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Article

Performance evaluation of hybrid constructed wetlands for the treatment of municipal wastewater in developing countries

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ABSTRACT

In developing countries, high cost of conventional wastewater treatment is a major hindrance in its application. Constructed wetlands (CWs) offer low-cost and effective solution to this issue. The current study aimed to evaluate an innovative maneuver of CWs *i.e.* hybrid flow constructed wetlands (HCWs) for municipal wastewater (MWW). The HCWs included two lab scale CWs; one horizontal and one vertical, in series. Local plant species were used. HCWs were operated in both, batch and continuous mode. Batch mode was used to (1) optimize detention time and (2) find pollutants removal efficiency. Continuous operation (at batch optimized retention time) was carried out for the evaluation of mass removal rate, r ($g\cdot m^{-2}\cdot d^{-1}$), volumetric rate constant, K_v (per day) and areal rate constant, K_a ($m\cdot d^{-1}$). Among two local plants tested, *Pistia stratiotes* gave better removal efficiency than Typha. Optimum detention time in HCWs was found to be 8 days (4 + 4 each). The optimum COD, BOD, TSS, TKN and P removal observed for *Pistia stratiotes* planted HCWs was 80%, 84%, 82%, 71% and 88% respectively. Effluent standards for COD, BOD and TSS were met at optimum conditions. The values of K_a and K_v demonstrated that more removal occurred in vertical flow as compared to horizontal flow CW.

1. Introduction

According to United Nations Children's Fund (UNICEF) study, almost 2000 million gallons per day of untreated sewage is discharged into surface water bodies in Pakistan [1]. This has led to the deterioration of surface water quality, threatened the aquatic life and outbreak of numerous water-borne diseases. In addition, over exploitation of freshwater resources by the agricultural sector has consumed the fresh water reserves of Pakistan. Resultantly, Pakistan has stepped into a water scarce country. Being an agriculture economy, there is a dire need to conserve fresh water resources through wastewater treatment and reuse [2].

Safe disposal of municipal wastewater is a major challenge confronted by the municipal authorities in developing countries. Current mainstream wastewater technologies are not always the solutions in developing regions. High capital and operational cost and weak institutional capacity are the major hindrance in their application. At many places, these failed due to the above reasons [3–7].

Low-cost and simple wastewater treatment technologies are the solution in the above context. These are based on the principles of affordability, environment friendliness, ease of operation, sustainability while meeting effluent standards [8]. Conventional low-cost wastewater treatment technologies include waste stabilization ponds, anaerobic filters, green filters, septic tanks, slow sand filtration, and constructed wetlands [8]. Among these, constructed wetlands (CWs) are one of the popular low-cost natural treatment options for wastewater. CWs are engineered ecosystems which consist of macrophytes and the substrate. Macrophytes are the water floating or submerged plants, whereas the substrate is the support layer of media (soil or gravel) required for plant growth. A combination of biological, physical and chemical phenomena, through macrophytes, media and microbes, are responsible for the removal of pollutants in these wetlands [9–11].

Generally, the constructed wetlands can be classified based on hydrology. Two most common types of these include free surface flow and subsurface flow types. In free surface flow type, the flow of water is above the substrate layer whereas, in subsurface flow type, the water flows beneath the substrate. Subsurface flow CWs have further two categories, *i.e.* horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) [12].

The concept of CWs is popular for small to medium sized communities where decentralized approach for wastewater treatment is favored. These not only treat wastewater but also provide natural habitat to native and migratory wildlife [13]. In addition, it enhances the esthetic value to the semi-urban and rural areas [14]. A wide variety of wetlands are in operation worldwide [15,16]. The government of Taipei, Taiwan is successfully operating 14 CWs to enhance the water quality of Danshui river since 2004 [17]. The removal of pollutants in these wetlands depends upon the source of wastewater, their hydrology, and type of

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plants used. So far, studies have focused on various configurations of CWs with varying hydraulic parameters and plant types. A brief overview of the research carried out in recent past is summarized in Table 1.

The studies in Table 1 indicate that removal efficiencies for different pollutants may be correlated with the plant species and the type of constructed wetlands. BOD removal ranged between 29% and 94%. The COD removal between 44% and 88%. Effective removal of nitrogen and phosphorus was not observed. *Pistia stratiotes, Water Hyacinth* and *Phragmites* were the most commonly used macrophytes. It may be observed that most of the work focused on HFCWs. Hybrid systems, *i.e.* combination of VFCWs and HFCWs, were studied less but identified as a potential option for the enhanced removal of pollutants by [1]. Hybrid CWs proved an efficient system for the treatment of domestic wastewater in combination with anaerobic baffle reactor [23].

