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An alternative arrangement of gravel medium in tidal flow reed beds treating pig farm wastewater

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Abstract

The effect of using coarse grain in the upper layer of a gravel-based reed bed is investigated. The aim for testing the “anti-sized” arrangement of gravel media is to seek a solution for the practical problem of medium clogging in reed beds that frequently takes place during the treatment of high strength wastewaters. Results from parallel operations of an anti-sized and a conventional “mono-sized” reed bed reveal that the former has the advantage of greater pollutant removal efficiencies. A specific clogging tendency rate is defined to quantitatively describe the clogging behaviour. Calculation of the clogging tendency rate reveals that the anti-sized reed bed has a clear advantage over the mono-sized bed because of improved ability to counteract clogging. Greater pore space in the upper layer of the anti-sized bed allows the suspended solids to be filtered and penetrate farther into the bed matrix, thereby allowing the solid-storage capacity of the matrix to be used more effectively and prolonging the operational life time of the bed. As such, the anti-sized arrangement of reed bed media may provide a viable solution for the problem of clogging.

Keywords

Clogging; constructed wetland; gravel; tidal flow; wastewater treatment

INTRODUCTION

Constructed reed bed system has been recognized as an effective and popular ‘green’ wastewater treatment technique (IWA, 2000). The media of reed beds promote settling of suspended solids (SS) and provide surfaces for the attachment of biofilms that decompose soluble pollutants. Gravels are employed as the main medium material in most reed beds in Europe due to their wide availability and high permeability. Conventionally, multiple layers of gravel are arranged in reed beds in a way that the sizes of the gravel increase progressively from the top to the bottom layer. However, a number of studies have reported the occurrence of clogging during the operation of reed beds with the conventional medium arrangement (Blazejewski and Murat-Blazejewska, 1997; Kern and Idler, 1999; Langergraber *et al*, 2002; Zhao *et al*, 2003).

At present clogging is considered to be one of the most serious operational problems occurring in both horizontal and vertical flow reed beds (Langergraber *et al*, 2002). When clogging occurs, pore spaces inside reed bed matrices are blocked and the infiltration rate of wastewater is considerably reduced. As a result, the oxygen supply into the matrices diminishes and the treatment ability of the reed beds decreases rapidly. The exact mechanisms of clogging are not yet fully understood. It is generally believed that as wastewater progresses through the reed bed media the SS are separated from the wastewater by sedimentation and filtration. The organic content of captured solids is then decomposed by microorganisms, while the inorganic content gradually mineralizes and becomes part of the media. The production of biomass due to the growth of microorganisms is another factor that causes clogging. In addition, the growth of plant rhizomes and roots, chemical precipitation and deposition, and the formation and accumulation of humic substances may also be part of the cause. Reviews of the clogging phenomenon in the reed beds are recently reported by Langergraber *et al* (2002) and Spychala and Blazejewski (2002).

Ideally reed beds should be able to operate under a broad range of hydraulic and organic loadings while high treatment efficiency is maintained. However, operational problems such as clogging have limited their applications. It is particularly difficult to treat high strength wastewaters in the reed beds partly because of clogging. Several researchers have suggested methods to counteract clogging. These include pretreatment of wastewater, use of sufficiently porous medium, bed resting, backwashing, alternative feeding strategy and dosing of additives (Platzer and Mauch, 1997; Langergraber *et al*, 2002; Spychala and Blazejewski, 2002). This study focuses on the effectiveness of a new “anti-sized” arrangement of media in reed beds operated with a tidal flow strategy that has been shown to enhance oxygen supply and wastewater distribution (Sun *et al*, 1999).

MATERIALS AND METHODS

Configuration of the anti-sized reed bed

An anti-sized reed bed was constructed using a Perspex column of 900 mm in height and 95 mm in diameter. The column was filled with 26 ± 7 mm washed round gravel to a depth of 150 mm as the supporting layer, followed by a middle layer of 4 ± 2 mm washed gravel and a top layer of 10 ± 3 mm round gravel, as shown in Figure 1. A conventional “mono-sized” reed bed was constructed with identical configurations except for its top layer that was filled with the same type of gravel as in the middle layer. Each bed was planted with a single common reed, *Phragmites australis*.

