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Performance of various media in vertical flow constructed wetland for the treatment of domestic wastewater

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ABSTRACT

Studies were conducted on six pilot-scale vertical flow constructed wetland (VFCW) systems for the treatment of real domestic wastewater. All the six VFCWs had identical configurations and was filled with sand at the top and gravel at the bottom. The middle layer of each wetland system was filled with organic media (wood mulch, sugarcane bagasse and coir) and inorganic media (gravel, brick rubbles and pebbles), respectively. All the VFCWs were planted with wetland plant *Typha latifolia*. During the experimental study, the wetlands were loaded with real domestic wastewater. Performances of the wetlands were evaluated for the removal of organics, nutrients and bacterial contamination. The organic media wetlands had a removal efficiency of biochemical oxygen demand (BOD_5) (75%–88%), chemical oxygen demand (COD) (72%–82%), ammonia nitrogen (NH_4-N) (63%–70%), nitrate nitrogen (NO_3-N) (77%–80%), total nitrogen (TN) (67%–68%) and total phosphorous (TP) (66%–80%). The control and inorganic media wetlands had a removal efficiency of BOD_5 (91%–94%), COD (82%–85%), NH_4-N (51%–77%), NO_3-N (59%–63%), TN (42%–56%) and TP (58%–68%). Total suspended solids and fecal coliform removal was above 88% and 95%, respectively, in all the wetlands irrespective of the media.

Keywords: Vertical flow constructed wetland; *Typha Latifolia*; Organic media; Inorganic media

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1. Introduction

Constructed wetlands (CWs) are considered as a low cost and sustainable alternative for wastewater treatment, especially suitable for developing countries [1]. Constructed wetlands have been used in the treatment of various wastewaters such as dairy wastewater [2], domestic wastewater [3], olive mill wastewater [4], industrial effluents [5], agricultural runoff [6], boron mine effluent [7], landfill leachate [8] and other polluted waters. Constructed wetlands, in contrast to natural wetlands, are manmade systems that are designed, built and operated to emulate the functions of natural wetlands. It is created for the purpose of pollutant removal from wastewater [9]. It is a natural wastewater treatment process which involves complex interaction between soil, water, plants and microorganisms. The basic classification of CWs is based on the type of macrophytic growth (emergent, submerged, free floating and rooted with floating leaves). Further classification is usually based on the water flow regime (horizontal or vertical flow). The horizontal flow (HF) system is the one where wastewater flows from inlet to outlet in horizontal path through porous media [10]. Vertical flow constructed wetlands (VFCWs) are fed intermittently with a large batch of wastewater which then gradually percolates vertically down through the bed and is collected by a drainage network at the base. The bed drains completely free and it allows air to refill the bed. This kind of dosing leads to good oxygen transfer that supports nitrification [11,12]. Usually common reeds (*Phragmites karka)* or cattails (*Typha angustifolia)* are used as wetland plants [13]. Many technologies have been tried throughout the world to increase the treatment efficiency in constructed wetland such as (i) change in operation strategies such as effluent recirculation, artificial aeration, tidal operation, flow direction reciprocation, bio-augmentation and earthworm integration; (ii) modification in the configuration

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such as circular flow corridor CW, baffled subsurface flow CW, tower hybrid CW, microbial fuel cell CW; (iii) supply of electron donors to enhance the removal of selected inorganic oxygenated anions such as addition of organic carbon in CW, using organic filtration media in CW, step-feeding in CW [14]. However, some of these variations require complicated arrangement and the setup incurs significant operating and maintenance costs. In order to enhance the pollutant removal efficiency, especially the removal of nutrients from the wastewater, recent studies have investigated the effects of alternative arrangement of wetland media in the wetland systems [15–17]. Alternative arrangement of wetland media, which generates the necessary conditions to 'coordinate' various microbial degradation processes, can be an attractive and economical option for enhancing the performances of nutrient removal in vertical flow wetlands [18]. A limited number of studies have been carried out on alternative media arrangement in wetland systems; for example: zeolite [1], slag [19], lightweight aggregate [20] and alum [21] have been studied. These studies generally reported improved performances in the removal of common pollutants (such as organics, suspended solids and phosphorus) from wastewaters. For improving the removal of nitrogen from wastewater, wetland media that are rich in organic carbon contents have been tested [16,17,22]. Numerous studies that were conducted around the world on constructed wetlands provide voluminous literature; though, not much research has been done on constructing a wetland by changing the wetland media. Based on the concept of using a media which is rich in organic carbon content as the wetland media, a research was carried out in VFCW using organic media such as wood mulch, sugarcane bagasse and coir and compared with inorganic media such as gravel, brick rubble and pebbles. The main objective of the study is to understand the efficiency and system performance of the wetlands in terms of removing organics, nutrients and bacterial contamination from the domestic wastewater when wetland systems contain organic media and inorganic media. The study also aims at finding the efficient organic media for the wetland treatment process.

2. Materials and methods

2.1. Study area and wastewater

The present study was conducted in the sewage treatment plant (STP) located at Anna University, College of Engineering, Guindy campus, Chennai, Tamil Nadu, India (13° 00′39.19″ N, 80° 14′7.54″E). Domestic wastewater generated in the university campus and hostel is channelled by pipes to the STP where it is treated by activated sludge process and reused for gardening. The influent for the study was collected from this STP after primary treatment (screening and primary settling). The primary treatment was done to avoid clogging in the wetland system.

