Field scale evaluation of seasonal wastewater treatment efficiencies of free surface-constructed wetlands in ICRISAT, India

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The disparity between volume of wastewater generated and treated has resulted in severe water pollution and eutrophication of the water bodies in most Indian cities. Constructed wetlands (CWs) present a low-cost wastewater treatment option; however, field scale studies with real life wastewater are limited. *Eichhornia crassipes* (water hyacinth), *Typha latifolia* (*Typha*) and *Pistia stratiotes* (water lettuce) grow abundantly in eutrophicated water bodies, and are known for their nutrient uptake ability. In the present study, the wastewater of a nearby urban residential colony was treated by two-field scale free water surface CWs operating under identical hydraulic loading. The first treatment cells, in each of these two CWs were vegetated with *Typha.* The second treatment cells were vegetated with water hyacinth (CW-1) in one of the CWs and with water lettuce (CW-2) in the other. Wastewater treatment efficiencies of these free water surface CWs were evaluated, in terms of the removal efficiencies for key parameters, viz. chemical oxygen demand (COD), ammoniacal and nitrate nitrogen, phosphate, sulphate and total suspended solids (TSS). The CW-1 showed greater seasonal variation in performance. A steady removal efficiency of 35–40% was observed for ammoniacal nitrogen in both the free water surface CWs throughout the year, though removal efficiency of nitrate nitrogen reduced significantly during the winter. Plant sample analysis showed that the N, P and K uptake capacities of water lettuce were 1.53, 1.55 and 1.34 times higher than that of water hyacinth, for identical wastewater loading. The dry weight of the harvested biomass for water lettuce, during summer months, was much higher at 5.63 g/m^2/d compared to 3.8 g/m^2/d for water hyacinth.

Keywords: Constructed wetland, domestic wastewater, field scale, free water surface, macrophytes.

Introduction

INDIA may become a water-scarce country by 2025. Thus recycle to reuse water needs greater attention. About 38,354 million litres per day (MLD) sewage is generated in major cities of India, however, the total sewage treatment capacity in these cities is only 11,786 MLD[1]. A large portion of these surplus sewage of 26,568 MLD leads to widespread water pollution. Raw sewage being a perennial source of water often gets utilized for peri-urban agriculture. In Hyderabad[2] several thousand hectares of land in the Musi river basin is being utilized to grow cereals such as paddy, vegetables (spinach, amaranthus, mint and coriander), flowers (jasmine) and even fodders (paragrass). Energy and skill intensive wastewater treatment technologies are often not feasible alternative in areas where electricity supply is scarce and unreliable.

Constructed wetlands (CWs) are convenient choice for wastewater treatment in areas with limited resources, because of the low construction cost with minimal or no energy and/or skill input[3]. Phytoremediation of wastewater includes identification of efficient aquatic plant; estimation of plant uptake by the growing plants, optimization of harvesting schedule and investigation of beneficial use of the plant biomass during post harvesting[4]. Macrophytes such as water hyacinth and water lettuce grow abundantly in eutrophicated water bodies, whereas *Typha* is ubiquitous on the banks of eutrophicated water bodies. Phytoremediation potential of these plants is well known, though field scale performance assessment is scarce[5–7]. High photosynthetic surface area makes these two macrophytes among the earth's most productive communities[4]. For a phytoremediation system to work efficiently, optimal plant growth is the key parameter. Many environmental factors can influence plant growth and its performance such as temperature, pH, solar radiation and salinity of the water[8,9].

The growth rate of water hyacinth is strongly dependent upon the concentration of available nitrogen (N) and phosphorus (P) in the water[10]. Sato and Kondo[11] reported that its maximum growth rate can be achieved at 28 mg/l of total N and 7.7 mg/l of total P. According to Reddy *et al.*[10], 5.5 mg of N/l and 1.06 mg of P/l are required for survival of water hyacinth growth, whereas to achieve maximum growth N, P and K (potassium) are added at the rate of 20 mg N/l, 3 mg P/l and 52 mg K/l respectively. According to Delgado *et al.*[12] water hyacinth prefers ammonium over nitrate. DeBusk *et al.*[13] evaluated

