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Purification capacity of a highly loaded laboratory scale tidal flow reed bed system with effluent recirculation

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Abstract

The purification capacity of a laboratory scale tidal flow reed bed system with final effluent recirculation at a ratio of 1:1 was investigated in this study. In particular, the four-stage reed bed system was heavily loaded with strong agricultural wastewater. Under the hydraulic and organic loading rates of $0.43 \text{ m}^3/\text{m}^2\cdot\text{d}$ and $1055 \text{ gCOD}/\text{m}^2\cdot\text{d}$, respectively, the average removal efficiencies obtained for COD, BOD₅, SS, NH₄-N and P were 77%, 78%, 66%, 62% and 38%, respectively. Even with the high loading rates, about 30% of NH₄-N was converted into NO₂-N and NO₃-N from the mid-stage of the system where nitrification took place. The results suggest that the multi-stage reed bed system could be employed to treat strong wastewater under high loading, especially for the substantive mass removal of solids, organic matter and ammoniacal-nitrogen. Tidal flow combined with effluent recirculation is a favourable operation strategy to achieve this objective.

Keywords: Agricultural wastewater, constructed wetland, nitrification, recirculation, reed bed, tidal flow

1. Introduction

Although the treatment behaviour of constructed wetland systems (also known as reed beds) has been extensively studied in the last decade, few of the studies focused on high strength effluent (IWA, 2000). Some wastewaters produced from rural regions, e.g. wastewater from pig farms, are high in pollutant concentration (COD up to 130 g/l) in spite of their small flow rate. This is certainly a challenge for reed bed systems, which are considered one of the most effective and economical methods to treat wastewaters in rural regions. Therefore, understanding the behaviour of reed beds treating high strength wastewater with high loading rate is needed. Effluent recirculation has been employed in some studies to enhance the treatment efficiency (Kantawanichkul et al., 2001; Sun et al., 2003). It is reported that the recirculation of effluent can enhance pollutants-microorganisms interaction by allowing a longer retention time without significantly changing the operation of the beds. It is well known that reed bed technology works on the principle that biofilms attached onto the bed medium break down pollutants in wastewater passing through the bed (Brix, 1994). Reeds have the ability to transfer a certain amount of oxygen to their roots, stimulating microbial activities and enhancing the breaking down of pollutants (Brix, 1994; IWA, 2000). It is believed that effluent recirculation benefits the purification capacity of reed bed systems, especially in the case of treating high strength wastewaters.

Several studies have been conducted to investigate the treatment of high strength wastewater by reed bed system under “tidal flow” operation strategy in which the bed matrices are rhythmically filled (saturated) with wastewater and then drained (unsaturated) for natural aeration (Green et al., 1997; Revitt et al., 1997; Sun et al., 1999a; Sun et al., 1999b). A preliminary study on three different operational conditions demonstrated that the highest pollutant removal efficiencies can be achieved with relatively short saturated period and long unsaturated period (Zhao et al., 2003a); this highlights the importance of oxygen transfer into bed matrices during the treatment of high strength wastewaters. In addition, the study recommended that the fifth bed played a minor role in pollutant removal as it only provided a “polishing” step for the final effluent (Zhao et al., 2003a).

In this study, a four-stage reed bed system was operated under a “tidal flow” strategy with final effluent being recirculated to the first stage. The recirculation ratio was set as 1:1, as it has been reported as the optimum ratio (Kantawanichkul and Neamkam, 2001). Pig farm wastewater was

used for the preparation of raw wastewater. The study focused mainly on the treatment capacity of the system with the operation of “tidal flow” and effluent recirculation.

2. Experimental section

The reed bed system consisted of four identical beds in series. Each bed was 95 mm in diameter, 900 mm in height, and was contained in a Perspex column. Individual beds were filled with 26.4±7.2 mm round gravel to a depth of 150 mm as a supporting layer. It was followed by a top layer of 4.4±1.5 mm gravel with a depth of 650 mm. Young *Phragmites australis*, obtained from a local nursery, was planted in the top layer of each bed (Fig. 1).

