Optimising the performance of a lab-scale tidal flow reed bed system treating agricultural wastewater

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Abstract A gravel-based tidal flow reed bed system was operated with three different strategies in order to investigate its optimal performance for the treatment of a high strength agricultural wastewater. According to the three strategies, individual reed beds were saturated and unsaturated with the wastewater for different periods while reasonably stable hydraulic and organic loadings were maintained. Experimental results demonstrated that the system produced the highest pollutant removal efficiencies with a relatively short saturated period and long unsaturated period, highlighting the importance of oxygen transfer into reed bed matrices during the treatment. Significant removals of some major organic and inorganic pollutants were achieved under all three operational conditions. Nitrification was not the major route of ammoniacal-nitrogen removal when the system was under high organic loading. Due to the filtration of suspended solids and the accumulation of biomass, gradual clogging of the reed bed matrices took place, which caused concerns over the long-term efficiency of the tidal flow system.

Keywords Agricultural wastewater; clogging; constructed wetland; reed bed; tidal flow

Introduction

Since the 1980s constructed wetlands and reed beds have been successfully used world-wide as a popular treatment alternative for a variety of wastewaters, including industrial, domestic and agricultural effluents, urban runoff, mine drainage and landfill leachate (IWA, 2000). As a "green" technology, the reed bed system is considered to be effective, economical and environment-friendly. Tidal flow reed beds emerged in recent years as a novel system in that the bed matrix is rhythmically filled with wastewater then drained (Green *et al*., 1997; Revitt *et al*., 1997; Sun *et al*., 1999a; Zhao *et al*., 2004). During the filling process, air is expelled and the reed bed matrix is gradually submerged with the wastewater, providing maximum media-wastewater contact. When the whole bed is fully saturated, the wastewater begins to drain and air is drawn from the atmosphere into the bed matrix to promote aeration and assist aerobic microbial activities in biofilms attached to the media and the roots of the reeds. It has been demonstrated that the tidal flow operation enhances oxygen supply and prevents poor water distribution in conventional reed bed systems. However, commercial practices of the tidal flow system have not been carried out due to lack of suitable design criteria and performance data leading to the optimal operation of the system.

In this study, three different operating conditions of a gravel-based tidal flow reed bed system are investigated to discover the optimal operation strategy. The tidal flow system consists of five stages of individual beds filled with gravels and planted with common reeds, *Phragmites australis*. The removals of pollutants, including COD, BOD_5, ammoniacal-nitrogen (NH_4-N), phosphorus (P), and suspended solids (SS) are analysed. The optimum operating condition is evaluated based on the removal efficiency of these pollutants.

Materials and methods

The reed bed system

The lab-scale reed bed system used in this study is shown schematically in Figure 1. It consisted of five identical beds that were made of Perspex columns of 900 mm in height and 95 mm in diameter. Each bed was filled with 26.4 ± 7.2 mm washed round gravel to a depth of 150 mm as a supporting layer, followed by a top layer of 4.4 ± 1.5 mm washed gravel with a depth of 650 mm. A single common reed, *Phragmites australis*, was planted in the top layer of each bed. The system was placed in a special experimental area with an overhead air extraction system and a permanent metal rig for holding the beds. The experimental area was fully sealed by a heavy-duty plastic curtain to minimise the release of unpleasant odour.

Experiment process

The reed bed system was previously started-up via batch and continuous operation for four months to establish an environment in which chemical processes, microorganisms and the reeds constituted the operative substrates (Zhao *et al*., 2003). During the current study, the system was operated with a tidal flow strategy that allowed the five single beds (Stages 1–5) to be alternately filled and drained with wastewater. In order to avoid the excessive accumulation of biomass, the system was rested for one week after each week of operation.

Diluted pig slurry was prepared in a feed tank with SS, COD, BOD_5, NH_4-N and PO_4-P levels up to 894 mg/l, 4,254 mg/l, 3,150 mg/l, 159 mg/l and 50 mg/l, respectively. As shown in Figure 1, 2.1 litres of diluted pig slurry were pumped from the feed tank into the first stage of the reed bed system, totally submerging the bed before being pumped out and passed through the system sequentially from the first to the fifth stages. Controlled by pumps and timers, each “tide” was completed in four hours, giving a hydraulic loading of about 1.6 m^3/m^2d on each bed. Details of the three operating conditions applied in this investigation are presented in Table 1. The period of individual reed beds being filled with the wastewater is named as “saturated time”, whereas the period of the beds being drained and unsaturated with the wastewater is named as “unsaturated time”.

