Greywater treatment using horizontal, vertical and hybrid flow constructed wetlands

C. Ramprasad and Ligy Philip*

Department of Civil Engineering, Environment and Water Resource Engineering Division, Indian Institute of Technology Madras, Chennai 600 036, India

The performance evaluation of three pilot scale sub-surface flow constructed wetlands (CW), i.e. horizontal flow (HFCW), vertical flow (VFCW) and a baffle type-hybrid (HYCW) was studied. The units were continuously fed with greywater and were planted with *Phragmites australis.* The inflow concentrations of BOD, COD, TSS, NO_3, TP and FC were in the range of 72–120 mg/l, 216–320 mg/l, 224–320 mg/l 10.3–14.6 mg/l, 2.9–3.8 mg/l and 50–120 CFU/100 ml respectively. The average removal efficiencies of BOD, COD, TSS, TP, TN and FC in HYCW were 95 ± 2%, 96 ± 3%, 98 ± 2%, 92 ± 2%, 98 ± 2% and 98 ± 2% respectively and comparatively more than the other two constructed wetlands.

Keywords: Constructed wetlands, hybrid flow, horizontal flow, organics and nutrients, *Phragmites australis*, vertical flow.

THE availability of adequate clean water is a common problem experienced in various parts of the world, due to ever growing population, indiscriminate discharge of wastes, climate change and poor water management practices. According to Lazarova *et al.*[1], by the year 2025, 75% of world's population will suffer from severe to moderate water problem and around 50% of the population will face real restraints in water supply. The condition would be much worse in developing countries due to rapid urbanization, population growth and uncontrolled human activities[2]. In India it has been projected that domestic contribution to the total water consumption will increase from 5% in 2000 to 11% by 2050. It is expected that average per capita water consumption will double from 89 l/day in 2000 to 167 l/day by 2050 (ref. 3). The best way to overcome this problem is to treat and reuse the wastewater in a decentralized manner.

The recycling and reuse of water is important in arid and semi-arid regions due to severe water scarcity. Reusing treated water for gardening and landscaping alone could reduce the potable use by as much as 50% (ref. 4). In Israel, about 70% of wastewater is treated and reused for irrigation, while in Kuwait about 30% of treated wastewater is used for agricultural needs. However, in India, less than 25% of the wastewater is collected and treated, and in that, only <3% is being reused for irrigation[5].

Domestic wastewater can be classified into two categories: (i) Greywater (GW), which is the wastewater generated from activities such as bathing, cooking, dish washing and laundry and (ii) black water (BW), which is the wastewater generated from toilets. Due to substantial difference in their qualities and quantities, separating greywater and black water would ease the treatment process, thereby allowing a large volume of water to be efficiently recycled[6]. A wide range of treatment technologies such as membrane bioreactor (MBR), sequential batch reactor (SBR) and various other physico-chemical and biological treatment methods have been employed to treat greywater[7]. Most of these systems are expensive and need frequent maintenance, besides requiring skilled personnel for operation[8]. Also, they require uninterrupted power supply[9]. Constructed wetland is a sustainable alternative for treatment of greywater.

Constructed wetland (CW) is a green treatment technology, which mimics natural wetlands, and has been widely used to treat various kinds of wastewater such as domestic sewage, agricultural wastewater, industrial effluent, mine drainage, landfill leachate, storm water, polluted river water and urban runoff in the last few decades[10]. Constructed wetlands are classified into different categories based on (i) flow pattern (horizontal, vertical and hybrid) and (ii) type of vegetation like floating, emergent and sub-mergent[11]. Numerous studies have focused on the design, development and performance of CWs. Earlier studies reported that CWs were effective in removing various pollutants such as organic matter, nutrients, trace elements, pharmaceutical contaminants and pathogens from wastewater[10]. However, no report is available on the evaluation of baffled type constructed wetland for the treatment of greywater. Though many studies deal with the performances of horizontal flow constructed wetlands (HFCW) and vertical flow constructed wetlands (VFCW) for treating wastewater and greywater, a comparison of the performance of various types of constructed wetlands, i.e. horizontal, vertical and hybrid baffled type in a common platform for the treatment of greywater on a pilot scale system is lacking.

The present study focused on three pilot scale sub-surface flow wetland configurations namely, HFCW,

*For correspondence. (e-mail: ligy@iitm.ac.in)

VFCW and a new hybrid flow constructed wetland (HYCW), planted with native plant species (*Phraghmities australis*) for the treatment of greywater. Removal efficiencies of various pollutants such as organics (COD, BOD_5 and total organic carbon, solids (TSS)), nutrients (TN, nitrate, ammonia and TP), faecal coliforms and heavy metals were assessed under various operating conditions.

Materials and methods

Description of treatment units

Three pilot scale plants namely (i) horizontal flow, (ii) vertical flow and (iii) hybrid flow were designed and constructed as per UN-HABITAT manual on constructed wetland[12] at the Indian Institute of Technology Madras, Chennai, India campus (12.9915°N, 80.2336°E). The wetland units were sized using the basic plug flow reactor eq. (1) for BOD_5 loading as recommended by UN-HABITAT, 2008.

$$A_h = \frac{Q_d(\ln C_t - \ln C_e)}{k_{BOD}}, \tag{1}$$

where A_h is the surface area of the bed (sq m), Q_d, average flow rate of wastewater (cu m/day), K_{BOD}, the rate constant (m/day), C_i, the average BOD_5 of the influent (mg/l) and C_e, average BOD_5 of the effluent (mg/l).

The pilot plants were operated for a period of two years. The systems were fed continuously with settled GW from student's hostel by gravity. The GW from hostels was collected in a separate pipeline which did not contain any kitchen wastewater or BW. Basins of the systems had dimensions 10.1 m (length) × 2.55 m (width) × 1.3 m (depth), with a surface area of 25.8 sq. m per basin as shown in Figure 1 *a*. The depth was measured from the bottom liner to the top cover of the CWs. The treatment bed was constructed with a slope of 1 in 100 and the tanks were water-proof. The HFCW system was filled with sand and brickbats (1 : 1 v/v ratio) up to a depth of 0.9 m for the entire length except for 0.5 m at both ends. The inlet and outlet zones (first and last 0.5 m) were filled with <10 mm size gravel to achieve uniform flow conditions and prevent the bed from getting clogged as shown in Figure 1 *b*. The VFCW was filled with multi-layers of substrate as shown in Figure 1 *b* and three PVC pipes with perforations at every 10 cm distance were laid to distribute the influent GW. The third basin (HYCW) was constructed with baffle walls (6 in numbers) to have a zig-zag flow as shown in Figure 1 *b* and the bed was filled with sand and brick bats in 1 : 1 ratio. The vertical baffles were placed perpendicular to flow direction for the total flow length of 10.1 m with 1.1 m centre to centre spacing between them with a thickness of 7.62 cm.