The reed bed system was operated continuously in “tidal flow” strategy in which the “tide”, i.e. the rhythmical filling and draining of the bed medium, was generated in each stage by peristaltic pump controlled by timer. According to the previous study aimed at establishing the optimum system performance under “tidal flow” operation (Zhao et al., 2003a), the “tide” took place in a cycle of four hours, giving each bed one hour of wastewater-bed matrix contact and three hours of resting. Wastewater was prepared in a feed tank by diluting raw pig slurry collected from a local pig farm. After collection, the raw slurry was allowed to settle overnight and the supernatant, with an initial COD and SS of 64.6-127.4 g/l and 5.3-13.2 g/l, respectively, was diluted with tap water accordingly to achieve COD strengths in the range of 1300-3500 mg/l. This wastewater was batch loaded via peristaltic pumps into the reed bed system from the first to the fourth stage (Fig. 1). The flow rate of the initial influent was set as 28 ml/min. However, the final effluent from the system was recycled to the first stage (Fig. 1) with the ratio of 1:1 (Kantawanichkul and Neamkam, 2001). Therefore, the actual flow rate of the system was 56 ml/min throughout the experiments, providing a hydraulic loading of 0.43 m³/m²·d on the system. The reed bed system was previously started-up via batch and continuous operation for four months (Zhao et al., 2003b), followed by a continuous operation period of three months without effluent recirculation. During this study, the system was operated alternatively with one week for dosing and another week for resting to prevent the excessive accumulation of biomass in the beds (Sun et al., 1998; Langergraber et al., 2002).

Fig. 1 [here]

Wastewater samples were collected from the inlet and outlet of each stage of the system and analyzed immediately after collection for BOD₅, COD, SS, NH₄-N, NO₂-N, NO₃-N, phosphorus (P) and pH. BOD₅ was determined using a BODTrack apparatus (CAMLAB Ltd., UK) that continuously monitored the consumption of oxygen (in mg/l) by the wastewater samples; the reading of oxygen consumption after five days being taken as the BOD₅ value. During the BOD₅ analysis no 'seeding' was carried out for the samples as they contained sufficient amount of microorganisms. NH₄-N was tested with a Sension II pH/ISE meter and an ammonia electrode (CAMLAB Ltd, UK) that enables direct reading of ammoniacal-nitrogen level in wastewater once the pH value of the wastewater is adjusted to above 11. The pH was tested using a Piccolo II portable pH measuring stick, which was submerged in the samples during the testing. The remaining parameters, i.e. COD, SS, NO₂-N, NO₃-N and P, were analysed using a HACH DR2010 Colorimeter (CAMLAB Ltd, UK) according to its standard calibration and operation: The COD value was read directly on the colorimeter after the sample was digested at 150 °C for 2 hours in a vial according to the dichromate method; The SS value was read directly with the colorimeter; NO₂-N value was read after ten minutes of reaction with NitraVer2 reagent in a 10 ml glass standard cell supplied with the colorimeter; NO₃-N was read after five minutes of reaction with NitraVer5 reagent in a 25 ml standard glass cell; PO₄-P value was read on the colorimeter after reaction with Molybdovanadate reagent in the 25 ml cell for three minutes.

In order to observe the biofilm attachment on gravel, selected gravel samples from the first stage of the system were subjected to scanning electron microscope (SEM) observation. Samples were mounted on aluminium stubs using a small amount of epoxy resin. After drying at ambient temperature for 24 hours they were sputter-coated with 30nm of gold to ensure electrical conductivity and were then observed using a JEOL JSM 6400 Scanning Electron Microscope.

3. Results

3.1. The overall performance of the system

During the experiment, each set of samples was taken after several days' operation to ensure the system being monitored under stable conditions. Influent water quality varied considerably over the experimental period due to the change of characteristics of the raw pig slurry collected on different

dates. The mean influent concentrations (after mixing with recycled effluent) of COD, BOD₅, SS, NH₄-N and P were 2,464 mg/l, 1,359 mg/l, 500 mg/l, 121 mg/l and 45 mg/l, respectively. Accordingly, the COD loading rate was 1055 g/m²·d. Table 1 shows the mean treatment results in the system. Fig. 2 illustrates the COD and BOD₅ removal efficiencies over time. It appears that the reed bed system is more stable and efficient after one month's operation from the start of this investigation.

