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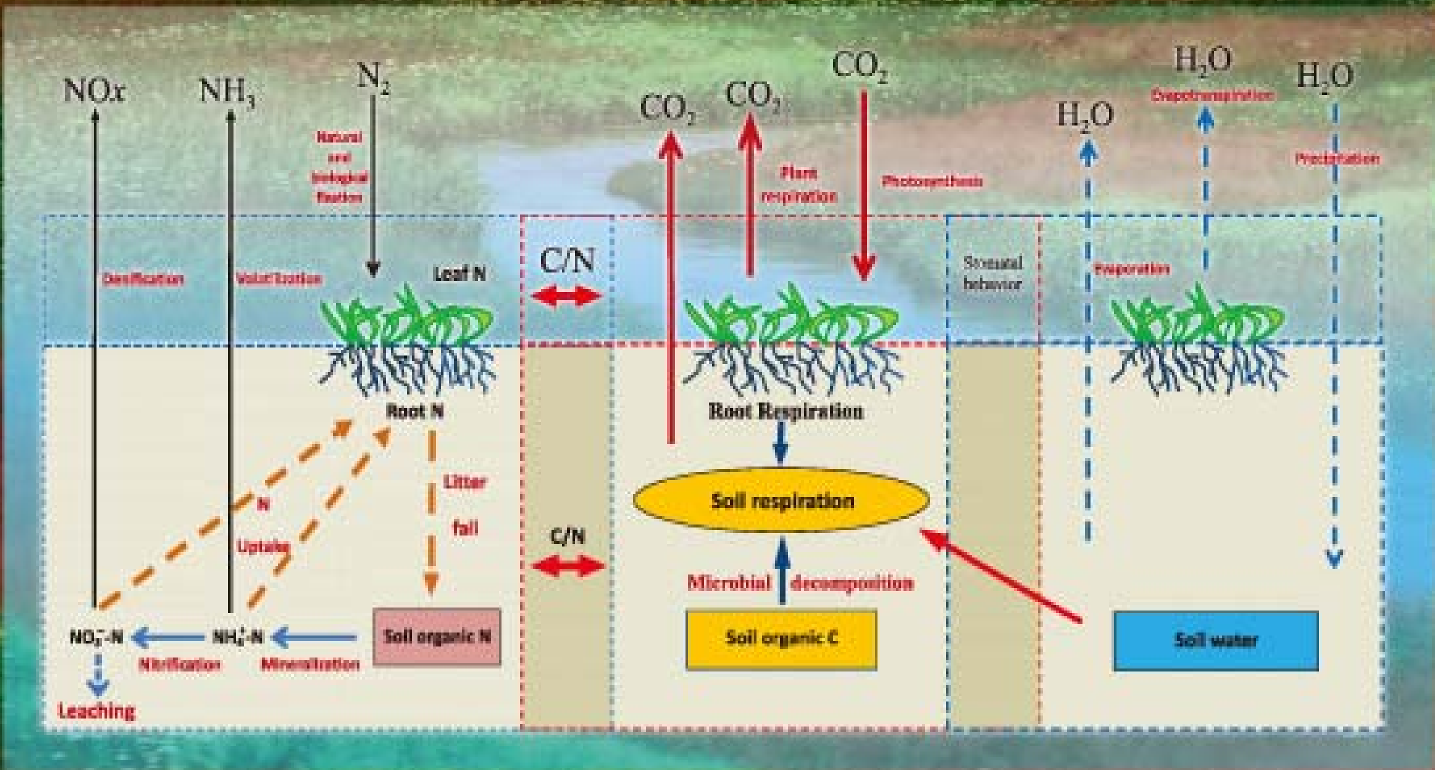

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Pollutant removal from municipal wastewater employing baffled subsurface flow and integrated surface flow-floating treatment wetlands

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ABSTRACT

This article reports pollutant removal performances of baffled subsurface flow, and integrated surface flow-floating treatment wetland units, when arranged in series for the treatment of municipal wastewater in Bangladesh. The wetland units (of the hybrid system) included organic, inorganic media, and were planted with nineteen types of macrophytes. The wetland train was operated under hydraulic loading fluctuation and seasonal variation. The performance analyses (across the wetland units) illustrated simultaneous denitrification and organics removal rates in the first stage vertical flow wetland, due to organic carbon leaching from the employed organic media. Higher mean organics removal rates (656.0 g COD/(m^2·day)) did not completely inhibit nitrification in the first stage vertical flow system; such pattern could be linked to effective utilization of the trapped oxygen, as the flow was directed throughout the media by the baffle walls. Second stage horizontal flow wetland showed enhanced biodegradable organics removal, which depleted organic carbon availability for denitrification. The final stage integrated wetland system allowed further nitrogen removal from wastewater, via nutrient uptake by plant roots (along with nitrification), and generation of organic carbon (by the dead macrophytes) to support denitrification. The system achieved higher *E. coli* mortality through protozoa predation, *E. coli* oxidation, and destruction by UV radiation. In general, enhanced pollutant removal efficiencies as demonstrated by the structurally modified hybrid wetland system signify the necessity of such modification, when operated under adverse conditions such as: substantial input organics loading, hydraulic loading fluctuation, and seasonal variation.

Introduction

Municipal wastewater contains widely variable amount of organics and inorganics such as nitrogen, phosphorus, and other solids, depending on water usage patterns in different countries (Vymazal, 2009). Such pollutants of variable concentrations in municipal wastewater can be treated via steel-and-concrete, and natural treatment technologies. The former technology often entails substantial operation and maintenance costs (Arias and Brown, 2009; Antoniadis et al., 2010), whereas such problems are generally encountered by the latter technologies.

Constructed wetland treatment systems, generally referred to as low-cost, green treatment technologies, are dependent on an inter-connected network of plants, media, biomass, and water which facilitate physical, chemical, and biological removal of contaminants from wastewater (Fountoulakis et al., 2009). Such systems exhibit better efficiencies of organics removal, when employed for wastewater treatment (Vymazal and Kröpfelová, 2009); however, higher nitrogen removal performances are often difficult to achieve. To overcome these drawbacks,

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extensive research is being carried out in adjustment of operational and environmental parameters, employing alternative media, structural, and arrangement modification of wetlands (Saeed and Sun, 2012).

To date, a few studies reported the role of media (i.e. organic type), for improving classical nitrogen reduction (from wastewater) in treatment wetlands (Saeed and Sun, 2011b; Tee et al., 2012). The mechanism for such media oriented performance is involved with leaching of organic carbon (C) from the employed media (into bulk wastewater), that increases organic C availability to support denitrification (along with organics removal).

Other studies modified structural configurations of wetlands, for enhancing removal mechanism. Baffled horizontal flow (HF), bio-rack, towery, and integrated down flow-up flow wetlands fall under this category (Ye and Li, 2009; Chang et al., 2012; Tee et al., 2012; Wang et al., 2012a). Enhanced removals were observed in such engineered wetlands, due to flow direction through aerobic-anaerobic portions, and improved wastewater contact time with increased root surfaces of macrophytes. As such, combination of appropriate media, along with structural modification of treatment wetlands could further accelerate removal bio-kinetics.