Previous studies emphasized on the search of novel plants and pollutants removal efficiencies. However, wetland operation can also be evaluated based on parameters including mass removal rate of pollutant (r), areal rate constant (K_a) and volumetric rate constant (K_v). Mass removal rate (r), in contrast to removal efficiency, accounts for the effect of hydraulic loading rate on the removal of each pollutant. This removal rate is useful for developing optimum influent load through regression analysis [24].

First order kinetics governs the treatment in wetlands, hence was considered suitable for the design. The areal (K_a) and volumetric (K_v) rate constants affect the kinetics of treatment in CWs. They are useful in assessing the contribution of each unit in the pollutant removal [24–26]. These operational parameters may be useful in the design and operation of these wetlands. However, little has been explored in the past regarding their evaluation and application. Moreover, single units of constructed wetlands *i.e.* either vertical or horizontal flow were extensively studied and evaluated. Hybrid flow approach needs to be investigated. Hence, this study was conducted with the following objectives: (1) study of hybrid CWs and (2) determine operational parameters (r, K_a and K_v) to find out a sound design basis.

2. Materials and Methods

2.1. Wastewater characterization

Municipal wastewater (MWW) was used in the study. The wastewater was characterized using biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total kjeldhal nitrogen (TKN) and phosphorus (P). Standard methods were used for the estimation of each parameter [27].

2.2. Selection of macrophytes

Preliminary screening of the local species of widely available macrophytes was carried out. Three plants *viz. Pistia stratiotes*, *Typha angustifolia* and *Water Hyacinth* were selected for initial screening. These plants were obtained from botanical garden of Government College University (GCU) Lahore.

Three microcosms of horizontal flow constructed wetlands were planted with these plants. Four layers of substrate including coarse gravel, fine gravel, Chenab sand and garden soil from the local canal having thickness of 0.01 m, 0.01 m, 0.02 m and 0.06 m respectively were laid at the bottom of each wetland. The substrate was selected based on the local and easy availability of the materials.

The wetlands were fed with wastewater, and the plants were allowed to grow for a period of 14 days. The number of plants in each microcosm was noted and taken as an indicator of the plant growth. *Pistia stratiotes* was found to grow in maximum numbers *i.e.* 30 after 14 days of growth period. Typha with 11 plants was the next. However, Water Hyacinth was not found to grow and only 5 plants were observed after growth period of 14 days. Hence, *Pistia stratiotes* and *Typha angustifolia* were selected based on maximum growth, *i.e.* number of plants grown in each wetland, in local climatic conditions.

2.3. Setup of lab scale hybrid constructed wetlands (HCW)

Two lab scale macrosomes of hybrid constructed wetlands (HCW) were setup for the treatment of pre-settled municipal wastewater. The pre-settling time was 45 min. Each setup consisted of one vertical flow constructed wetland (VFCW) and one horizontal flow constructed wetland (HFCW) installed in series. The dimensions of VFCW were 0.38 m × 0.38 m × 0.76 m ($L \times W \times D$). The corresponding surface area and volume of VFCW were 0.14 m^2 and 0.11 m^3, respectively. The dimensions of HFCW were 0.76 m × 0.38 m × 0.38 m ($L \times W \times D$). The surface area and volume of HFCW were 0.29 m^2 and 0.11 m^3, respectively.

In the first setup (designated as Case-1), *Typha angustifolia* was planted in both the VFCW and HFCW. Subsurface flow was required for the growth of Typha. Hence, it was ensured by providing a constant water level of 5 cm below the surface.

In second setup, (designated as Case-2) *Pistia stratiotes* was planted in the hybrid setup. It required surface flow for its growth. Hence, a freeboard of 5 cm was provided. Layers of coarse gravel (dia = 2–2.5 cm), fine gravel (dia = 0.4–1 cm), Chenab sand (0.09 mm effective size) [28] and garden soil were laid down in both VFCW and HFCW as substrate. The schematics of HCW are shown in Fig. 1.

Proper provisions of sunlight and avoidance from precipitation were ensured for the growth of these plant species in macrosomes of CWs. The treatment was carried out in the months of January to March. The average ambient temperature varied from 15 to 28 °C. The minimum to maximum humidity was 29% in March to 46% in January. The average sunlight hours per day were minimum (6.50) in January and maximum (7.40) in March.