Table 1 [here]

Fig. 2 [here]

Fig. 3 shows the evolution over time of nitrogen forms including NH₄-N, NO₂-N and NO₃-N in the reed bed system. Each of the nitrogen forms was presented as the ratio of its concentration in the effluent divided by its concentration in the influent. Fig. 3 shows clearly that the ratio of NH₄-N decreases in time, indicating the increase of NH₄-N removal over the system during the operation. The higher removal efficiency of NH₄-N was associated with the increase of NO₂-N and NO₃-N in the system, suggesting the nitrification and the possible denitrification processes taking place in the system, especially after one month's operation. Fig. 4 shows the range of P removal between 27% and 50% throughout the system, with a mean removal of 38% being achieved. Fig. 4 also illustrates the removal of SS that shows a pattern similar to the removal of COD, BOD₅ and NH₄-N as the most efficient situation of the system being achieved after one month's operation.

Fig. 3 [here]

Fig. 4 [here]

3.2. The treatment efficiency in individual stages

In order to examine the role of individual stages for the removal of pollutants, the removal fraction in each stage was expressed as a percentage of the overall removal achieved in the system, as illustrated in Fig. 5. The most important feature in Fig. 5 is the noticeably high removal fractions in the first stage of the system regardless of the type of pollutants. This reflects the key role of the first stage in the overall removal of pollutants. However, it is noted also from Fig. 5 that the removal of nutrients (NH₄-N and P) displayed a relatively equal behaviour in individual stages of the system.

This may be attributed to the difference in removal mechanisms between carbonaceous substrates and inorganic nutrients.

Fig. 5 [here]

A typical profile of nitrogen forms across the reed bed system is illustrated in Fig. 6. It can be seen that $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$ started rising from the third stage where a rapid decrease of $\text{NH}_4\text{-N}$ was observed, suggesting that the nitrification process took place as nitrifying bacteria converted $\text{NH}_4\text{-N}$ in the influent to $\text{NO}_2\text{-N}$ and further to $\text{NO}_3\text{-N}$. Accordingly, the pH level was found to decrease across the system from 6.9 in the influent to 6.4 in the final effluent. However, the nitrification process was not the main cause of the removal of $\text{NH}_4\text{-N}$ in the system. Computed values show that only 29 % of $\text{NH}_4\text{-N}$ was converted to either $\text{NO}_2\text{-N}$ or $\text{NO}_3\text{-N}$.

Fig. 6 [here]

3.3. Biofilm development

The development of biofilms on substrate surfaces inside the reed beds was qualitatively described by the SEM observation as shown in Fig. 7. The original 'clean' gravel and the gravel from the upper section of the first stage of the system were observed under SEM. By comparing the images in Fig. 7, the development of the biofilm is evident, as it is clearly visible that the gravel surface was covered by slimes that indicate the growth and activities of microorganisms. It is believed that the microbial biofilms developed and immobilized on the gravel surfaces play a controlling role in pollutant biodegradation in the reed bed system.

Fig. 7 [here]

4. Discussion

This study addressed the treatment behaviour of a reed bed system operated under high hydraulic and organic loading rates with effluent recirculation. Results from the study demonstrated that the reed bed system under investigation can be operated under hydraulic and organic loading rate as high as $0.43 \text{ m}^3/\text{m}^2\cdot\text{d}$ and $1055 \text{ gCOD}/\text{m}^2\cdot\text{d}$ respectively, with COD, BOD_5 , SS, $\text{NH}_4\text{-N}$ and P

removal efficiencies of 77%, 78%, 66%, 62% and 38%, respectively, being achieved. A high hydraulic loading of $0.04 \text{ m}^3/\text{m}^2\cdot\text{d}$ was reported in the literature for the treatment of pig farm wastewater using combined vertical and horizontal flow reed bed system (Kantawanichkul et al., 2001). It is well recognized that the hydraulic loading rate is one of the most important factors affecting the purification process; the value has been recommended in the range between $0.025\text{--}0.050 \text{ m}^3/\text{m}^2\cdot\text{d}$ (Brix, 1994). Clearly, the hydraulic loading rate used in this study is higher by one order of magnitude than those reported. With regard to the organic loading rate, Table 2 provides a comparison of the COD removal loading rate (or removal rate) in $\text{gCOD}/\text{m}^2\cdot\text{d}$ from the literature. It can be seen that the COD removal loading rate in this study is comparable with results from other studies, in particular with results from similar reed bed systems treating strong wastewaters.