Apart from media oriented performance improvement, or structural modification of wetlands, different arrangements of vertical flow (VF) and HF wetland systems (i.e. hybrid systems) had also been examined (Belmont et al., 2004; Abidi et al., 2009; Tunsiper, 2009) for accelerating bio-reactions. The role of the last stage wetland in such hybrid system is extremely critical. For example, a last stage VF system can further accelerate nitrification and organics removal, whereas a final stage HF system can support denitrification (Vymazal, 2005; Saeed et al., 2012). However, in both cases, either nitrification or denitrification becomes the limiting factor (due to absence of aerobic/anaerobic conditions), which may not meet the stringent pollutant discharge criteria in many countries. Considering these drawbacks, incorporation of a surface flow (SF), or floating treatment wetland (that employs floating mat with emergent macrophytes on water surface) as a final stage unit can further reduce nitrogen contents, as it allows substantial bio-kinetic metabolisms around the rhizosphere (Headley and Tanner, 2006; Zachritz II et al., 2008).

This study was designed to investigate the removal efficiency of structurally modified VF and HF systems (with organic and inorganic media), arranged in series with an integrated SF-floating treatment wetland, and to provide municipal wastewater treatment in Bangladesh. The main objective of this study was to examine overall removal mechanisms for pollutants (nitrogen, organics, *E. coli*) of the developed engineered wetland systems, which are subjected to hydraulic loading (HL) fluctuation and seasonal variation.

1 Materials and methods

1.1 Municipal wastewater

Municipal wastewater was collected from a local outlet (prior to disposal into open channels) in Dhaka, Bangladesh. The wastewater was stored in a tank before being dosed as influent, into the experimental wetland system.

1.2 Configuration of the pilot-scale experimental wetlands

The pilot-scale experimental systems were established on campus, Ahsanullah University of Science and Technology, Dhaka, Bangladesh, and consisted of a VF, a HF, and an integrated SF-floating treatment wetland (**Fig. 1**). The VF and HF units were made of steel sheets, whereas the integrated SF-floating treatment wetland was made of plastic sheet. The wetland units were arranged to form three consecutive treatment stages in series: VF wetland as the first stage, followed by the HF wetland, and the integrated SF-floating treatment wetland as the final stage.

The length, width, and height of VF were 0.7, 0.7 and 1.0 m respectively. The VF system included four baffles (0.5 m length, 0.18 m distance between the baffles), as shown in **Fig. 2**. The baffles had clear spaces of 0.2 m (from the opposite steel sheet), to allow the flow of wastewater throughout the media.

The length, width, and height of the HF unit were 2.5, 1.0, and 1.1 m, respectively. The HF included three baffles (0.7 m length, 0.61 m distance between the baffles). The baffles of the HF were constructed to direct the wastewater (Tee et al., 2012) through anaerobic (i.e. lower portion), and aerobic pockets (i.e. upper portion) of the employed media.

The length, width, and height of the combined SF-floating treatment unit were 1.40, 1.01, and 0.78 m, respectively. The floating mat was constructed employing perforated plastic containers (1.01 m length, and 0.15 m width), and was placed at a distance 0.85 m from the outlet of the combined unit. Such arrangement allowed 1.25 m water surface length (with macrophytes) in the


VF wetland HF wetland Combined SF and Floating treatment wetland

Fig. 1 Photo plate of the experimental wetland units.

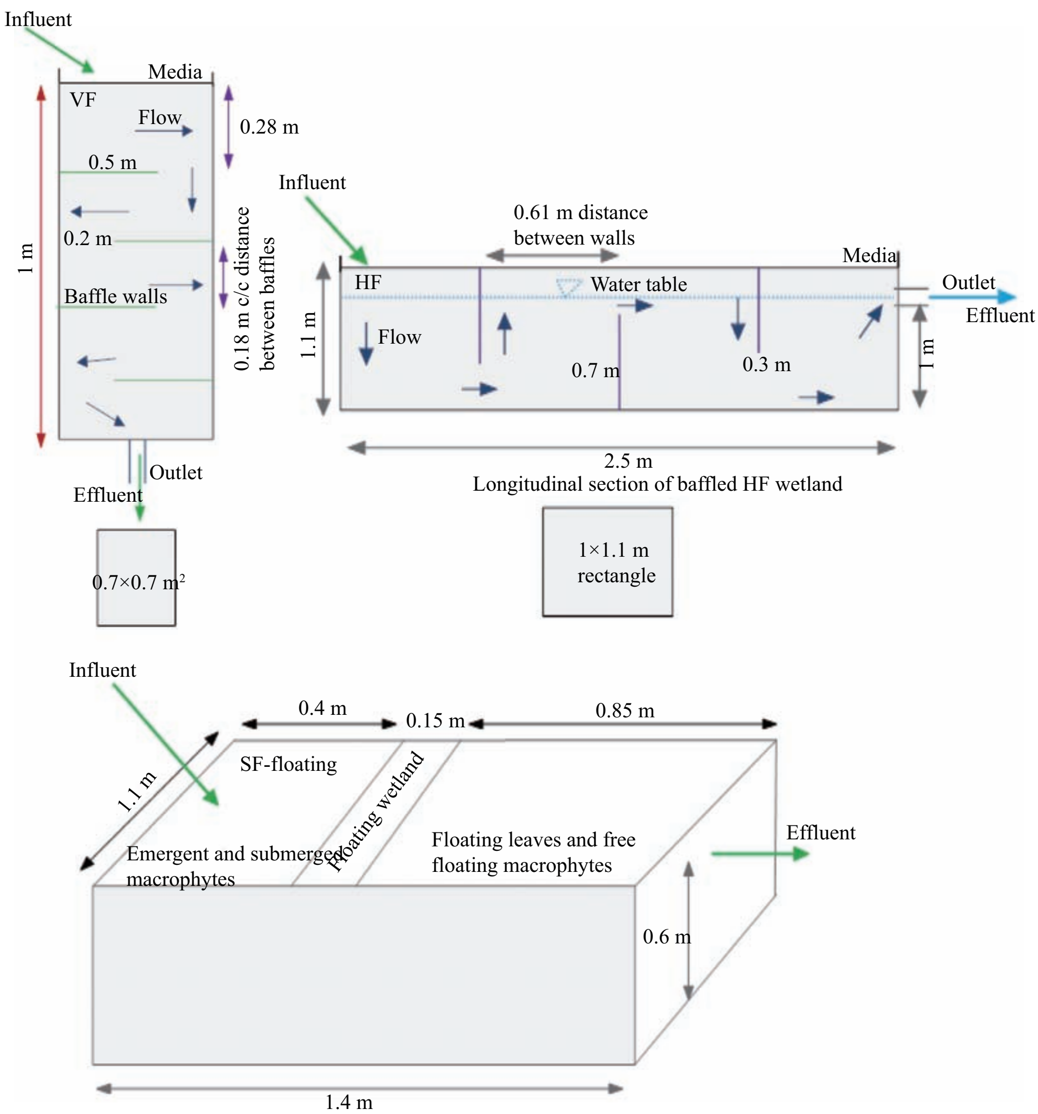

Fig. 2 Structural components of VF; HF; and combined SF-floating treatment wetlands.

combined unit, thereby resembling the characteristics of SF as illustrated in **Fig. 2**.

Five types of locally available substrates (i.e. saw-dust, coal, pea gravel, small sized gravel, and sylhet sand) were employed as the main media. The VF consisted of saw-dust (size 600.0 μm), and coal (size 2.75–9.50 mm). The HF was filled with small sized gravel (size 2.36–2.75 mm), and sylhet sand (size 300.0–600.0 μm). The main media of SF unit included small sized gravel, sylhet sand, and mixture of large sized gravel-oyster shell. The porosities of the packed saw-dust, coal, small gravel, pea-gravel, and sylhet sand were 44.0%, 42.0%, 40.0%, 25.0%, and 26.0% respectively.