2.4. Operation of hybrid constructed wetlands

2.4.1. Batch mode treatment

After the proper nurturing of macrophytes in the wetlands, the treatment of MWW was carried out in batch mode HCWs [25]. The batch treatment was carried out to optimize the process parameters. The pre-settled MWW was fed to the VFCW. The hydraulic retention time in VFCW was 1 day. MWW was then drained to HFCW and

Table 1
Overview of the research work related to CWs for municipal wastewater treatment

Macrophytes used	Results
Horizontal flow constructed wetlands	
Pistia and water hyacinth [12]	Effluent BOD (5–7 mg·L^{-1}), COD (40–50 mg·L^{-1}), very low levels of TSS (3–5 mg·L^{-1}), turbidity (1–2 NTU).
Phragmites karka [18]	Removal found: BOD = 50%, COD = 44%, TSS = 78%, NH_4-N = 49%, PO_4^- P = 52%
Typha latifolia or *Scirpus* sp. [19]	COD removal = 59%
Phragmites [20]	Removal found: TSS = 90%, BOD = 75%, COD = 80%; Hydraulic retention time (HRT) = 5 days
Cat tail and reeds [21]	For normal setup removal found: BOD = 27%, COD = 96%, TSS = 40%, N = 58%
	For integrated setup, removal found: BOD = 32%, COD = 94%, TSS = 36%, N = 41%
Hybrid vertical flow and horizontal flow constructed wetlands	
Phragmites australis, *P. australis* & *Phalaris arundinacea* [22]	Removal found: NH_4-N = 78.3%., BOD = 94%, COD = 84%