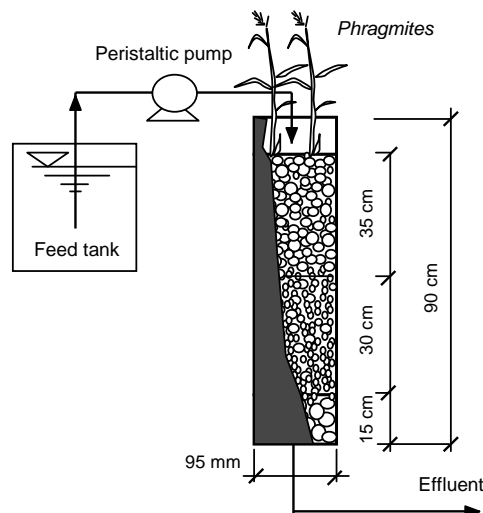


Fig. 1 Schematic description of the anti-sized reed bed

Experiment procedure

Wastewater was prepared by diluting pig slurry from a local farm to achieve COD and SS strength in the range of 1200-4500 mg/l and 230-1050 mg/l, respectively. The diluted pig slurry was stored in a feed tank where it was pumped into the anti- or the mono-sized reed beds at the same flow rate. Prior to the current experiment the reed beds underwent a start-up period of three months to allow the roots of the reeds to develop and the colonies of microorganisms to be established (Zhao *et al*, 2003). The ‘tides’, rhythmical filling and draining of the beds with the wastewater, took place in a cycle of four hours that gave each bed three hours of wastewater-media contact and one hour of draining/aeration time before the next cycle started. The operation produced a hydraulic loading of about $1.6 \text{ m}^3/\text{m}^2\text{d}$ on each bed. The experiments were conducted initially with a relatively low organic loading; this was followed by trials at a higher organic loading. Both the anti-sized and mono-sized reed beds, which were operated in parallel, were rested for 4-7 days after each week of operation in order to avoid excessive accumulation of biomass in the beds.

Sampling and monitoring

Three sets of samples were collected from the inlet and outlet of the two beds during each week of operation. The samples were analyzed immediately after collection for SS, COD, BOD₅, NH₄-N, NO₂-N, NO₃-N, P and pH. A Piccolo pH meter was used in the pH testing. BOD₅ was determined using a BODTrack apparatus (CAMLAB Ltd., UK), whereas NH₄-N was analyzed with a Sension pH/ISE meter and an ammonia electrode. All remaining parameters were analyzed using a HACH DR2010 Colorimeter (CAMLAB Ltd, UK). The water level of each bed after the fill-up step of the tidal flow operation was recorded during the experiment.

RESULTS

Overall performance

Table 1 presents the average treatment results from the reed beds under low and high organic loadings. Figs. 2 and 3 demonstrate the efficiencies for the removals of COD, BOD₅, NH₄-N and P under different loadings.

Table 1. Average performance of the reed beds under low and high loadings (error bars denote SD)

