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Research article

Optimization of operating parameters of hybrid vertical down-flow constructed wetland systems for domestic sewerage treatment

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ABSTRACT

In this work, three hybrid vertical down-flow constructed wetland (HVDF-CW) systems with different compound substrates were fed with domestic sewage and their pollutants removal performance under different hydraulic loading and step-feeding ratio was investigated. The results showed that the hydraulic loading and step-feeding ratio were two crucial factors determining the removal efficiency of most pollutants, while substrate types only significantly affected the removal of COD and NH_4^+-N. Generally, the lower the hydraulic loading, the better removal efficiency of all contaminants, except for TN. By contrast, the increase of step-feeding ratio would slightly reduce the removal rate of ammonium and TP but obviously promoted the TN removal. Therefore, the optimal operation of this CWs could be achieved with low hydraulic loading combined with 50% of step-feeding ratio when TN removal is the priority, whereas medium or low hydraulic loading without step-feeding would be suitable when TN removal is not taken into consideration. The obtained results in this study can provide us with a guideline for design and optimization of hybrid vertical flow constructed wetland systems to improve the pollutants removal from domestic sewage.

1. Introduction

Constructed wetlands (CWs), which is consisted of wetland plants, wetland substrate, micro-organisms and other constituent elements, are effective systems to treat wastewater through the complex combination of physical, chemical and biological processes (Cui et al., 2013; Dordio and Carvalho, 2013; Li et al., 2015; Liu et al., 2015). In a mature constructed wetland system, a large number of micro-organisms and substrates, plants and other organisms interconnected to form an independent ecosystem (Xu et al., 2015). When wastewater flows into the wetlands, suspended solids (SS) can be intercepted by substrates and plant roots, while dissolved organic pollutants can be removed by biofilm through adsorption, assimilation and dissimilation.

Vertical flow wetland system is a comprehensive integration of surface flow wetlands and subsurface flow wetlands, in which water flows through the packed bed vertically from the top to the bottom, is collected through the collection pipes laid at the bottom and discharged. Studies have shown that the vertical flow wetland beds are a reliable treatment system for wastewater purification with excellent oxygen transfer properties to treat water with high ammonia-nitrogen content such as sewage and urban wastewater (Cooper, 2005; Fan et al., 2013; Xu et al., 2015). However, the conventional vertical flow wetland system exhibits several disadvantages including pipeline blockage (clogging), which will lead to accumulation of water on the surface of the down-flow pool and decreased activity of aerobic microbes in the vertical flow. In addition, the low oxygenation capacity of the system could limit the total nitrogen (TN) removal efficiency, as carbon source is insufficient during the process of denitrification, the removal of nitrogen is further inhibited (Ding et al., 2012).

In our previous study, we have developed a series of hybrid constructed wetland systems, including re-circulated hybrid tidal flow CWs (Cui et al., 2012), hybrid baffled subsurface-flow CWs (Cui et al., 2013), and horizontal flow combined with vertical flow baffle hybrid CWs (Cui et al., 2015). How to further improve the oxygen enrichment ability and TN removal efficiency of the CW system is still a problem to be overcome. Based on this, in the present study, the removal efficiencies for TN, TP, COD, BOD_5, and NH_4^+-N by three adapted hybrid vertical down-flow constructed wetland (HVDF-CW) systems with different hydraulic loadings and step-feeding ratios were evaluated to examine the abilities of the three

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systems to treat domestic wastewater.

2. Materials and methods

2.1. HVDF-CW systems

Domestic wastewater was collected and fed to the primary sedimentation basin to remove large particles, and then run through the HVDF-CW system. HVDF-CW is composed of bed body and water distributors, the impermeable bed wall is made of cement plastered brick, and the bottom of the bed is made of concrete structure. Hybrid vertical down-flow constructed wetland system, The dimension of the Stage 1 units of HVDF-CW is 100 × 100 × 130 cm (length × width × height), that of the Stage 2 units is 100 × 100 × 110 cm (length × width × height). The water distributor of HVDF-CW are perforated PVC pipe located at about 10 cm below the top of the substrate surface, shown in Fig. S1 (Supporting Information). Wastewater is pumped to the HVDF-CW at the top of the Stage 1 unit via the primary water distributors, the down-flow of the wastewater through the Stage 1 unit mixes with the wastewater providing step-feeding ratio at the bottom, then flow into the Stage 2 unit for another vertically down-flow processing. Three different systems were constructed based on Table 1.