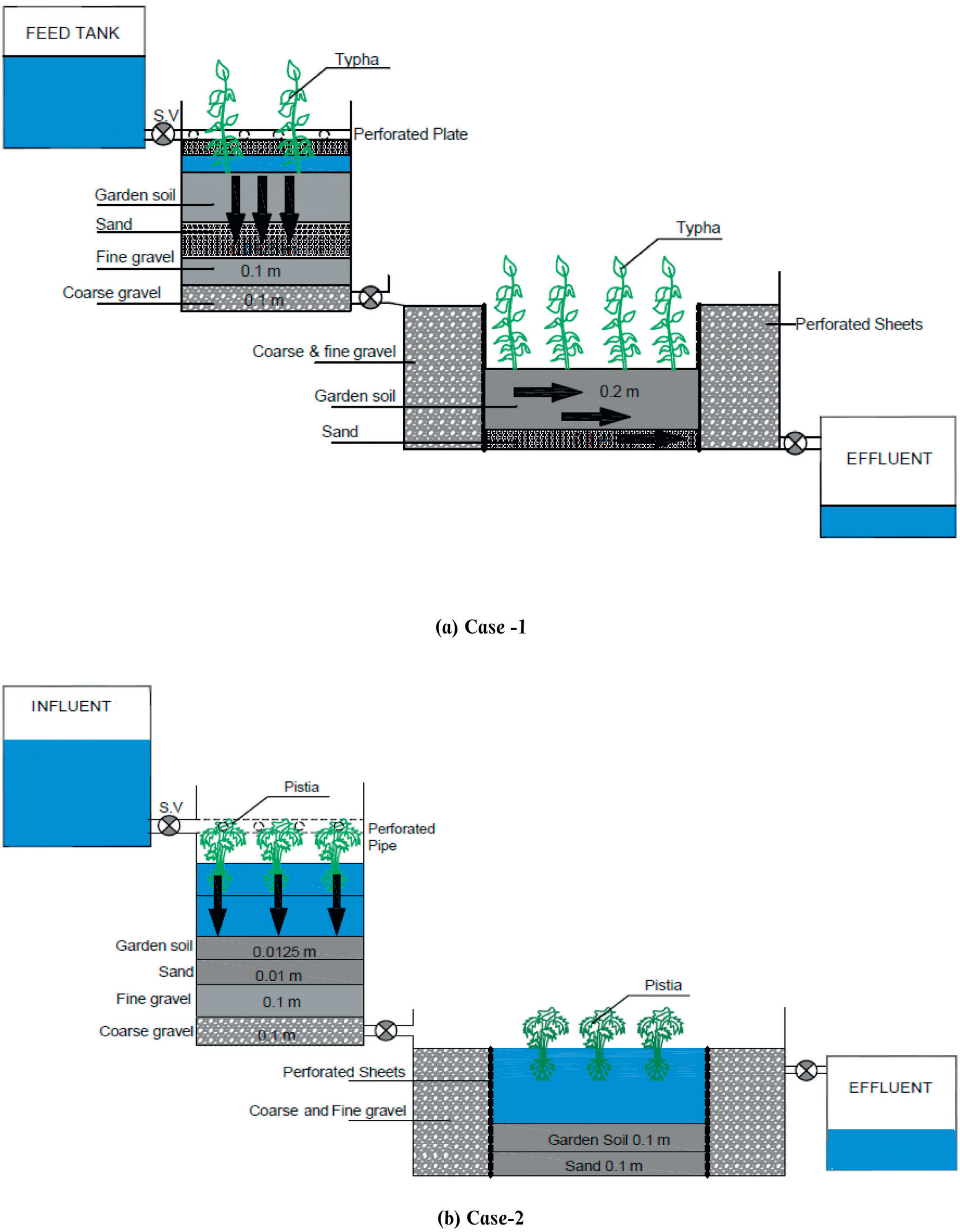

Fig. 1. Schematics of hybrid constructed wetlands (SV: Sluice valve).

retained in it for 1 day. Effluent samples from each CW were collected and analyzed after fixed retention time for specified parameters. This batch treatment was repeated for varying retention times ranging from 1 to 8 days.

2.4.2. Continuous mode treatment

For the assessment of HCWs based on their operational parameters including r, K_a and K_v, these were operated in continuous mode. The hydraulic loading rates applied were 0.14 m·d^{-1} and 0.1 m·d^{-1} for VFCW and HFCW respectively. These loading rates corresponded to the retention time optimized for each HCW in batch studies.

2.5. Sampling and data analysis

The samples for analysis were taken from influent of VFCW, at the outlet of VFCW before its discharge into HFCW, and at the outlet of HFCW. This whole cycle was repeated for varying hydraulic retention times (HRTs) ranging from 1 to 8 days. The samples were then analyzed for BOD, COD, TSS, TKN, and P using standard methods [29]. The removal efficiency of each parameter was calculated using the Eq. (1) as follows:

$$\mathrm{R.E} = \left(\frac{C_{\mathrm{in}} - C_{\mathrm{out}}}{C_{\mathrm{in}}}\right) \times 100\% \quad (1)$$

where:

R.E. Removal Efficiency, %
C_{in} Inflow Concentration, mg·L^{-1}
C_{out} Outflow Concentration, mg·L^{-1}

The mass removal rate, r was determined using the expression given in Eq. (2);

$$r = q\,(C_{\mathrm{in}} - C_{\mathrm{out}}) \quad (2)$$

where:

r mass removal rate, g·m^{-2}·d^{-1}
q hydraulic loading rate, m·d^{-1}

The degradation of pollutants in HCWs was modeled as first order kinetics. The first order rate constants can be defined on areal basis as K_a and on volumetric basis as K_v. The areal rate constant (K_a) and volumetric rate constant (K_v) is determined using Eqs. (3) and (4) as follows [30]:

$$K_{\mathrm{a}} = -q\ln\frac{C_{\mathrm{out}}}{C_{\mathrm{in}}} \quad (3)$$

where:

K_a areal rate constant, m·d^{-1}

$$K_{\mathrm{v}} = \frac{-\ln\frac{C_{\mathrm{out}}}{C_{\mathrm{in}}}}{t} \quad (4)$$

where:

K_v volumetric rate constant, d^{-1}

3. Results and Discussion

3.1. Wastewater characterization

The average values of wastewater characterization (for 5 samples) are given in Table 2.

It is clear from Table 2 that the average phosphorus was found to vary significantly among the samples collected with the COV of 14.3%, highest among rest of the parameters. Next to P was the TSS with variation of 11.4%. TSS varied from 149 mg·L^{-1} to 190 mg·L^{-1} with an average of 168.6 mg·L^{-1}. The COD varied between 380 mg·L^{-1} to 474 mg·L^{-1} with an average of 451 mg·L^{-1}. The COV for COD was observed to be 10%. BOD, TSS and TKN were found to be relatively consistent with COV of 6.6%, 6.4% and 3.5% respectively. BOD values varied between 188.6 mg·L^{-1} to 224.5 mg·L^{-1} with an average of 208 mg·L^{-1}. The minimum TKN for MWW was observed to be 35 mg·L^{-1} while the maximum was 40 mg·L^{-1}, average being 37.5 mg·L^{-1}.

Table 2
Wastewater characterization

Sr. No.	Parameter	Average /mg·L^{-1}	SD	COV /%
1.	TSS	168.6	19.3	11.4
2.	BOD	208	13.7	6.6
3.	COD	451	45.2	10
4.	TKN	37.5	1.85	4.9
5.	P	1.4	0.2	14.3

3.2. Performance evaluation of HCWs in batch mode

The results of the batch mode performance evaluation of both the cases of HCWs are presented in the following sections with respect to each parameter mentioned in Section 2.5.