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hyacinth in secondarily treated municipal wastewater and reported plant productivity of 16 $g/m^2/d$. Snow and Ghaly[14] found water hyacinth yields were 83 and 49 g/m^2 with hydraulic retention times (HRT) of 6 and 12 days respectively. Adeniran[15] observed that the CWs vegetated with water hyacinth require only 13% of the energy compared to conventional sewage treatment plant for the same quantity of sewage; and concluded that it is a viable and cost effective option for the treatment of domestic sewage in a developing economy. If not harvested at an appropriate time, nutrients from the plants are leached back into the water and old plants after death cause anaerobic conditions in water[16]. Regarding the removal of inorganic nitrogen, Reddy *et al.*[17] reported a near 80% reduction, while Sheffield[18] observed 94% inorganic nitrogen and 40–55% ortho-phosphate reduction. For total phosphate, Reddy *et al.*[17] reported 32% reduction, while Ornes and Sutton[19] achieved a higher removal rate of 80%. Bramwell and Devi Prasad[20] observed during a pilot scale study an average decrease in total N and total P by 27.6% and 4.48% respectively.

Water lettuce is an winter hardy plant, having a minimum growth at temperature 15°C (ref. 21). In general, the specific growth rate of water lettuce is slightly higher compared to the water hyacinth in dry season. However, the rainy spell reduces the growth of the water lettuce because of the lower solar radiation, which is needed for its growth[22]. Fonkou *et al.*[23] stated that water lettuce doubles its biomass in just over 5 days; triples in 10 days, quadruples in 20 days and has its original biomass multiplied by a factor of 9 in less than one month. This evolution indicates that 25 days is the maximum time needed for the plant in the system[24]. A growth rate of 220 kg/ha/day to 600 kg/ha/day has been reported in eutrophicated ponds[25]. According to Makhanu[26], water lettuce comprises 95% water and 5% dry matter, out of which silica, potassium, nitrogen and protein are 50%, 30%, 15% and 5% respectively. Because this plant reproduces rapidly and decays, the efficacy of the system is intimately linked to its careful management through periodic harvesting of part of the biomass produced, especially in tropical or subtropical areas, water lettuce (large-leaved floating plant) may be used for phytoremediation of wastewater[27,28]. This is because compared to other native plants this invasive plant shows a much higher nutrient removal efficiency with their high nutrient uptake capacity, fast growth rate and big biomass production[29]. A 200-fold difference in dry weight of water lettuce was reported by Aoi and Hayashi[30] between cultivated in rain water and treated sewage water. Awuah *et al.*[31] used lettuce in their study of bench-scale continuous-flow wastewater treatment system with feed of sewage. They observed that lettuce removed nitrate by 70%, total phosphorus by 33% and ammonia by 95%. Ingersoll and Baker[32] reported nitrate removal efficiency of water lettuce ranged from 31% to 51%.

The present study is an attempt to compare the performance of two 'free surface', horizontal flow CWs. Raw domestic wastewater from a nearby urban colony was utilized for the study.

Materials and methods

Constructed wetlands

The study was conducted in two identical horizontal flow free surface CWs. The inner dimension and design is shown in Figure 1 *a*. Cell A and D are the inlet and outlet tanks respectively. B and C are the cells with vegetation in which phytoremediation takes place. Both cell B and C were filled with multiple layers of gravel and a top layer of coarse sand, these layers acted as the filter bed providing physical screening. The media in B and C cells comprised three gravel layers each of 25 cm thickness (Figure 1 *b*). These gravel layers were covered with a 10 cm coarse river sand layer in both B and C cells. A 15 cm water column was maintained on the top of the media in both B and C cells. The flow regimen of wastewater is shown in Figure 1 *c*. The B cell was vegetated with *Typha* in both the CWs whereas C cells of CW-1 and CW-2 were having free floating macrophytes, water hyacinth and water lettuce respectively. The wetland inlet was fitted with flow regulator and flow metre while the outlets were provided with only flow metre. A U-shaped bend (Figure 2) was provided before the flow meter in the inlet pipe to prevent excessive clogging.

