CW operated for 8 years in Rabat (Morocco) (Boano et al., 2020). Various studies reported the persistence of FC in organic sediments and low die-off rates in wastewater (Anderson et al., 2005). The data suggests that accumulation of suspended solids within the filtration media have contributed to low die-off of FC (Reed, 1993). Poor TP and TSS removal in the planted HSSF-CW as compared to unplanted HSSF-CW could be attributed to the development of infection in *Canna indica*.

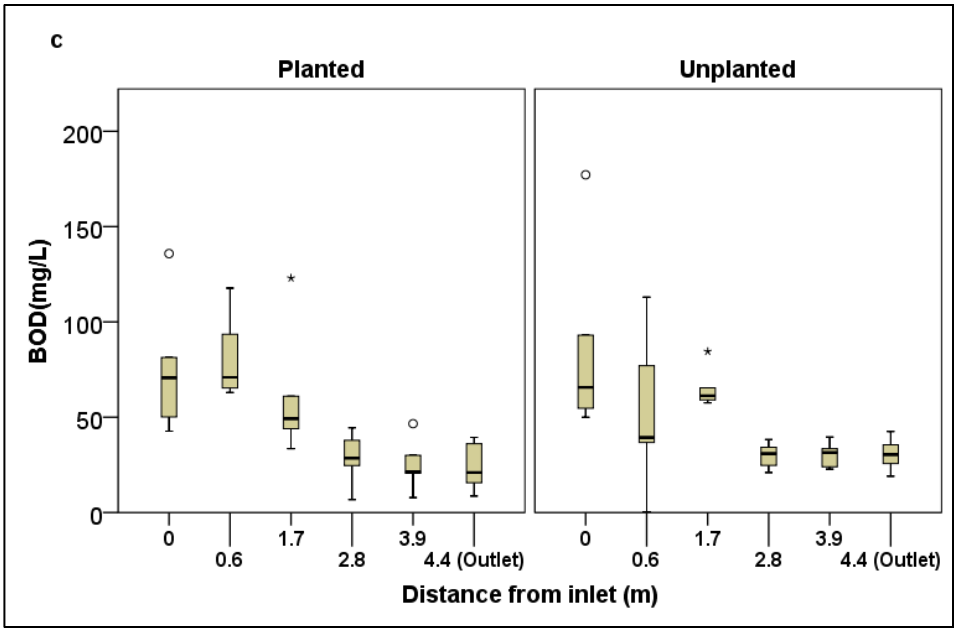
Table 1: Influent and effluent contaminant levels in planted and unplanted HSSF-CW

Parameters (n = 5)	**Planted HSSF-CW**			**Unplanted HSSF-CW**		
	Inlet (Mean± SD)	Outlet (Mean± SD)	Percent change	Inlet (Mean± SD)	Outlet (Mean± SD)	Percent change
Temperature (°C)	24.4 ± 1.7	23.2 ± 1.0	-	25.0 ± 1.8	23.3 ± 1.1	-
pH	8.0 ± 0.2	7.7 ± 0.1	-	8.3 ± 0.0	7.9 ± 0.1	-
EC (µS/cm)	1842 ± 301	1812 ± 269	-	2425 ± 312	2264 ± 281	-
TSS (mg/L)	125.8 ± 67.5	87.1 ± 69.4	-5 %	203.0 ± 103.7	69.5 ± 37.8	61 %
Nitrate-N (mg/L)	1.9 ± 2.0	4.0 ± 4.0	-297 %	2.3 ± 0.8	7.5 ± 5.8	-387 %
Ammonium-N (mg/L)	87.1 ± 28.2	76.1 ± 24.0	7 %	114.3 ± 28.9	98.4 ± 25.7	11 %
TN (mg/L)	114.0 ± 31.5	95.9 ± 18.6	12 %	153.5 ± 16.7	140.8 ± 8.7	8 %
Ortho-P (mg/L)	10.1 ± 0.7	10.5 ± 1.4	-5 %**	17.0 ± 2.8	15.1 ± 1.8	10 %**
TP (mg/L)	10.7 ± 0.5	11.5 ± 1.5	-7 %**	18.2 ± 3.7	16.0 ± 2.8	11 %**
DO (mg/L)	0.43 ± 0.16	0.29 ± 0.02	26 %	0.40 ± 0.04	0.28 ± 0.03	29 %
BOD_5 (mg/L)	76.1 ± 36.8	24.1 ± 13.2	67 %	88.1 ± 52.5	30.6 ± 9.0	61 %
COD (mg/L)	233.8 ± 116.7	108.5 ± 52.0	53 %	321.3 ± 201.2	170.6 ± 63.8	38 %
FC (MPN/ 100 mL)	1.37×10^5 ± 8.88×10^4	1.89×10^4 ± 1.67×10^4	1 log	2.73×10^5 ± 2.91×10^5	1.27×10^4 ± 1.10×10^4	1 log