Sampling and analyses

Samples of influents and effluents from each stage were collected three days a week and analysed on the same day of collection. The COD and BOD_5 were determined according to

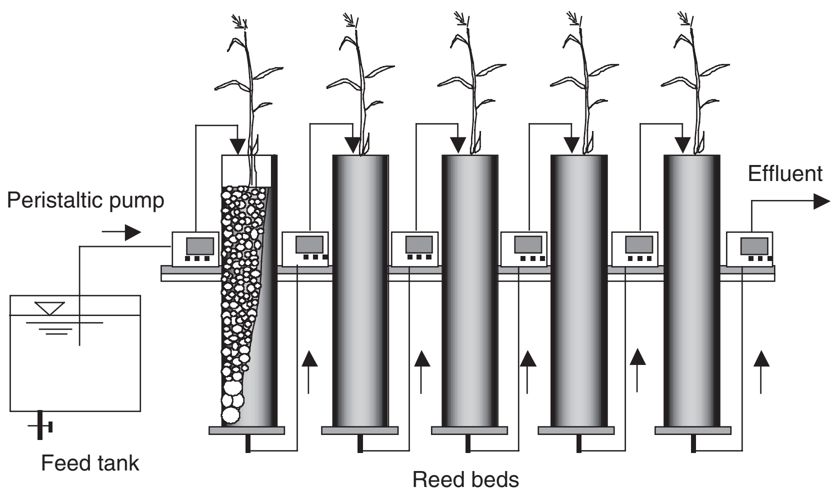

Figure 1 Schematic diagram of the tidal flow reed bed system

Table 1 Operating conditions of the reed bed system

Parameters	Operating conditions 1	2	3
Pump cycle operation	Every 4 hr@6 times/day	Every 4 hr@6 times/day	Every 4 hr@6 times/day
Bed saturated time (hr per cycle operation)	3	2	1
Bed unsaturated time (hr per cycle operation)	1	2	3
Retention time in the system (hr/d)	15	10	5
Pump flow rate (ml/min)	56	56	56

standard methods. NH_4-N was analysed using a Sension II pH/ISE meter and an ammonia electrode. NO_2-N, NO_3-N, P and SS values were measured with an HACH DR/2010 spectrophotometer. A Piccolo II portable pH meter was used for pH measurement.

Results

The overall performance

The overall efficiencies of pollutant removal across the whole system under the three operating conditions are illustrated in Figure 2.

As shown in Figure 2, considerable increases of removal efficiencies in COD, BOD_5 and NH_4-N were observed as the operation strategy was changed from condition 1 to conditions 2 and 3. Such a trend was not so significant for SS removal although condition 3 did produce the highest removal percentage, around 80%. It was noted that the removal efficiency of P remained virtually constant in all three conditions. Overall, results in Figure 2 demonstrate that a shorter saturated time and a longer unsaturated time give greater pollutant removal efficiency, and aeration by convection and diffusion in the unsaturated time may have played a controlling role for the removal of pollutants in the current tidal flow reed bed system.

Organic removal

Figure 3 illustrates the variation and removal of COD and BOD_5 across the reed bed system. During the operation period, pig slurry was diluted with tap water to reach initial COD and BOD_5 values in the range 3,420–4,254 mg/l and 2,310–3,150 mg/l, respectively. It is noted from Figure 3 that the removal percentages of COD and BOD_5 follow the trend of an