2.2. Configuration of pilot-scale wetland systems

Six experimental setups of VFCWs (VF1, VF2, VF3, VF4, VF5, VF6) were designed and constructed based on United Nations Habitat Manual [23] on design of constructed wetland. The wetlands were all of same configuration of diameter 0.55 m and height 0.75 m. Of the 0.75 m height, 0.15 m at the top was left as freeboard. The remaining 0.6 m was divided into three equal portions of 0.2 m each. The top and bottom portions of all the wetlands were filled with sand and gravel, respectively. The middle layer was filled with gravel, wood mulch, bagasse, coir, brick rubble and pebbles, respectively, in each wetland as shown in Fig. 1. Sampling ports were provided at every 0.2 m depth. Bottom sampling port was used for the collection of effluents. The wetland filled with gravel in the middle (VF1) acted as the control wetland system which is also an inorganic media wetland. Details of VFCW and media used are discussed in Tables 1 and 2, respectively. Twenty rhizomes of height 15 cm of locally available macrophytes (*Typha latifolia)* were planted in each wetland. The planted *Typha latifolia* rhizomes were collected from a local water channel inside the campus itself. After plantation all the wetland systems were waterlogged for 8 weeks allowing the establishment of macrophytes.

2.3. Operation of the wetland system

After the establishment of macrophytes, the systems were fed with real domestic wastewater. Domestic wastewater from the STP was transferred to two influent tanks of 90 L capacity each. Two separate influent tanks were used for operational convenience only and it represented a single system. Both the influent tanks were identical in construction and had the same influent. The tanks were topped up with influent wastewater continuously. These influent tanks fed

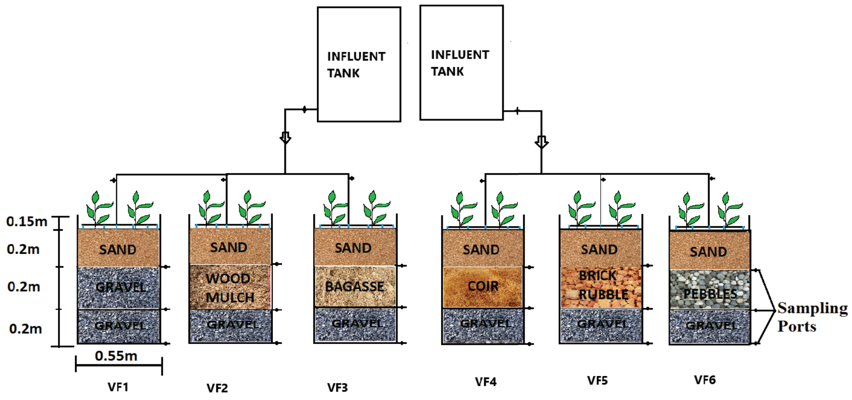

Fig. 1. Schematic diagram of vertical flow wetland system arrangement.

the six wetlands by means of separate pipelines. The influent wastewater was fed above the top layer (sand surface) of the wetland by means of multiple holes in the pipeline for even distribution. An outlet valve was placed at the bottom of each wetland for the collection of treated water by gravity, which also acted as a sampling port for the effluent. Each of the six wetland system was loaded with 25–30 L/d of domestic wastewater at the rate of about 1 L per hour from the influent tanks for a period of 12 weeks. A breathing period of two days was given after every 5 d of loading. This type of intermittent supply and breathing period was given to increase the oxygen diffusion and to avoid bio clogging in the wetlands [24].

After 12 weeks of continuous loading and as the systems stabilized, a shock load of 60 L of wastewater was batched into each of the wetland system and retained within the wetland. Effluent samples were collected after the first day, third day, fifth day and seventh day. After the seventh day, the wetlands were completely drained and a resting period of one day was given. Then the next loading of 60 L was batched into the system. This cycle of loading and breathing (resting of wetland bed) was done for a period of 12 weeks. All the influent and effluent samples were tested during each week for the same parameters as in continuous phase. This methodology was adopted to monitor the carbon leaching from the organic media in the wetlands.

2.4. Flow rate and sizing of the wetland system

The average water inflow rate per household is 135 L/pe/d (typical value for small rural settlement in India) which in turn generates 100–108 L/person/d as a domestic wastewater. As a pilot scale, each wetland system is designed for one fourth the influent flow of this domestic wastewater.

The wetland is sized based on Eq. (1) proposed by Kickuth:

$$A_h = \frac{Q_d(\ln C_i - \ln C_e)}{K_{\text{BOD}}} \tag{1}$$

where A_h = surface area of bed (m^2); Q_d = average daily flow rate of sewage (m^3/d); C_i = influent BOD$_5$ concentration (mg/L); C_e = effluent BOD$_5$ concentration (mg/L); K_{BOD} = rate constant (m/d) for vertical flow wetland.

As per the UN habitat manual, the surface area of a VF system should be about 0.8–1.5 m^2/pe. The surface area of each VF wetland system in this study is 0.98 m^2/pe thus fulfilling the abovementioned criteria.

The operational parameters are given in Table 3. Samples of influent and effluent were collected from all the wetland systems to determine the following parameters: pH, temperature, EC and dissolved oxygen (DO), total suspended solids (TSSs), biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), ammonia nitrogen (NH$_4$–N), nitrate nitrogen (NO$_3$–N), total nitrogen (TN), total phosphorous (TP) and fecal coliform (FC). The values of pH and EC were measured by pH meter (4500 H+ B) and conductivity meter (2510 C B), respectively. Temperature was measured by digital water temperature thermometers. DO was analyzed by Winkler method, titration (5210 O B) and BOD was analyzed by closed reflux titrimetric method (5210 BOD B). TSS was analyzed by gravimetric method (2540 D) and COD

Table 3
Operational details of the wetlands

Mode of operation	OLR (g COD/m^3 d)	HLR (m/d)	Theoretical HRT (d) – considering void ratio as 0.45
Continuous phase	40–60	0.104	3.2
Batch mode	–	–	7 d