Plantation and sampling

Young *Phragmites australis*, commonly known as common reed were cut from a nearby pond and planted in HFCW and VFCW in February 2013 whereas in HYCW, the plantation was done in October 2013. Reeds were planted to obtain a density of 6 plants/sq. m. The harvesting was done only once during the study period (October 2013) from HFCW and VFCW beds. Plants were cropped, leaving behind approximately 50 cm from the top of the porous medium. Water samples from both inlet and outlet were collected on weekly basis for analysis.

Analytical methods

The physico-chemical and biological analyses were carried out for both raw and treated water samples. The water quality parameters such as pH, BOD_5, COD, TOC, TSS, TN, ammonia nitrogen (NH_4–N), nitrate nitrogen (NO_3–N), TP and FC were analysed. The Eutech cyberscan PCD 650 multi parameter kit (Thermo Scientific, Singapore) was used for the pH measurement. BOD_5, COD, TSS, NH_4–N, NO_3–N and TP were carried out according to Standard Methods for the Examination of Water and Wastewater[13]. TOC and TN were measured using total organic carbon analyzer V600 series (Shimandzu, Japan). Faecal coliform count was measured by chromocult nutrient media (EC) plates supplied by Sartorius, Germany. Heavy metals such as chromium, nickel, copper, zinc, arsenic, cadmium and lead were analysed using atomic absorption spectrometer (NexION 300X, Perkin Elmer, USA).

Statistical analysis

In order to study the performance of the three wetland systems (HFCW, VFCW and HYCW) with respect to the removal of various contaminants from greywater, a paired sample *t* test was performed at 95% significance level using IBM SPSS 20 statistics software. Effluent qualities of three pairs of the wetlands (viz. HFCW–VFCW, HFCW–HYCW and VFCW–HYCW) were compared for various parameters such as COD, TSS, TN, TP and FC (see Supplementary Table 1).

Results and discussion

Characterization of influent greywater

The collected greywater samples were analysed for various parameters. The minimum and maximum values of pH, COD, BOD_5, TOC, TN, TSS, NH_4–N, NO_3–N, TP, FC and heavy metals such as total chromium, nickel, copper, zinc, arsenic, cadmium and lead are presented in

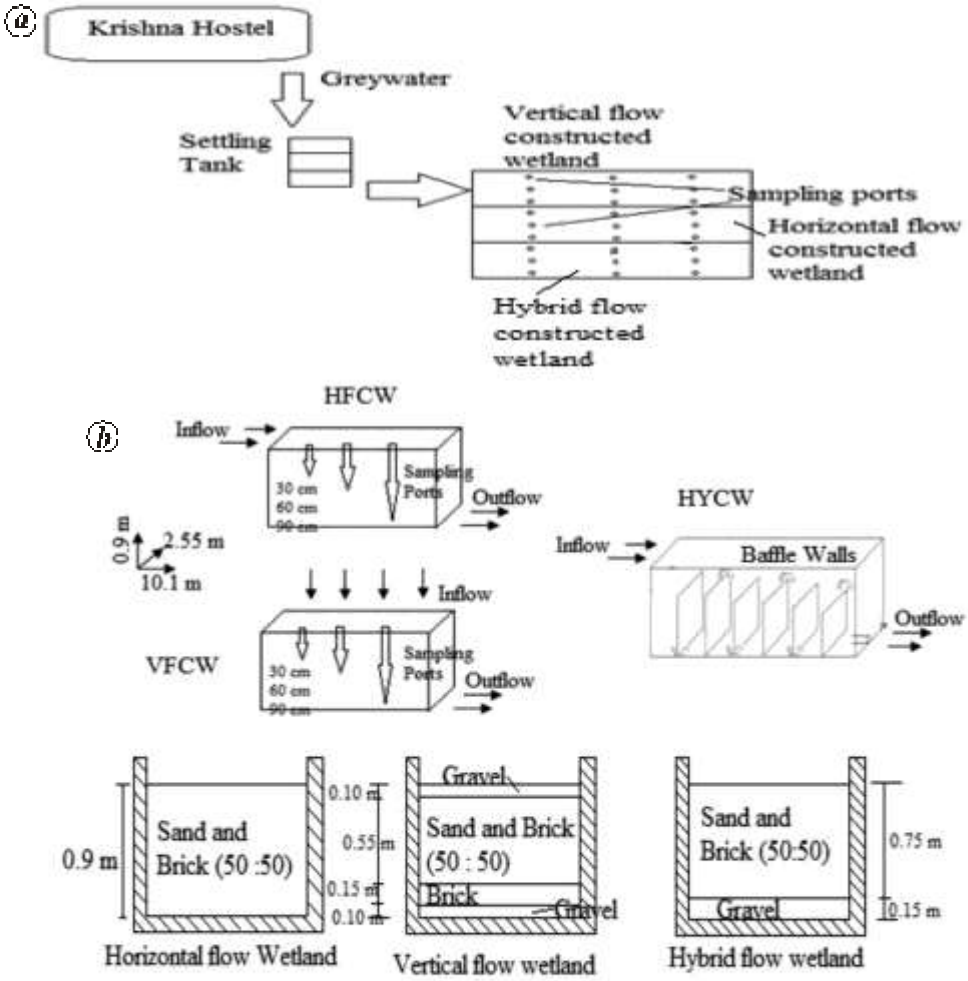

Figure 1. ***a***, Schematic diagram of pilot scale constructed wetland. ***b***, Cross-sectional view of HFCW, VFCW and HYCW system.

Table 1. The values of influent COD (216–320 mg/l), BOD_5 (82.9–138.2 mg/l), TSS (224–320 mg/l), TOC (23–36.5 mg/l), TN (17–28.8 mg/l), FC (50–120 CFU/100 ml) and TP (2.9–3.8 mg/l) were comparable with the earlier reported values[14] except a faecal coliforms. The faecal coliform number was found to be less than the previously reported values. The reason being the per capita water consumption in the study area was more and the greywater originated from hostels where only young men lived. The chances of a faecal coliform in the GW is due to urination during bathing, cleaning and washing of soiled clothes, sweat from the body parts, washing of under garments, etc. As the served population was young men, the chances of washing soiled clothes were less, which in turn reduced the faecal contamination.