Table 2 [here]

The effectiveness of this reed bed system under high loadings may be attributed to the following factors. Firstly, the strategy of tidal flow operation has been demonstrated as beneficial not only to overcome poor water distribution problem, but also to enhance the oxygen mass transfer and diffusion from the open air into the reed beds (Green et al., 1997; Revitt et al., 1997; Sun et al., 1999a; Sun et al., 1999b). Secondly, effluent recirculation can considerably improve purification capacity by enhancing interactions between wastewater and microorganisms either on gravel surface or in the rhizosphere of the reeds. In addition, the recirculation of effluent enhances oxygen transport due to the pumping and re-distributing of the wastewater that exposes it to the air; this will then enhance the respiration and aerobic activities of the microorganisms (Kantawanichkul and Neamkam, 2001; Kantawanichkul et al., 2001; Sun et al., 2003).

It has been demonstrated in this study that the first stage plays a key role in the system for the reduction of pollutants, especially in terms of COD, BOD_5 and SS (Fig. 5). The first stage contributes to 52%, 41% and 44% of the total COD, BOD_5 and SS removal, respectively, whereas compared with the first stage the remaining stages of the system contribute considerably less to the removal of pollutants in terms of carbonaceous substrates. The high efficiency of the first stage may be explained by the rapid degradation of easily degradable pollutants in the raw wastewater that flows through and interacts with the bed matrices and biofilms (see Fig. 7) (Metcalf and Eddy,

2003). However, the behaviour of nutrient removal in individual stages displays a different feature, as shown in Fig. 5. On first inspection, the removal of $\text{NH}_4\text{-N}$ and P appears similar in individual stages of the system although considerably lower removal percentages were obtained in the second stage for both $\text{NH}_4\text{-N}$ (16%) and P (20%) and a higher removal percentage was obtained in the third stage for $\text{NH}_4\text{-N}$ (32%). This may reflect that the adsorption process by the bed matrix and plants is the dominant mechanism for nutrient removal. Although the reason for the low removal behaviour in the second stage is unclear, the highest removal of $\text{NH}_4\text{-N}$ in the third stage is due to the occurrence of nitrification, as shown in Fig. 6. However, reduction of $\text{NH}_4\text{-N}$ is not balanced in mass by the increase in $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$. Therefore it is reasonable to speculate that some other process may be involved in the $\text{NH}_4\text{-N}$ reduction. These may include assimilation toward biomass yield and reed uptake, etc. (Vymazal et al., 1998).

5. Conclusions

- A multi-stage reed bed system can be operated successfully under hydraulic and organic loading rates as high as $0.43 \text{ m}^3/\text{m}^2\cdot\text{d}$ and $1055 \text{ gCOD}/\text{m}^2\cdot\text{d}$, respectively. With tidal flow operation and effluent recirculation ratio of 1:1, removal efficiencies of 77%, 78%, 66%, 62% and 38% can be achieved for COD, BOD_5 , SS, $\text{NH}_4\text{-N}$ and P, respectively.
- The first stage of the system is the leading stage to remove the pollutants of both carbonaceous and nutrient substrates. The remaining stages appear to play an equal role in the further reduction of pollutants, particularly in the case of carbonaceous substrate removal.
- Nitrification and possible denitrification take place in the mid-stages of the system under high organic loading. About 30% of $\text{NH}_4\text{-N}$ was converted to $\text{NO}_2\text{-N}$ and $\text{NO}_3\text{-N}$. However, nitrification is not the major contribution for $\text{NH}_4\text{-N}$ removal in the current study.
- Reed bed systems have the potential to be employed to treat high strength wastewater under high loading rates for substantial pollutant removal. Tidal flow with final effluent recirculation is the favourable operation strategy to achieve this objective.