Constructed wetland operation and maintenance

The porosity of the filter bed comprising gravel and sand in different cells of CW was evaluated via pilot scale experiments with identical media columns. The porosity of the bed was 0.55. As we get the volume of CW from the inner dimensions (Figure 1 *a*) as 30 m^3, considering the porosity of 0.55, overall wastewater retention capacity was computed as 16.2 m^3. This implies a 3.3 m^3/day or 2.29 l/min of flow rate considering a designed HRT of 5 days. The HRT here represents the time a water drop takes to travel from the inlet to outlet of a CW. The optimum HRT for CWs reported in the literature is 3–5 days, however as we expect the bed porosity to decrease over time due to clogging of the filter bed (which will reduce the HRT gradually) a designed HRT of 5 was opted. For simplicity of operation and to avoid cost escalation (as our objective is to develop a low cost and less skill intensive wastewater treatment technique) associated with sophistication, a flow rate of 2 l/min was set as the designed flow. In line with the same objective of cost effectiveness, household mechanical flow meters (costing about US$ 7 each) were incorporated (Figure 2) both at the inlet and outlet of each CW. Moreover, most of the sophisticated

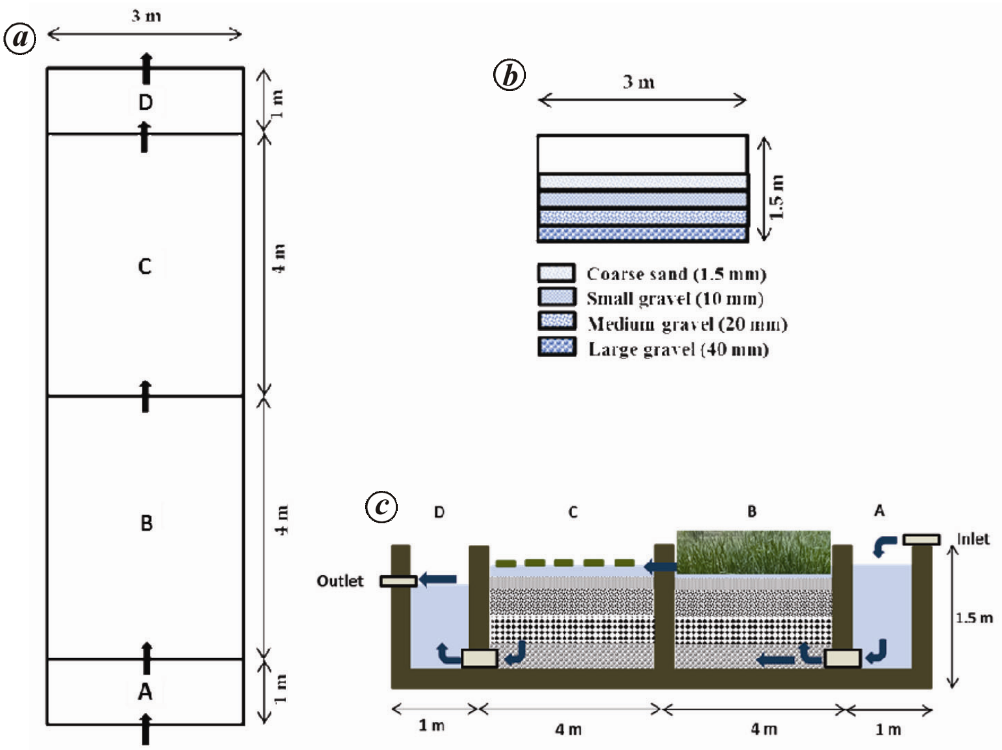

Figure 1. Design of the constructed wetlands: ***a***, Top view with internal dimensions; ***b***, Media layers and ***c***, Flow regimen.

