Evaluating wastewater treatment efficiency of two field scale subsurface flow constructed wetlands

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Constructed wetlands (CWs) are human-made systems designed to treat a variety of industrial, domestic and agricultural wastewaters. We study here the efficiency of domestic wastewater treatment by two field scale subsurface flow CWs under different hydraulic loading rates (HLRs). Each CW had inlet and outlet chamber for wastewater collection with *Pistia stratiotes* (water lettuce), two treatment sections consisting of sand and gravel media and four plant species *Typha latifolia* (Broadleaf cattail) and *Cymbopogon citratus* (lemon grass – first CW) and (*Pennisetum purpureum schum* and *Pennisetum americanum* L (Hybrid napier) and *Urochloa mutica* (Paragrass – second CW). The wastewater source was from a residential urban colony. The HLRs for the first and second CW for a three-month period averaged 4.45 cm/day and 5.77 cm/day respectively. The CW was monitored for quality of wastewater inflows and outflows and nutrient accumulation in plants and sand media. Results showed that the chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen and total phosphate removals in the first and second CW over a three-month period averaged 42%, 74%, 39% and 41% and 34%, 82%, 14% and 35% respectively. Both the CWs showed similar rates of TSS removal irrespective of the type of wetland plant species. Over the three-month period, average COD, total nitrogen and the phosphate removals were greater in the first CW compared to the second CW. These results confirm the efficacy of field scale subsurface flow CWs to improve the quality of domestic wastewater in rural communities of developing countries like India.

Keywords: Constructed wetlands, domestic wastewater, field scale, subsurface flow.

Introduction

CONSTRUCTED wetlands (CWs) are human-made systems that mimic the functions of a natural wetland and have been primarily used to treat domestic and municipal wastewaters[1]. They have also been used to treat different sources of wastewaters such as industrial, agricultural runoff, landfill leachate as well as urban and highway runoff[2]. For the past four decades, CWs have been increasingly used as sustainable treatment systems compared to the conventional treatments (wastewater-treatment plants) due to its low operation and maintenance costs[3]. The CWs do not require any large and complex mechanical equipment compared to the conventional wastewater-treatment plants which are associated with high energy inputs. As CWs do not require high energy inputs, they can be designed for small/medium rural communities and peri-urban areas for single households and residential blocks. There are two major types of CWs namely subsurface flow and free water surface (FWS), each having different modes of operation, advantages and disadvantages. The subsurface flow CWs have wastewater flowing through the gravel and coarse sand media (no wastewater ponding above the coarse sand surface). The sand media in subsurface flow CWs are required for growth of wetland plants such as *Typha latifolia*, paragrass and lemon grass. In FWS CWs a water column is maintained for growth of wetland plants such as water hyacinth and *Pistia stratiotes*[4]. The subsurface flow CWs consist of four main components – wastewater, sandy media, microbes and vegetation which facilitate the excessive removal of nitrogen, phosphorus and heavy metals such as lead, cadmium, chromium and zinc[5]. These four main components operate simultaneously to remove contaminants by physical, chemical and biological processes[6]. The plants in CWs play a major role by causing settling of suspended particulate matter, primary cause for reduction in biochemical oxygen demand (BOD). Another important function of plants is the uptake and storage of contaminants in their above and below ground biomass[7]. However, if wetland plants are not regularly harvested, they return the nutrients to the sandy media through senescence of its leaves, stems and roots. Also besides the nutrient uptake and storage, plant roots provide a large surface area for increasing microbial growth activities[8]. Klomjek and Nitisoravut[9] quantified the effect of using eight plant species in a CW for improving wastewater quality. They reported that cattail (*Typha angustifolia*) had better nitrogen assimilation potential and the Asia crabgrass was most efficient for BOD_5 removal (the amount of the dissolved oxygen required by aerobic microbes to breakdown the organic

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*For correspondence. (e-mail: a.tilak@cgiar.org) matter at 20°C for 5 days is known as BOD$_5$). This CW with 8 plant species removed 72–78.9%, 43–56%, 67–76.5% and 28–44.9% BOD$_5$, suspended solids, NH$_3$-N and total phosphorus respectively. Most of the subsurface CW studies in the literature have been pilot scale or laboratory scale with very few demonstrating field scale approach.