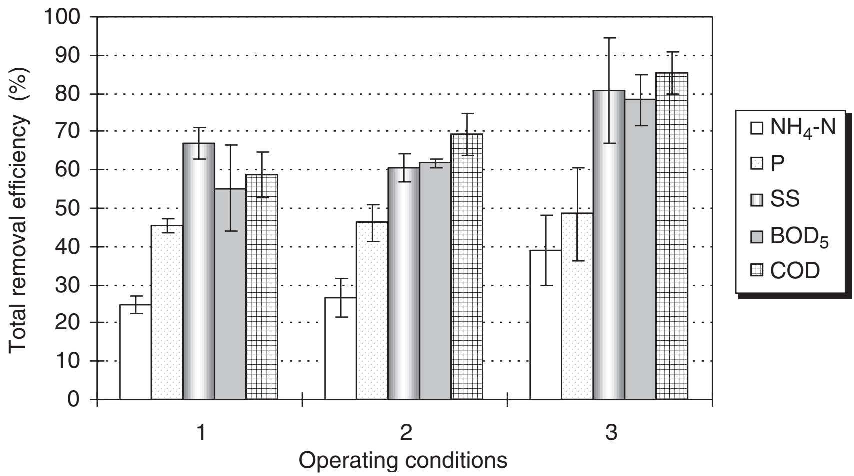

Figure 2 Overall treatment efficiencies in the reed bed system under three operating conditions (error bars denote SDs)

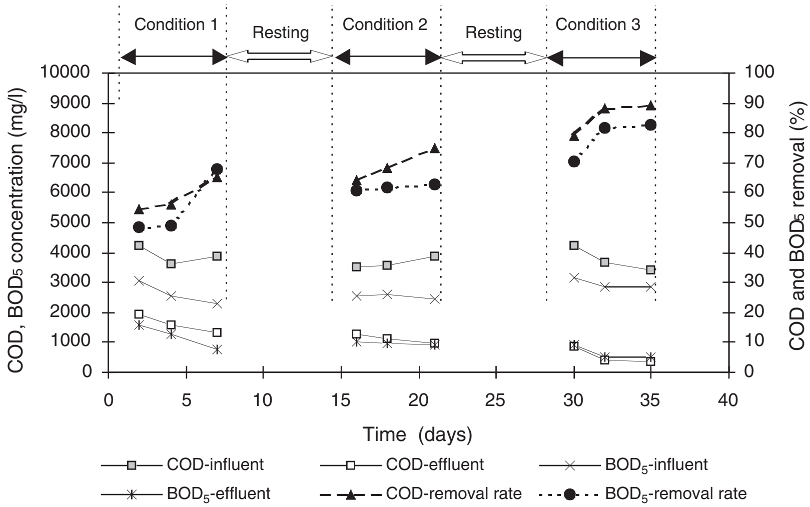

Figure 3 Variation and removal of COD and BOD_5 in the reed bed system

increase with time during continuous runs under the same operation condition. In addition, the removals increase as conditions change from 1 to 3. The increase of removal efficiency under the same operating condition is a possible result of the progressive establishment of a stable treatment status, whereas the improvement of removal efficiency from operating condition 1 to 3 is attributed to the aeration of the reed bed matrices during the prolonged unsaturated time that enhances the oxygen transfer.

Figure 4 illustrates typical changes of COD and BOD_5 in different stages of the system. The first three stages of the reed bed system undertake 77–92% of the total removals of COD and BOD_5. Under all three operation conditions, there were no significant reductions of organic pollutants in the 4th and 5th stages. The 5th stage only provided a polishing process.

Nutrients removal

Figure 5 presents variations of nitrogen forms, including NH_4-N, NO_2-N and NO_3-N, across the reed bed system. Figure 5 shows clearly that a significant reduction of NH_4-N was achieved during the operation of the system, especially under condition 3 as there is a "gap" which appears between the two lines of NH_4-N concentrations of the influent and effluent. Also from Figure 5, changes of NO_2-N and NO_3-N between influent and effluent over the reed bed system can be observed. Under conditions 1 and 2, NO_2-N and NO_3-N levels in the effluents are higher than those in the influents, indicating that the nitrification process was occurring during the experiment. Under condition 3, nitrification and denitrification processes may have occurred simultaneously in the reed bed system; this resulted in a slight decrease of NO_2-N and NO_3-N levels. Calculated average removals of the total