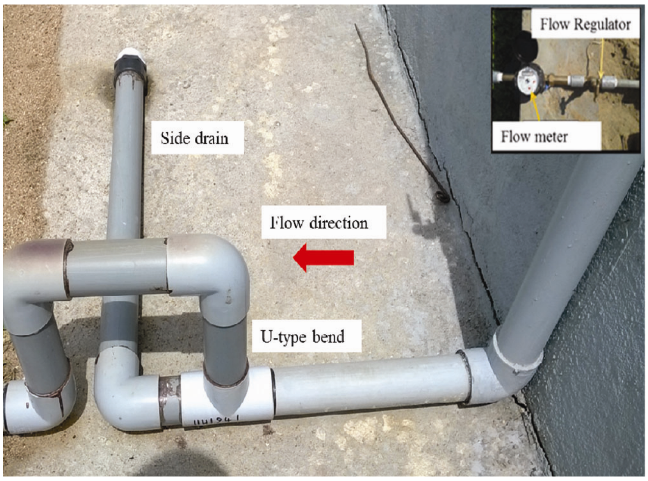

Figure 2. The U-bend, sludge drain flow meter and flow regulator at the wetland inlet.

flow meters available in the market based on light sensors, motion sensors or pressure transducers are not suitable for wastewater applications. As these flow meters were available for 2.54 cm pipes (common diameter for household water supply lines in India), the flexibility in choosing the diameter of the inlet and outlet pipes got restricted. Furthermore, full bore condition, which is critical for the proper functioning of these flow meters, could not be ensured for pipes with greater diameters for the designed flow rate. Initially frequent clogging upstream of the flow regulator was a major maintenance challenge. By incorporating bar screens (30 cm mesh size) surrounding the foot valve of the wastewater pump (Kirloskar, 6 HP, diesel operated), the problem could be mitigated significantly. An additional arrangement of a U-shaped bend (Figure 2) as mentioned in the previous section could further decrease the frequency of clogging. This steep vertical bend of about 35 cm on the flow path of the wastewater made sure that only grit-free wastewater moves upward. The fine grit particles because of their higher momentum travel linearly and get deposited in the side drains. These side drains were cleaned weekly. As wastewater was rich in N, P and K, the growth of fine micro-algae was spontaneous; this fine algal growth too gave some degree of clogging over a period of operation. Weekly cleaning of the flow regulators and flow meters was most economical and effective from a maintenance point of view as it takes only about 5 min to clean an inlet line. As none of the interventions (bar screen or U-shaped bend) was expensive, the method adopted seems to be an economical way to protect a CW from too much grit load and thus enhancing its operational life. In order to avoid variable flow rate in the CWs in this study due to different pipe length and varying water head, each inlet line was calibrated against a timer for a particular head. Near constant head was maintained in the overhead tank. Wastewater from a local urban housing society was used for this study.

Analytical methods

Inlet and outlet wastewater from each CWs was collected every week and various parameters were analysed using standard methods (Appendix 1). Plant samples were dried (to a constant weight in oven at 65 + 5°C) and ground for the analysis. The samples were analysed for N, P, K, sulphur (S), boron (B), calcium (Ca), magnesium (Mg), total iron (Fe), zinc (Zn), arsenic (As), chromium (Cr) and lead (Pb) in the Charles Renard Analytical Laboratory, ICRISAT, Patancheru. Total N, P and K in plant materials were determined by digesting the samples with sulphuric acid-selenium. Nitrogen and P in the digests were analysed using an auto-analyser (Skalar SAN System, AA Breda, Netherlands), and K in the digests was analysed using an atomic absorption spectrophotometer (SavantAA, GBC Scientific Equipment, Braeside, VIC, Australia)[33]. Zinc in plant samples was determined by digesting them with tri-acid mixture, and Zn in digests was analysed using atomic absorption spectrophotometer[34]. Total S, B and metal concentrations in plant samples were determined by inductively coupled plasma emission spectrophotometer (ICP-AES) (Prodigy High Dispersion ICP, Teledyne Leeman Labs, Hudson, New Hampshire, USA) in the digests prepared by digesting the samples with nitric acid[35].