The present study focuses on field scale demonstration of subsurface flow CWs having a unique combination of wetland plant species such as water lettuce, cattail, lemon grass, hybrid napier and paragrass. The specific objectives of this three-month (January–March 2015) field scale study were to: (i) quantify the effect of having different hydraulic loading rates (HLRs) and hydraulic retention time (HRT) each month for comparing the treatment efficiencies of two subsurface flow CWs; (ii) determine the nitrogen and phosphorus accumulation in wetland sand media for two subsurface flow CWs; (iii) quantify the nitrogen and phosphorus uptake of 5 wetland plant species and (iv) determine the effective species for nitrogen and phosphorus removal.

Materials and methods

Site location

The two field scale subsurface CWs are located on the campus of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India. These two CWs received domestic wastewater from an urban residential colony nearby ICRISAT campus. Both the CWs received the same inlet wastewater during the three-month period.

Field scale CWs

The domestic wastewater from an urban residential colony is transported into a settling tank (60–70 m^3 capacity) using a Kirloskar diesel pump. The treatment capacity of each CW is 5 m^3/day depending upon the retention time (3–5 days). Both the CWs are divided into four chambers, A to D (Figure 1). The chambers not only serve as a wastewater inlet and outlet collection unit but they also maintain the hydraulic head. The treatment chambers (B and C) in both CWs have coarse sand (3–5 mm diameter) and gravel media (40 mm, 20 mm and 10 mm size). The dimensions of treatment chambers B and C in each CW are shown in Figures 1 and 2. The thickness of filter media (sand + gravel) layer in both CWs is 1 m. The individual depths of three gravel sizes (40 mm, 20 mm and 10 mm) and the sand media were 25 cm respectively. In chambers B and C, the 40 mm gravel was kept at the bottom, followed by 20 mm and 10 mm gravels. The sand media was placed on top of the 10 mm gravels in both the CWs (Figure 1). All the five wetland plant species were obtained from the ICRISAT campus. The paragrass was established in the second CW on 17 February 2015. The schematic view of the first and second CW is shown in Figures 3 and 4 respectively.

Inlet and outlet flow monitoring

The influent and effluent flow rates were measured daily using mechanical Itron flow meters (Figure 5 *a*). The

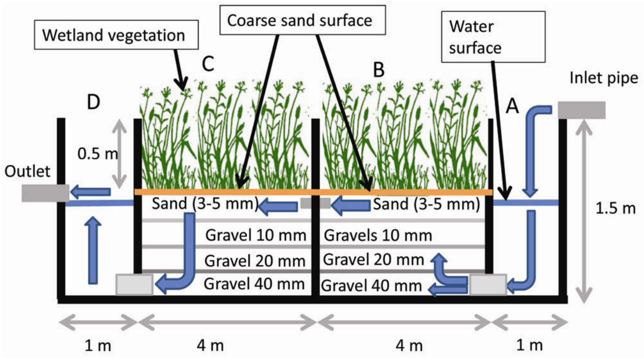

Figure 1. Cross-section of first and second subsurface flow CWs consisting of four treatment chambers (A to D).

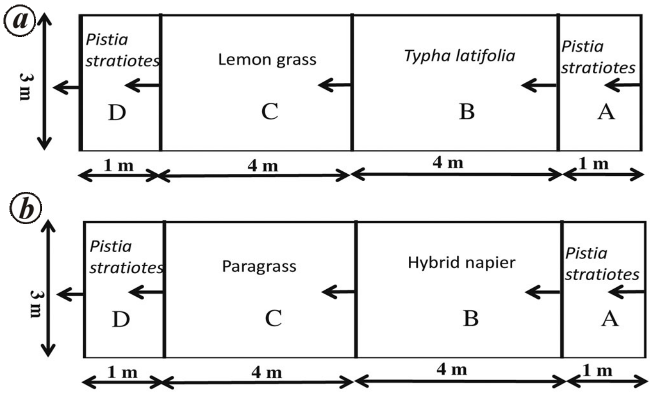

Figure 2. Top view of both field scale subsurface flow CWs with arrows showing the direction of wastewater flow: ***a***, first CW showing wetland plant species in each treatment chamber (A–D); (***b***) Second CW showing wetland plant species in each treatment chambers (A–D).

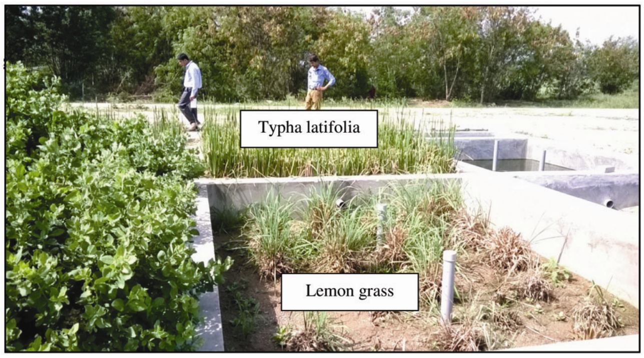

Figure 3. Schematic view of the first field scale subsurface flow CW.