3.2.1. COD

Fig. 2 shows R.E. at different HRTs and corresponding effluent COD.

It may be observed in Fig. 2, that the R.E. initially increased with an increase in hydraulic retention time (HRT). At 4 days, it touched the maximum value, which was 79% and 80% for Cases 1 and 2, respectively. The corresponding effluent concentrations were 105 mg·L^{-1} and 100 mg·L^{-1} for Case 1 and Case 2 respectively. The national environmental quality standards (NEQs) for COD of municipal effluents to be disposed into inland waters is 150 mg·L^{-1}. The effluent from HCWs meets the national standards for both the cases (105, 100 < 150 mg·L^{-1}).

The results are in line with the removals reported in literature for different macrophytes planted hybrid constructed wetlands [22,31–33].

It was further observed that increasing HRT beyond 4 days reduced removal. This may be due to the fact that saturation point of macrophytes was reached. Possible decay after 4 days may be the reason of decrease in removals. It can be further inferred that *Pistia stratiotes* was slightly better than Typha.

3.2.2. BOD

Fig. 3 shows BOD removal. The trend is like that of COD. The maximum BOD removal observed was 78% and 84% at HRT of 4 days in Case 1 and Case 2 respectively. The corresponding residual BOD in the effluent was 50 and 36 mg·L^{-1} for Case 1 and Case 2, respectively. The national standard of BOD for municipal effluents discharged into inland waters is 80 mg·L^{-1}. Effluents from both Case 1 and Case 2 met the national standard of BOD *i.e.* 80 mg·L^{-1}.

An average of 97.6% BOD removal was observed in hybrid constructed wetlands with natural ventilation [34]. Similar removal was observed in literature for hybrid constructed wetlands planted with different macrophytes [31,32,35].

Increase in HRT beyond 4 days deteriorated the removal for the same reasons stated for COD. *Pistia stratiotes* performed better as compared to the Typha.

3.2.3. TSS

Fig. 4 shows the results for TSS. Beyond 4 days, there was no significant improvement in the removal. The removals at 4 days were 74% and 82% for Cases 1 and 2, respectively. The results are in line with those observed in literature for TSS removal in hybrid constructed

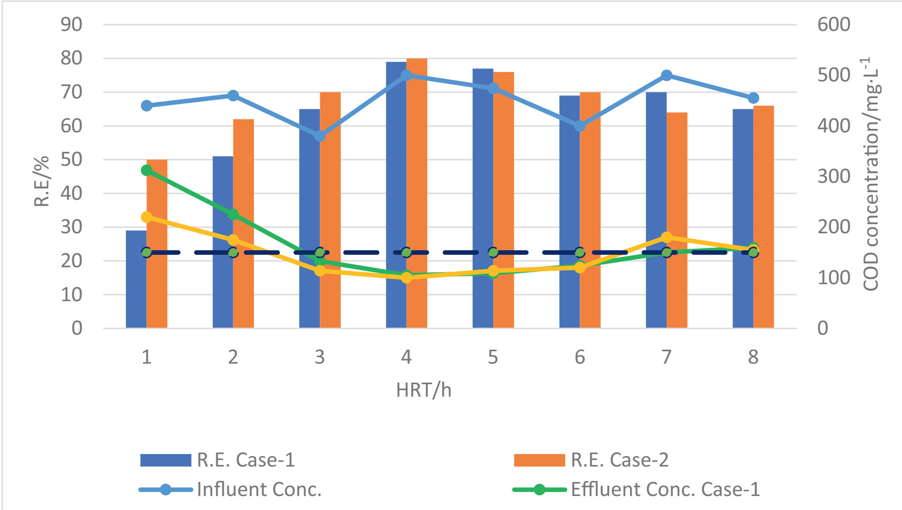

Fig. 2. Influent, effluent and removal efficiency of COD in HCWs.