The saw-dust media of VF achieved 0.6 m depth, overlying on coal substrates having 0.3 m depth; these substrates were supported by large stones (0.1 m depth), to facilitate effluent drainage. In HF, the depth of the employed media was: small gravel (0.2 m-bottom part), sylhet sand (0.7 m-middle part), and small gravel (0.1 m-top part). In SF-floating treatment unit, the main media (gravel and sand) achieved 0.25 m depth, allowing 0.35 m water depth (from the top of media); the depth of the media (mixture of large gravel-oyster shell) in the floating treatment wetland mat was 0.12 m. The total surface areas of the VF and HF were 0.49 m^2, and 2.50 m^2 respectively.

1.3 Macrophytes

The experimental wetland units were planted with nineteen types of macrophytes (**Table 1**), collected from local water channels and nurseries. The plants included emergent (VF, HF, SF, and floating wetlands), submerged (SF), free floating, and floating leaved macrophytes (SF). After plantation, all the wetland units were water logged up to a period of ten weeks, allowing necessary growth of the macrophytes. After plant establishment, the water content was drained, for the passage of wastewater through the

Table 1 Macrophyte types in experimental pilot-scale wetland system

	Plant type	Scientific name
VF	Emergent	*Phragmites australis, Cyperus difformis, Dracaena sanderiana, Canna indica.*
HF	Emergent	*Phragmites australis, Cyperus papyrus, Cyperus difformis, Dracaena sanderiana, Hydrocotyle umbellate, Echinodorus cordifolius, Colocasia esculenta, Caladium sp., Hymenocallis littoralis, Canna indica.*
SF	Emergent	*Phragmites australis,Echinodorus cordifolius,Ludwigia adscendes, Alternanthera philoxeroides.*
	Submerged	*Hygrophila polysperma, Bacopa caroliniana.*
	Rooted floating	*Nymphea pubescens, Nymphoides indica.*
	Floating leaved	*Salvinia auriculata, Salvinia minima, Pistia stratiotes.*
Floating wetland	Emergent	*Phragmites australis, Cyperus papyrus, Echinodorus cordifolius.*

wetland systems.

1.4 Operation of the wetland systems

The pilot-scale wetland train was fed with municipal wastewater for nineteen weeks; wastewater dosing was commenced from autumn period, and was continued until the end of winter period. Municipal wastewater was dosed manually into the surface of the VF, five days a week, two times a day with 3 hr interval between successive dosings. The volume of the influent wastewater was varied (i.e. artificial fluctuation) every week; 306.0 mm/day in one week, followed by 204.0 mm/day in the following week, and was continued up to nineteen weeks.

Wastewater was applied into the VF, where it flowed downwards as directed by the baffle walls towards outlet (**Fig. 2**). The effluent of the first stage VF wetland A was transferred into the HF, under gravitational force. Wastewater maintained downwards and upwards flow path (while moving towards outlet), as directed by the baffle walls inside the HF maintaining 1.0 m water depth. The effluent of the HF was transferred into the combined SF-floating treatment unit by gravity. Wastewater in such unit passed through the macrophytes of SF, and the hanging roots of the floating treatment wetland towards outlet, producing final effluent of the system.

1.5 Sampling and analyses

Wastewater was collected from the outlet of each wetland on a weekly basis. Sixteen sets of samples (across each experimental wetland unit) were analyzed for pH, redox potential (Eh), dissolved oxygen (DO), NH_4-N, NO_2-N, NO_3-N, turbidity, BOD_5, and COD. Eleven sets of samples were analyzed for *E. coli* measurement, and five sets of samples were analyzed for phosphorus (P) measurement. Analyses of nitrogenous compounds, P and COD were carried out using a digital reactor block, and Palintest 5000 colorimeter based on standard procedures, as highlighted by the supplier (i.e. ELE International, UK). pH, Eh, and DO were measured by ELE 970 DO_2 probe, and 370 pH meter (i.e. ELE International, UK). BOD_5 measurement was carried out with a manometer BOD instrument, and an incubator operated at 20°C. Wastewater turbidity was measured with a turbidity meter (ELE International, UK). *E. coli* in the samples was measured with Macconkey agar, and an incubator operated at 37°C (as indicated by the supplier).

2 Results and discussion

2.1 Overall performance

Table 2 indicates mean removal performances across the experimental wetland units. VF achieved higher BOD_5 removal percentages, when compared with nitrification and denitrification rates. BOD_5 removal efficiencies were also higher, as the wastewater passed through the HF; however such stage demonstrated lower nitrogen removal performances. In addition, the experimental HF was efficient in terms of P and *E. coli* removal from wastewater. The SF-floating treatment showed substantial denitrification and *E. Coli* removal performances, from influent wastewater (effluent of HF). However BOD_5 removal performances in such stage were lower (over COD removal), when compared with the previous stages.

2.2 Profiles of environmental parameters

Figure 3 shows the profiles of pH, Eh, and DO as the influent municipal wastewater passed through the experimental wetland systems. The weekly profiles of the environmental parameters (in raw municipal wastewater) were substantially variable. **Figure 3** also indicates gradual concentration increment of such parameters (except effluent pH values across VF wetland A), as the wastewater passed through each treatment stage

It should be noted that higher effluent DO and Eh concentrations were observed across the effluent of HF. In general HFs are believed to be operated under reducing conditions. Higher effluent DO and Eh concentrations from HF had also been reported previously (Vymazal and Kröpfelová, 2008; Liu et al., 2011). As such, effluent Eh and DO concentrations are not good indicators for describing the environmental conditions inside the media of wetland systems (Vymazal and Kröpfelová, 2008), due

Table 2 Mean pollutant removal performances across the experimental wetland units

	Raw conc.	VF		HF		SF-floating		Overall removal
		Effluent conc.	Removal	Effluent conc.	Removal	Effluent conc.	Removal	
pH	7.1 (0.2)*	6.8 (0.2)		7.1 (0.2)		7.3 (0.3)		
DO (mg/L)	0.06 (0.03)	0.10 (0.06)		0.13 (0.04)		0.17 (0.03)		
Eh (mV)	–17.0 (148.0)	109.1 (75.8)		152.1 (79.2)		152.4 (83.2)		
Turbidity	86.8 (53.5)	22.8 (7.9)	73.7%	8.2(9.6)	63.7%	1.1 (2.7)	86.5%	98.7%
NH_4-N (mg/L)	107.5 (71.2)	54.1 (46.2)	50.0%	38.4(43.7)	28.9%	19.1 (23.0)	50.5%	82.3%
NO_2-N (mg/L)	2.9 (4.5)	2.1 (3.1)	30.1%	1.2 (1.7)	42.7%	0.4(0.5)	60.4%	83.6%
NO_3-N (mg/L)	115.5 (42.1)	51.8 (21.1)	55.1%	45.5 (19.9)	12.2%	12.0 (6.0)	73.8%	89.6%
BOD_5 (mg/L)	1903.0(1013.0)	431.7 (217.0)	77.3%	73.3 (39.1)	83.0%	57.8 (30.0)	21.1%	97.0%
COD (mg/L)	4048.0(1092.0)	1491.0(360.7)	63.1%	658.0(205.0)	55.8%	223.1(44.0)	66.1%	94.4%
P (mg/L)	23.1(11.5)	14.4(6.02)	37.5%	8.3 (4.1)	63.5%	5.9 (3.4)	27.3%	74.1%
E. coli (CFU/100 mL)	257318.0(248865.0)	129345.0(154984.0)	49.7%	2500.0(3685.0)	98.1%	83.3 (252.0)	96.6%	99.9%

* Standard deviations are presented within the bracket.

to possible coexistence of aerobic and oxygen limited zones inside the wetland matrices (Saeed and Sun, 2012).