Table 1. Average calibrated inflow, outflows, HLR and HRT for two subsurface flow CWs

	Average inlet calibrated inflows (l/min)		Average outlet flows (l/min)		HLR (cm/day)		HRT (days)	
Month	First CW	Second CW	First CW	Second CW	First CW	Second CW	First CW	Second CW
January	1.36	0.83	1.07	0.64	6.53	3.98	11.47	18.75
February	0.44	1.64	0.17	1.39	2.11	7.87	36	9.53
March	0.99	1.14	0.53	0.90	4.73	5.47	15.73	13.71
Average	0.93	1.20	0.59	0.97	4.45	5.77	21	14

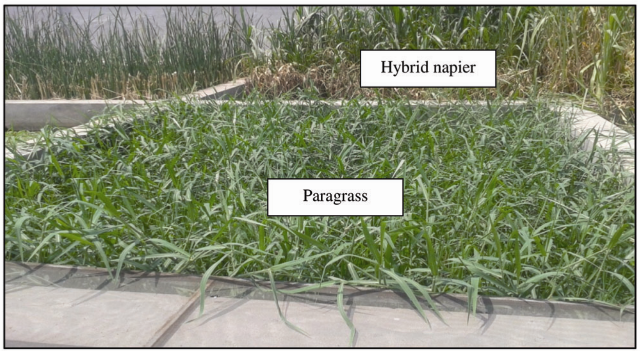

Figure 4. Schematic view of the second field scale subsurface flow CW.

suspended particles were allowed to settle in the inlet tank before entering the CWs. Despite this, the inlet pipes were frequently clogged and U-shaped bends were made in the inlet pipes (Figure 5*b*) to reduce clogging. These U-shaped pipe bends were helpful in removing the suspended particles to a certain extent. The inlet pipe had flow regulator (house-old tap) to calibrate the flow. For both CWs, calibrated wastewater inflow rates were different for each month as shown in Table 1. The outlet only had flow meter but there was no flow regulator.

Computing HLR and HRT for CWs

For computing HLR and HRT, the following equations are used[10].

$$\text{HLR} = \frac{\text{Average flow } (Q) \text{ entering CW}}{\text{Surface area (As) of CW}}, \quad (1)$$

$$\text{HRT} = \frac{n*L*W*D}{\text{Average flow } (Q) \text{ passing through CW}}, \quad (2)$$

where n is the media porosity, L, W and D are the length, width and depth respectively of the CW.

Wastewater characterization

The wastewater samples were collected twice every month and analysed in the ICRISAT laboratory for ammoniacal–nitrogen, nitrate–nitrogen, phosphate, chemical oxygen demand (COD) and total suspended solids (TSS) using the APHA standard methods[11–15].

Sand and plant sampling

The sand and plant sampling was carried out each month from January to March for both the CWs. The coarse sand sampling was conducted using a sand auger (Riverside auger-50 cm extension rod, coupling sleeves (2 numbers), and T handle with rubber grip) manufactured by AIC Agro Instruments (P) Ltd, Kolkata, India. The coarse sand samples were collected from chambers B and C at depths of 0–5 cm. The sand samples brought to the laboratory were air dried for two days and passed through 2 mm sieves. The samples were analysed for total nitrogen, total phosphorus, available phosphorus, exchangeable Ca and Mg. The total nitrogen was analysed using the thiosulphate modification of Kjeldahl method to include nitrate and nitrite[16]. The available P and the total P were analysed using the methods given in Olsen and Sommers[17] and Tandon *et al.*[18] respectively. The Ca and Mg in the sand media were analysed using the method given in Thomas[19]. For plant sampling, the above-ground biomass was harvested and transported to the laboratory in cloth bags. They were kept in the oven at 65°C for 3–4 days. After drying, the samples were ground using a Willey grinder machine (Nebraska, USA) to a fine powder. The dry weight of the powder was recorded and analysed in the ICRISAT laboratory. The total nitrogen and total phosphorus were analysed using sulphuric acid-selenium digestion method[20]. The plant calcium (Ca) and magnesium (Mg) were analysed using the nitric acid-hydrogen peroxide digestion[21].