Table 1
Details of six VF wetland systems

Wetlands	VF1	VF2	VF3	VF4	VF5	VF6
Top layer (0.2 m)	Sand	Sand	Sand	Sand	Sand	Sand
Middle layer (0.2 m)	Gravel	Wood mulch	Sugarcane bagasse	Coir	Brick rubbles	Pebbles
Bottom layer (0.2 m)	Gravel	Gravel	Gravel	Gravel	Gravel	Gravel
Typha latifolia	20 Nos	20 Nos	20 Nos	20 Nos	20 Nos	20 Nos

Table 2
Details of media used in the VF wetland systems

Substrates	Description
Sand	Sand of size 2–4 mm and pack porosity of 35% was obtained from the Anna University construction site
Wood mulch	A mixture of solid wood chips and humus material purchased from a local warehouse. Size 10–20 mm and pack porosity 53%
Sugarcane bagasse	Obtained from sugar factory, size 10–20 mm and pack porosity of 50%
Coir	Obtained from coir factory with a length 80–100 mm and pack porosity of 54%
Brick rubbles	Collected from Anna University construction site, size 20–30 mm and pack porosity of 59%
Pebbles	Collected from Anna University STP site, size 20–30 mm and pack porosity of 61%
Gravel	Gravels obtained from the Anna University construction site, of size 10–20 mm and pack porosity 42%

by open reflux titration method (5220 B), NH_4–N by distillation followed by titration (4500 NH_3-B, C), NO_3–N by ultraviolet spectrophotometric screening method (4500-NO_3-B), TN were analyzed by using total organic carbon analyzer. Analyses of TP were done by spectrophotometry-stannous chloride method (4500 P D). All the tests were carried as per the APHA manual, standard methods for wastewater treatment process [25]. FC was tested as per Indian standard methods of sampling and microbiological examination of water IS (1622: 1981).

2.5. Meteorological conditions

Meteorological data during the experimental period were obtained from the Indian Meteorological Department, Chennai. An average temperature of 29°C, average humidity of 78% and average rainfall of 176.5 mm was observed during the experimental period. Variations due to evapotranspiration were not considered in this study.

2.6. Statistical analysis of wastewater

Statistical analysis was performed using the software SPSS Version 12.0 (SPSS Inc., Chicago, USA). The data were analyzed through one-way analysis of variance to compare the pollutant removal performances of constructed wetland units. All results were expressed as the mean values. Significant levels are reported as non-significant when $p > 0.05$ and significant when $p < 0.05$. All of the variables were tested and ensured that they were normally distributed.

3. Results and discussion

3.1. Influent and effluent characteristics

The design of a wastewater treatment system depends on the influent wastewater characteristics. The influent and effluent characteristics were studied weekly for 12 weeks during the continuous phase and the results are tabulated in Table 4. Similarly, the influent characteristics and effluent characteristics on the first, third, fifth and seventh day were studied for 12 weeks for batch loading. The influent was also tested for surfactants but it was below detectable level. The surfactants may have been diluted as the influent was from university campus and hostel where the use of laundry detergent is minimal.

3.2. Performance of the wetland systems during the continuous phase

Removal efficiency calculations were based on mass balance.

$$\text{Percentage removal efficiency} = \frac{C_i - C_e}{C_i} \times 100 \tag{2}$$

where C_i and C_e are the inlet and outlet concentrations, mg/L.

The percentage removal of pollutants during the continuous phase is represented in Fig. 3.

Table 4
Mean pollutant concentration in the influent and effluent across the wetland systems

Parameters	Unit	Influent	Effluent concentration VF1	Effluent concentration VF2	Effluent concentration VF3	Effluent concentration VF4	Effluent concentration VF5	Effluent concentration VF6	Standard limits for reuse
pH	–	8.03±0.12	7±0.9	6.9±0.3	6.6±0.2	6.6±0.8	7.0±0.1	7.4±0.5	5.5–9.0
DO	mg/L	2.5±0.2	3.9±1.1	5.2±0.8	4.4±1.6	5.9±2.1	5 ±2.3	5.6±2.4	>2
EC	ms/cm	2.8 ±1.5	2.04±0.4	2.3±0.3	1.9±0.34	2.3±1.2	2.45±0.6	2.07±0.5	NA
Temperature	°C	27.3±1	26.9±0.4	26.7±.9	26.5±0.1	26.4±0.1	26.5±0.2	26.8±0.4	NA
Total suspended solids	mg/L	283±26.8	29.8±0.7	29.3±1.5	33.3±3.06	28.1±1.7	26.5±0.5	29.23±0.87	10
BOD	mg/L	212±6.4	13.3±3	27±2.6	53.3±4.16	24.33±3.7	18±3.46	19.6±2.65	<5
COD	mg/L	346±50.3	51.3±3	72.6±2.52	96.67±1.53	63.67±2.31	58.3±2	61.5±3	10
NH_4–N	mg/L	30.6±1.2	15±1	10±1	11.2±1.99	9.23±1.46	8.97±1.31	7.13±0.75	50
NO_3–N	mg/L	22.1±3.3	8.1±0.5	5.1±0.2	4.5±0.36	4.93±0.42	9±0.50	8.9±0.17	10
Total nitrogen	mg/L	78.6±8.6	46±2	25.5±1.9	25±1	25±1.31	34.4±1.5	38.3±1.5	NA
Total phosphate	mg/L	7.6±0.78	2.7±0.2	1.5±0.3	2.60±0.2	1.9±0.3	2.43±0.31	3.20±0.1	5
Fecal coliform	MPN/100 mL	2,000±200	43±3.2	40±5	52±3.79	35±2.65	64±4.04	69±4.93	Not detectable/100 mL

NA – not available.
All values are average of 12 samples.