Parameters		Anti-sized reed bed			Mono-sized reed bed		
		Influent, mg/l	Effluent, mg/l	Removal, %	Influent, mg/l	Effluent, mg/l	Removal, %
Low loading	COD	1268 ± 53	643 ± 158	49 ± 14	904 ± 24	564 ± 116	38 ± 13
	BOD ₅	695 ± 59	440 ± 113	37 ± 18	498 ± 53	338 ± 77	32 ± 9
	SS	300 ± 62	130 ± 44	57 ± 6	170 ± 38	86 ± 19	49 ± 23
	NH ₄ -N	34 ± 7	30 ± 10	12 ± 13	37 ± 1	32 ± 3	14 ± 8
	NO ₂ -N	8.9 ± 5.1	5.8 ± 4.3	—	2.0 ± 0.6	1.5 ± 1.2	—
	NO ₃ -N	7.8 ± 1.8	5.4 ± 1.2	—	3.3 ± 0.9	2.6 ± 0.6	—
	P	20 ± 1	12 ± 0	40 ± 1	15 ± 2	10 ± 1	33 ± 8
	pH	7.2 ± 0.1	7.6 ± 0.3	—	7.3 ± 0.1	7.5 ± 0.2	—
High loading	COD	4110 ± 359	2116 ± 788	49 ± 19	3900 ± 307	2808 ± 296	28 ± 10
	BOD ₅	2402 ± 281	1612 ± 506	33 ± 16	2643 ± 395	1900 ± 161	28 ± 12
	SS	948 ± 96	551 ± 224	42 ± 28	667 ± 193	420 ± 109	37 ± 19
	NH ₄ -N	100 ± 4	93 ± 7	7 ± 5	114 ± 8	110 ± 9	4 ± 2
	NO ₂ -N	3.7 ± 2.1	7.0 ± 1.7	—	2.7 ± 2.3	1.7 ± 2.9	—
	NO ₃ -N	4.2 ± 1.9	5.5 ± 0.6	—	5.5 ± 1.9	5.0 ± 0.9	—
	P	55 ± 4	41 ± 7	25 ± 10	48 ± 2	39 ± 1	19 ± 2
	pH	7.2 ± 0.3	7.3 ± 0.4	—	7.2 ± 0.5	7.4 ± 0.5	—

As shown in Table 1, in general the anti-sized reed bed demonstrates greater treatment ability than the mono-sized bed. Percentage removals of over 49% and 33% are obtained for COD and BOD₅, respectively, in the anti-sized bed regardless of the organic loadings. In Fig. 2 both reed beds show a similar trend in the removal of organic carbonaceous pollutants, decrease in removal efficiency at increasing loadings. However, the removals in the anti-sized reed bed are generally higher due to greater oxygen supply into the bed matrix when the matrix was drained and aerated. Table 1 also shows small percentage reduction of ammoniacal-nitrogen. Decrease in the percentage removal is observed at increasing NH₄-N loadings, as shown in Fig. 3. The values of NO₂-N and NO₃-N in the wastewater remain virtually unchanged as noted in Table 1. The change of nitrite and nitrate levels in the wastewater is related to nitrification. Thus, it is likely that nitrification is not the predominant process to remove ammoniacal-nitrogen in the reed beds at the current operational condition.