Results

Hydrology monitoring

The results on the hydrologic inflows and outflows associated HLRs and HRT for both CWs are shown in Table 1. The following discussion quantifies how the HLR and HRT affected the effluent wastewater quality in the first and second CW.

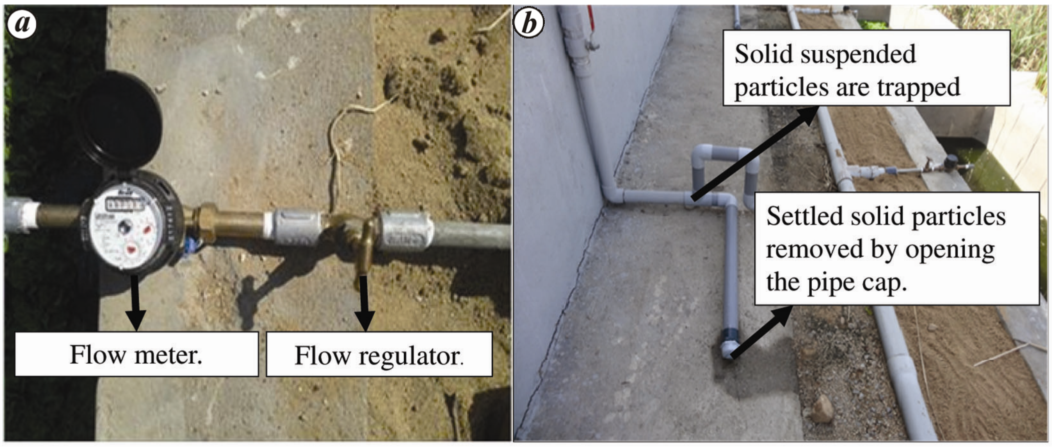

Figure 5. ***a***, Itron flow meter and a tap regulator. ***b***, U-shaped bend for trapping large particles.

Effect of HLR and HRT on effluent wastewater characteristics

Inlet wastewater concentrations for both CWs: The mean inlet concentrations of COD, TSS, NH_4-N, NO_3-N and phosphate in January were 144 mg/l, 54 mg/l, 96 mg/l, 2.76 mg/l and 3.62 mg/l respectively. The mean inlet concentrations of COD, TSS, NH_4-N, NO_3-N and phosphate in February were 192 mg/l, 38 mg/l, 63 mg/l, 2.91 mg/l and 4.12 mg/l respectively.

Effluent wastewater concentrations for first CW: The mean effluent concentrations of COD, TSS, NH_4-N, NO_3-N and phosphate in January were 64 mg/l, 8 mg/l, 62 mg/l, 1.69 mg/l and 3.55 mg/l respectively. The mean percentage reductions for COD, TSS, NH_4-N, NO_3-N and phosphate in January were 55%, 85%, 35%, 39% and 2% respectively. The mean effluent concentrations of COD, TSS, NH_4-N, NO_3-N and phosphate in February were 64 mg/l, 4 mg/l, 28 mg/l, 2.33 mg/l and 1.05 mg/l respectively. The mean percentage reduction in February was 66%, 89%, 55%, 20% and 75% respectively.

Effluent wastewater concentrations for second CW: The mean effluent concentrations of COD, TSS, NH_4-N, NO_3-N and phosphate in January were 96 mg/l, 2 mg/l, 71 mg/l, 1.70 mg/land 2.93 mg/l respectively. The mean percentage reduction for COD, TSS, NH_4-N, NO_3-N and phosphate in January were 33%, 96%, 26%, 38% and 19% respectively. The mean effluent concentrations of COD, TSS, NH_4-N, NO_3-N and phosphate in February were 144 mg/l, 8 mg/l, 41 mg/l, 2.14 mg/l and 4.03 mg/l respectively. The mean percentage reduction in February was 25%, 78%, 35%, 26% and 2.2% respectively.

Hydrologic comparisons of first and second CW: In the first CW, the COD, TSS, NH_4-N and phosphate reductions were considerably greater in February compared to January. This was due to the lower HLR and greater HRT in February compared to January (Table 1). In the second CW, the COD, TSS, NO_3-N and phosphate removals were greater in January due to low HLR and higher HRT compared to that in February (Table 1). The average HLR and the average HRT for the first and second CW for the three-month period were 4.45 cm/day and 21 days and 5.77 cm/day and 14 days respectively (Table 1).

Wastewater characterization

Tables 2 and 3 show the untreated wastewater and the treated wastewater parameters respectively for both CWs and they consisted of TSS, COD, total nitrogen and total phosphate. The treatment efficiency of each parameter for both CWs is compared with the literature values.