3.3. pH and DO

As shown in Fig. 2(a), the average pH of the influent was slightly alkaline nature (8.03 ± 0.12). After passing through the constructed wetland, the effluent pH decreases in all the wetlands. This indicates that there is a decomposition of organic matter which may lower the pH value. According to Metcalf and Eddy Inc. [26] and Sun et al. [27] during the nitrification process a large amount of alkalinity is consumed as an inorganic carbon source by the nitrifying bacteria quantitatively 8.64 mg HCO_3 – per mg of NH_4-N oxidized. This is in agreement with the earlier research by Kadlec and Knight [28]. Significant nitrification can result in substantial drop of pH in wastewater. Such a result is consistent with the fact that there was a significant reduction of NH_4-N concentration in the effluents of the wetland system. There was not much variation in the pH among the wetland system effluents.

Fig. 2(b) shows the DO variation in the influent and effluent samples. DO content of the influent was 2.5±0.2 mg/L. The DO content of the organic media wetlands VF2, VF3, VF4 were 5.2±0.8, 4.4±1.6, 5.9±2.1 mg/L, respectively. The inorganic media wetlands VF5, VF6 DO content were 5±2.3 and 5.6±2.4 mg/L, respectively. DO content of control wetland was 3.9±1.1 mg/L. From the results, it was observed that DO content increases in the effluent of all the wetlands. Higher DO content was noticed in VF4 wetland system. It was also noted that DO content increases when there is a decrease in temperature.

3.4. EC and temperature

Electrical conductivity is the reciprocal of the electrical resistivity of a liquid solution. Electrical conductivity is most often used as an indicator of total dissolved solids concentration of a solution.

The influent electrical conductivity was 2.8±1.5 ms/cm as shown in Fig. 2(c). Electrical conductivity in the effluent of VF wetland systems was in the range of 1.9±0.34–2.45 ±0.6 ms/cm. The average EC of the effluent was slightly less as compared with the values for the influent during the period of study. Like pH, there is not much variation in the EC level among the wetland system effluents.

Weekly wetland samples were analyzed for temperature. The average influent and effluent water temperatures were 27.3°C±1°C and 26.4°C±1°C, respectively, and this was within the meteorological mean temperature of 29°C.

3.5. Total suspended solids

TSS removal efficiencies were above 88%. All wetlands showed similar removal percentages in the range of 88% to 91%. VF5 showed the highest percentage removal of 91% (26.5±0.5 mg/L). TSS removal efficiencies were high when compared with other studies [10]. Fig. 3(a) indicates that irrespective of the media used the VF wetland system is effective in TSS removal. TSSs are removed by flocculation, sedimentation and filtration/interception [29]. Wetland systems are effective in TSS removal because of the relatively low velocity and high surface area in the wetland media. Wetland system act similar to gravel filters and thereby provides opportunities for TSS separations by gravity sedimentation, straining, physical capture and adsorption on biomass film attached to gravel and root systems. As the TSS are predominately removed by filtration, the sand and gravel media in all the wetland system increases the chances for the suspended solids to be trapped and retained in the bed matrices, thereby improving TSS reduction.

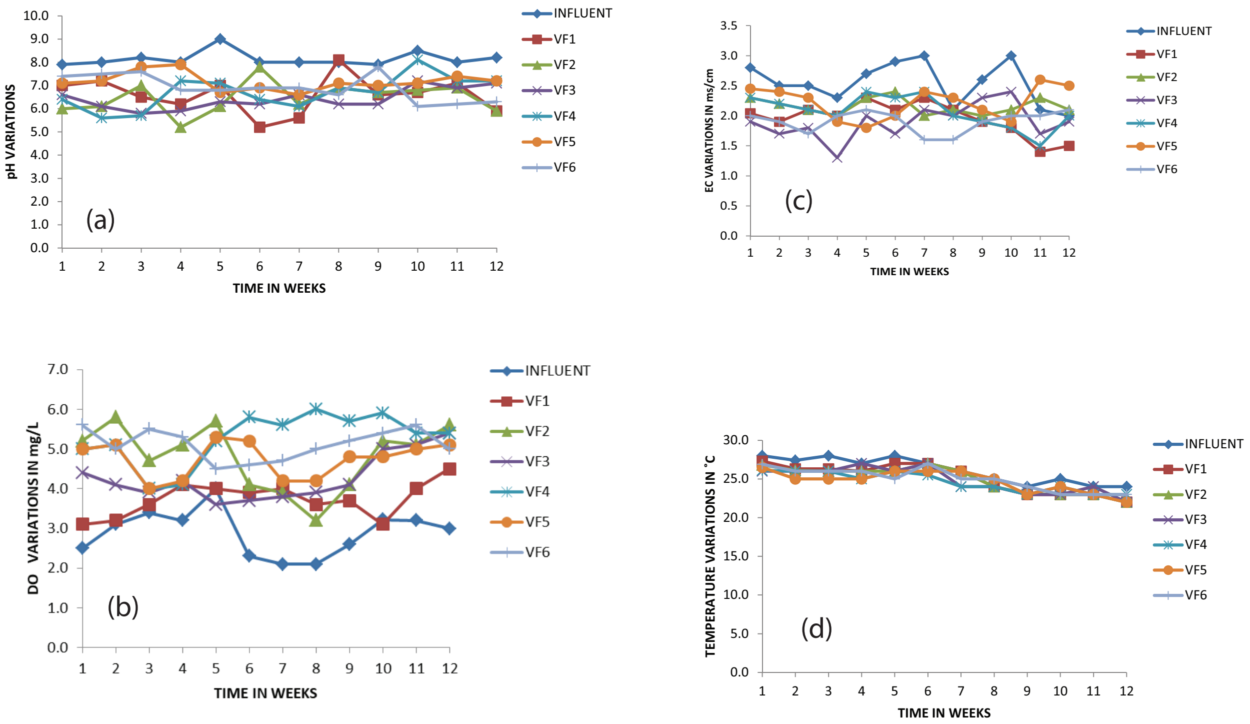

Fig. 2. Variation of (a) pH, (b) DO, (c) EC, (d) temperature during the continuous phase.