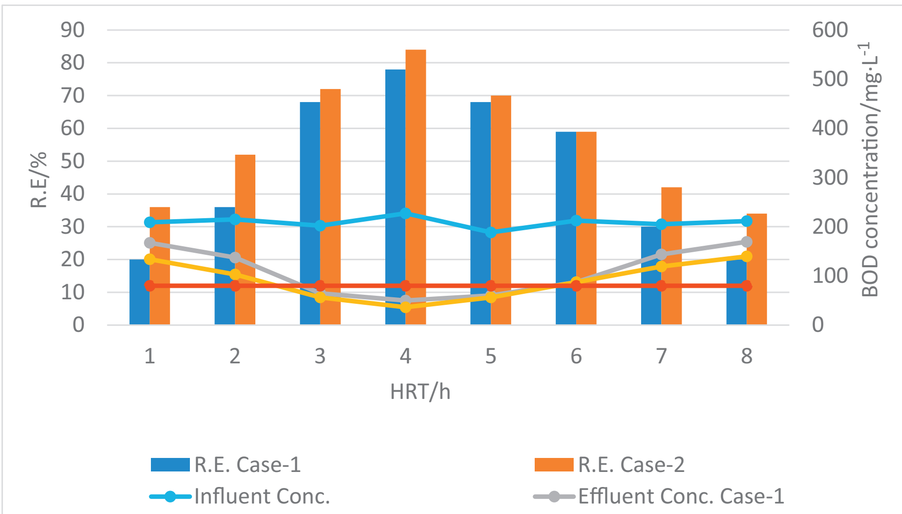

Fig. 3. Influent, effluent and removal efficiency of BOD in HCWs.

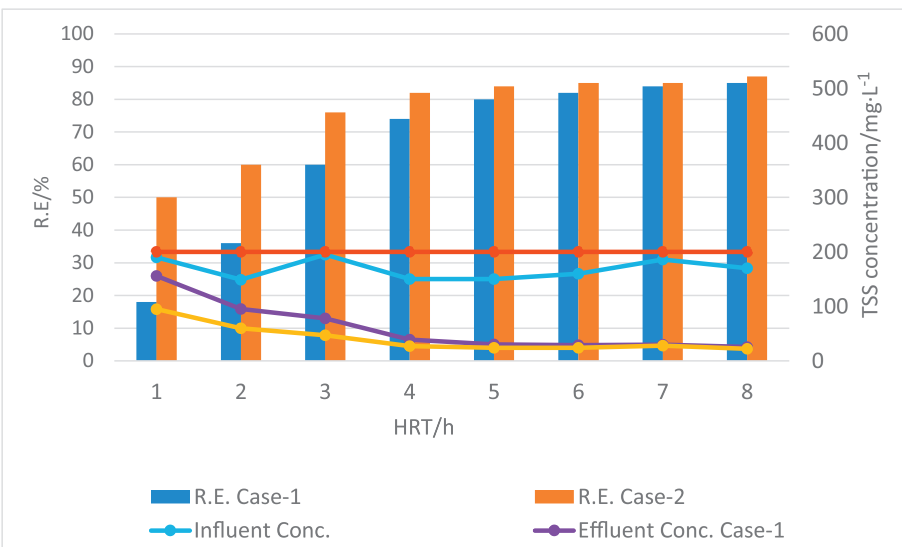

Fig. 4. Influent, effluent and R.E of TSS in HCWs.

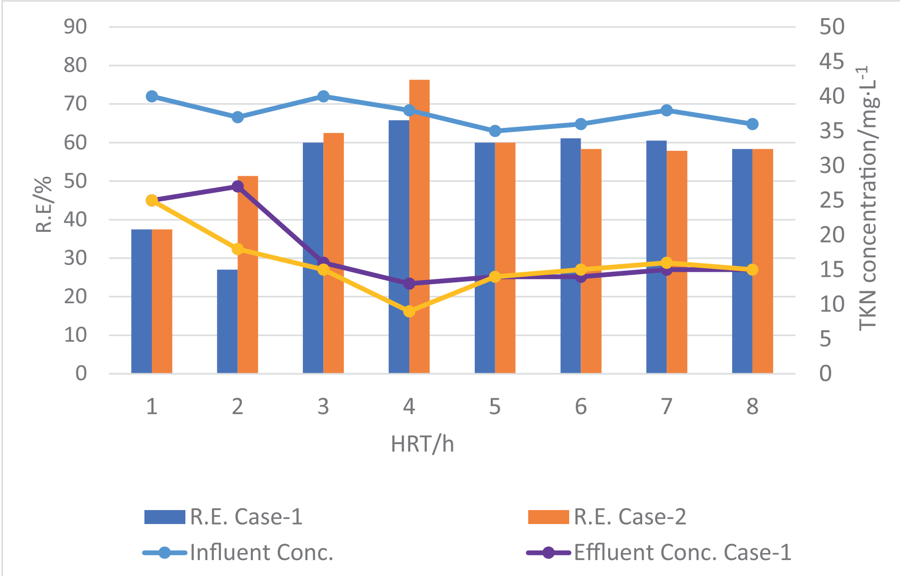

Fig. 5. Influent, effluent and R.E. of TKN for HCWs.

wetlands [31,33,35]. The corresponding effluent concentrations were 39 mg·L^{-1} and 27 mg·L^{-1}. The municipal effluents discharged into receiving water bodies must have TSS concentration less than equal to 200 mg·L^{-1} as per the NEQs. Effluents from HCWs in both cases meet the national standards. *Pistia stratiotes* gave better removal (82%) as compared to Typha (74%).