Total suspended solids (TSS)

In the first CW, average inlet and outlet TSS concentrations were 38.5 mg/l and 10 mg/l respectively, with a reduction efficiency of 74%. In the second CW, the outlet TSS concentration was 7 mg/l with a reduction efficiency of 82%. These results showed that irrespective of the type of wetland plants, both the CWs had similar removal efficiencies. The treated wastewater having TSS levels less than 30 mg/l can be used in agriculture for growing food crops[22]. A pilot scale study evaluated the treatment efficiency of four horizontal subsurface flow CWs in a three-stage system over a 6-year period[23]. The TSS reduction was 95%. Another pilot scale experiment used three wetland species (*Schoenoplectus validus*, *Juncusingens* or both species of macrophytes) and one control[24]. The total TSS reduction observed over a 10-month period was 85%. The results obtained in this study with regard to TSS removals are similar to those reported in the literature.

Chemical oxygen demand (COD)

The average inlet COD was 148 mg/l with a maximum and minimum value of 224 mg/l and 64 mg/l respectively

(Table 2). The average outlet COD for the first and second CW was 87 mg/l and 102 mg/l having a reduction efficiency of 41% and 31% respectively. A pilot scale subsurface flow CW having wastewater source from an upflow anaerobic sludge blanket (UASB) reactor quantified COD removal rates for control, *Phragmites mauritianus* and *Typha latifolia* respectively. Results showed removal rates to be 33.6%, 56.3% and 60.7% for control, *Phragmites mauritianus* and *Typha latifolia* respectively[25]. The present results are comparable with the above study from the literature.

Nitrogen and phosphate removals

The average inlet total nitrogen was 3.8 meq/l and the outlet total nitrogen in the first and second CW averaged 2.33 meq/l and 3.26 meq/l respectively (Tables 2 and 3). The total nitrogen reduction efficiency of the first and second CW averaged 39% and 14% respectively over a three-month period. The average inlet phosphate concentration was 4.6 mg/l and the outlet phosphate concentration in the first and second CW averaged 2.7 mg/l and 3 mg/l respectively. The phosphate reduction efficiency of the first and second CW was 41% and 35% respectively (Tables 2 and 3). A subsurface flow CWs was used to treat swine wastewater under different HRTs (8.5 day, 4.3 day and 14.7 day). The total nitrogen and total phosphorus removals averaged 10–24% and 47–59% respectively[26]. Schulz *et al.*[27] used emergent plants in a CW study for treating aquaculture effluents. Results showed that the total nitrogen and total phosphorus removals averaged 20–41% and 49–68.5% respectively. The total nitrogen and phosphate removals in this study are similar to the literature values.

Nitrogen and phosphorus accumulation in sand media

First CW: We measured the accumulation of total nitrogen and phosphorus in the pre-treatment and the post-treatment sand media in both CWs (Table 4). The average total nitrogen accumulation in treatments B and C increased by 48% and 4% respectively, while the average total phosphorus accumulation in treatments B and C increased by 74% and 54% respectively (Table 4). The average available P, a nutrient source for plants, also increased in the treatments B and C by 93% and 88% respectively. There was no change in the exchangeable Ca between the pre-treatment and the post-treatment sand media in both CWs. However, the exchangeable Mg in the treatments B and C increased by 25% and 42% respectively in the post-treatment compared to pre-treatments and media.

Second CW: The average total nitrogen accumulation in treatments B and C increased by 68% and 58% respectively, while the average total phosphorus accumulation in treatments B and C increased by 74% and 62% respectively (Table 4). The average available P, a nutrient source for plants, also increased by 93% and 93% in treatments B and C respectively compared to available P of the pre-treatment sample (Table 4). However, the exchangeable Mg in treatments B and C increased by 47% and 50% respectively in post-treatment compared to pre-treatment sand media.

Table 2. Characteristics of untreated wastewater used in the study

Parameters	Average value	Maximum value	Minimum value
TSS (mg/l)	38.5	64	4
COD (mg/l)	148	224	64
Phosphate (mg/l)	4.6	23	2.39
Total nitrogen (meq/l)	3.8	6.08	0.033

TSS, Total suspended solids; COD, Chemical oxygen demand; Average, max. and min. value of 19 samples represented over a 3-month period (January–March 2015).