** Significant difference ($p < 0.05$) in % reduction.

The mean TN, TP, BOD_5, COD and DO concentration measured for all time points in samples taken along the length of the HSSF-CWs were plotted (Fig 2). Linear reduction in contaminant concentrations were observed in both systems for each parameter except for TN and TP. A reduction of 39 % and 18 % in TN and 24 % and 26 % in TP concentrations at the sample point 3.9 m along the HSSF-CWs (sample points 8 & 9, Fig 1) were observed in the planted and unplanted HSSF-CW systems respectively (Fig 2). However, both parameter concentrations were observed to increase at the outlet (sample point 10, Fig 1) relative to the concentration at sample points 8 and 9. This could be attributed to either re-suspension and dislodging of suspended particles and biofilms or short-circuiting of inflows in the constructed wetlands (Fu et al., 2018; Geranmayeh et al., 2018). Short-circuiting leads to increased hydraulic conductivity in the diagonal flow path which in turn reduces the HRT thereby affecting the treatment performance of the HSSF-CW (Wang et al., 2014; Guo et al., 2015; Shih et al., 2017).




c
Planted
Unplanted
BOD(mg/L)
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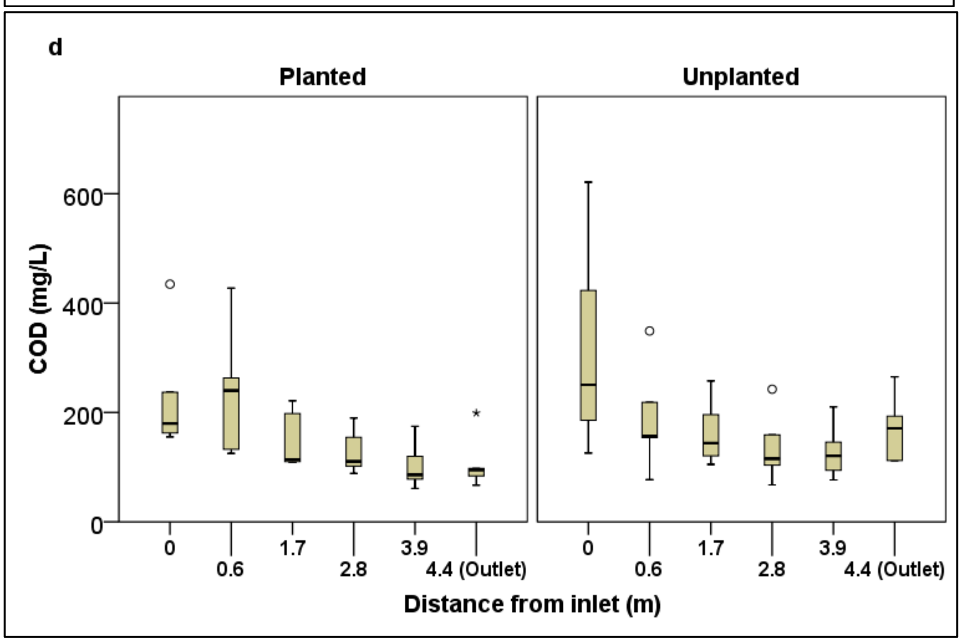
50
100
150
200
0
0.6
1.7
2.8
3.9
4.4 (Outlet)
Distance from inlet (m)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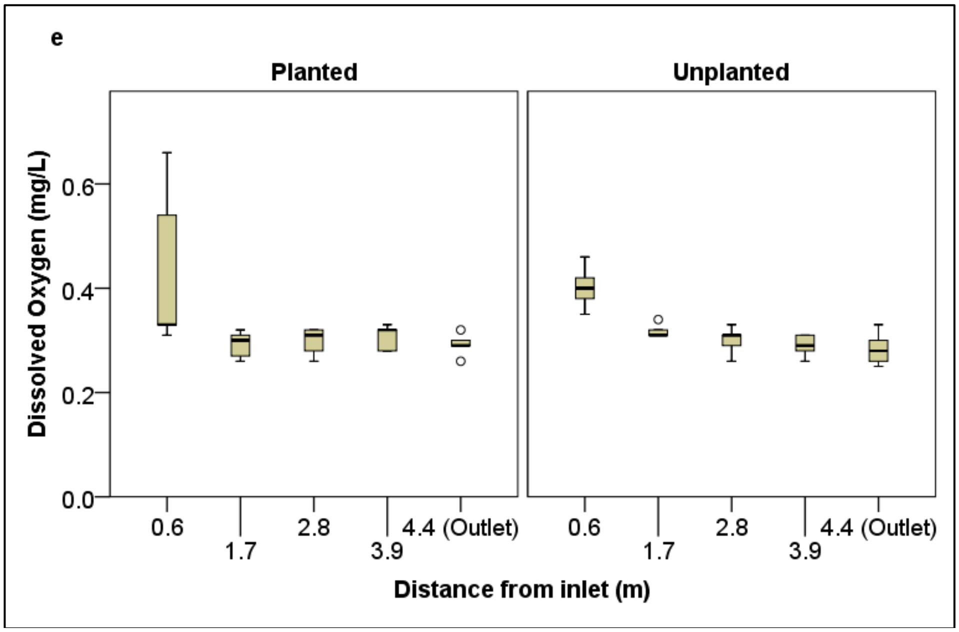