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Tables

Table 1. Overall treatment efficiency (%) of the reed bed system (mean and SD)

Parameter	COD	BOD ₅	SS	NH ₄ -N	P
Mean value	77.3	77.7	65.9	61.8	37.9
SD	8.3	12.1	21.0	29.6	8.5

Table 2 Comparison of COD removal loading rate (gCOD/m²·d)

COD removal rate (g/m ² ·d)	Reed bed system	Wastewater	Reference
996	Vertical bed with passive aeration	Dairy	Green et al., 2002
900	Vertical bed with passive aeration	Municipal	Admon et al., 2002
105	Combined vertical and horizontal flow reed bed system with effluent recycling in ratio of 1:0.5	Pig farm	Kantawanichkul et al., 2001
57	3-stage vertical flow system with recycling	Pig farm	Sun et al., 2003
797	4-stage tidal flow system with effluent recycling in ratio of 1:1	Pig farm	This study

Figure captions:

Fig. 1 The schematic of the experimental reed bed system

Fig. 2 The removal efficiency over time of COD and BOD₅ in the reed bed system

Fig. 3 The variation of NH₄-N, NO₂-N and NO₃-N in the reed bed system

Fig. 4 The removal efficiencies of phosphorus and suspended solids in the reed bed system

Fig. 5 Removal fractions in individual stages of the system

Fig. 6 Typical profile of nitrogen across the reed bed system

Fig. 7 SEM images (1500 × magnification) of gravel surface from upper section in the first stage of the reed bed system: raw gravel (left), gravel covered with biofilm (right)