2.3 Nitrogen and organics removal

Nitrification is the first step of classical nitrogen removal route (from wastewater), that is often observed in treatment wetlands. Biological nitrification and organics removal in constructed wetlands often follow contradictory pathways; higher degradation of biodegradable organics generally depletes the availability of oxygen inside the media, thereby inhibiting aerobic nitrification. As such, higher BOD_5 removal and lower nitrification performances (compared to organics removal, **Table 2**) might be linked to greater oxygen consumption by the former process in VF, that could not be replenished by atmospheric oxygen diffusion (due to lower porosity of the employed media) to enhance the latter route. These results are in agreement with the findings of Saeed and Sun (2013), where the authors employed porous sugarcane bagasse media (69.0% porosity) in VF, and recorded greater atmospheric oxygen diffusion inside the media, to support enhanced nitrification and organics removal.

Higher oxygen consumption (in VF) by biodegradable organics removal mechanism can also be illustrated through theoretical oxygen demand rate (ODR, g/(m^2·day)) equation (Platzer, 1999):

$$\text{ODR} = [\text{BOD}_{\text{in}} - \text{BOD}_{\text{out}}] + 4.3[\text{NH}_{4\text{in}} - \text{NH}_{4\text{out}}]$$

where, BOD_{in} and BOD_{out} are defined as mean input and output BOD across VF (mean input 483.08 g/(m^2·day), output 109.69 g/(m^2·day)), respectively; NH_{4in} and NH_{4out} can be defined as mean input and output NH_4 respectively across VF (mean input 27.35 g/(m^2·day), output 14.49 g/(m^2·day)), respectively. Mean ODR for supporting observed nitrification and organics removal in VF can be calculated as 428.71 g O_2/(m^2·day). The majority portion of this calculated ODR (373.3 g O_2/(m^2·day)) was required for accomplishing observed organics removal rates. Lower porosity of the media (of VF) could have limited additional oxygen diffusion inside the bed, thereby reducing the autotrophic nitrification.

The interference of BOD removal mechanism on autotrophic nitrification is further demonstrated by **Fig. 4**. Nitrification rates were reduced with increase of influent BOD/NH_4-N ratios, further supporting the interference of organics removal on nitrification process. However, nitrification was not diminished drastically despite higher organics loading (in VF, **Table 2**), which does not coincide with the findings of previous studies (Sun et al., 1998; Wu et al., 2011). Such contradictory performance could be attributed to the effective usage of the trapped oxygen,

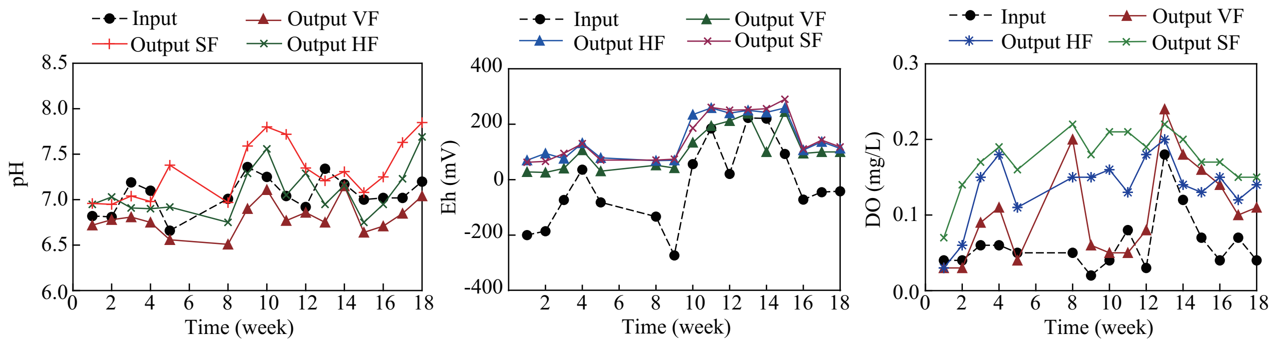

Fig. 3 Profiles of environmental parameters across the experimental wetland systems.

due to flow direction throughout the media by the baffle walls (**Fig. 2**). Subsequently, the following second stage HF demonstrated lower nitrification performances and higher biodegradable organics removal rates (**Table 2**). The predominant anoxic/anaerobic environment inside the bed of HF (due to water logging conditions) could have limited nitrification, and fostered anaerobic organics removal (Garcia et al., 2010).

First stage VF showed higher NO_3-N removal performances, when compared with nitrification efficiencies (**Table 2**). The removal of NO_3-N in wetland systems is generally accomplished by denitrification (Bachand and Horne, 2000), which is critically dependent on the presence of organic C in wastewater. In addition, substantial organics removal rates often diminish organic C availability in wastewater, restricting denitrification metabolism (Lavrova and Koumanova, 2010; Luanaigh et al., 2010). As such, simultaneous denitrification and higher organics removal performances in VF indicate that, organic C requirement (for denitrification) might not be supported by the input BOD_5 quantity in wastewater. This is also justified by **Fig. 4**, that represents the correlation plot of influent BOD/NO_3-N ratios vs. denitrification rates in VF. As observed in **Fig. 4**, no clear correlation trend was observed between incoming BOD/NO_3-N ratios vs. NO_3-N removal rates, illustrating that influent BOD quantity (in wastewater) was not the limiting factor for supporting denitrification.

These findings indicate that, the employed organic sawdust and coal media could have provided required organic C (through internal leaching), to support the measured denitrification. The role of different organic substrates (i.e. rice husk, wood mulch, coco-peat, and sugarcane bagasse), in terms of fostering denitrification (through internal C leaching) had been demonstrated previously in wetland systems (Saeed and Sun, 2011a, 2013; Saeed et al., 2012; Tee et al., 2012). The results of this study further support the application of the organic media (i.e. saw dust and coal) in wetland systems, to achieve denitrification (through internal C leaching) despite enhanced organics removal rates.

The generation of internal organic C from the organic media (in VF) is further demonstrated in **Fig. 5**. Lower effluent NO_3-N concentration values coincided with greater effluent COD values for VF, confirming the dependency of denitrification on C leaching (from the organic media) as discussed in the previous paragraphs.

It should be noted that the correlation plot between effluent COD vs. NO_3-N reduction in HF showed no clear trend (**Fig. 5**). For HF, such pattern illustrates lack of organic C (inside the HF reactor) to support denitrification, and is in agreement with the observed diminished NO_3-N removal efficiencies (**Table 2**). Higher BOD_5 removal in HF (due to flow direction by the baffles through anaerobic-aerobic pockets) might have depleted organic C availability, that could not be balanced internally as the employed media was of inorganic type.