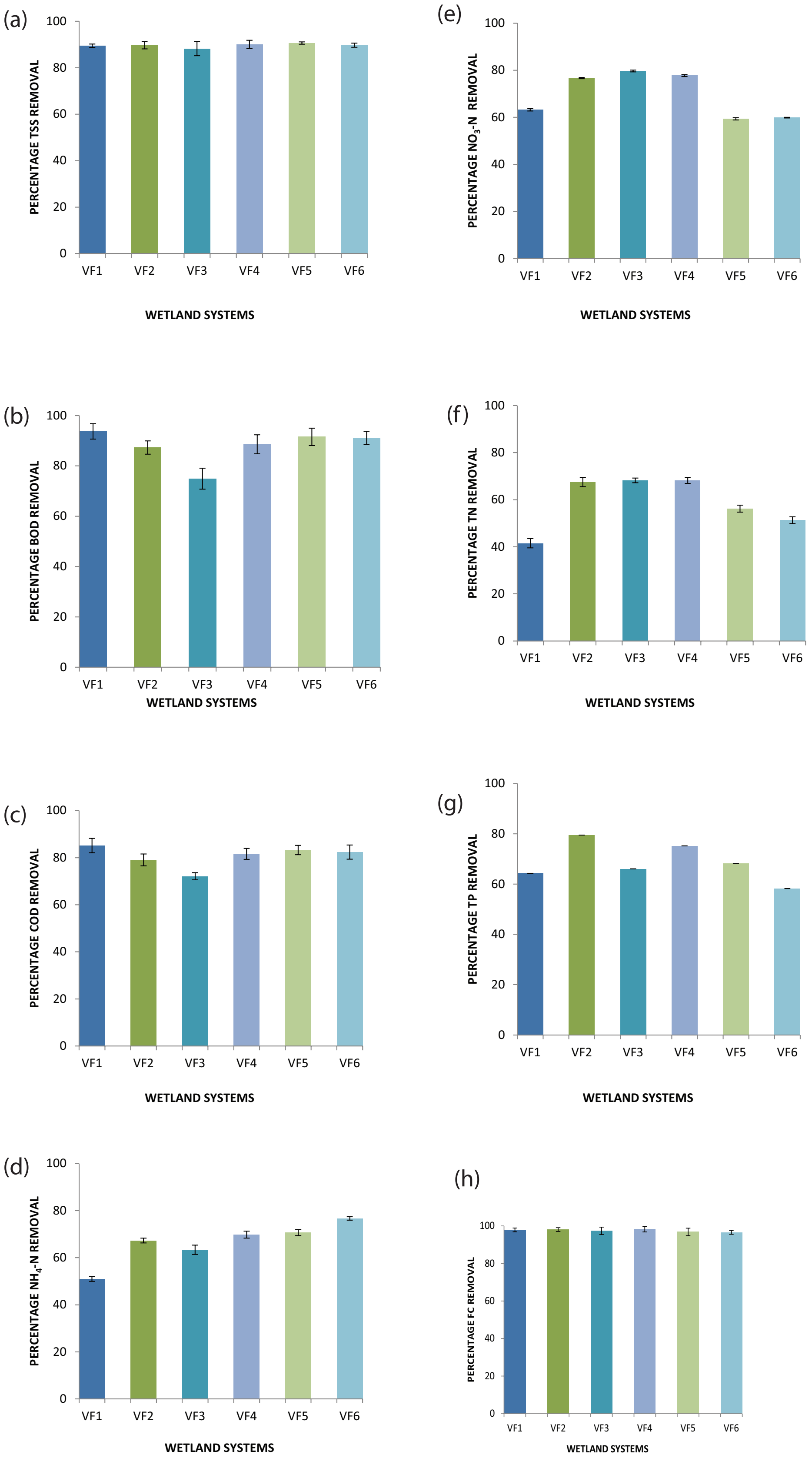

Fig. 3. Performance of wetlands during the continuous phase – removal percentage of (a) TSS, (b) BOD, (c) COD, (d) NH_4-N, (e) NO_3-N, (f) TN, (g) TP, (h) FC (bars represent standard deviation of the mean).

3.6. BOD_5 and COD

The control wetland VF1 had a BOD_5 removal of 94% and COD removal of 85%; wetland VF2 had a BOD_5 removal of 87% and COD removal of 79%; wetland VF3 had a BOD_5 removal of 75% and COD removal of 72%; wetland VF4 had a BOD_5 removal of 89% and COD removal of 82%; wetland VF5 had a BOD_5 removal of 92% and COD removal of 83%; wetland VF6 had a BOD_5 removal of 91% and COD removal of 82% as shown in Figs. 3(b) and (c), respectively. The inorganic media wetland system (VF1, VF5 and VF6) showed better removal efficiency of BOD_5 as well as of COD than organic media wetland (VF2, VF3, VF4). This may be due to leaching of organic carbon from the organic media, which may contribute to the BOD_5 load in the reactor [16]. The effluent concentration BOD_5 and COD in the bagasse wetland VF3 was 53.33±4.16 mg/L and 96.67±1.53 mg/L, respectively. According to the Central Pollution Control Board (CPCB) of India, the standard values for discharging treated wastewater in surface water bodies is BOD_5 of 30 mg/L and COD of 250 mg/L while for discharging in land irrigation BOD_5 value of 100 mg/L and of COD of 250 mg/L [30,31]. Therefore, the treated water from VF3 can be used for irrigation purpose only. Further treatment of the effluent from bagasse wetland (VF3) is required if the wastewater is to be discharged into surface waters. All other organic media and inorganic media wetland effluents (BOD_5 and COD) concentration were below CPCB limit.