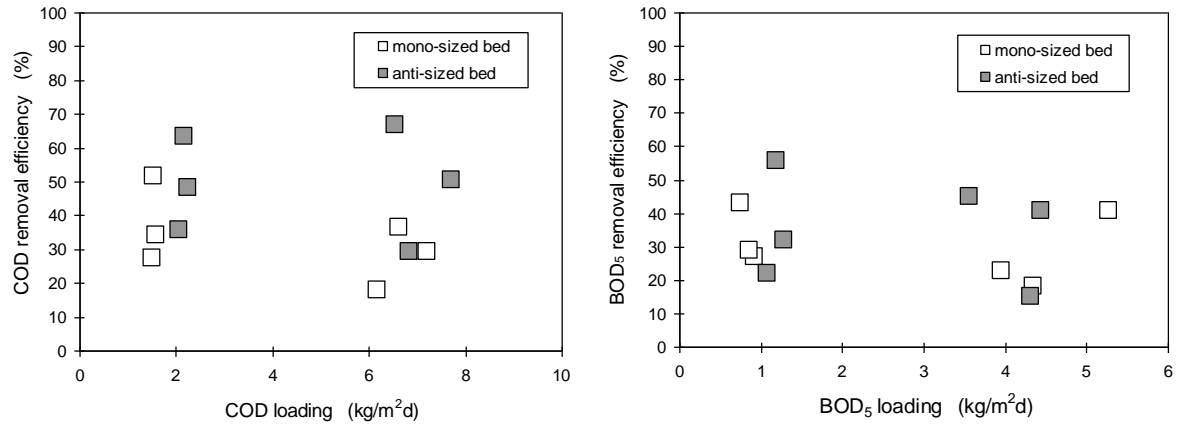


Fig. 2 The percentage removal of COD and BOD₅ versus loadings

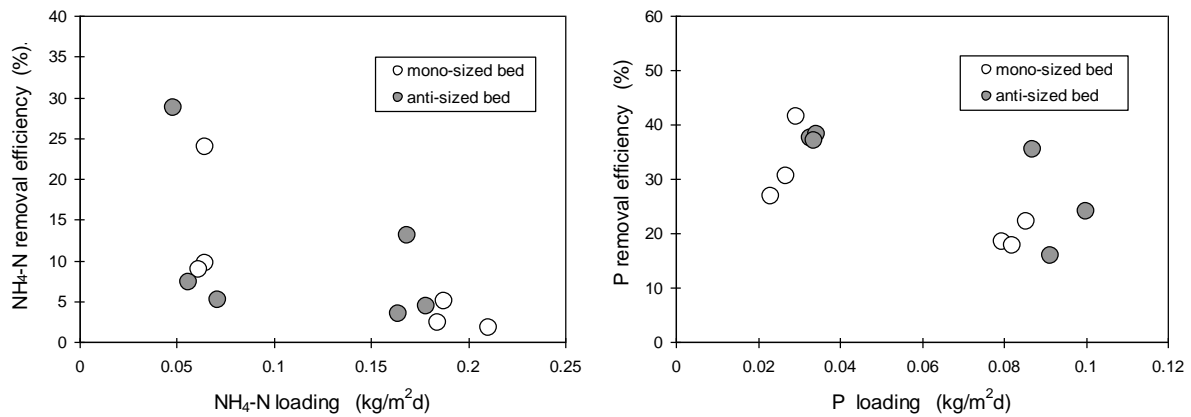


Fig. 3 The percentage removal of NH₄-N and P versus loadings

Table 1 shows that a significant amount of phosphorus is removed from the wastewater in both anti- and mono-sized reed beds, but the percentage removal of P is slightly higher in the anti-sized bed. In general, the efficiency for the removal of phosphorus decreases with loading, as shown in Fig. 3. It is believed that the principal mechanisms for the removal of phosphorus in reed bed are chemical precipitation and adsorption by the media. However, such mechanisms do not justify the difference in phosphorus removals in the two beds. The specific surface area of gravel media in the anti-sized bed is smaller due to the larger sizes of the gravel; this indeed could have decreased its ability to remove phosphorus. Therefore, it is reasonable to speculate that the higher P removal percentage achieved in the anti-sized bed may be associated with the nutrient assimilation process during the growth of biomass and the greater amount of SS removed in the reed bed.

The removal of suspended solids

As noted in Table 1 both reed beds are capable of removing a substantial amount of SS from the wastewater. With influent SS level in the range of 232 to 355 mg/l during the low-loading operation and 866 to 1054 mg/l during the high-loading operation, the anti-sized reed bed removes 5-8% more suspended solids than the mono-sized bed, even as the SS input into the mono-sized bed (in term of g/m²d) is only 57-70% of the amount into the anti-sized bed. Therefore the anti-sized reed bed is considerably more efficient in the removal of SS than the mono-sized bed. This may be attributed to the improved sedimentation and filtration ability of the anti-sized reed bed as a result of the relatively larger void space in the top layer of the bed matrix. Calculation using the flow rate data and the change of SS levels during the overall experiment period reveals the amount of suspended solids accumulated in each reed bed. The result, as shown in Fig. 4, provides clear evidence that the

anti-sized bed is capable of capturing more suspended solids than the mono-sized bed when they are operated at the same condition.