Nitrogen and phosphorus accumulation comparison with literature

The total nitrogen and phosphorus accumulation in this field scale study ranged from 0.15 to 0.47 g/kg and 0.11 to 0.17 g/kg respectively, over a three-month period. A study showed that the total nitrogen accumulation in two CWs averaged 0.7–0.9 g/kg (ref. 28). The higher total nitrogen accumulation in the above study was due to a higher HRT of 20–21 days compared to the retention time averaging 14 days in the second CW. A subsurface flow CW study[29] reported phosphorus accumulation in 13 Danish sands ranging from 0.04 to 0.45 g/kg.

Nitrogen and phosphorus uptake in wetland plants

Pistia stratiotes: The inlet and outlet treatment chambers of the first and second CW contained *Pistia stratiotes*. The nitrogen content of *Pistia stratiotes* included its leaves and roots (whole plant nutrient content together). The nitrogen contents in *Pistia stratiotes* in the inlet and outlet chamber for the first CW averaged 37.4 g/kg and 33.5 g/kg, and in the second CW it averaged 42.8 g/kg and 33.9 g/kg respectively. The phosphorus contents in *Pistia stratiotes* in the inlet and outlet chamber for the first CW averaged 8.4 g/kg and 9.46 g/kg, and in the second CW it averaged 9.47 g/kg and 7.89 g/kg respectively (Table 5). Polomski *et al.*[30] quantified nitrogen and phosphorus uptake of *Pistia stratiotes* in a laboratory scale CW study. Results showed that the average nitrogen and phosphorus contents were 16.21 g/kg and 2.3 g/kg,

Table 3. Treated wastewater characteristics from first and second subsurface flow CW

Parameters	Average value		Max. value		Min. value	
	First CW	Second CW	First CW	Second CW	First CW	Second CW
TSS (mg/l)	10	7	16	12	4	2
COD (mg/l)	87	102	128	192	64	64
Phosphate (mg/l)	2.7	3	3.84	4.03	1.05	2.93
Total nitrogen (meq/l)	2.33	3.26	3.96	4.00	0.0272	0.03

TSS, Total suspended solids; COD, Chemical oxygen demand. Average, max. and min. value of 19 samples represented over a 3-month period (January–March 2015).

Table 4. Nutrient accumulation in sand media for the first and second CW

Treatment chambers	Total N (g/kg)		Total P (g/kg)		Available P (g/kg)		Exch Ca (g/kg)		Exch Mg (g/kg)	
	First CW	Second CW	First CW	Second CW	First CW	Second CW	First CW	Second CW	First CW	Second CW
Raw sample	0.15		0.044		0.001		0.95		0.071	
B1	0.39	0.59	0.19	0.17	0.008	0.010	0.93	0.84	0.096	0.096
B1	0.47	0.79	0.18	0.23	0.019	0.036	1.00	0.98	0.123	0.220
B1	0.16	0.23	0.10	0.12	0.019	0.011	0.90	0.97	0.084	0.108
B1	0.13	0.27	0.21	0.13	0.011	0.003	0.89	0.88	0.077	0.111
Average	0.29	0.47	0.173	0.168	0.014	0.015	0.93	0.921	0.095	0.134
C1	0.17	0.61	0.13	0.14	0.005	0.013	0.95	0.88	0.093	0.144
C1	0.15	0.54	0.093	0.15	0.008	0.019	0.99	0.98	0.135	0.256
C1	0.19	0.13	0.064	0.072	0.013	0.022	0.99	0.98	0.157	0.077
C1	0.10	0.14	0.094	0.085	0.004	0.007	0.95	0.85	0.105	0.091
Average	0.15	0.357	0.095	0.115	0.008	0.015	0.97	0.928	0.122	0.142

respectively. The nitrogen and phosphorus removal by *Pistia stratiotes* in this study is comparable to the above study.

Typha latifolia (cattail) and Cymbopogon citratus (lemon grass) (first CW): The nitrogen and phosphorus content in the *Typha latifolia* averaged 27.1 g/kg and 2.96 g/kg respectively over a three-month period (Table 5). The nitrogen and phosphorus uptake of *Typha latifolia* evaluated in a CW which received winery wastewater averaged 11.68 g/kg and 0.31 g/kg respectively[31]. Costa *et al.*[32] evaluated the nitrogen and phosphorus removals of *Typha latifolia* in a subsurface flow CW receiving effluent wastewater from a trickling filter unit. Results showed that the aboveground nitrogen and phosphorus contents averaged 24 g/kg and 4.4 g/kg respectively. The nitrogen and phosphorus uptake of *Typha latifolia* in our study are comparable to the literature values. The average nitrogen and the phosphorus contents in the aboveground biomass of *Cymbopogon citratus* averaged 15.8 g/kg and 2.29 g/kg respectively. This is the first report of the aboveground nitrogen and phosphorus uptake of lemon grass in a CW.