Results and discussion

Wastewater characteristics

The domestic wastewater used in this study was from a local housing society which was analysed on a weekly basis throughout the study period of July 2014 to June 2015. Table 1 represents the characteristics of the wastewater in terms of average concentration of different parameters. Diurnal and seasonal variation was observed in parameters such as chemical oxygen demand (COD) (164 mg/l to 228 mg/l) and inorganic nitrogen (40 mg/l to 70 mg/l). Remaining parameters including pH stayed more or less consistent throughout the study period. The wastewater had a moderate COD value of 210 mg/l and the total inorganic nitrogen concentration (sum of ammoniacal nitrogen and nitrate nitrogen) was 64.7 mg/l. Moreover, a phosphate concentration of 13.5 mg/l made the wastewater nutrient rich. Thus if this water gets released in natural water bodies untreated, will trigger algal bloom and result in high chlorophyll concentration, such a situation is known as eutrophication. However, a nutrient-rich wastewater is more amenable to bioremediation than wastewater containing pesticides or other xenobiotic compounds. The wastewater was having high salinity and in particular high concentrations of sodium and chloride. The high concentrations of other alkali metals such as K, Ca and Mg resulted in a high total alkalinity which reflects the high acid neutralizing capacity of the water. The wastewater belongs to 'very hard' category (>140 mg/l) as the total hardness is 370 mg/l as $CaCO_3$. The presence of anionic species such as chloride (59.75 mg/l) and sulphate (24.83 mg/l) in water along with these alkali metal ions is further confirmed with moderately high electrical conductivity value of 2.43 ms/cm. The wastewater was analysed for eight heavy metals, among them concentrations of three, viz. Cd, Ni and Zn were consistently below the detectable limit. Concentration of lead in the inlet wastewater varied between 0.01 mg/l and BDL throughout the study period. The concentrations of other four heavy metals too were low.

Wastewater treatment efficiency of CW-1 and CW-2 during summer months

Nine months from July to October 2014 and Feb 2015 to June 2015 were identified as summer months from the weather data[36]. The normal temperature during these months remained above 25°C and maximum temperature stayed higher than 30°C consistently. The average inlet and outlet wastewater concentrations of key parameters during the summer months for both the CWs (Figure 3) are given in Table 2. A comparison of the removal efficiencies of CW-1 and CW-2 is presented in Figure 4.

Table 1. Wastewater characteristics of the inlet wastewater for the CWs

Parameters	Inlet concentration
Arsenic (mg/l)	0.04
Boron (mg/l)	0.04
Cadmium (mg/l)	BDL
Calcium (mg/l)	75.48
Chlorides (mg/l)	59.75
Chromium (mg/l)	0.01
Cobalt (mg/l)	0.05
Chemical oxygen demand (mg/l)	210.85
Copper (mg/l)	0.04
Detergents (mg/l)	1.59
Electrical conductivity (ms/cm)	2.43
Fluorides (mg/l)	1.70
Lead (mg/l)	BDL or 0.01
Magnesium (mg/l)	32.75
Manganese (mg/l)	0.48
Ammoniacal nitrogen (mg/l)	61.96
Nickel (mg/l)	BDL
Nitrate nitrogen (mg/l)	2.71
pH	7.68
Phosphates (mg/l)	13.5
Potassium (mg/l)	18.49
Sodium (mg/l)	78.51
Sulphates (mg/l)	25.32
Sulphur (mg/l)	8.54
Total dissolved solids (mg/l)	1214
Total alkalinity (mg/l)	294
Total hardness (mg/l as $CaCO_3$)	370
Total iron (mg/l)	0.15
Total suspended solids (mg/l)	60.4
Zinc (mg/l)	BDL

Table 2. Performance of CWs treating domestic wastewater during summer

Key parameters	Concentrations in the inlet wastewater	Concentrations in the outlet of CW-1	Concentrations in the outlet of CW-2
Ammoniacal nitrogen (mg/l)	63.81	39.30	41.68
Nitrate nitrogen (mg/l)	2.56	1.93	1.41
Phosphate (mg/l)	16.72	5.17	3.93
Sulphate (mg/l)	25.42	10.78	9.62
Chemical oxygen demand (mg/l)	163.8	96.00	64.00
Total suspended solids (mg/l)	41.2	16.44	25.45

Table 3. Plant sample analysis data and biomass generation rate for different *Typha* and macrophytes