Organic matter removal

The results of the analysis indicate that there was significant reduction of organics in all three wetland systems. The reduction of BOD and COD in three different wetlands is shown in Figure 2. It was observed that COD was reduced from an initial concentration of 216–320 mg/l to 16 ± 8 mg/l (95.4%) in HFCW, 8 ± 8 mg/l (97%) in VFCW and 8 ± 8 mg/l (97%) in HYCW. The residence time of the wetland varied from 8.9 days to 12.5 days. Similarly, there was significant reduction in BOD_5 from an initial concentration of 82.9–138.2 mg/l to 6.1 ± 2.7 mg/l (93.4%) in HFCW, 4.7 ± 1.8 mg/l (94.9%) in VFCW and 4.5 ± 1.7 mg/l (95.1%) in HYCW systems, whereas the concentration of TOC was reduced to 1.7 ± 1.6 mg/l (94.5%) in HFCW, 1.4 ± 1.3 mg/l (95.5%) in VFCW and 1.2 ± 1.02 mg/l (96%) in HYCW from an initial concentration of 23.0–36.5 mg/l (Supplementary Figure 1). It was also observed from the statistical evaluation (95% confidence limit) that the percent removal values of organic pollutants in HYCW show a statistically significant ($P > 0.05$) difference from VFCW and HFCW as shown in Supplementary Table 1. The removal of organic matter in various constructed wetland systems is mainly due to a combination of physical

Table 1. Characterization of influent greywater

Parameters	Units	Minimum	Maximum	USEPA standard limits for reuse
pH	–	7.24	8.34	5.5 to 9.0
Chemical oxygen demand (COD)	mg/l	216	320	10
Biochemical oxygen demand (BOD)	mg/l	72	120	<5
Total suspended solids (TSS)	mg/l	224	320	10
Total organic carbon (TOC)	mg/l	23	36.48	NA
Total nitrogen (TN)	mg/l	17	28.82	10
Ammonia nitrogen (NH_4–N)	mg/l	12.32	17.84	10
Nitrate nitrogen (NO_3–N)	mg/l	10.28	14.56	<5
Total phosphate (TP)	mg/l	2.934	3.84	1
Faecal coliform (FC)	CFU/100 ml	50	120	Nil
Total chromium (Cr)	µg/l	212.2	268.4	50
Nickel (Ni)	µg/l	38.4	57.2	30
Copper (Cu)	µg/l	41.2	50.6	50
Zinc (Zn)	µg/l	1616.7	2125.7	2000
Arsenic (As)	µg/l	33.3	43.2	10
Cadmium (Cd)	µg/l	32.7	51.2	10
Lead (Pb)	µg/l	146.6	228.5	100

filtration, plant uptake and microbial removal mechanisms. The removal efficiencies observed in the present study for COD, BOD and TOC are better than those previously reported[11]. A slightly higher organic pollutant removal was observed in HYCW system. It could be due to the presence of baffles which provides a longer hydraulic pathway and residence time thus allowing more adsorption and microbial degradation of the pollutants[15].

Reduction of nitrogenous compounds

Nitrogen is considered as the primary pollutant in wastewater. Nitrogen exists both in organic and inorganic forms in wastewater. The transformation and removal of nitrogen in sub-surface horizontal, vertical and hybrid flow constructed wetlands are accomplished by biological processes, i.e. ammonification, nitrification, de-nitrification, plant uptake, biomass assimilation, i.e. dissimilatory nitrate reduction, and physico-chemical routes such as ammonia volatalization and adsorption[2,10,16].

Significant reduction of nitrogenous compounds was observed in all the three wetlands. The overall average removal efficiency of TN during evaluation was observed to be 93.2% (1.8 ± 1.9 mg/l) in HFCW system, 95.7% (1.1 ± 1.8 mg/l) in VFCW system and 95.9% (1.1 ± 1.09 mg/l) in HYCW, with the initial concentration ranging from 18.2 to 32.1 mg/l. The removal efficiency obtained in the present study is higher than that reported earlier, mainly due to the combined effect of heterotrophic denitrifiers and autotrophic denitrifiers and higher residence time available for microbes to convert available nitrates completely to nitrogen gas. Also at elevated temperatures (between 20°C and 38°C) the bacteria were active[2,10,16]. Zurita *et al.*[17] showed that the removal efficiency of TN was 45.8% for HFCW and 48.2% for VFCW system and the retention time falls within 4 days with water temperature ranging from 18.9 to 21.1°C. Another study[16] showed that the removal efficiency of TN (initial TN concentration was 18.6–66 mg/l) was about 60% for HFCW system and 62.5% for VFCW system with the retention time ranging from 7.7 to 11 days and the temperature ranging from 20°C to 21.1°C. Another study[10] showed that TN removal was more for VFCW system (80.2%) than HFCW system (70.4%). In addition, the retention time was in the range of 0.93–1.14 days and temperature was 15–37°C. Similar to total nitrogen, the concentration of nitrate-nitrogen was significantly reduced from the initial concentration of 14.12–18 mg/l, during the period of evaluation (Figure 3 *a* and *b*). The average removal efficiency was found to be 93% (1.02 ± 1.97 mg/l) for HFCW system, 94% (0.9 ±2.2 mg/l) for VFCW system and 97% (0.88 ± 2.3 mg/l) for HYCW with the retention time in the range of 8.9–12.5 days and the temperature varying from 25°C to 38°C. The removal of nitrogenous compounds showed statistically significant difference ($P > 0.05$) between the three reactors (HFCW, VFCW and HYCW) under the same operating conditions (Supplementary Table 1). The denitrification process is considered as the major mechanism for the removal of NO_3–N and TN, where the nitrates are converted to nitrogen gas by various facultative bacterial groups. In addition to the denitrification process, two other processes such as plant uptake and microbial assimilation are also responsible for removal of nitrates[10,16]. Among the three beds, HYCW showed comparatively higher removal efficiency than HFCW and VFCW (Figure 3 *a* and *b*) due to the higher retention time. Unique arrangement of baffles created a better contact of the wastewater with the microbes and plants and enabled the use of entire bed effectively.

Reduction of suspended solids

The removal rates of suspended solids are effective in wetland systems as shown in Figure 4. The average removal of TSS was 91.5% (22 ± 10 mg/l) for HFCW system, 93.7% (16 ± 8 mg/l) for VFCW system and 96.8% (8 ± 2 mg/l) for HYCW system from an initial concentration of 224–296 mg/l. It was also found statistically that there was no significant difference ($P < 0.05$) in concentration of solids in treated water between HFCW and VFCW. However, there was significant difference ($P > 0.05$) between other pairs HFCW–HYCW and VFCW–HYCW as shown in Supplementary Table 1. Similar results are reported by Abou-Elela *et al.*[16]. The removal of solids is mainly due to physical process such as sedimentation and filtration[16]. The results suggest that HYCW system performed better than VFCW and HFCW system in terms of TSS removal, due to higher residence time available in HYCW.