Third stage SF-floating treatment demonstrated highest NO_3-N removal performances, when compared with other experimental wetland units. Since denitrification was limited in previous stage HF it could be stated that, the influent wastewater (i.e. effluent of HF) across the third stage unit did not contain necessary organic C for accomplishing denitrification. As such, internal production of organic C could have intensified NO_3-N reduction in the final stage unit. Lower BOD_5 removal performances (of the integrated system, **Table 2**) also support the generation of organic C, to foster denitrification. It could be possible that the leaves and roots of the macrophytes (of the integrated system) leached organic C into wastewater internally (through decay process), thereby accelerating denitrification (Wang et al., 2012b). Simultaneously, the profiles of environmental parameters such as: increase of effluent pH values (**Fig. 3**), and marginal increment of effluent redox potential values across final stage wetland C further indicate favorable conditions for denitrification (**Table 2**).

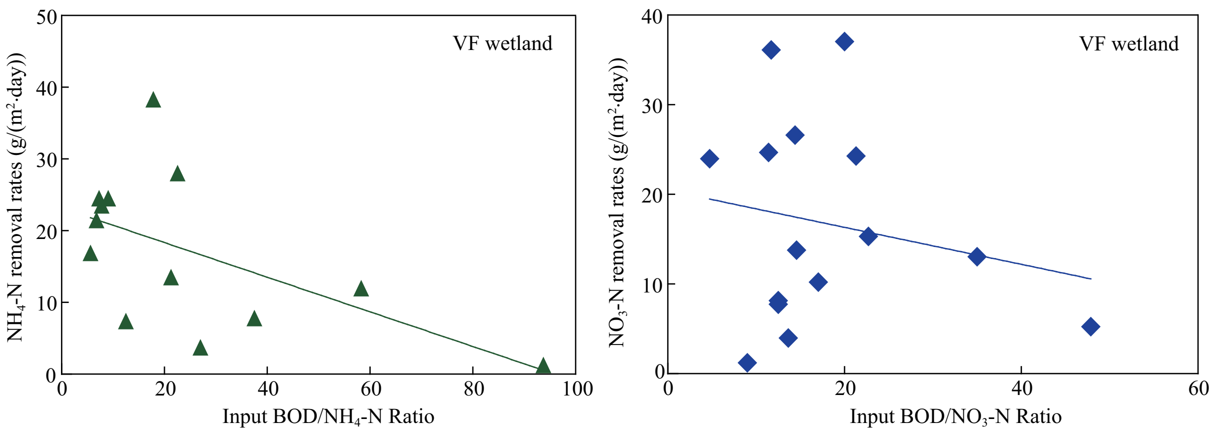

Fig. 4 Correlation between nitrification and denitrification rates vs. input BOD/NH_4-N, BOD/NO_3-N ratio in VF.

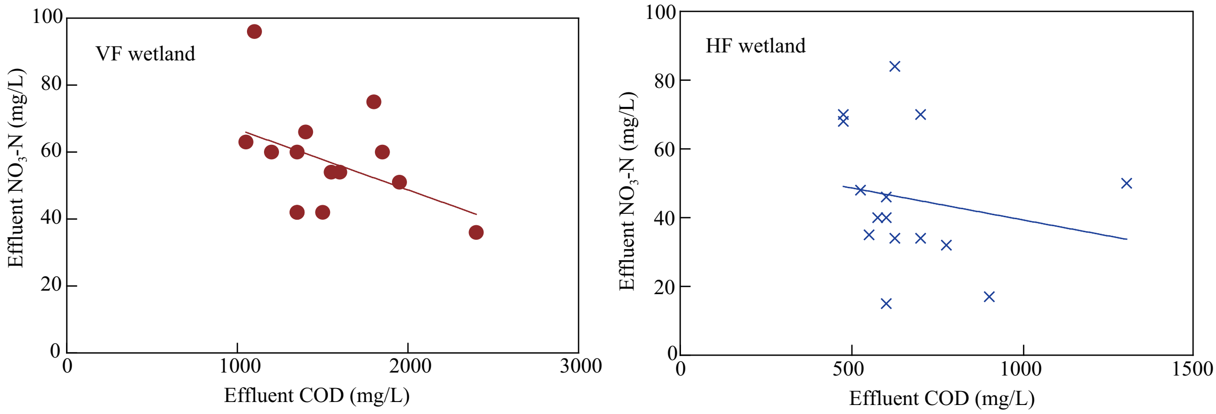

Fig. 5 Correlation plots between effluent COD and NO_3-N concentration in VF and HF.

2.4 *E. coli* removal

Second stage HF, and final stage integrated system demonstrated enhanced *E. coli* removal performances (**Table 2**). Since the redox potential values gradually increased in the effluents of successive wetland units (**Fig. 3**), it could be stated that *E. coli* removal might have been achieved via protozoa predation (in oxygen rich zones), and oxidation process (Decamp and Warren, 2000; Wand et al., 2007; Papadimitriou et al., 2010). In addition, penetration of UV radiation through the water column of the SF portion (**Fig. 2**), could have assisted further *E. coli* mortality (MacIntyre et al., 2006) in the final stage wetland.

2.5 Effect of hydraulic loading fluctuation and seasonal variation

Figure 6 presents the effect of input HL fluctuation i.e 204.0 and 306.0 mm/day between successive weeks on pollutant removal performances of the experimental wetland train. The HL fluctuation (within the experimental range) did not produce significant nitrogen and organics removal performance deviation in VF, and HF (except the generation of NO_3-N by HF at 204.0 mm/day loading). Such NO_3-N accumulation (at 204.0 mm/day loading) could be linked to higher nitrification rates due to increased retention time; and the lack of organic C to support NO_3-N reduction.

In general, the findings of this study are paradoxical to the observations of the previous studies where the wetland systems exhibited significant diminished performances, when subjected to loading increment (Konnerup et al., 2009; Trang et al., 2010). Such contradictory performance of the experimental systems could be attributed to the presence of baffle walls, that prevented short circuiting of the flow (at higher loading), and maintaining sufficient contact between biofilms, and root zones (via flow diversion), thereby hindering performance deviations.

It should be noted that the last stage integrated SF-floating treatment wetland showed contradictory organics and nitrogen removal performances, at upper (306.0 mm/day) and lower (204.0 mm/day) HL ranges. Organics removal performances were almost similar at both HL ranges (**Fig. 6**). However, NH_4-N and NO_3-N removal performances were higher at greater HL conditions (306.0 mm/day). The last stage integrated SF-floating wetland unit was planted with different types of macrophyte . Simultaneously, influent N concentrations across integrated SF-floating wetland were lower (**Table 2**), when compared with previous stages. As such, greater HL conditions (306.0 mm/day) might have allowed substantial increase of input nitrogen loads, enhancing the competition between macrophytes and biomass for available N (Breen, 1990), thereby resulting higher nitrogen removal performances.

With regards to *E. coli* removal, the first stage VF showed lower efficiencies at upper loading range (i.e. 306.0 mm/day), probably due to higher incoming coliform concentrations, which could not be removed at reduced retention time.

Temperature is an important environmental factor, that often controls biological nitrification in wetland systems. Previous studies indicated that temperature ranges between 16.5–32°C are favorable for nitrification in constructed wetlands (Demin and Dudeney, 2003; Katayon et al., 2008). **Figure 7** shows the performance of the experimental wetland systems when operated during autumn (mean temperature 24.0–31.0°C), and winter (mean temperature 9.5–13.0°C). Nitrification process was higher during autumn period in all wetland units, coinciding with the findings of previous studies (Demin and Dudeney, 2003; Katayon et al., 2008). NH_4-N oxidation difference (between the two periods) was sharp in VF. These results further confirm that autotrophic nitrification was the main route for oxidizing NH_4-N in VF, as biological nitrification proceeds substantially at higher temperature (Langergraber et al., 2007). In contrast the difference of the achieved nitrification rates was not substantially greater in integrated SF-floating system, possibly due to nitrogen uptake via macrophytes (Lim et al., 2001), in-conjunction with biological nitrification.