Plant species	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Sulphur (mg/kg)	Biomass (dry) generation during summer ($g/m^2/day$)	Biomass (dry) generation during winter ($g/m^2/day$)
Typha	22,534	3,911	26,924	7,158	10.03	4.91
Water lettuce	41,294	10,473	28,987	3,115	7.40	5.63
Water hyacinth	26,817	6,757	21,493	6,343	8.20	3.80

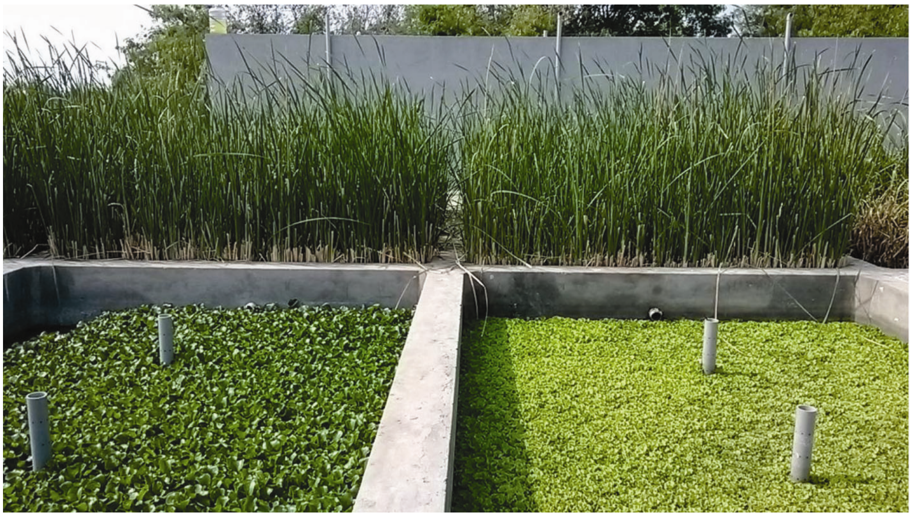

Figure 3. Field scale CWs used for this study, CW-1 (left) and CW-2 (right).

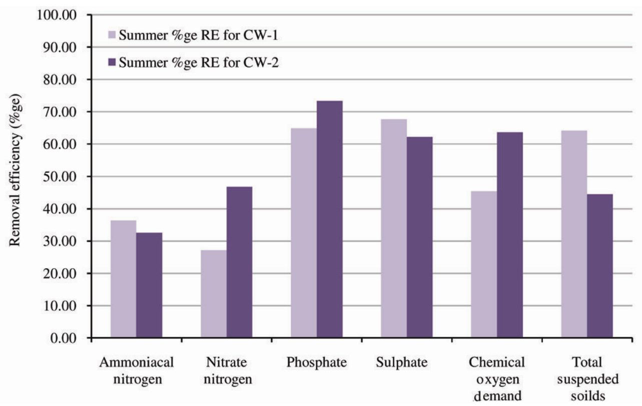

Figure 4. Comparison of removal efficiency of CW-1 and CW-2 for key wastewater parameters during summer months.

Slightly, higher removal efficiency for ammoniacal nitrogen was observed in CW-1 than CW-2 whereas the removal efficiency for nitrate nitrogen was much higher in CW-2. In order to derive a clearer interpretation, the removal efficiency if calculated according to total inorganic nitrogen (which is a sum of ammoniacal nitrogen and nitrate nitrogen), shows CW-2 has a higher removal efficiency (43%) than that observed for CW-1 (41%). Analysis of the plant samples and quantification of the harvested biomass (as per dry weight) further highlighted the significantly higher plant uptake capacity (Table 3) for water lettuce than water hyacinth. Similarly, a 1.5 times greater phosphate uptake capacity of water lettuce at 10,473 mg/kg was reflected by a higher sulphate removal efficiency (73%) observed for CW-2. Sulphate uptake capacity of water hyacinth and *Typha* both being much higher than water lettuce; a higher removal efficiency for sulphate as observed consistently in CW-1 was not unexpected (Figure 4). However, the difference in the removal efficiencies was only a mere 5%. It is clear that the *Typha*