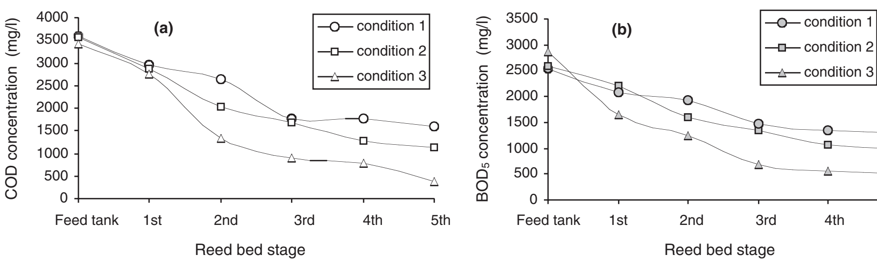

Figure 4 Profile of COD (a) and BOD_5 (b) concentrations in the reed bed system

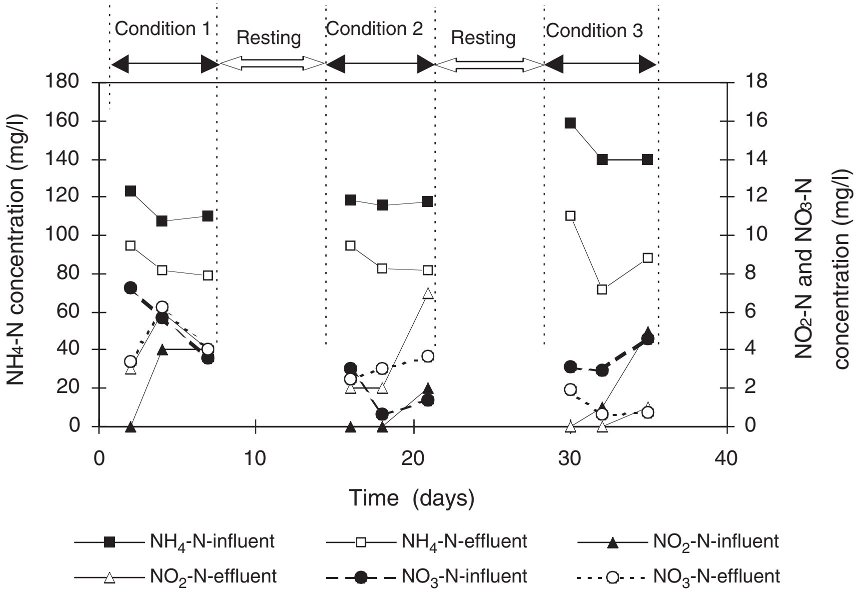

Figure 5 Variations of NH_4-N, NO_2-N and NO_3-N across the reed bed system

nitrogen mass of NH_4-N, NO_2-N and NO_3-N under conditions 1, 2 and 3 are 24 ± 3%, 25 ± 2% and 40 ± 10%, respectively.

The typical profile of nitrogen and phosphorus in each stage of the system is illustrated in Figure 6. Continuous reduction of NH_4-N across each reed bed stage can be observed in Figure 6(a), whereas Figure 6(b,c) shows the change of NO_2-N and NO_3-N in the system. The biological removal of ammonia usually causes the levels of nitrite and nitrate to rise, as ammoniacal-nitrogen is being transformed by nitrifying bacteria. In general, NO_2-N and NO_3-N values increased gradually during the experiment as the wastewater passed through the reed beds, demonstrating a certain degree of nitrification in the system. However, the nitrite and nitrate values did not rise significantly. In addition, the pH of the wastewater increased from 6.7 in the feed tank to 7.8 in the final effluent, while extensive nitrification normally causes the pH to drop. Therefore, nitrification may not be the main process of ammonia removal in the current system. The removal is likely to be a collective result of various processes, which include biomass assimilation, adsorption, plant uptake and volatilization. Under high organic loading, the process of assimilation may play a significant role in the removal of ammoniacal-nitrogen, because a considerable amount of nitrogen can be assimilated into biomass during the removal of organic matter. Further study is needed to quantify the exact contribution of assimilation to the removal of ammoniacal-nitrogen in reed beds.

The trends of phosphorus reduction follow a certain pattern at all operational conditions, as shown in Figure 6(d). The percentage removal of phosphorus remains reasonably stable regardless of the condition changes. The removal of phosphorus in the current reed bed system may be attributed to the adsorption of PO_4-P by the bed media, uptake by the reeds and chemical precipitations. The biological activities taking place inside the reed bed matrices may only have a limited impact on the removal of phosphorus from the wastewater.