Pennisetum purpureum schum and Pennisetum americanum L (hybrid napier) and Urochloa mutica (paragrass) (second CW): The average nitrogen and phosphorus uptake of hybrid napier in this study averaged 22.2 g/kg and 2.84 g/kg respectively. The nitrogen and phosphorus contents in the paragrass averaged 34 g/kg and 8.87 g/kg respectively (Table 5). However, there is lack of data in the literature with regard to nitrogen and phosphorus uptake of paragrass and hybrid napier in CWs receiving domestic/industrial wastewater. This field scale CW study is the first on report on the aboveground nitrogen and phosphorus uptake of the above two species.

Effect of plant harvesting on nitrogen and phosphorus uptake

In the first CW, the increase in nitrogen and phosphorus contents of *Pistia stratiotes* on 31 March with respect to its contents on 17 March was 63% and 62% respectively (Table 5). This increase was due to harvesting of *Pistia stratiotes* on 11 March 2015. The *Typha latifolia* was harvested on 18 February and the nitrogen and phosphorus contents were significantly greater on 17 March compared to 24 February. The percentage increase in nitrogen and phosphorus contents on 17 March compared to its contents on 24 February were 62% and 58% respectively (Table 5). The *Cymbopogon citratus* was harvested on 10 February and results showed that nitrogen and phosphorus contents were greater on 17 March compared to 17 February by 74% and 42% respectively (Table 5).

Table 5. Nutrient accumulation in the wetland plants for the first and second CW

	First CW			Second CW		
Sampling date	Plant type	Total N (g/kg)	Total P (g/kg)	Plant type	Total N (g/kg)	Total P (g/kg)
9 January	*Pistia stratiotes*	41.5	10.2	*Pistia stratiotes*	49.2	12.6
17 February		43	10.7		46.2	11.3
17 March		17.6	3.5		29.7	5.8
31 March		47.4	9.1		46.0	8.03
Average		37.4	8.4		42.8	9.47
9 January	*Typha latifolia*	25.7	2.7	*Hybrid napier*	18.5	2.65
24 February		13.4	1.7		20.1	2.33
17 March		35.7	4.1		24.2	2.84
31 March		33.6	3.2		25.9	3.55
Average		27.1	2.96		22.2	2.84
9 January	*Lemon grass*	9.8	1.9	*Paragrass*	NA	NA
17 February		6.2	1.4		18.9	2.71
17 March		24.1	2.4		40.4	11.6
31 March		23.1	3.36		42.6	12.3
Average		15.8	2.29		34.0	8.87
9 January	*Pistia stratiotes*	37.2	10.0	*Pistia stratiotes*	NA	NA
17 February		30.7	11.2		45.3	12.03
17 March		30.1	6.2		16.3	3.48
31 March		36.1	10.3		40	8.16
Average		33.5	9.46		33.9	7.89

*NA, Not available.

In the second CW, the increase in nitrogen and phosphorus contents of *Pistia stratiotes* on 31 March compared with that on 17 March was 35% and 37% respectively (Table 5). This increase was due to harvesting of *Pistia stratiotes* on 11 March 2015. The hybrid napier was not harvested in the three-month monitoring period. The nitrogen and phosphorus contents of paragrass increased from 18.9 g/kg to 42.6 g/kg and 2.71 g/kg to 12.3 g/kg from 17 February to 31 March. Paragrass was established in the second CW on 17 February 2015 and its nitrogen and phosphorus uptake increased by 56% and 78% over a period of 44 days. This showed that paragrass can be successfully established in CW and showed good potential for nitrogen and phosphorus uptake.

Discussion

Mechanism of TSS and COD removal in both CWs

The major principle of TSS and COD removals in CWs is the sedimentation, filtration and physical entrapment in the void pores of the sand and gravel media[33]. The higher HRT allows for greater physical settling of suspended particles, which reduces the TSS and the higher residence time allows wetland plants to effectively uptake nutrients thereby reducing the effluent concentrations. Besides sedimentation and settling, a reduction in suspended solids can be due to van der Waals forces of attraction which can attract or repulse based on surface charges[34].