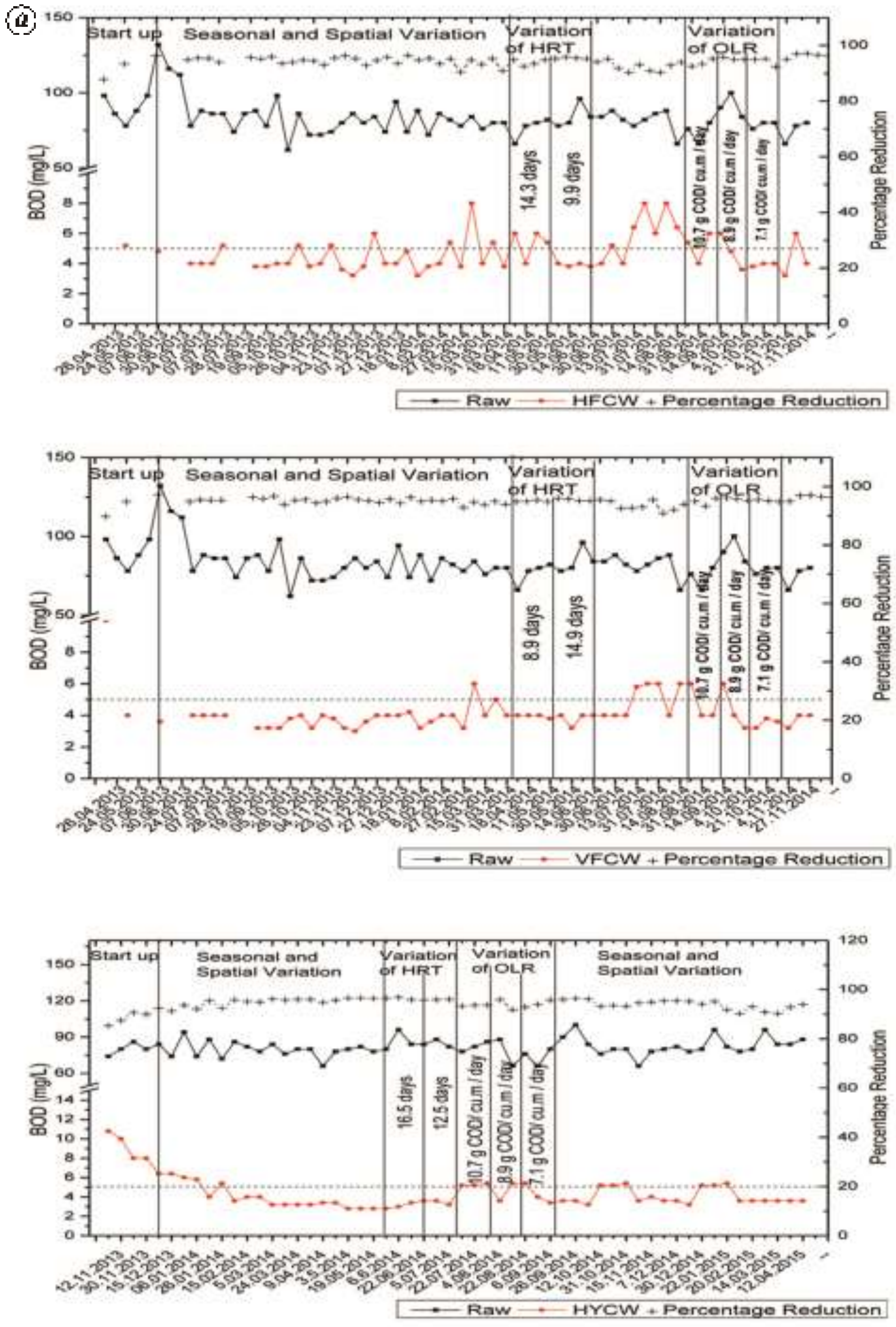

Figure 2 *a*. BOD removal efficiency (%) of the pilot scale constructed wetlands (HFCW, VFCW and HYCW).