2.2. Substrate filling

In both the Stage 1 and Stage 2 units of HVDF-CW system, the bottom layer of the bed is filled with gravel with a diameter a 3–5 cm to a height of 10 cm, the height of the main substrate layer is 100 cm. The solid particles that fill the substrate layers in the first and second stage units of the three systems are presented in Table 1. The water distributors are located 10 cm below the top of the substrate layer, hence the valid height of the substrate layer in the Stage 1 unit is 90 cm, while that of the Stage 2 unit is 80 cm.

2.3. Operation and management

The system was operated on a 5: 2 wet-to-dry operating ratio (wastewater flowed through the system for five consecutive days then treatment was stopped and the system was dried for two days. 5: 2 wet-to-dry operating ratio is chosen as it is compatible with the work schedule of the operations managers), hydraulic load rates controlled by valves were 0.6 (low), 1.2 (medium) and 2.4 (high) $m^3/m^2 \cdot d$ at an effluent height of 80 cm, respectively. The primary water is introduced into the secondary tank as carbon source, and the flow ratio of primary water to secondary water was tuned at 0: 1, 1: 3 and 1: 1, that is, the step-feeding ratio is 0, 25% and 50%. The construction cost of a CW system in this study is about 600–700 RMB (~100 USD), and the average operation cost is 0.15 RMB/m^3 by considering the costs of electricity (0.08 RMB/m^3), manpower (0.04 RMB/m^3) and electro-mechanical equipment maintenance (0.03 RMB/m^3).

2.4. Water sampling and analysis

Dormitory wastewater from Guangzhou Iron and Steel Institute was pumped into HVDF-CW for treatment, the water quality parameters are shown in Table 2 below:

2.5. Statistical analysis

SAS8.1, SPSS 16.0 and Excel 2003 were used for data analysis including variance, correlation analysis, mean value, and standard deviation calculation. Duncan Multiple Range Test method (DMRT law, $P = 0.05$) was chosen for multiple comparisons by SAS. Multivariate and Repeated measures function were selected for general linear model (GLM) variation analysis of 3 factors (hydraulic loading, substrate types and step-feeding ratio) with three level on five indexes (removal rate of COD, BOD, Ammonium, TP and TN, respectively) by SPSS 16.0, and the results were displayed with significant values and observed mean values in supplementary tables. Correlations analysis of five indexes was conducted as well by utilizing the correlate (bivariate) function of SPSS.

3. Results

3.1. COD and BOD_5 removal

The COD removal by hybrid vertical down flow constructed wetlands (HVDF-CW) with different step-feeding ratio was shown in Fig. 1(a–c). Obviously, with the increasing of hydraulic loading rate, the purification effect of COD declined with different step-feeding ratio. Under low hydraulic loading rate (Fig. 1a), the COD removal efficiency of Systems IV1 and IV2 increased with increasing step-feeding ratio, and System IV3 showed the highest removal efficiency when the step-feeding ratio is 25%.

As observed in Fig. 1b, under medium hydraulic loading rate, the COD removal by System IV3 decreased with the increasing of step-feeding ratio, and Systems IV1and IV2 showed the highest removal efficiency when the step-feeding ratio is 25%. In System IV1, the substrate used for the Stage 2 is medium coarse sand with low surface area, which can intercept the pollutants. When step-feeding influent were pumped directly into the Stage 2 and reached a critical mass, organic matters intercepted by the substrate can not been degraded timely by the absorbed microorganism, resulted in the low efficiency of COD removal. When step-feeding influent was not pumped into the Stage 2 unit, the Stage 1 unit would play a crucial role in COD removal. With the increasing of step-feeding influent, the Stage 2 unit need to process more organic pollutants, hence System IV2 achieved a high COD removal efficiency. When the Stage 2 unit was supplied with 50% of step-feeding influent, the effect of the Stage 1 unit on COD removal attenuated, led to a low COD removal efficiency of System IV2. Under high hydraulic loading rate (Fig. 1c), the three hybrid CW systems showed the highest COD removal efficiency when the step-feeding ratio is 25%. Under medium and high hydraulic loading, with the increasing of step-feeding ratio, the Stage 1 of System IV3

Table 1
The specific structure of HVDF-CW systems.

System name	Cell body name	Types of substrate	Plant species
System IV1	Stage 1	Blast furnace slag	Windmill grass
	Stage 2	Medium coarse sand	*Canna indica*
System IV2	Stage 1	Pisolite	Windmill grass
	Stage 2	Blast furnace slag	*Canna indica*
System IV3	Stage 1	50%blast furnace slag&50% medium coarse sand	Windmill grass
	Stage 2	Coal ash	*Canna indica*