Fig 2: Variation in mean concentrations of a) TN b) TP c) BOD_5 d) COD and e) DO with distance from the inlet. The bands show the median value for each group; bottom and top of boxes show the first and third quartiles; and whiskers show maximum and minimum values with 1.5 of IQR of upper and lower quartiles.

Despite a decreasing trend across the length, an increase in TP concentration was observed at the outlet of both systems. This could be attributed to the reappearance of phosphorus that was temporarily removed and stored in the sediments via precipitation (see Fig 2). Anoxic conditions along the length of CW leads to redox-sensitive mobilization and release of phosphorus thereby contributing to poor TP removal efficiencies (Fig 2 e) (Søndergaard et al., 2003).

3.2 Impact of vegetation on contaminant load reduction

A mass balance approach was applied to estimate the contribution of plants to nutrient and organic matter removal. During the study period, both systems were operated at similar HLR (84 mm/day). The BOD_5 and COD mass loading rates were similar for each system however the TN and TP mass loading rates were dissimilar (Table 2). This could be attributed to the performance of the conventional septic tank and the plug flow septic tanks connected upstream of the unplanted and planted systems respectively. Given the difference in mass loading between the systems with respect nutrients, the pollutant removal data is normalized by estimating the percentage of contaminant load removal to enable comparison between the systems (Fig 3).