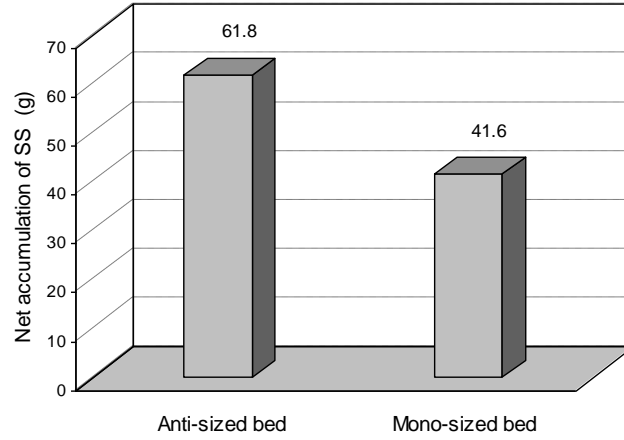


Fig. 4 Net accumulation of SS (g) in the reed beds

The occurrence of clogging

Clogging was observed to take place in both anti- and mono-sized reed beds during the experiment. The level of wastewater in the reed beds during the formation of each tide increased steadily as the experiment proceeded. This was a clear indication of decrease in void space and increase in the resistance to filtration in the bed matrices, which was most likely caused by the trapped SS and the growth of biomass. To quantitatively describe the phenomenon of clogging a specific clogging tendency rate (ψ) is defined in the following form

$$\psi = \frac{h_t - h_0}{h_0} \times 100\%$$

In the above equation h_0 and h_t refer to the height of tides in the beds at the start of the experiment and the height after t days' operation. The height was measured as the top level that the wastewater reached when the beds were saturated with the wastewater during the fill-up step of the tidal flow operation. Fig. 5 presents the calculated results of ψ in the mono- and anti-sized beds. As shown in Fig. 5, clogging of the matrices of both reed beds developed steadily during the experiment, as indicated by the increase in the ψ value. However, the clogging tendency rate was considerably lower in the anti-sized bed than in the mono-sized bed.

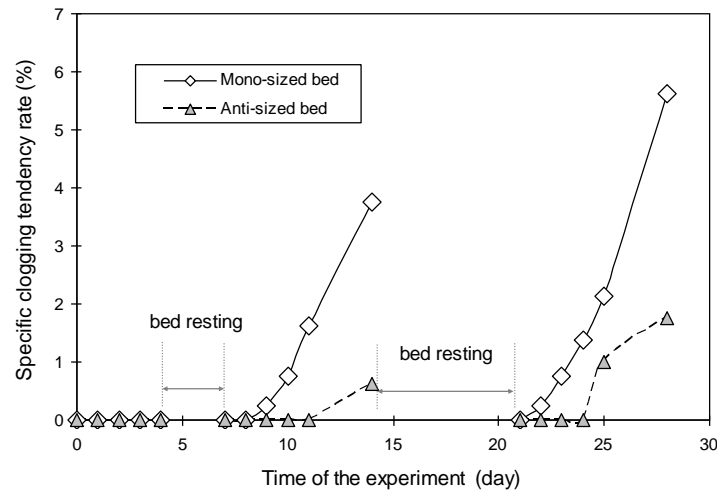


Fig. 5 Value of the specific clogging tendency rate (ψ) during the experiment period

DISCUSSION

The first objective of this study was to compare the efficiencies for the removal of pollutants, i.e. COD, BOD₅, NH₄-N, phosphorus and suspended solids, in gravel-based constructed reed beds with anti-sized and conventional mono-sized medium arrangements. It was shown that the anti-sized arrangement was more efficient because higher percentage removals of several major pollutants were obtained in the anti-sized bed compared with the mono-sized bed (Table 1 and Fig. 2); this is believed to be a result of enhanced oxygen supply via the relatively larger void space and aeration channels in the top layer of the anti-sized bed. It has been widely recognized that the removal of carbonaceous pollutants and ammonia in reed beds depends heavily on the supply of oxygen, particularly in the process of high strength wastewater treatment (Vymazal *et al.*, 1998; Browning and Greenway, 2002). Anti-sized medium arrangement is therefore a favourable choice for tidal flow reed beds treating strong wastewaters. However, the employment of larger gravels in the top layer may reduce the total surface area for the growth of biofilms inside the bed matrices. It is therefore not advisable to deploy excessively large sized media in the reed beds because the growth of biofilms may become a restricting factor for the treatment process if the surface area becomes inadequate.