Mechanisms of NH_4-N and NO_3-N removal in both CWs

Ammonia volatilization is the process where NH_4-N is in equilibrium between gaseous and liquid forms. Ammonium volatilization is generally insignificant if wastewater pH is below 7.5 and low for pH 7.5–8 (ref. 35). Significant volatilization occurs if the pH is higher than 9.3. In the first CW, the pH in all the treatment chambers was 7.5–8.5 (data not shown). From these measured pH values, ammonia volatilization was probably not the major mechanism of nitrogen loss. Ammonium ion (NH_4^+) is adsorbed as exchangeable ion on clays and organic matter. The adsorbed NH_4^+ is loosely attached to the sand particles and released into the wastewater upon subject to changing water chemistry. For example, in case of alternate flooding and drying, the adsorbed ammonium attached to the sand particle can increase and in case of drying the adsorbed NH_4-N is converted into NO_3-N in the presence of aerobic conditions[36]. Mineralization rates are dependent upon pH (6.5–8.5), temperature (40–60°C), C/N ratio, available nutrients, texture and structure of soil media. The pH of wastewater in this study was in the optimal range and inlet wastewater had high NH_4-N concentrations varying from 30 to 109 mg/l over a three-month period. Both the CWs had inlet NO_3-N concentrations ranging from 1.08 to 3.9 mg/l and the production of NO_3-N inside the treatment chambers (1.69–3.08 mg/l) was considerably lower compared to NH_4-N. The important factors affecting nitrification are temperature

(30–40°C), pH (6.6–8.0), alkalinity, C source, moisture, microbial population, NH_4-N and dissolved oxygen. In this study, temperature and pH varied from 19.7°C to 27°C and 7.5 to 9 respectively and were not in the range given above. The pH and temperature are point scale readings taken at one particular time (no continuous measurements were done) and they only provide a snap shot, but do not represent the entire picture of a CW. Also the nitrate produced might be undergoing denitrification as the pH and temperature were suitable for denitrification. Denitrification is the conversion of NO_3-N into dinitrogen gas through a series of intermediate process – nitrite, nitric oxide and nitrous oxide[37]. It requires NO_3-N as the electron acceptor, available organic substrate, absence of O_2, temperature, presence of denitrifiers and suitable Eh conditions (anoxic or anaerobic) ranging from +100 mV to +350 mV, optimum pH from 6 to 8. In this study, conditions were probably favourable for denitrification, pH ranging from 7 to 8.5, Eh varying between 120 and 190 mV, Eh less than 300 mV (anoxic conditions), and presence of NO_3-N for denitrification to occur. Though denitrification at this site was not quantified, it could be the major N loss mechanism for both the CWs.

Mechanisms of phosphorus removal in both CWs

Major mechanisms of phosphorus removal in CWs are the plant and microbial uptake, and retention/adsorption onto sand media. Adsorption/retention of phosphorus is controlled by redox potential, pH and exchangeable Ca, Mg and Fe. At pH greater than 7, phosphorus is adsorbed onto insoluble calcium (Ca–P). P sorption takes place in two steps: (i) exchange of phosphate between the soil–water and soil particles (adsorption); (ii) the phosphate then slowly penetrates into the solid phase[38]. The phosphorus can also be released from the wetland soils in case of high anaerobic conditions (reduction of Fe(III) and Mn(IV)). The solubility of the adsorbed P to the wetland soils is influenced by the pH and the oxidation reduction potential (ORP). For a wastewater pH varying from 5 to 8, solubility of P is low if ORP is 300 mV resulting in lower concentration in soil pore water. As the ORP decreases from +300 mV to –250 mV, the P solubility increases and so does its concentration in the soil pore-water. In both the CWs, results showed that most of the phosphate bonded with exchangeable Ca as the soluble P was 10.6 times lower in magnitude than the total P (Table 4). The ORP in both CWs varied from 120 to 190 mV and the wastewater pH varied from 7.5 to 8.5 for the three-month period. These conditions will result in lower availability of P in the pore water and greater P adsorbed to exchangeable Ca and Mg.

Conclusions

The first CW with *Pistia stratiotes*, *Typha latifolia* and lemon grass attenuated more nitrogen and phosphorus compared to the second CW with *Pistia stratiotes*, hybrid napier and paragrass. The high nitrogen and phosphorus removal in the first CW compared to the second CW were due to the low average HLR and the high average HRT. *Pistia stratiotes* was the highest accumulator of nitrogen and phosphorus, followed by paragrass, *Typha latifolia*, hybrid napier and the lemon grass. It is critically important that wetland species should be regularly harvested to maximize their nitrogen and phosphorus uptake capacities. This study showed that field scale subsurface flow CWs are a viable tool for improving wastewater quality in rural parts of India.

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