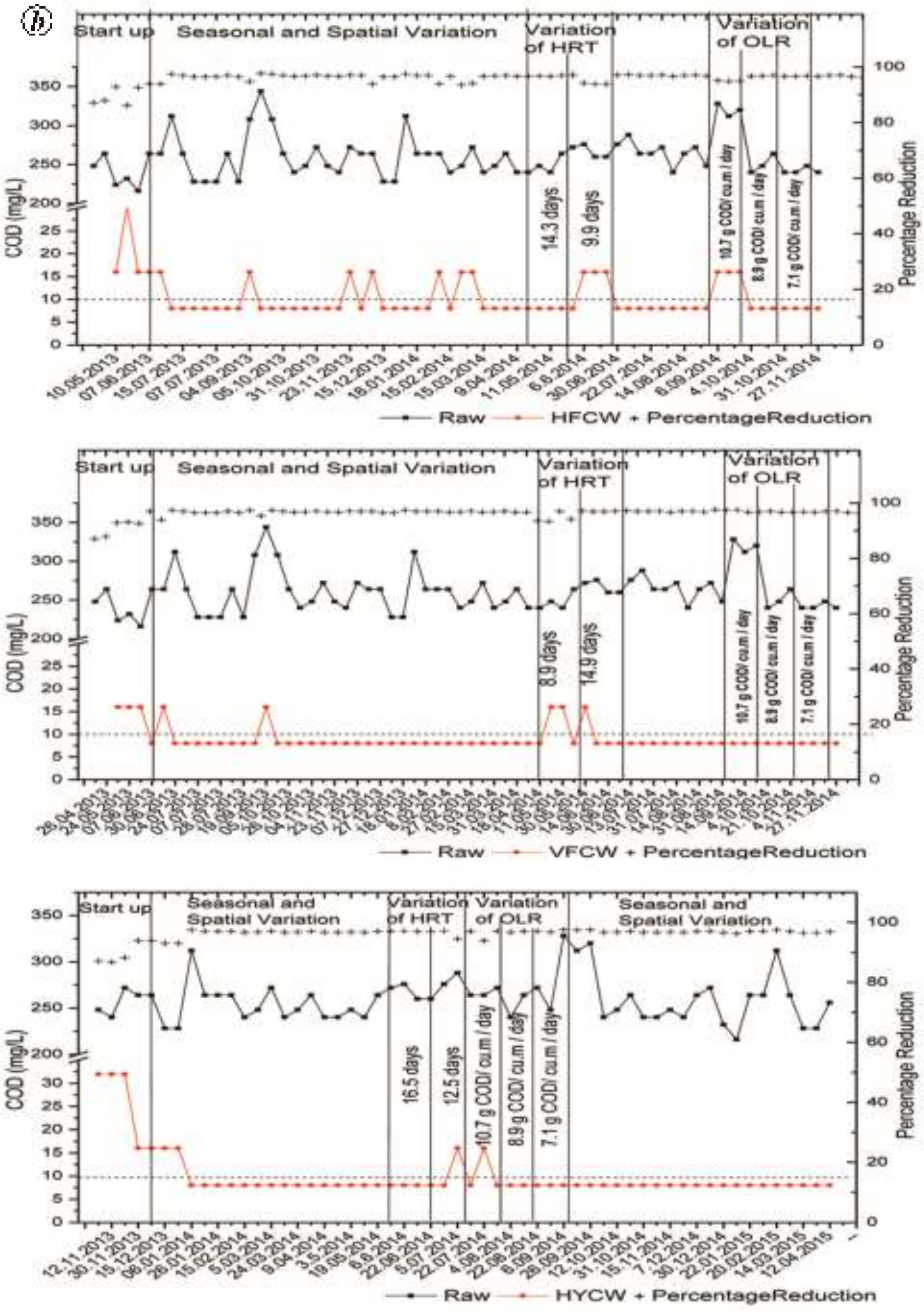

Figure 2 *b*. COD removal efficiency (%) of the pilot scale constructed wetlands (HFCW, VFCW and HYCW).

Reduction in total phosphate

The removal of phosphate in constructed wetland is mainly due to three mechanisms; adsorption, precipitation and plant uptake with successive harvest and soil/plant accretion[16]. HYCW system was marginally more effective in phosphorus removal than VFCW and HFCW as shown in Figure 3 *c*. The removal efficiency was 91.4% (0.268 ± 0.17 mg/l) for HFCW, 92.3% (0.232 ± 0.13 mg/l) for VFCW system and 92.4% (0.232 ± 0.06 mg/l) for HYCW from the initial raw greywater concentration of 2.9–3.8 mg/l. Advantage of HYCW system over VFCW and HFCW in removal of TP from greywater is due to unique flow pattern created inside the hybrid system. HYCW system consists of both horizontal and vertical flow pattern combined in a single unit. The vertical flow direction strengthens the filtration of TP, while the horizontal flow patterns expedite the settlement of TP[15]. The removal efficiency obtained in the present study is better than the previously reported ones by Zurita *et al.*[17], who obtained only 44% removal of phosphate in HFCW and 50% removal in VFCW system. Abou-Elela *et al.*[16] also found slightly better removal efficiency of 68% for VFCW compared to 63% for HFCW systems; the initial TP concentration was between 1.5 and 6.3 mg/l. The reason for higher removal of TP is mainly due to dense growth of plants (6 plants/sq. m) and higher retention time available in the systems. It was also confirmed from the statistical test that there was no significant difference ($P < 0.05$) for TP removal between HFCW and VFCW. The overall TP removal efficiency of HYCW showed a statistically significant difference ($P > 0.05$) between VFCW and HFCW systems (Supplementary Table 1).

Reduction of bacterial contamination

Wetlands are proven to be capable of removing a wide range of pollutants and bacterial contamination[11]. The wetland systems eliminate bacterial contamination through a combination of physico-chemical and biological processes. These mechanisms include (i) physical processes such as sedimentation and filtration by roots, (ii) chemical processes such as biocides secretion, (iii) biological process like antibiosis, lytic and bacteria attack and (iv) natural death[17]. Among all the three constructed wetlands studied, HYCW showed significant reduction of a faecal coliform which is about 96.8% whereas the reduction of faecal coliform for HFCW and VFCW was found to be 93.5% and 95.7% respectively (Figure 5). It was also noticed that the per cent removal of coliform obtained for each of the three pairs of treatment schemes studied (HFCW–VFCW, HYCW–VFCW and HFCW–HYCW) showed statistically significant difference ($P > 0.05$) at 95% confidence level as shown in Supplementary Table 1. The results obtained in reduction of a faecal coliform were comparable to earlier studies[2]. Regardless of higher removal rates in the wetlands, the residual pathogens may not comply with USEPA standards limits for reuse. Hence, a small dose of disinfectant is advisable before reuse.