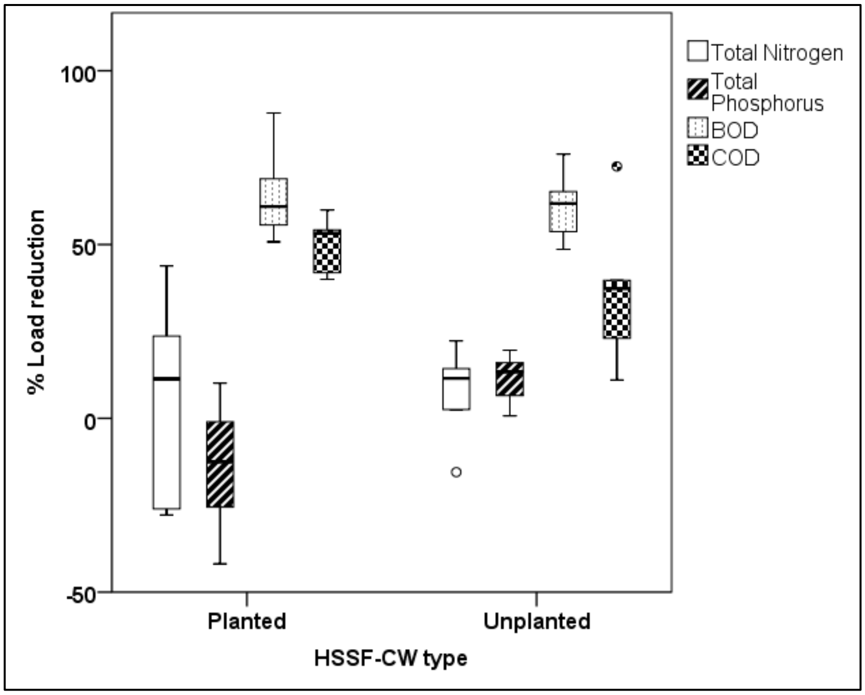

Fig 3: Percentage reduction in contaminant load, planted vs. unplanted HSSF-CW.

Table 2: Contaminant loading and removal rates, percentage load reduction by planted and unplanted HSSF-CWs.

Parameter (n = 5)	**Planted HSSF-CW (Mean ± SD)**			**Unplanted HSSF-CW (Mean ± SD)**		
	Loading rate ($gm^{-2}day^{-1}$)	Removal rate ($gm^{-2}day^{-1}$)	% Load removal	Loading rate ($gm^{-2}day^{-1}$)	Removal rate ($gm^{-2}day^{-1}$)	% Load removal
TN	9.6 ± 2.9	1.7 ± 2.7	13 ± 24	12.8 ± 2.7	1.2 ± 1.6	8 ± 13
TP	0.9 ± 0.1	-	-	1.5 ± 0.4	0.2 ± 0.1	12 ± 7
BOD_5	6.6 ± 3.3	4.6 ± 2.7	68 ± 14	7.5 ± 4.6	4.9 ± 3.9	61 ± 10
COD	19.3 ± 8.6	10.7 ± 5.5	54 ± 7	25.1 ± 14.6	11.2 ± 13.5	36 ± 22

An average of 13 % and 8 % TN load and - 6 % and 12 % TP load reduction was observed in planted and unplanted systems respectively. Time series plots of the TN and TP load reduction indicates increased nutrient load removal in the planted HSSF-CW up to 90 days from planting the Canna lilies (Fig 4). This could be attributed to nutrient uptake by plants in the form of ammonium, amino acids and nitrates during the growing phase (da Costa et al., 2013; Vymazal, 2007). In October 2019 i.e. after 102 days of planting *Canna indica,* yellow pustules were observed in the leaves of the plants accompanied by premature drying and falling of the leaves. The infection could have inhibited growth and development of the Canna lilies resulting in reduced nutrient uptake and subsequent poor nutrient load reduction (Abrego et al., 1957; Marycruz et al., 2018). This appears to be confirmed by reduced TP uptake and percentage load reduction after 102 days in the planted system (Fig 5).

The relative contribution of plants in the removal of nutrients was estimated to be less than 5% (Table 2). Contribution of plants to the COD and BOD_5 load removal were estimated at 18 %, and 7% respectively suggesting that biofilms play an important role in contaminant removal (Iasur-Kruh et al., 2010; Wu et al., 2019). In terms of loading rate, 0.09 gm/m^2/day of TN, 0.3 gm/m^2/day of BOD_5 and 1.9 gm/m^2/day of COD was removed by plants. A similar study by da Costa et al., 2013 reported 1.06 % TN load assimilation by the plant biomass. Proper maintenance of wetland vegetation, which includes regular harvesting of plants, inspection for pest infestation, weeds and pathogen infections, is essential to enhance performance of plants in contaminant removal.