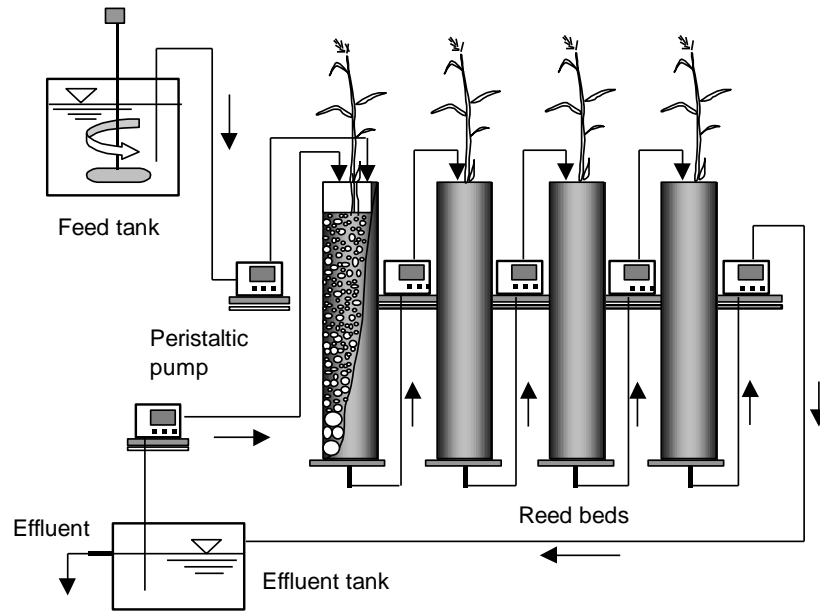


Fig. 1 The schematic of the experimental reed bed system

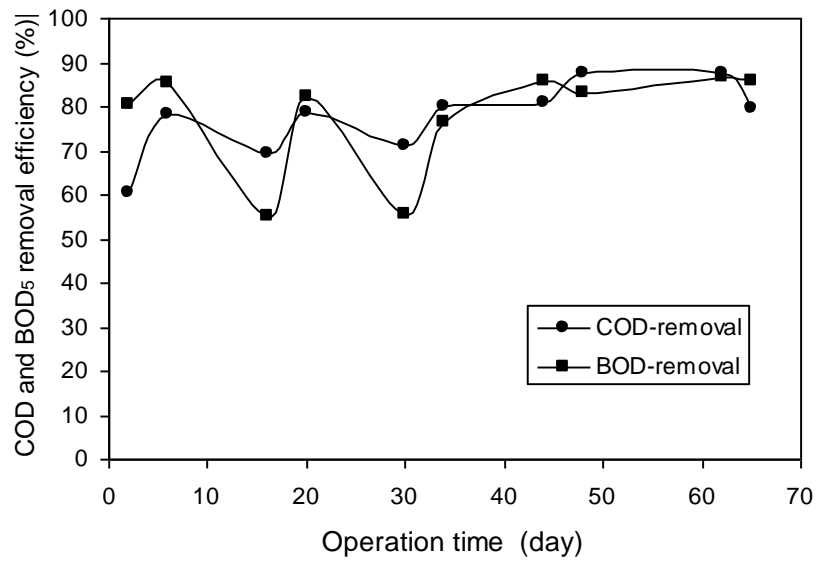


Fig. 2 The removal efficiency over time of COD and BOD₅ in the reed bed system

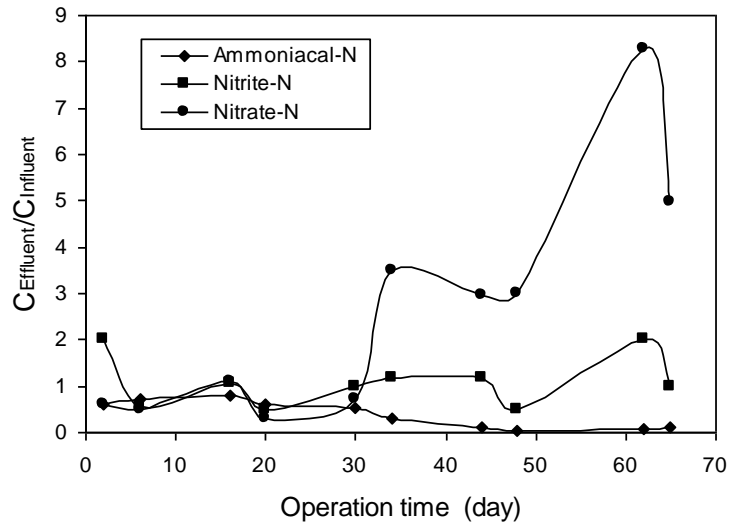


Fig. 3 The variation of NH₄-N, NO₂-N and NO₃-N in the reed bed system

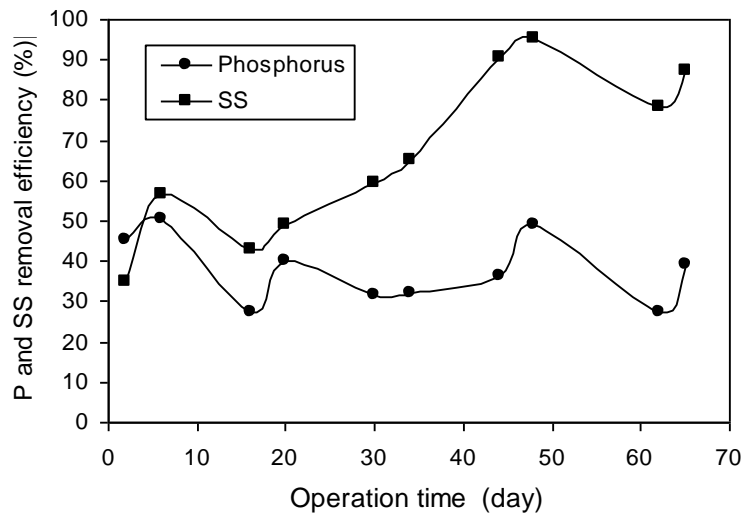


Fig. 4 The removal efficiencies of phosphorus and suspended solids in the reed bed system