Removal of suspended solids and clogging of bed matrices

As demonstrated in Figure 2, significant removal of SS, 61–81%, was achieved under the three operating conditions. Part of the reason for the scattering of SS data was due to the fluctuations of SS levels of the diluted pig slurry. Nevertheless, the reed bed system under

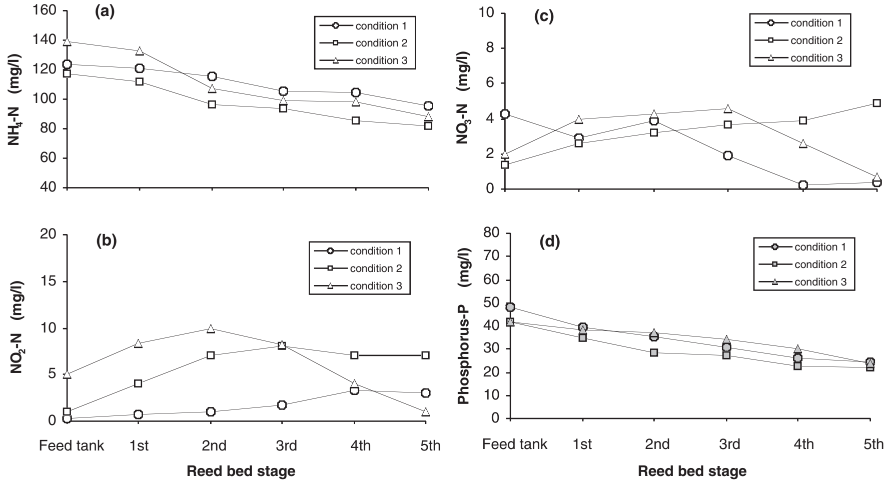

Figure 6 Typical profile of NH_4-N (a), NO_2-N (b), NO_3-N (c) and P (d) in the reed bed system

investigation showed high SS removal ability. Figure 7 provides a profile of SS in different stages of the system under operating condition 3. It is observed that SS are removed predominantly in the first two stages. In particular, the first stage contributed up to 58% of the total SS removal. Clogging of bed matrices was observed under all operating conditions, and the clogging was most serious in the first two stages. A direct evidence of clogging is the detection of progressively increasing water level in the first two stages during the saturated time of the tidal flow operation. Originally, water level in each reed bed was set to precisely reach the top of the bed matrix when 2.1 litres of wastewater were pumped into it. The change of water level during the saturated time was an indication of the resistance to filtration, which was most likely to be caused by the accumulation of solids and the growth of biomass. Visual observation found that the first stage was heavily blocked by visible particles and unidentified slimy substances.

Discussion

One of the advantages of the tidal flow operation is the enhancement of oxygen supply (Sun *et al.*, 1999b). Intensified oxygen flux into reed bed matrices is highly desirable in the treatment of high strength wastewaters, as a large amount of oxygen is required by aerobic

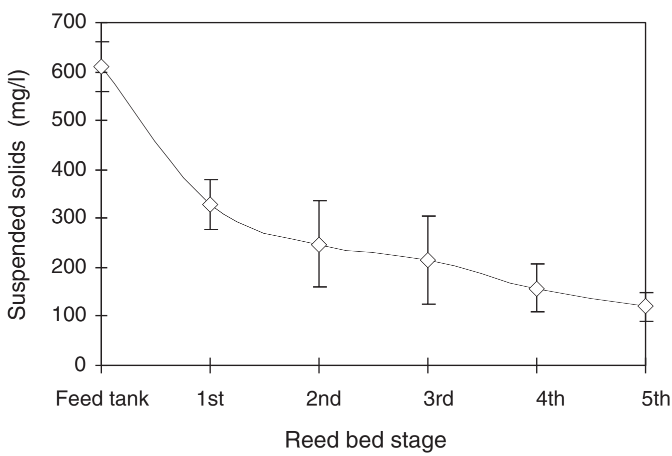

Figure 7 Profile of SS in the reed bed system under operating condition 3 (error bars denote SDs)

microbes to decompose organic pollutants (quantified by BOD_5 or COD) and by nitrifying bacteria to convert ammonia into nitrite and nitrate. The ability of reed bed systems to transfer oxygen and to produce high pollutant removal efficiencies is considered an important parameter in evaluating the systems. From the current study, the most appropriate operational strategy has been identified by comparing pollutant removal efficiencies under three different operating conditions; the result clearly supports the strategy of a short saturated time and a long unsaturated time.