3.7. NH_4-N, NO_3-N and TN

Nitrogen removal in a constructed wetland system includes uptake by plants and other living organisms. It is also removed by nitrification, denitrification, ammonia volatilization and cation exchange for ammonium [32].

3.7.1. NH_4-N

The organic wetland VF2 had a NH_4-N removal of 67%. Bagasse wetland VF3 had a NH_4-N removal of 63% which is similar to earlier reported removal rates [16]. VF4 had a NH_4-N removal efficiency of 70%. Similarly, VF5 and VF6 had removal efficiency of 71% and 77%, respectively. Among the six wetlands, higher removal rate of NH_4-N was observed in pebble media wetland. The organic and inorganic media wetlands show better performance in NH_4-N removal than control wetland (51%). Higher removal NH_4-N efficiency in organic and inorganic wetlands shows that significant nitrification process occurs in these wetland systems. Nitrification process is mainly dependent on the presence of DO [33]. Higher oxygen diffusion into the wetland system for nitrification is due to its porous nature [16]. Results indicate that wetlands with greater DO values had a higher removal rate of NH_4-N. Greater DO values can be attributed to the porous characteristic of the media. This statement is supported by the results of coir, brick rubbles and pebble media wetlands which have a porosity of 54%, 59% and 61%, respectively.

3.7.2. NO_3-N and TN

The control wetland VF1 had a NO_3-N and TN removal of 63% and 42%, respectively, whereas organic media wetland VF2, VF3, VF4 had a NO_3-N removal efficiency of 77%, 80%, 78%, respectively, and TN removal of 67%, 68% and 68%, respectively. The inorganic media wetlands VF5 and VF6 show a NO_3-N removal efficiency of 59% and 60%, respectively, and TN removal efficiency of 56% and 51%, respectively, as shown in Figs. 3(e) and (f), respectively. Abovementioned results indicate organic media wetlands show better TN removal when compared with inorganic media wetlands. Higher NO_3-N and TN removal rates were observed in coir media wetland. This clearly indicates that efficient denitrification has occurred in organic media wetlands. Catering of organic carbon from the organic media increases the denitrification process. Higher effluent BOD and COD concentration was associated with lower effluent NO_3-N concentration across VF wetland columns VF2, VF3, VF4 (wood mulch, sugarcane bagasse and coir substrates) indicating the generation of organic carbon from the substrate for denitrification. Denitrification is carried out by microorganisms under anaerobic (anoxic) conditions, with nitrate as the terminal electron acceptor and organic carbon as the electron donor; this reaction occurs in the absence of oxygen and requires an organic carbon source. The products of denitrification are N_2 and N_2O gases that will readily exit the wetlands. For efficient denitrification process, availability of organic carbon is the main constraint. Various organic substrates, for example: sugarcane bagasse [17], rice husk [22] and wood mulch [16] were employed previously as the main media in VF and HF wetland systems to foster the denitrification process. Songliu et al. [34] recorded increased denitrification rates, when the external carbon source was added. These findings illustrate the feasibility of organic media substrate for pollutant removal in constructed wetlands, particularly for nitrogen elimination. In contrast, the trend was completely opposite in control and inorganic media wetland. The denitrification process was limited in these wetlands due to lack of organic carbon as there was no leaching of carbon from the media resulting in NO_3-N accumulation.

3.8. Total phosphorous

The phosphorous removal in constructed wetland may take place due to adsorption, plant intake, accretions of wetland soils, complexation, microbial immobilization, retention by substrates and precipitation [33,35]. Among these factors, the substrate may play the greatest role and could be most amenable. Thus, it is important to select those substrates that present the highest phosphate adsorption capacity. The phosphorous reduction in the wetland may be due to adsorption of some phosphorous by the gravel media in the wetland system. The adsorption capacity of gravel was about 37.7 mg/g [33]. In this study, the phosphorous removal efficiency of the control wetland system was 64%. Phosphorus removal in other wetlands were VF2 (80%), VF3 (66%), VF4 (75%), VF5 (68%) and VF6 (58%). Among these wetlands, wood mulch and coir wetlands, VF2 and VF4, showed a good removal efficiency of 80% and 75%, respectively, which was also attained in earlier studies [3]. Among all the wetlands, wood mulch wetland outperformed the other wetland units in phosphorous removal. The humus material in the wood mulch and coir substrate (organic media) might have played a major role in terms of higher phosphorous removal via TP adsorption [16].

3.9. Fecal coliform

Fecal coliform removal in VF1, VF2, VF3, VF4, VF5 and VF6 were 98%, 98%, 97%, 98%, 97%, 97%, respectively. Fecal coliform removal rate of above 97% was observed in all the wetlands irrespective of the media. Similar results were observed in the study conducted earlier [3]. The dominance of aerobic conditions in the top portion of the these wetland systems is believed to have played a major role in the removal of fecal coliforms through the following ways: (1) by promoting the growth of heterotrophic protozoa organisms which often play the dominant role for *E. coli* removal in constructed wetlands via predation [36,37] and (2) by *E. coli* oxidation, enhancing mortality of coliforms [16,38]. Fecal coliform is destroyed either by predation or by UV irradiation. This clearly indicates that VF constructed wetland irrespective of media used is efficient in fecal coliform removal. The effluent, if discharged on surface water body or used for irrigation purpose needs no further treatment as it complies with CPCB standards. However further disinfection is required if it is reused for domestic purposes.

3.10. Performance of the wetland systems during the batch mode

3.10.1. Effect of hydraulic residence time

As mentioned under the section 2.3, the influent had been retained in the wetland for 7 d and the effluent samples were taken on the first day, third day, fifth day and seventh day (12 samples each). The influent and effluent concentrations of each parameter were analyzed and are represented in Fig. 4.