Table 4. Performance of the CWs treating domestic wastewater during winter

Key parameters	Concentrations in the inlet wastewater	Concentrations in the outlet of CW-1	Concentrations in the outlet of CW-2
Ammoniacal nitrogen (mg/l)	56.4	34.75	34.32
Nitrate nitrogen (mg/l)	3.09	2.96	2.90
Phosphate (mg/l)	3.82	1.81	1.53
Sulphate (mg/l)	25.66	19.26	14.38
Chemical oxygen demand (mg/l)	352	64.00	128.00
Total suspended solids (mg/l)	118	2.00	4.00

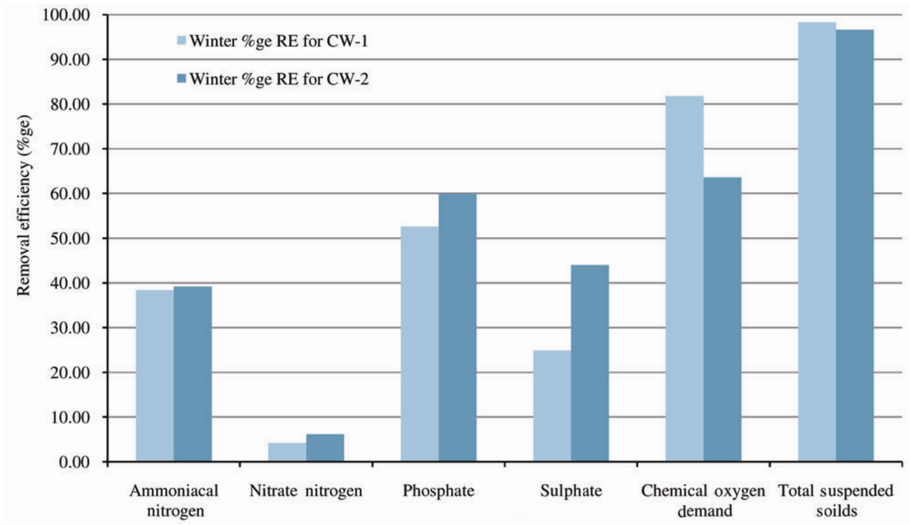

Figure 5. Comparison of removal efficiency of CW-1 and CW-2 for key wastewater parameters during winter months.

(common in the B cells of both the CWs) and microbial activity in the root zone overshadowed the difference in uptake by macrophytes during these months. Removal efficiency for COD was significantly higher in CW-2 (64%) than that observed for CW-1 (45%). Growth of microalgae in the outlet chamber (cell D, Figure 1 *a*) was observed during the summer months, as a result of this growth the TSS concentration at the outlet increased, reducing the overall TSS removal efficiency in both the cells. The availability of free water surface in the first few days after harvesting, resulted in the growth of microalgae in the two free water surface cells (cell C, Figure 1 *a*) vegetated with macrophytes. As macrophytes grew back, covering the entire cell surfaces of the C cells, the microalgae growth was brownish and subsequently disappeared. This pattern of macrophytes and microalgae growth was observed repeatedly.

Wastewater treatment efficiency of CW-1 and CW-2 during winter months

Three months from November to December in 2014 and January to June in 2015 were identified as winter months from the weather data[36]. The normal temperature during these months remained below 25°C and maximum temperature remained below 30°C consistently. A much slower plant growth was observed during these months (Table 3). Inorganic nitrogen concentration in the wastewater can be roughly estimated from the summation of the ammoniacal nitrogen and nitrate nitrogen. The total inorganic nitrogen removal efficiency (Table 4) remained same in CW-1 (37.9% and 37.4% during summer and winter months respectively) as well as CW-2 (35.1% and 36.6% during summer and winter months respectively). However, though the removal efficiency of ammoniacal nitrogen increased in both the CWs, a significant drop in the removal efficiency of nitrate nitrogen was observed in both the CWs. Microbial degradation plays a key role in conversion of ammoniacal nitrogen to nitrate nitrogen, with the latter gets readily absorbed by plants. Bacteria of two genus *Nitrosomonas* and *Nitrobacter* play key role in this process[37]. *Nitrosomonas* bacteria first convert ammonia into nitrites; subsequently *Nitrobacter* bacteria convert the nitrites into nitrates[38]. The field conditions during the winter months presented near-optimal-growth condition[39] for both *Nitrosomonas* (pH 6.0–9.0, temperature 20–30°C) and *Nitrobacter* (pH 7.9 and 28°C). This may explain the higher ammoniacal-nitrogen removal observed. However, a much slower plant growth might