Biodegradable organics removal efficacy was slight-

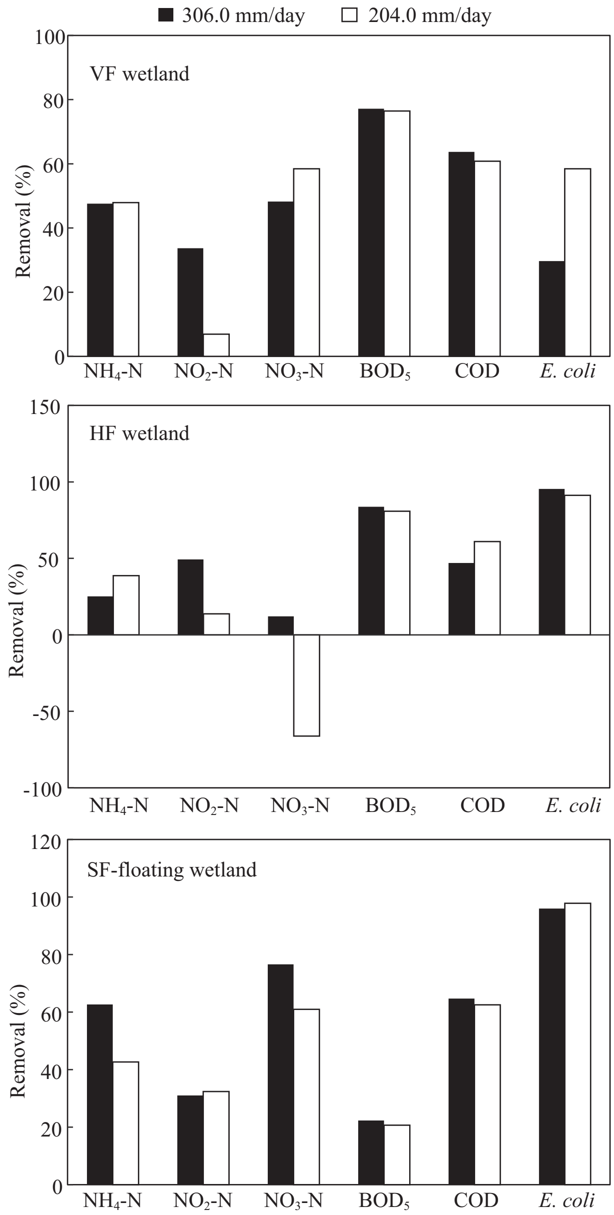

Fig. 6 Impact of HL variation on pollutant removal performances in experimental wetlands.

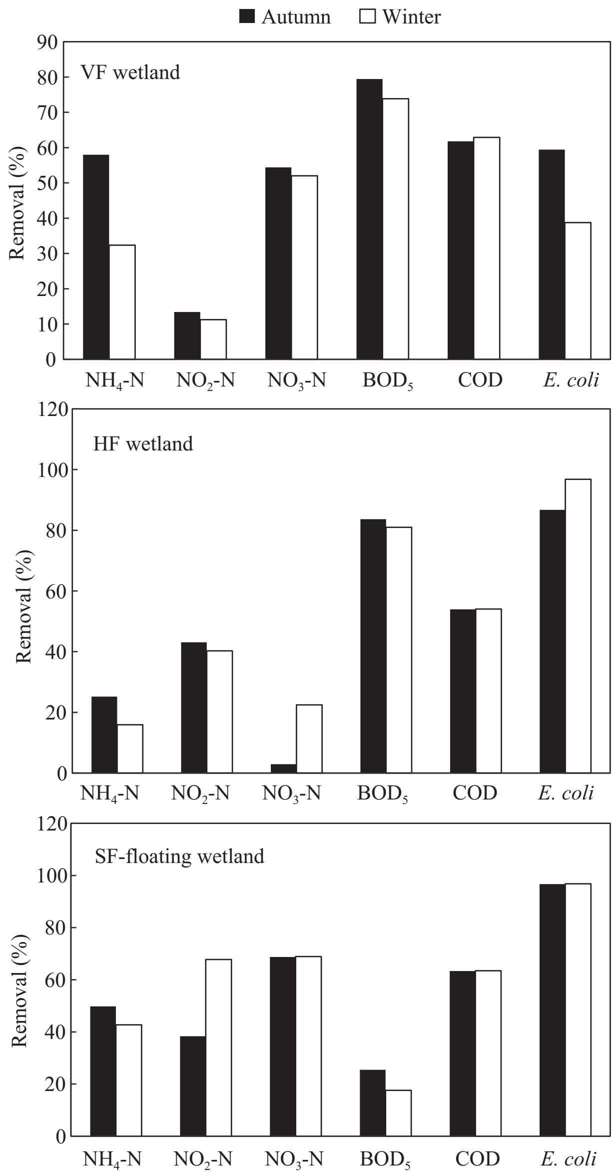

Fig. 7 Impact of seasonal variation on pollutant removal performances in experimental wetlands.

ly higher during autumn period in all the experimental wetland systems (**Fig. 7**). These findings imply that, temperature variation (within the experimental range) did not affect biodegradable organics removal mechanism critically (in the experimental wetlands). Similarly NO_3-N removal differences (between autumn and winter) were not sharp in VF and integrated SF-floating wetland, as denitrification proceeds slowly at low temperature (e.g. 5°C, US EPA, 1975), that is well below the experimental ranges.

Overall, efficient performance of the integrated SF-floating treatment wetland (regardless HL and seasonal variation), illustrates possible amalgamation of such unit in a hybrid system as a final polishing step, to provide further treatment of wastewater (prior to environmental disposal).

2.6 Loading-removal profiles

Figure 8 signifies the correlation profile between input loading and observed removal rates of nitrogen, organics, and *E. coli*, as the wastewater passed through the experimental wetland units. Denitrification, organics, and *E. coli* removal rates showed higher correlation values, with increasing input loadings. Such results illustrate the efficiencies of the structurally modified experimental wetlands to support these bio-reactions, regardless HL and seasonal variation (Section 2.5).

It should be noted that the experimental wetland train was operated under substantial input organics loadings (**Fig. 8**), that were rarely reported in the literature. Simultaneously influent nitrogen and organics concentrations (BOD_5 = 500.0–3625.0 mg/L; COD = 2375.0–6400.0 mg/L) were also much higher, than the reported values across other wetland systems (of different countries) employed for municipal and domestic wastewater treatment (Vymazal, 2009). Nevertheless, overall pollutant removal efficiencies of the employed system were higher (**Table 2**), exceeding the performances of other wetland systems operated under elevated input organics loadings (Zhao et al., 2004; Sun et al., 2005).

In terms of HL, the experimental system also achieved greater removal performance, when compared with the wetland systems of Chang et al. (2012), operated under higher HL (250 mm/day) for domestic wastewater treatment. Such findings signify the importance of modifying structural configurations (of wetland systems), and overcome adverse conditions such as loading and seasonal variation.