3.10.2. Impact of hydraulic residence time on TSS removal

Initial concentration of TSS in the influent was 183±74 mg/L. TSS concentration decreased in all six wetlands as the retention days progressed. In organic media wetlands VF2, VF3, and VF4 higher TSS removal efficiency was on fifth day. In inorganic media wetlands (excluding control wetland), maximum TSS removal efficiency was obtained on seventh day. Higher TSS removal efficiency was noticed in VF1 (96%) on third day. TSS concentration of the effluent decreased for all the wetlands as the days progressed irrespective of wetland media. As the residence time increased there are more chances of filtration and adsorption of TSS on biomass film and root system. This might have reduced the TSS concentration in the effluent.

3.10.3. Impact of hydraulic residence time on organics removal

As can be seen from Figs. 4(b) and (c), the effluent BOD_5 and COD concentration show a decreasing trend in each inorganic media wetlands (VF1, VF5, VF6) with the increase of residence time. In organic media wetlands (VF2, VF3 and VF4), maximum removal efficiency was noticed on the first day itself. However, organic pollutant concentration in the effluent increased as the days progressed. This clearly indicates that there is a carbon leaching from the organic media which increases the BOD_5 and COD concentration of the effluent. This was predominantly noticed in sugarcane bagasse wetland (VF3). This phenomenon could be due to the fact that, theoretically, sugarcane bagasse straw can release more available carbon for promoting denitrification followed by wood mulch and coir releasing the least [39,40]. On the other hand, the organic media might have some components such as lignin making the COD concentration increase which is difficult for microorganisms to degrade [39,40]. From the graph, it was observed that the inorganic media wetland was effective in organic matter removal. In organic media wetlands, organic pollutants such as BOD_5 and COD were effectively removed within 24 h but as the days progressed, the BOD_5 and COD pollutants gradually increased. It also should be noted that the control wetland-VF1 was more efficient in BOD_5 and COD degradation (95% and 89%, respectively) on seventh day.

3.10.4. Impact of hydraulic residence time on NH_4 -N, NO_3-N, TN and TP removal

Nitrification is an aerobic process which needs oxygen for conversion of ammonia or ammonium to nitrite followed by the oxidation of the nitrite to nitrate. Nitrification is performed by small groups of autotrophic bacteria and archaea. The oxidation of ammonia into nitrite is performed by two groups of organisms, ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) In soils, the most studied AOB belong to the genera *Nitrosomonas* and *Nitrosococcus*. The second step (oxidation of nitrite into nitrate) is done mainly by bacteria of the genus *Nitrobacter* and *Nitrospira*. Previous studies have shown that much more nitrifying bacteria can be detected in intermittently aerated CWs [41]. Nitrification is an indispensable step for TN elimination and is the primary step when NH_4-N is transformed into NO_3–N. An efficient nitrification often requires high DO concentration. As shown in graph, the NH_4-N concentration of all six wetland systems decreased in the first and third day itself and subsequently remained constant. This is true for organic as well inorganic media wetland irrespective of their porosity. It could be noticed that maximum NH_4-N removal occurred in the VF6 wetland, it reached above 88% on the first day. Furthermore, the effluent NH_4-N concentrations in all systems were below 10 mg/L which was far lower than the central pollution control board discharge standards.

Denitrification is an anoxic and microbially facilitated process where nitrate is reduced and ultimately produces molecular nitrogen (N_2) and gaseous nitrogen oxide products. Facultative anaerobic bacteria perform denitrification as a type of respiration that reduces oxidized forms of nitrogen in response to the oxidation of an electron donor such as organic matter. Denitrifying microbes require a very low oxygen concentration of less than 10% and organic carbon for energy. In the organic media wetland system, the organic carbon needed for denitrification is supplied by the media. Higher nitrate removal and high BOD and COD value in the effluent can be attributed to this. The concentration of NO_3-N and TN in organic media wetland decreased as days progressed. This shows that there was an effective denitrification process in the organic media wetland systems. Maximum nitrate removal was obtained on the seventh day in VF4. The inorganic media wetlands show a lower removal efficiency of nitrate as the days progressed.

The initial concentration of TP was 10.9±0.78 mg/L. Maximum removal of TP was on the first day itself. As the days increased there was no significant reduction in TP among the wetlands. Higher TP removal was obtained in wood mulch and coir wetland on first day.

3.10.5. Impact of hydraulic residence time on fecal coliform removal

Fecal coliform count in the effluent decreased over the days as seen in Fig. 4(h). High removal efficiency (99%) was