3.2.4. TKN

Fig. 5 shows the results for TKN. The removal trend almost followed COD and BOD. The maximum removal was achieved at 4-days, which was 66% and 76% for Cases 1 and 2, respectively. The results are similar to those observed in literature [22,36–38]. The corresponding effluent TKN concentrations were 13 and 9 mg·L^{-1} for Cases 1 and 2, respectively. No national standard exists for TKN.

The decline or stagnation in the TKN removal could possibly be due to no further uptake of TKN by the macrophytes. The presence of organics (carbon) is also proportional to the TKN removal. At increased HRT, carbon was present in lesser amounts, negatively affecting the removal of TKN. Moreover, ammonification, nitrification–denitrification and sedimentation also aid in the removal of TKN. Nitrification required oxic conditions and anoxic conditions were essential for denitrification. These complex process conditions are difficult to maintain, hence, resulting in lesser removal of TKN as compared to BOD, COD and TSS [30].

3.2.5. P

Fig. 6 shows the results for P. Maximum removal was observed at 4 days, which was 86% and 83% for Cases 1 and 2, respectively. The corresponding effluent concentration were 0.25 and 0.3 mg·L^{-1}, for Cases 1 and 2, respectively. No national standard exists for P.

Similar trends of P removal have been observed for P removal in constructed wetlands [33,35,39,40]. Possible mechanism of P removal in HCWs may be through adsorption [41,42]. After 4 days, the drop in the removal of P could be the result of unavailability of further sorption sites for the P [43]. Higher uptake of P (88.6%) was demonstrated by *Pistia stratiotes* (Case 2) at optimum HRT of 4 days. At HRT more than 4 days, removal of P tends to decrease.

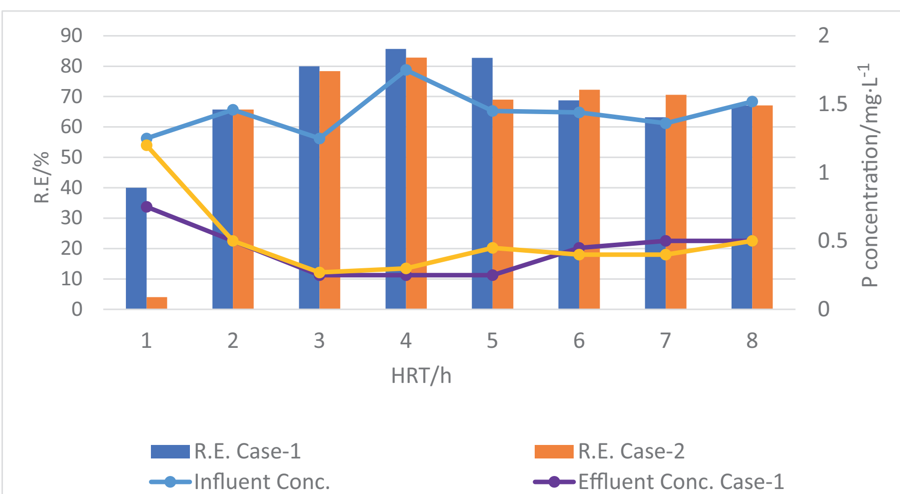

Fig. 6. Influent, effluent and R.E. of P for HCWs.

Table 3
Operational parameters for pollutants in HCWs, for Case 1 and Case 2

Type of CW	q /m·d^{-1}	Average influent conc./ mg·L^{-1}	Average effluent conc. /mg·L^{-1}	Removal efficiency /%	r /g·m^{-2}·d^{-1}	K_v/ d^{-1}	K_a /m·d^{-1}
BOD							
VF- Case-1	0.14	188.6	107.7	42.90	11.41	0.14	0.08
VF- Case-2	0.14	188.6	35	81.44	21.66	0.42	0.24
HF- Case-1	0.1	107.7	35	67.50	7.27	0.28	0.11
HF- Case-2	0.1	91.4	26.9	70.57	6.45	0.31	0.12
COD							
VF- Case-1	0.14	500	140	72.00	50.76	0.32	0.18
VF- Case-2	0.14	500	160	68.00	47.94	0.28	0.16
HF- Case-1	0.1	160	130	18.75	3	0.05	0.02
HF- Case-2	0.1	140	110	21.43	3	0.06	0.02
TKN							
VF-Case-1	0.14	92.26	40.18	56.45	7.29	0.21	0.12
VF-Case-2	0.14	92.26	43.82	52.5	6.78	0.19	0.10
HF-Case- 1	0.1	40.18	22.82	43.21	1.74	0.14	0.06
HF-Case- 2	0.1	43.82	25.62	41.53	1.82	0.13	0.05
P							
VF-Case- 1	0.14	1.6	0.45	71.88	0.12	0.32	0.18
VF-Case- 2	0.14	1.6	0.35	78.13	0.18	0.38	0.21
HF-Case-1	0.1	0.45	0.28	36.67	0.02	0.11	0.05
HF-Case- 2	0.1	0.35	0.2	42.86	0.02	0.14	0.06