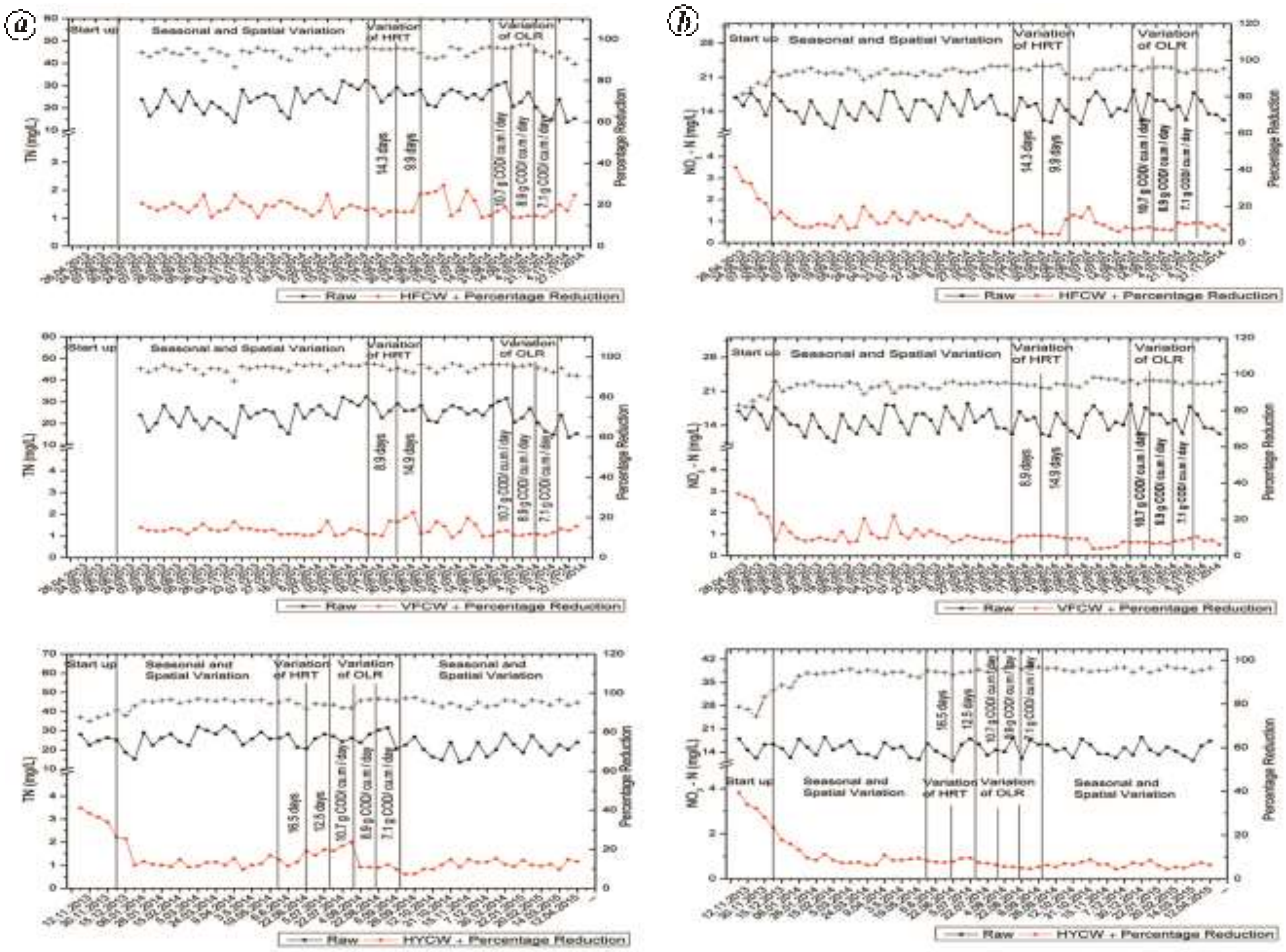

Figure 3 *a*, *b*. TN and NO_3 removal efficiency (%) of the pilot scale constructed wetlands (HFCW, VFCW and HYCW).

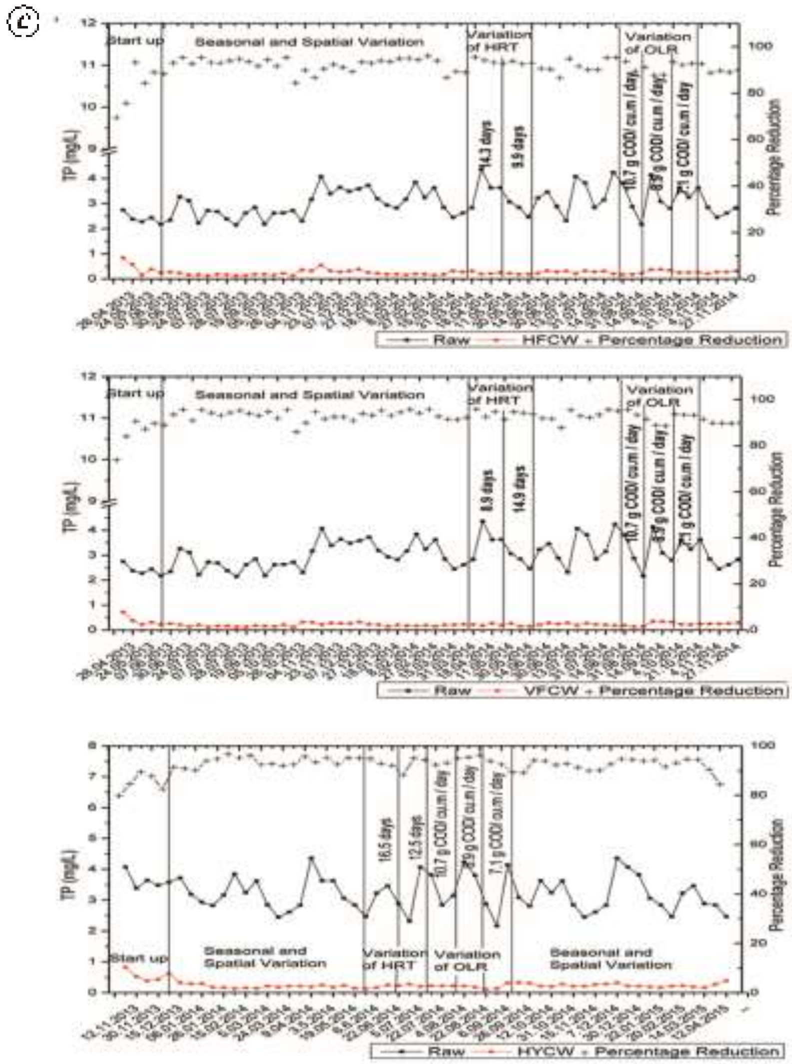

Figure 3 *c*. TP removal efficiency (%) of the pilot scale constructed wetlands (HFCW, VFCW and HYCW).

Reduction of heavy metals

The percentage reduction of heavy metals concentration in HFCW, VFCW and HYCW systems in summer and winter seasons is shown in Supplementary Figure 2. The three wetlands performed in a similar manner with respect to the removal of heavy metals. Heavy metal removal occurred through different pathways such as (i) adsorption of metals in the soils and sediments; (ii) sedimentation; (iii) cation and anion exchange, complexation; (iv) precipitation and co-precipitation as insoluble ions, (v) plant uptake and (vi) microbial metabolism[2,18]. The initial concentration of heavy metals was in the following ranges: Cr concentration 212.2–268.8 μg/l; Ni concentration 38.4–57.2 μg/l; Cu concentration 41.2–50.6 μg/l; Zn concentration 1616.7–2125.7 μg/l. As concentration varied from 33.3 to 43.2 μg/l, Cd was 32.7 to 51.2 μg/l and Pb was 146.6 to 228.5 μg/l. The sources of heavy metals may be detergents, personal care products and pipe fittings.

In HYCW system the removal efficiency for the heavy metal followed the order of Cu (96.4%) > Cr (92.9%) >Pb (91.7%) > Ni (89.3%) > As (76.4%) > Zn (75.8%) > Cd (71.9%). In VFCW system the removal efficiency of heavy metals during summer followed the same order of Cu (96.4%) > Cr (92.5%) > Pb (91.5%) > Ni (89%) > As (76.4%) > Zn (73.9%) > Cd (69.1%). Similar trend was observed in HFCW system during the summer season; it followed the order of Cu (94.3%) > Cr (90%) > Pb (87.6%) > Ni (87.3%) > As (70.4%) > Cd (67.4%) > Zn (65.6%). It was also found that all the three wetlands (HFCW, VFCW and HYCW) performed better in summer than in winter. The removal efficiency of heavy metals during the summer and winter seasons is shown in Supplementary Figure 2. The reason for higher removal of heavy metals during summer is due to higher uptake