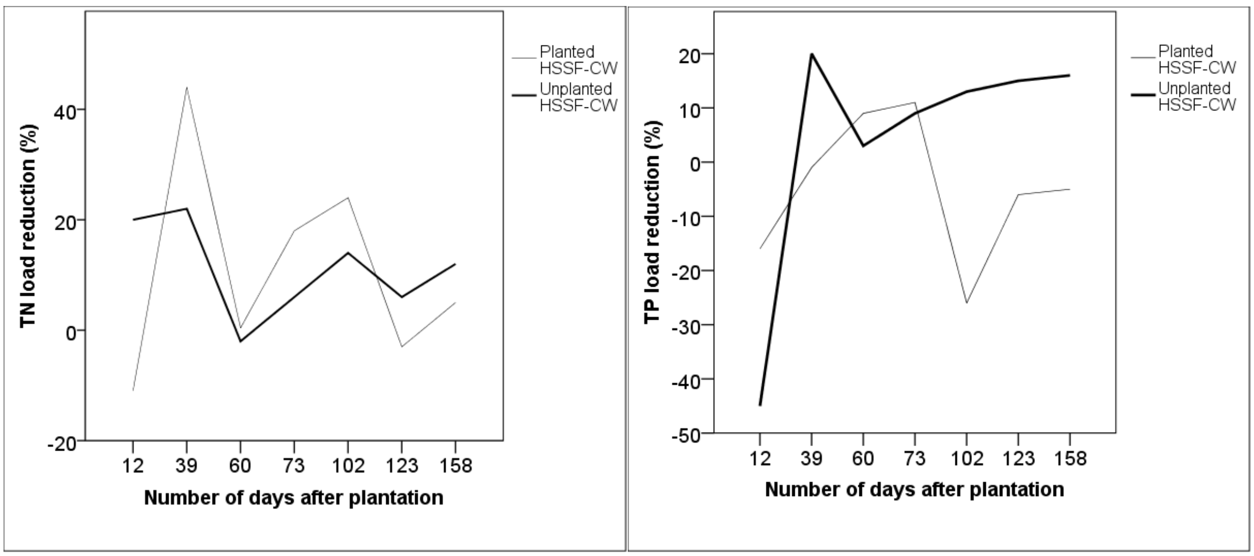

Fig 4: Percentage load reduction in nutrients with plant growth, planted vs. unplanted HSSF-CW

3.3 Pollutant removal kinetics

Kinetics of a wetland is closely related to the system design, and modelling helps in understanding the contaminant removal rate and scaling up of constructed wetland systems. Design parameters, environmental conditions and operating conditions directly affect the biochemical pathways within a wetland. Here, the first-order plug-flow model (equation 4) described by Sooknah & Wilkie, 2004 was used to understand and determine first order contaminants decay rates in both systems. Linear regression was used to estimate the kinetic volumetric base removal coefficient K at 25^{O}C for different contaminants and the corresponding correlation co-efficient R^2 (Table 3) (Fig 5).