Despite variations of the wastewater retention time in the current reed bed system, the hydraulic and organic loadings were kept reasonably constant under all the three operating conditions; therefore the energy requirement of the tidal flow operation remained largely unchanged. When the energy consumption rate is fixed, improvement in the overall efficiency of the system has to be made through optimizing the operational strategy. A key factor of the optimal operation is the appropriate balance between the period of wastewater-bed media contact (saturated time) and the period of aeration of the reed bed matrices (unsaturated time). The highest pollutant removal efficiencies achieved at operational condition 3 indicate that organic pollutants are retained inside the reed beds when their matrices are saturated with the wastewater. When the wastewater is drained and the matrices become unsaturated the pollutants are aerobically decomposed by microorganisms using oxygen transferred from the atmosphere into the beds. As the diffusion rate of oxygen in the gaseous phase is much higher than in the aqueous phase, a longer unsaturated time should certainly draw a higher amount of oxygen flux into the reed bed matrices. It is not clear, though, how the pollutants are retained inside the beds during the saturated time. This behaviour may be hypothetically described as "adsorption", which is a rapid process (Sun *et al*., 1998). Overall results from the current study suggest that each tide should be completed quickly during the tidal flow operation, leaving the bed matrices aerated for a longer period.

It is generally believed that the most likely manifestation of the removal of ammoniacal-nitrogen is the production of nitrite and nitrate, which is widely known as the nitrification process. However, it appears that nitrification in the current study is not the predominant process since the amount of NH_4-N being removed is much greater than the amount of NO_2-N and NO_3-N being generated. The reason may be attributed to the high organic pollutant content of the wastewater in this study. It has been reported that significant nitrification could not take place until the BOD_5 was reduced to 200 mg/l or even well below this value (Gray *et al*., 1996; Sun *et al*., 1999a). The removal of NH_4-N in the current study may result from a combination of processes that include nitrification, adsorption, assimilation associated with decomposition of organics, volatilization and plant uptake.

With regard to the SS removal, the results are adequate to suggest that significant removal of SS leads to considerable clogging of the reed beds, particularly in the first two stages of the system. To date, there is only limited information concerning the mechanism of clogging in reed bed systems (Blazejewski and Murat-Blazejewska, 1997; Bihan and Lessard, 2000). Nevertheless, it has been recognised that the sedimentation and filtration of SS inside reed bed matrices and the accumulation of biomass associated with the reduction of BOD_5 are the two main factors that cause clogging. In addition, the operation of tidal flow for a prolonged period can cause changes of resistance to the filtration of SS, which accelerates the process of clogging (Bihan and Lessard, 2000). To counteract clogging, a resting period for the reed beds is adopted in this study. To a certain degree, such resting has proved effective, as it stimulates the self-consumption of microorganisms inside the reed beds to avoid the excessive accumulation of biomass.

Conclusions

With enhanced oxygen transfer ability, tidal flow reed beds can be used to substantially reduce pollutants in high strength agricultural wastewaters. In the current lab-scale trial of the tidal flow system percentage removals of 86% and 78% were achieved for COD and BOD_5 from initial levels of 4,254 mg/l and 3,150 mg/l, respectively, under the hydraulic retention time of five hours per day. Significant removals of inorganic nutrients were also achieved. Nitrification did not appear to be the predominant process in the removal of NH_4-N. As a result of enhanced oxygen supply, the tidal flow reed bed system was generally more efficient with shorter saturated time (one hour per "tide" in this study) and longer unsaturated time (three hours per "tide"). The removal of phosphorus was found to be independent of the system's operating strategy. Extensive removals of SS and organic matter caused clogging of reed bed matrices. Further study is needed to identify the mechanisms of clogging and establish appropriate tactics to overcome this problem.

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