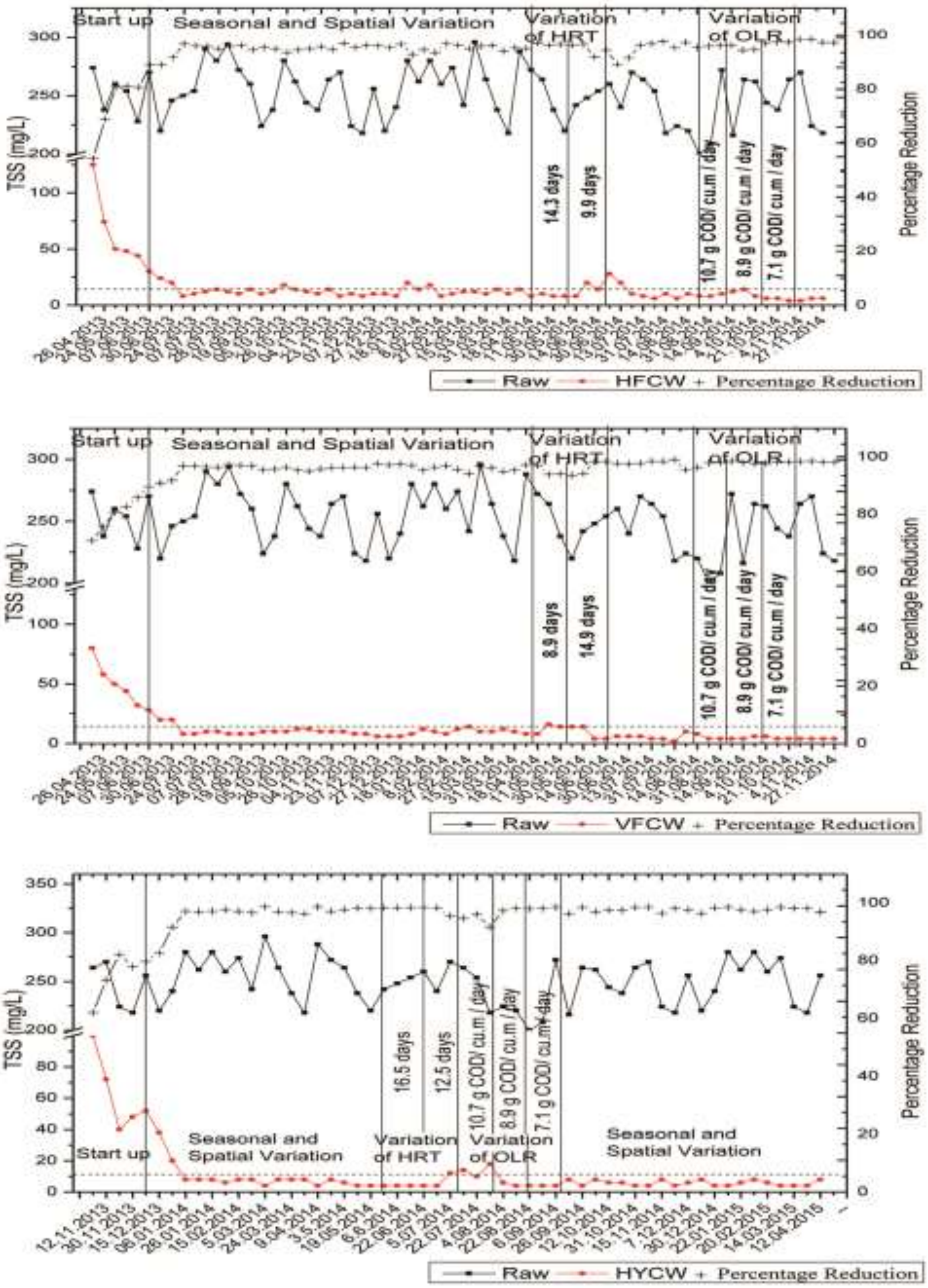

Figure 4. Total suspended solids removal efficiency (%) of the pilot scale constructed wetlands (HFCW, VFCW and HYCW).

by shoots and enhanced microbial activity[18]. It is also to be noted that during the longer run of the constructed wetland, the heavy metals get accumulated in the soil or taken-up by plants, making the wetland a sink instead of a source. Therefore, there is a need for longer studies on the wetlands to visualize the effects of wetlands age (maturation), degree of harvesting and different plant species on the removal efficiencies, especially one that deals with conservative/xenobiotic pollutants.

Conclusion

This study evaluated the performance of various constructed wetlands under different operating conditions. The CWs were operated under different hydraulic loading rates and organic loading rates in different seasons. The HFCW system showed an overall removal efficiency of 95.4% for COD, 93.4% for BOD, 95.5% for TOC, 93.2% for TN, 91.5% for TSS, 91.4% for TP and 93.5% for FC,