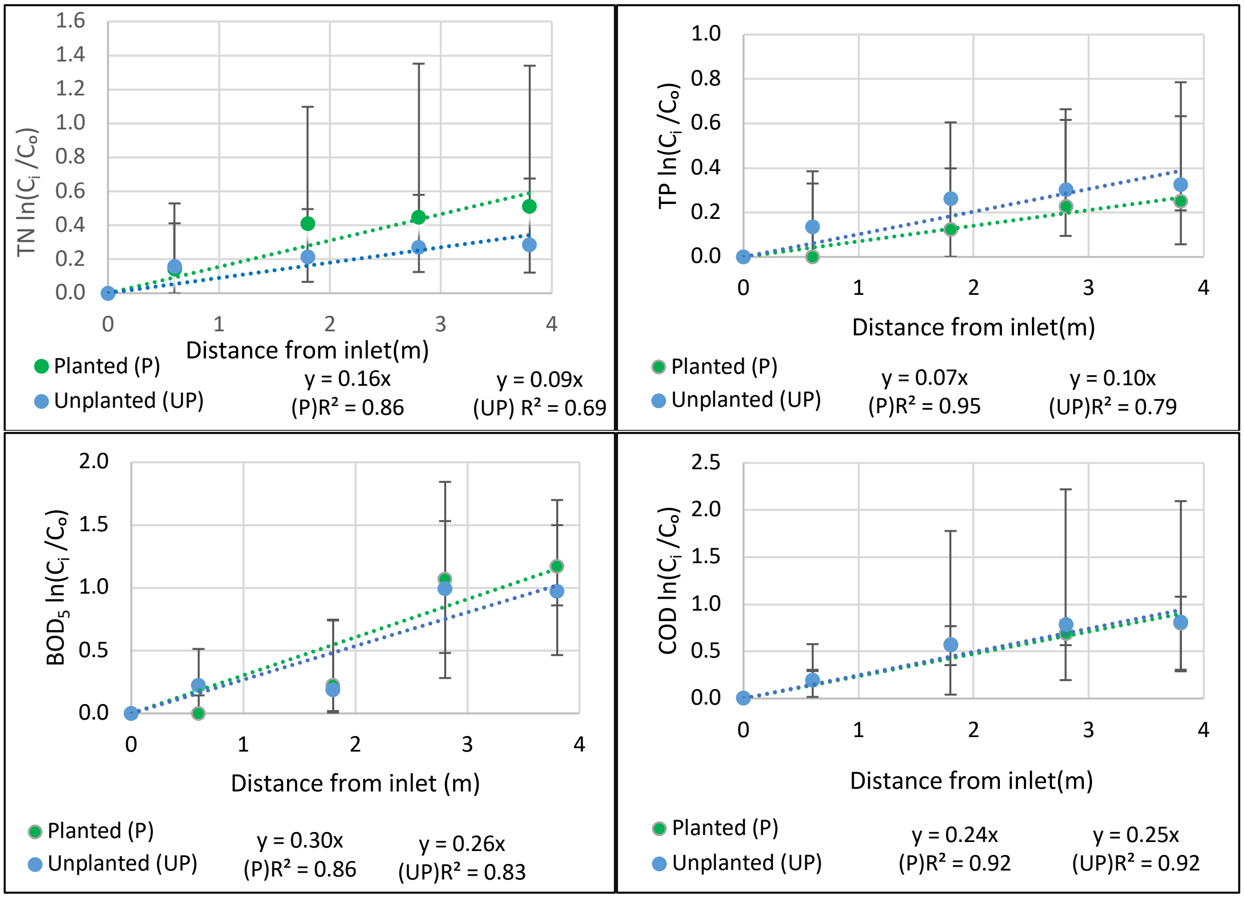

Fig 5: Linear regression of $\ln \frac{C_{inlet}}{C_{outlet}}$ of TN, TP, BOD_5, COD along planted and unplanted HSSF-CWs. The horizontal axis presents distance along the HSSF-CWs and vertical axis presents the natural logarithm of the ratio of the inlet to outlet contaminant levels.

Table 3: First-order removal rate constant K (day^{-1}) obtained from linear regression at 25 °C, correlation coefficient (R^2)

Parameters	Planted HSSF-CW		Unplanted HSSF-CW	
	K	R^2	K	R^2
TN	0.16 (K_{TN})	0.86	0.09 (K_{TN})	0.69
TP	0.07 (K_{TP})	0.95	0.10 (K_{TP})	0.79
BOD_5	0.30 (K_{BOD_5})	0.86	0.27 (K_{BOD_5})	0.83
COD	0.24 (K_{COD})	0.92	0.25 (K_{COD})	0.92

The TN, TP, BOD_5, and COD removal rate constants for the planted HSSF-CW were 0.16 day^{-1}, 0.07 day^{-1}, 0.30 day^{-1} and 0.24 day^{-1} respectively. Higher R^2 (~0.90) values were observed in the data describing performance of the planted HSSF-CW suggesting greater confidence in the application of first-order models to explain contaminant decay in the planted system. By contrast, in the case of unplanted system, variable factors such uptake/release of contaminants by biofilm microflora, biofilm diversity/density might have affected the contaminant decay rate in the system (Jegatheesan et al., 2003; Rossman, 1999).

The contaminant decay rate depends on design parameters (HRT, HLR), inflow characteristics, physical chemical and biological processes, and environmental conditions (temperature, rainfall) (Dornelas et al., 2009). Úsuga et al., 2017 reported contaminant decay rates of 0.22 day^{-1} for COD and 0.46 day^{-1} for BOD_5 at 24 °C at a HLR of 91 mm day^{-1}. Table 4 presents the volumetric rate constants reported in studies with HSSF-CW deployed in tropical regions. The decay rates reported in the literature cited are much higher than observed in the systems deployed at Berambadi. This might be due to the type of wastewater being treated and higher HLRs used in these studies. Garcia et al., 2010 reported improved organic pollutant removal efficiencies at high HLRs in HSSF-CW. Systems deployed at Berambadi received inflows with low contaminant loads and complex organic matter (biodegradable and non-biodegradable) from septic tank thereby contributing to lower contaminant decay rates.