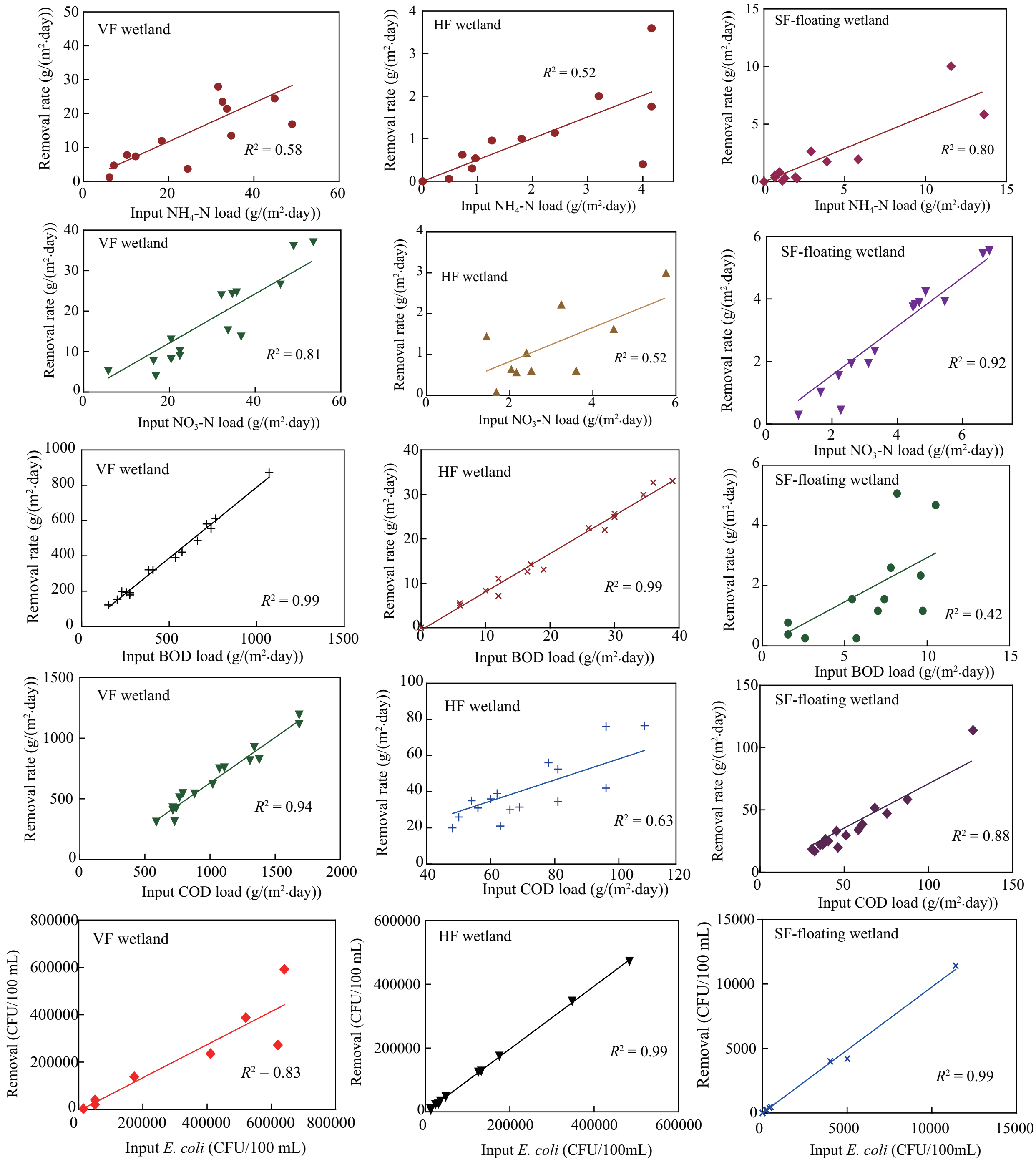

Fig. 8 Correlation profiles of input loading vs. removal in experimental wetland units.

It should be noted that, final effluent pollutant concentrations (particularly COD in **Table 2**) were higher across the three stage hybrid system, as it was operated under substantial input pollutant and hydraulic loadings (**Fig. 8**). These values might not fulfill stringent discharge guidelines in many countries. As such, field-scale trials are required to identify optimum loading ranges (across the baffled wetlands), and system arrangement prior to application. In general, the results indicate the importance of incorporating baffle walls in wetland systems for allowing space-efficient designs, particularly in countries such as Bangladesh where land availability is scarce.

3 Conclusions

Enhanced organics removal rates depleted oxygen availability, thereby reducing nitrification rates in first stage VF wetland; however, nitrification rates were not completely inhibited inside the first stage reactor. Such phenomena might be linked to effective usage of the trapped oxygen, due to flow direction throughout the media by the baffle walls. In addition, enhanced organics removal rates did not limit organic C availability for denitrification process (in VF), due to internal C generation from the employed organic media. Second stage HF wetland was inefficient in reducing incoming NO_3-N. Higher organics removal depleted organic C availability in the system, that could not support denitrification. In contrast, internal organic C generation (through the decay of dead macrophytes) intensified denitrification metabolism in the final stage integrated SF-floating wetland.

Higher overall observed removal performances (of the experimental hybrid wetland system) illustrate the necessity of structural modification, when operated under adverse conditions such as: substantial input organics loading, hydraulic loading fluctuation, and seasonal variation.

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REFERENCES

Abidi, S., Kallali, H., Jedidi, N., Bouzaiane, O., Hassen, A., 2009. Comparative pilot study of the performances of two constructed wetland wastewater treatment hybrid systems. Desalination 246, 370–377.

Antoniadis, A., Takavakoglou, V., Zalidis, G., Darakas, E., Poulios, I., 2010. Municipal wastewater treatment by sequential combination of photocatalytic oxidation with constructed wetlands. Catal. Today 151, 114–118.

Arias, M.E., Brown, M.T., 2009. Feasibility of using constructed treatment wetlands for municipal wastewater treatment in the Bogot Savannah, Colombia. Ecol. Eng. 35, 1070–1078.

Bachand, P., Horne, A., 2000. Denitrification in constructed free water surface wetlands: I. Very high nitrate removal rates in a macrocosm study. Ecol. Eng. 14, 9–15.

Belmont, M.A., Cantellano, E., Thompson, S., Williamson, M., Sánchez, A., Metcalfe, C.D., 2004. Treatment of domestic wastewater in a pilot-scale natural treatment system in central Mexico. Ecol. Eng. 23, 299–311.

Breen, P., 1990. A mass balance method for assessing the potential of artificial wetlands for wastewater treatment. Water Res. 24(6), 689–697.

Chang, J.J., Wu, S.Q., Dai, Y.R., Liang, W., Wu, Z.B., 2012. Treatment performance of integrated vertical-flow constructed wetland plots for domestic wastewater. Ecol. Eng. 44, 152–159.

Decamp, O., Warren, A., 2000. Investigation of *Escherichia coli* removal in various designs of subsurface flow wetlands used for wastewater treatment. Ecol. Eng. 14(3), 293–299.

Demin, O., Dudeney, A., 2003. Nitrification in constructed wetlands treating ochreous mine water. Mine Water Environ. 22(1), 15–21.

Fountoulakis, M., Terzakis, S., Chatzinotas, A., Brix, H., Kalogerakis, N., Manios, T., 2009. Pilot-scale comparison of constructed wetlands operated under high hydraulic loading rates and attached biofilm reactors for domestic wastewater treatment. Sci. Total Environ. 407(8), 2996–3003.