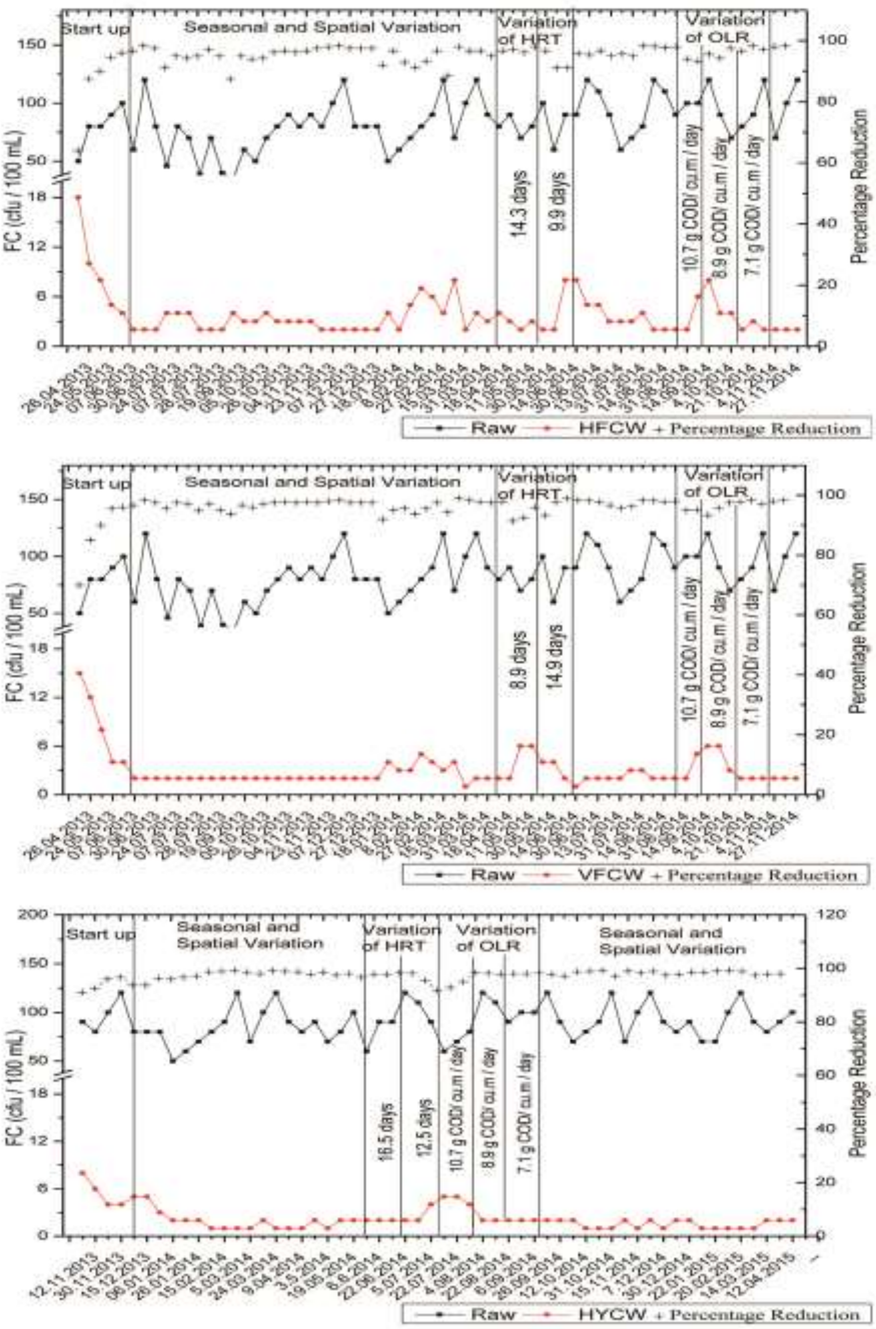

Figure 5. Faecal coliform count in influent and effluent of pilot scale constructed wetlands (HFCW, VFCW and HYCW).

whereas the removal efficiency of VFCW system was found to be 97% for COD, 94.9% for BOD, 95.5% for TOC, 95.7% for TN, 93.7% for TSS, 92.3% for TP and 95.7% for FC. Removal efficiencies were higher for HYCW: 97% for COD, 95.1% for BOD, 96% for TOC, 95.9% for TN, 96.8% for TSS, 92.4% for TP and 96.8%for FC. Further, all the three systems performed well under different operating conditions. It was found that treated water quality was well within the USEPA re-use standards limit.

1. Lazarova, V., Levine, B., Sack, J., Cirelli, G., Jeffrey, P., Muntau, H. and Brissaud, F., Role of water reuse for enhancing integrated water management in Europe and Mediterranean countries. *Water Sci. Technol.*, 2001, **43**(10), 25–33.
2. Vymazal, J., Removal of nutrients in various types of constructed wetlands. *Sci. Total Environ.*, 2007, **380**, 48–65.
3. Saumya, S., Akansha, S., Rinaldo, J., Jayasri, M. A. and Suthindhiran, K., Construction and evaluation of prototype subsurface flow wetland planted with Heliconiaangusta for the treatment of synthetic greywater. *J. Clean. Prod.*, 2015, **91**, 235–240.

4. Department of Health Western Australia (DHWA), *Draft Guidelines for the Reuse of Greywater in Western Australia*, Department of Health, Perth, Australia, 2002.
5. Crook, J., Mosher, P. J. J. and Casteline, J. M., Status and role of water reuse. *An International View*, Global Water Research Coalition. United Kingdom, London, 2005.
6. Gross, A., Shmueli, O., Ronen, Z. and Raveh, E., Recycled vertical flow constructed wetland (RVFCW) – a novel method of recycling greywater for irrigation in small communities and households. *Chemosphere*, 2007, **66**(5), 916–923.
7. Beck, S. E., Rodríguez, R. A., Salveson, A., Goel, N., Rhodes, S., Kehoe, P. and Linden, K. G., Disinfection methods for treating low TOC, light greywater to California Title 22 water reuse standards. *J. Environ. Eng.*, 2013, **139**(9), 1137–1145.
8. Chen, Z., Kuschk, P., Paschke, H., Kästner, M., Müller, J. A. and Köser, H., Treatment of a sulphate-rich groundwater contaminated with perchloroethene in a hydroponic plant root mat filter and a horizontal subsurface flow constructed wetland at pilot-scale. *Chemosphere*, 2014, **117**, 178–184.
9. Wurochekke, A. A., Harun, N. A., Mohamed, R. M. S. R. and Kassim, A. H. B. M., Constructed wetland of *Lepironia articulata* for household greywater treatment. *APCBEE Procedia*, 2014, **10**, 103–109.
10. Saeed, T. and Sun, G., A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: Dependency on environmental parameters, operating conditions and supporting media. *J. Environ. Manage.*, 2012, **112**, 429–448.
11. Vymazal, J., The use of sub-surface constructed wetlands for wastewater treatment in the Czech Republic: 10 years experience. *Ecol. Eng.*, 2002, **18**(5), 633–646.
12. UN-HABITAT, *Constructed Wetlands Manual*. UN-HABITAT Water for Asian Cities Programme Nepal, Kathmandu, 2008.
13. American Public Health Association. APHA, *Standard Methods for the Examination of Water and Wastewater*, Water Environment Federation, Washington, DC, 21st edn, 2005.
14. Antonopoulou, G., Kirkou, A. and Stasinakis, A. S., Quantitative and qualitative greywater characterization in Greek households and investigation of their treatment using physicochemical methods. *Sci. Total Environ.*, 2013, **454**, 426–432.
15. Tee, H. C., Lim, P. E., Seng, C. E. and Nawi, M. A. M., Newly developed baffled subsurface-flow constructed wetland for the enhancement of nitrogen removal. *Bioresour. Technol.*, 2012, **104**, 235–242.
16. Abou-Elela, S. I., Golinielli, G., Abou-Taleb, E. M. and Hellal, M. S., Municipal wastewater treatment in horizontal and vertical flows constructed wetlands. *Ecol. Eng.*, 2013, **61**, 460–468.
17. Zurita, F., De Anda, J. and Belmont, M. A., Treatment of domestic wastewater and production of commercial flowers in vertical and horizontal subsurface-flow constructed wetlands. *Ecol. Eng.*, 2009, **35**(5), 861–869.
18. Akratos, C. S. and Tsihrintzis, V. A., Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. *Ecol. Eng.*, 2007, **29**(2), 173–191.

ACKNOWLEDGEMENT. We acknowledge the Department of Science and Technology, Government of India for funding this research project.

Received 13 May 2016; accepted 27 July 2017

doi: 10.18520/cs/v114/i01/155-165