Table 4: Volumetric rate constants (K) obtained from studies on HSSF-CWs in tropical region (24-27 °C).

Wastewater type & location	Pre-treatment	Plant species	HLR (mm day^{-1}) & HRT (days)	K (day^{-1})	Reference
Blackwater, India	Septic tanks	*Canna indica*	84 3.7	K_{TN} : 0.16 K_{TP} : 0.07 K_{BOD} : 0.30 K_{COD} : 0.24	This study (Planted system)
Domestic sewage, India	Settling tank	*Canna indica*	386 1.0	K_{TP} : 0.66 K_{BOD} : 1.92 K_{COD} : 1.33	(Lekshmi et al., 2020)
Greywater, Sri Lanka	Settling tanks with grease trap	*Typha latifolia*	165 2.0	K_{TP} : 0.40 K_{BOD} : 0.76 K_{COD} : 0.56	(Karunaratne et al., 2011)
Domestic sewage, Thailand	Settling tank	*Canna* spp.	55 - 440 0.5 – 4.0	K_{TN} : 0.07 K_{TP} : 0.06 K_{COD} : 1.18	(Konnerup et al., 2009)
Landfill leachate, Colombia	None	*Phragmites australis*	91 2.2	K_{BOD} : 0.46 K_{COD} : 0.22	(Úsuga et al., 2017)

4. Conclusion

Constructed wetlands serve as a good choice for secondary treatment of wastewater. However, the design parameters, vegetation and environmental conditions influence the performance of the constructed wetlands. We observed a significant reduction in organic matter levels and the effluents from both systems met the discharge standards for TSS, BOD_5 COD and nitrate -N set by regulatory agencies in India. Similar BOD_5 and TN removal efficiency were observed in both planted and unplanted HSSF-CWs. Unplanted HSSF-CW provided higher TP removal efficiency (11%) as compared to planted HSSF-CW (-7%). The first-order model confidently explains the organic matter and nutrient degradation in the planted HSSF-CW. Low R^2 values observed for unplanted system could be due to the influence of other factors such as initial contaminant levels, biofilm thickness, microflora diversity etc. on contaminant degradation. Maximum nutrient uptake/removal is observed during the growth phase of plants in CW. Canna rust infection appeared to affect the contaminant removal especially the TP and TSS removal efficiency of planted HSSF-CW.

Our data demonstrates that planting is effective in improving treatment efficiency of constructed wetlands with respect TN and organics removal. In this case the effectiveness of planted system over unplanted system was limited by the development of rust infections in *Canna indica* plants. Therefore, maintenance of healthy vegetation is critical to achieve and sustain improved/longterm performance of constructed wetlands. The data suggests that adaptability to the local climatic conditions and susceptibility towards infections should be considered while selecting plant species for phytoremediation.

We can conclude that the planted HSSF-CW (*when maintained properly with plants being harvested at regular intervals) can be effectively deployed to treat inflows from anaerobic wastewater treatment systems. Importantly however the data from this study demonstrates that an unplanted system, which requires less maintenance than the planted system (*Canna indica*), can also improve septic tank effluents to achieve discharge consent. This is an important finding with respect to the scaling up of HSSF-CW deployment in southern India, as mitigating the requirement for planting and plant maintenance reduces system cost and ease of use for the community/householders.

CRediT authorship contribution statement

Priyanka Jamwal: conceptualization, data curation and analysis, review and editing, Funding acquisition, supervision formal analysis. Anjali V Raj: Sample analysis, data curation and analysis, Writing - review & editing. Lakshmi Raveendran: Fieldwork and sample collection and analysis. Shahana Shirin: Fieldwork and sample collection and analysis. Stephanie Connelly: Writing - review & editing, Funding acquisition. Jagadeesh Yeluripati: Writing - review & editing, Funding acquisition. Samia Richards: Writing - review & editing, Funding acquisition. Lakshminarayana Rao: Writing - review & editing, Funding acquisition. Rachel Helliwell: review & editing, Funding acquisition. Matteo Tamburini- wetland design and Funding acquisition.

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