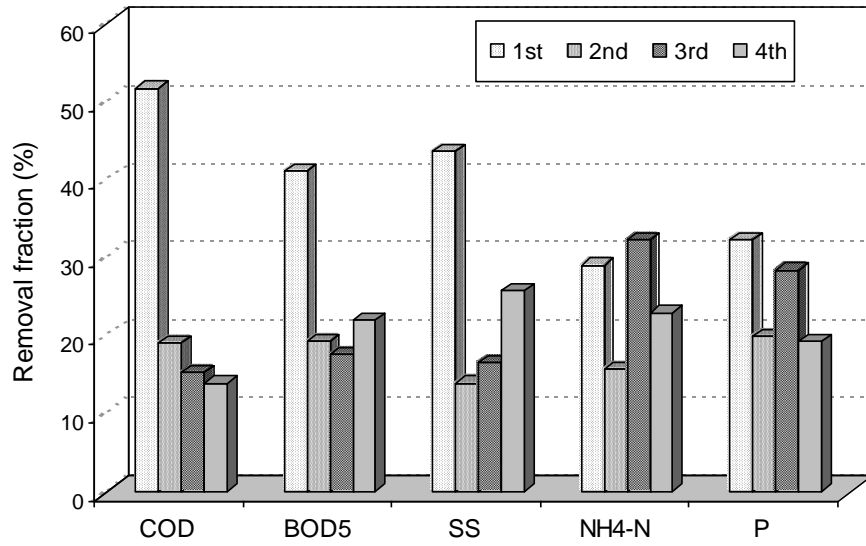


Fig. 5 Removal fractions in individual stages of the system

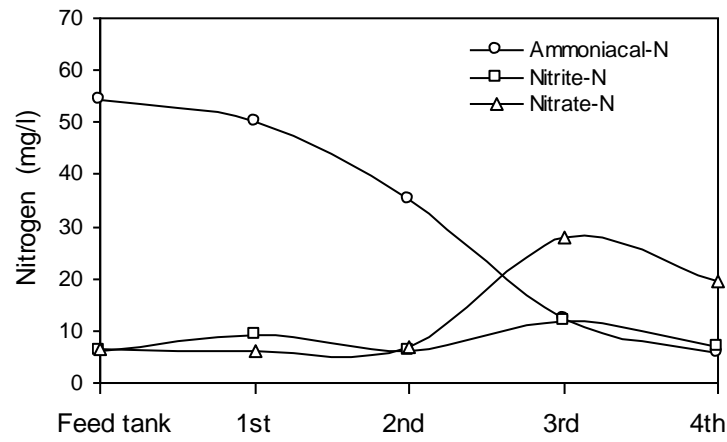


Fig. 6 Typical profile of nitrogen across the reed bed system

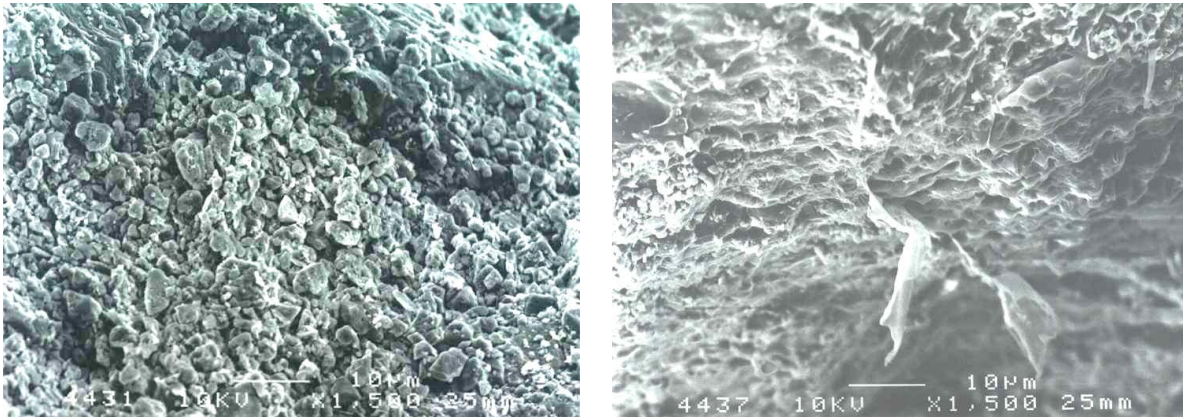


Fig. 7 SEM images (1500 × magnification) of gravel surface from upper section of the first stage of the reed bed system: raw gravel (left), gravel covered with biofilm (right)