3.3. Performance evaluation of HCWs based on operational parameters (continuous mode)

The HCWs were evaluated by determining the operational parameters in continuous mode operation with respect to each pollutant. Table 3 presents the above results for both cases.

Based on mass removal rate (r), the VFCWs were found more effective in pollutant removal than the HFCWs.

The removal rate of BOD in VF Case 1 is 11.41 g·m^{-2}·d^{-1}, which is greater than 7.27 g·m^{-2}·d^{-1} in HF Case 1. Similar trend was observed for BOD removal in Case 2. Better BOD removal achieved in VFCWs may be due to the aerobic degradation of organic compounds. Air is absorbed in wastewater through diffusion while it percolates through VFCWs. HFCWs usually work under anoxic conditions, which are difficult to maintain. This fact can be attributed to the low removal of BOD in HFCWs [44].

The BOD removal rate was observed to be dependent on influent BOD. It increased with increase in BOD. This was shown by the highest BOD removal rate of 21.66 g·m^{-2}·d^{-1} achieved with the influent BOD of 188.6 mg·L^{-1}.

Furthermore, comparison of Case-1 and Case-2 revealed that *Pistia stratiotes* efficiently treated the influent BOD (overall 28.11 g·m^{-2}·d^{-1}) than Typha (18.68 g·m^{-2}·d^{-1}). The values of rate constants K_a and K_v supported these facts. As shown in Table 3, highest K_a (0.24 m·d^{-1}) and K_v (0.42 d^{-1}) values were reported for VF Case 2. Hence, *Pistia stratiotes* planted VFCWs (Case 2) contributed more towards the BOD removal.

Out of VF and HF CWs, it was observed that the VFCWs were quite efficient in COD removal than HFCWs. The average mass removal rate observed in second unit of hybrid system *i.e.* HFCWs (3 g·m^{-2}·d^{-1}) was far less than that observed in VFCWs (49 g·m^{-2}·d^{-1}). It could be due to the reason that much of the COD was removed due to the maximum concentration gradient available in VFCWs, being the 1st unit of treatment. Hence, macrophytes uptake the COD load efficiently until their saturation.

The COD left over after VFCWs was then introduced in HFCWs which is much less (3.3 times) than influent to VFCWs. Hence, lesser COD removal was observed in the second unit (HFCW) of hybrid system. The highest K_a of 0.18 m·d^{-1} and K_v of 0.32 d^{-1} indicated the maximum removal observed in VF-Case-1 CW. The K_a of VF Case 2 is 0.16 m·d^{-1} and K_v of 0.28 d^{-1}, is comparable to that of VF Case 1. Both *Pistia stratiotes* and Typha were found almost equally proficient (>50%) in COD removal.

The nutrients also depicted similar trend as other pollutants. Vertical units were found more efficient in their removal than horizontal. The maximum rate for TKN and P removal, as shown in Table 3, were 7.29 and 0.12 g·m^{-2}·d^{-1} respectively in vertical CWs. While the lowest TKN of 1.74 g·m^{-2}·d^{-1} and P of 0.02 g·m^{-2}·d^{-1} were observed in horizontal CWs. The K_a and K_v values were higher for VFCWs than HFCWs for both TKN and P. Hence, vertical units contributed more towards the removal of pollutants than the horizontal.

4. Conclusions and Recommendations

The local plant species (*Typha angustifolia* and *Pistia stratiotes*) worked well, *Pistia stratiotes* being slightly better. Optimum detention time in both HFCW and VFCW come out to be 8 days (4 + 4 each). Effluent standards for COD, BOD and TSS were met. A combination of VFCW and HFCW is recommended. The practicality of the process favors the continuous mode of operation. The kinetic coefficients determined from the continuous mode operation in this study can be used for designing the constructed wetlands for municipal wastewater. The substrate recommended is coarse gravel (2–2.5 cm diameter), fine gravel (0.4–1 cm diameter), Chenab sand (0.09 mm effective size) and topmost layer of alluvial canal soil.

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