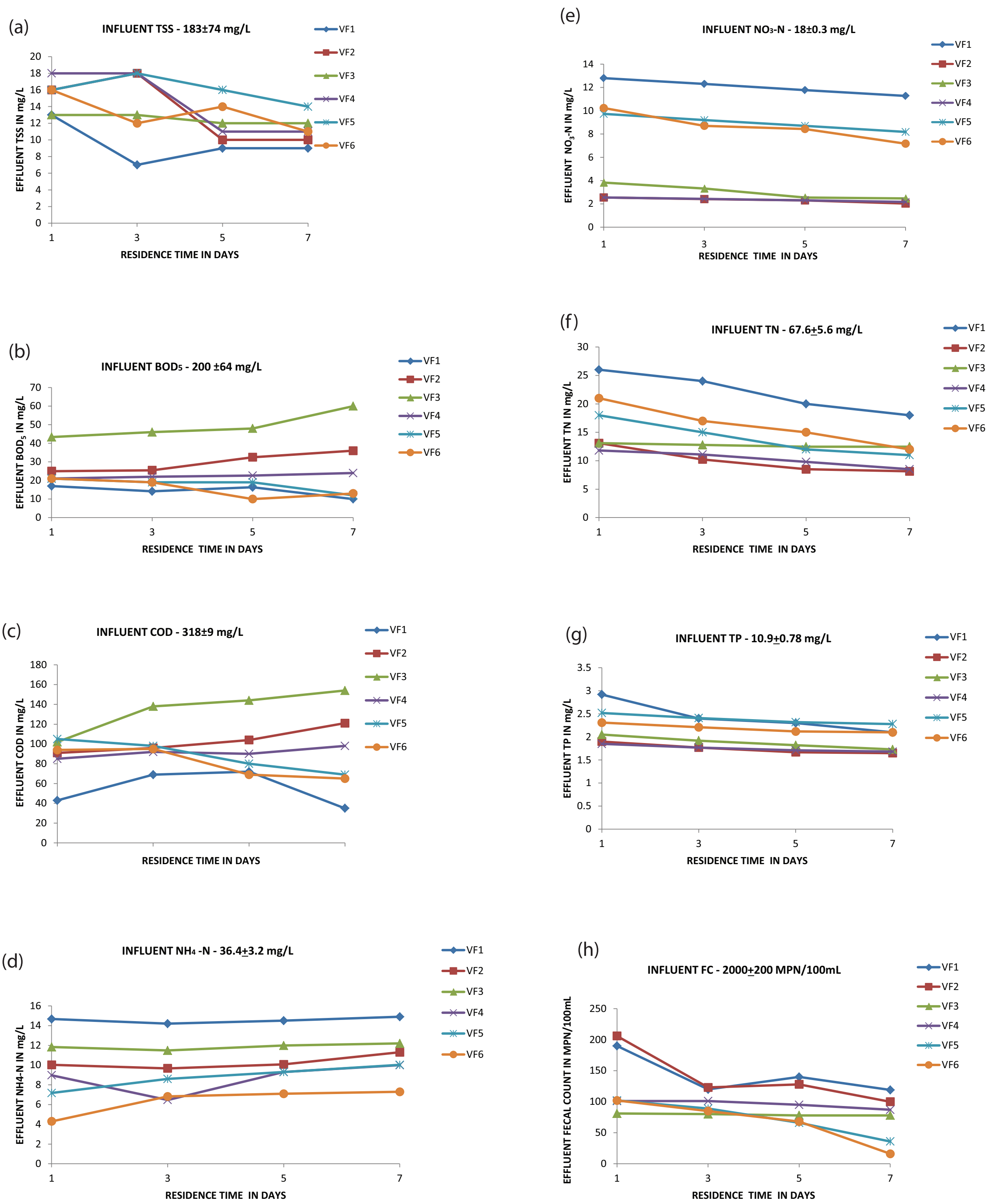

Fig 4. Variation of concentration of pollutant on the first, third, fifth and seventh day – (a) TSS, (b) BOD, (c) COD, (d) NH_4-N, (e) NO_3-N, (f) TN, (g) TP, (h) FC.

noticed in VF6 on seventh day. The removal efficiency on seventh day was 94%, 95%, 96%, 96% and 98% for wetlands VF1, VF2, VF3, VF4 and VF5, respectively. The high removal percentage is due to continuous exposure of the wetland to sunlight. Nearly 95% of fecal coliform was removed within 3 d irrespective of the wetland media used. Hence retention for more days is not essential. From this study, it is inferred that the media has no significant effect on the fecal coliform removal.

4. Conclusion

Overall the organic media and inorganic media enhanced the pollutant removal efficiency in vertical flow constructed wetland. pH, EC and temperature decrease during the treatment process whereas DO increases during the treatment process. All vertical flow wetland system shows higher TSS removal of more than 88%. BOD_5 and COD removal efficiency is relatively less in organic media wetlands when compared with inorganic media. This may be due to organic carbon leaching from the organic media. Carbon leaching from organic media wetlands, especially VF3 wetland, caused more BOD_5 and COD concentration in the effluent. The availability of organic carbon from the organic media wetlands foster the denitrification process and increased the NO_3-N removal rate when compared with the control wetland and inorganic media wetland. In control and inorganic media wetlands, the higher amount of organic degradation depleted the amount of organic carbon which is essential for denitrification process resulting in nitrate accumulation in the effluent. Due to the porosity of the organic media and inorganic media, there is availability of sufficient oxygen diffusion in the wetland. This enhanced the nitrification process which resulted in higher NH_4-N removal efficiency in these wetland systems. The humus material in the organic media enhanced the removal percentage of phosphorus in these wetlands. Special media such as calcite, marbles and shale can also be used when focusing on phosphorous removal in wetlands. Higher percentage of fecal coliform removal was achieved in all the wetlands due to dominance of aerobic conditions in the top portion of the wetland. Among the organic media wetlands, coir shows a consistent and stable removal of pollutants than wood mulch media and bagasse media. However, the use of organic substrate needs very careful evaluation due to the risk of excessive leaching of organic carbon from the organic media. A residence time of 3 d is sufficient for treating the domestic water in organic media filled wetland. A further increase in resident time may cause leaching of organic carbon which might increase the organic matter concentration. After 3 d, a resting period of 1 d can be adopted to avoid carbon leaching of the organic media. Further, to reduce the organic carbon leaching from the organic media wetlands, (i) hybrid system can be opted, where vertical wetland (VF) filled with organic media followed by horizontal flow wetland (HF) filled with inorganic media (gravels, brick rubbles, pebbles) can be employed or (ii) by employing organic media in well-aerated VF wetland or (iii) by limiting the quantity of organic media. The results show that addition of agricultural biomass could intensify the nitrogen removal significantly and can be used as an alternative for adding external carbon source for enhancing the denitrification process in wetlands. Also agricultural by-products (agricultural biomass) can be reused as wetland media as in a sustainable manner.

The pilot-scale experiment results suggest that use of agricultural waste rich in carbon source can be used as constructed wetland media and will be a sustainable technology.

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