Appendix 1. Analytical methods followed for wastewater analysis

Parameters	Analytical method adopted
Arsenic (mg/l)	3125 APHA Standard Methods (Ref)
Boron (mg/l)	4500-B B APHA Standard Methods (Ref)
Cadmium (mg/l)	3125 APHA Standard Methods (Ref)
Calcium (mg/l)	3500-Ca B of APHA Standard Methods (Ref)
Chlorides (mg/l)	4500-Cl^- B of APHA Standard Methods (Ref)
Chromium (mg/l)	3125 APHA Standard Methods (Ref)
Cobalt (mg/l)	3125 APHA Standard Methods (Ref)
Chemical oxygen demand (mg/l)	5220-C APHA Standard Methods (Ref)
Copper (mg/l)	3125 APHA Standard Methods (Ref)
Detergents (mg/l)	Adak *et al*., 2005 (Ref).
Electrical conductivity (ms/cm)	2510 B of APHA Standard Methods (Ref)
Fluorides (mg/l)	4500-F^- D of APHA Standard Methods (Ref)
Lead (mg/l)	3125 APHA Standard Methods (Ref)
Magnesium (mg/l)	3500-Mg B 3110 of APHA Standard Methods (Ref)
Manganese (mg/l)	3125 APHA Standard Methods (Ref)
Ammoniacal nitrogen (mg/l)	4500-NH3 F of APHA Standard Methods (Ref)
Nickel (mg/l)	3125 APHA Standard Methods (Ref)
Nitrate nitrogen (mg/l)	4500-NO3 B of APHA Standard Methods (Ref)
pH	4500-H^+ B of APHA Standard Methods (Ref)
Phosphates (mg/l)	4500-P D of APHA Standard Methods (Ref)
Potassium (mg/l)	3500-K B of APHA Standard Methods (Ref)
Sodium (mg/l)	3500-Na B of APHA Standard Methods (Ref)
Sulphates (mg/l)	4500-SO_4^{2-} E of APHA Standard Methods (Ref)
Sulphur (mg/l)	4100 B of APHA Standard Methods (Ref)
Total dissolved solids (mg/l)	2540 C of APHA Standard Methods (Ref)
Total alkalinity (mg/l)	2320 B of APHA Standard Methods (Ref)
Total hardness (mg/l as $CaCO_3$)	2340 C of APHA Standard Methods (Ref)
Total iron (mg/l)	3125 APHA Standard Methods (Ref)
Total suspended solids (mg/l)	2540 D of APHA Standard Methods (Ref)
Zinc (mg/l)	3125 APHA Standard Methods (Ref)

have resulted in reduced nitrate nitrogen uptake which resulted in a higher nitrate nitrogen concentration at the outlets in both the CWs. The sulphate removal efficiency of both the CWs dropped significantly during winter months; the drop was sharper CW-1 (67.64% during summer to 25% during winter) than in CW-2 (Figure 5). The marked change in growth rates of these plants was observed during the winter (Table 3). The sulphate removal efficiency of CW depends on microbial activity and plant growth rate. The reduced microbial activity during winter was reflected in the overall decrease in sulphate removal efficiency. A higher growth rate for water lettuce was probably the contributing factor to higher removal efficiency of sulphate in CW-2 compared to CW-1. A much lower growth of opportunistic microalgae was observed during the winter months compared to that observed during the summer.

Conclusion

Constructed wetlands vegetated with *Typha* and water lettuce (CW-2) showed higher wastewater treatment efficiency over the constructed wetlands vegetated with *Typha* and water hyacinth (CW-1). CW-2 was more robust to seasonal variations and interventions such as harvesting and sampling.

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