Garcia, J., Rousseau, D.P.L., Morato, J., Lesage, E., Matamoros, V., Bayona, J.M., 2010. Contaminant removal processes in subsurface-flow constructed wetlands: A review. Crit. Rev. Environ. Sci. Technol. 40(7), 561–661.

Headley, T., Tanner, C., 2006. Application of floating wetlands for enhanced stormwater treatment: A review. In: Research Report No. HAM2006–123 of National Institute of Water & Atmospheric Research Ltd. Hamilton, New Zealand.

Katayon, S., Fiona, Z., Noor, M.J.M.M., Halim, G.A., Ahmad, J., 2008. Treatment of mild domestic wastewater using subsurface constructed wetlands in Malaysia. Inter. J. Environ. Stud. 65(1), 87–102.

Konnerup, D., Koottatep, T., Brix, H., 2009. Treatment of domestic wastewater in tropical, subsurface flow constructed wetlands planted with Canna and Heliconia. Ecol. Eng. 35, 248–257.

Langergraber, G., Prandtstetten C, Pressl, A., Rohrhofer, R., Haberl, R., 2007. Optimization of subsurface vertical flow constructed wetlands for wastewater treatment. Water Sci. Technol. 55(7), 71–78.

Lavrova, S., Koumanova, B., 2010. Influence of recirculation in a lab-scale vertical flow constructed wetland on the treatment efficiency of landfill leachate. Bioresour. Technol. 101, 1756–1761.

Lim, P.E., Wong, T.F., Lim, D.V., 2001. Oxygen demand, nitrogen and copper removal by free-water-surface and subsurface-flow constructed wetlands under tropical conditions. Environ. Inter. 26(5-6), 425–431.

Liu, S.Y., Yan, B.X., Wang, L.X., 2011. The layer effect in nutrient removal by two indigenous plant species in horizontal flow constructed wetlands. Ecol. Eng. 37(12), 2101–2104.

Luanaigh, N.D., Goodhue, R., Gill, L.W., 2010. Nutrient removal from on-site domestic wastewater in horizontal subsurface flow reed beds in Ireland. Ecol. Eng. 36(10), 1266–1276.

MacIntyre, M.E., Warner, B.G., Slawson, R.M., 2006. *Escherichia coli* control in a surface flow treatment wetland. J. Water Health 4(2), 211–214.

Papadimitriou, C.A., Papatheodoulou, A., Takavakoglou, V., Zdragas, A., Samaras, P., Sakellaropoulos, G.P. et al., 2010. Investigation of protozoa as indicators of wastewater treatment efficiency in constructed wetlands. Desalination 250(1), 378–382.

Platzer, C., 1999. Design recommendations for subsurface flow constructed wetlands for nitrification and denitrification. Water Sci. Technol. 40(3), 257–263.

Saeed, T., Sun, G.Z., 2011a. A comparative study on the removal of nutrients and organic matter in wetland reactors employing organic media. Chem. Eng. J. 171(2), 439–447.

Saeed, T., Sun, G.Z., 2011b. Enhanced denitrification and organics removal in hybrid wetland columns: Comparative experiments. Bioresour. Technol. 102(2), 967–974.

Saeed, T., Afrin, R., Muyeed, A., Sun, G.Z., 2012. Treatment of tannery wastewater in a pilot-scale hybrid constructed wetland system in Bangladesh. Chemosphere 88, 1065–1073.

Saeed, T., Sun, G.Z., 2012. A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: Dependency on environmental parameters, operating conditions and supporting media. J. Environ. Manag. 112, 429–448.

Saeed, T., Sun, G., 2013. A lab-scale study of constructed wetlands with sugarcane bagasse and sand media for the treatment of textile wastewater. Bioresour. Technol. 128, 438–447.

Sun, G., Gray, K., Biddlestone, A., 1998. Treatment of agricultural wastewater in downflow reed beds: Experimental trials and mathematical model. J. Agr. Eng. Res. 69(1), 63–71.

Sun, G.Z., Zhao, Y.Q., Allen, S., 2005. Enhanced removal of organic matter and ammoniacal nitrogen in a column experiment of tidal flow constructed wetland systems. J. Biotechnol. 115, 189–197.

Tee, H.C., Lim, P.E., Seng, C.E., Nawi, M., 2012. Newly developed baffled subsurface-flow constructed wetland for the enhancement of nitrogen removal. Bioresour. Technol. 104, 235–242.

Trang, N.T.D., Konnerup, D., Schierup, H.H., Chiem, N.H., Tuan, L., Brix, H., 2010. Kinetics of pollutant removal from domestic wastewater in a tropical horizontal subsurface flow constructed wetland system: Effects of hydraulic loading rate. Ecol. Eng. 36(4), 527–535.

Tunsiper, B., 2009. Nitrogen removal in a combined vertical and horizontal subsurface-flow constructed wetland system. Desalination 247(1-3), 466–475.

US EPA (U.S. Environmental Protection Agency), 1975. Process Design Manual for Nitrogen Control. Office of Technology Transfer, Washington DC, USA.

Vymazal, J., 2005. Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. Ecol. Eng. 25(5), 478–490.

Vymazal, J., 2009. The use constructed wetlands with horizontal subsurface flow for various types of wastewater. Ecol. Eng. 35(1), 1–17.

Vymazal, J., Kröpfelová, L., 2008. Is concentration of dissolved oxygen a good indicator of processes in filtration beds of horizontal-flow constructed wetlands? In: Vymazal, J., (Eds.). Wastewater Treatment, Plant Dynamics and Management in Constructed and Natural Wetlands. Springer, Netherlands. 311–317.

Vymazal, J., Kröpfelová, L., 2009. Removal of organics in constructed wetlands with horizontal sub-surface flow: A review of the field experience. Sci. Total Environ. 407(13), 3911–3922.

Wand, H., Vacca, G., Kuschk, P., Kruger M., Kastner, M., 2007. Removal of bacteria by filtration in planted and non-planted sand columns. Water Res. 41(1), 159–167.

Wang, J., Zhang, L.Y., Lu, S.Y., Jin, X.C., Gan, S., 2012a. Contaminant removal from low concentration polluted river water by the bio-rack wetlands. J. Environ. Sci. 24(6), 1006–1013.

Wang, W.L., Gao, J.Q., Guo, X., Li, W.C., Tian, X.Y., Zhang, R.Q., 2012b. Long-term effects and performance of two-stage baffled surface flow constructed wetland treating polluted river. Ecol. Eng. 49, 93–103.

Wu, S.B., Zhang, D.X., Austin, D., Dong R.J., Pang, C., 2011. Evaluation of a lab-scale tidal flow constructed wetland performance: Oxygen transfer capacity, organic matter and ammonium removal. Ecol. Eng. 37(11), 1789–1795.

Ye, F.X., Li, Y., 2009. Enhancement of nitrogen removal in towery hybrid constructed wetland to treat domestic wastewater for small rural communities. Ecol. Eng. 35(7), 1043–1050.

Zachritz, W.I.I., Hanson, A., Sauceda, J., Fitzsimmons, K.M., 2008. Evaluation of submerged surface flow (SSF) constructed wetlands for recirculating tilapia production systems. Aquacult. Eng. 39(1), 16–23.

Zhao, Y., Sun, G., Allen, S., 2004. Purification capacity of a highly loaded laboratory scale tidal flow reed bed system with effluent recirculation. Sci. Total Environ. 330(1-3), 1–8.

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