It is shown in Table 1 and Fig. 3 that a generally more satisfactory performance for the removal of NH₄-N and phosphorus was obtained in the anti-sized bed. One of the reasons is the assimilation of phosphorus into the biomass that grew as carbonaceous pollutants were being removed. As more carbonaceous substrate was removed in the anti-sized bed, a greater amount of phosphorus was assimilated. In addition, it was reported that around 20% of ammonium in pig slurry was associated with fine and colloidal solids (Cannon *et al.*, 2000). Therefore, considerable amount of NH₄-N and P could be removed as SS were filtered out from the wastewater. It was obvious that nitrification process did not take place significantly in either of the reed beds, because significant nitrification normally results in clear decrease in pH and sharp increase in nitrite and/or nitrate in the wastewater, a phenomenon that was not detected in the experiment. The reason for the inadequate nitrification might be the high level of organic matter in the wastewater. It was reported that significant nitrification cannot take place until the BOD₅ was reduced to 200 mg/l or even well below this level (Gray *et al.*, 1996; Sun *et al.*, 1998).

The second objective of this study was to prevent or reduce clogging by the anti-sized medium arrangement. The reason for proposing the anti-sized arrangement is based on the following facts, (1) the most important factor to cause clogging is the filtration of SS that congests the void space of bed media (Blazejewski and Murat-Blazejewska, 1997; Langergraber *et al.*, 2002); (2) clogging takes place mainly in the top layer of the media, and the thickness of clogging layer has been reported to be in the range of 0-2.5 cm (Spychala and Blazejewski, 2002), 0-10 cm (Nguyen, 2000), 0-15 cm (Blazejewski and Murat-Blazejewska, 1997) and 0-30 cm (Kadlec and Watson, 1993); and (3) relatively higher organic loading and more rapid decomposition of carbonaceous pollutants in the top layer leads to considerable biomass production that also contributes to clogging according to Scholz and Xu (2002). The anti-sized medium arrangement allows the top layer of coarse gravels to remove a large amount of suspended solids, while smaller sized gravels in the lower layers further polishes the effluent. Therefore the solids reach deeper into the bed matrix. As a result, the solid-storage capacity of the reed beds is fully utilized and the effective depth of the beds is increased.

It has also been reported that clogging may be counteracted by the bio-decomposition of organic particulates when reed beds are rested (Blazejewski and Murat-Blazejewska, 1997; Platzer and Mauch, 1997). A resting period of 14 days was suggested by Langergraber *et al.* (2002). In the present study the resting lasted for 4-7 days. Significant decrease of ψ in both anti- and mono-sized beds after the resting, as Fig. 5 shows, demonstrated that the resting is beneficial to counteract

clogging. During the resting period a greater amount of air diffused into the anti-sized reed bed than the mono-sized bed due to difference in void spaces in their top layers; this extra amount of oxygen may have improved the aerobic decomposition of organic particles, resulting in lower values of the clogging tendency rate (ψ) in the anti-sized reed bed, as illustrated in Fig. 5. Enhanced SS removal in the anti-sized reed bed during the experiment provides evidence to support the above hypothesis. The anti-sized reed bed did not experience serious clogging problem although a large amount of SS were trapped in the bed matrix (Fig. 4). In contrast, clear clogging of the mono-sized reed bed was observed after around six days of operation. The first indication of clogging is the rising height of the tides in the tidal flow operation, suggesting reduction in the void space and increased resistance to filtration in the bed. The top layer of the mono-sized bed was observed to be heavily congested by visible particles and slimes, as the operation continued.

It should be noted that the current description of clogging development using the specific clogging tendency rate is a rather simple approach considering the intrinsic complex nature of the clogging phenomenon. As such, further research is needed. Due to the clogging of the mono-sized reed bed, in which the treatment process was detrimentally affected, the enhanced treatment ability of the anti-sized reed bed was proved. Predominately, it is the reduced clogging that justifies the viability of the anti-sized medium arrangement. Although clogging has been recognized as a critical problem and several solutions have been proposed, the problem is far from solved. The anti-sized medium arrangement provides a viable option for a possible solution to the problem of clogging.

CONCLUSIONS

A new 'anti-sized' reed bed was developed when coarse gravels were used in the upper layer and smaller gravels were used in the lower layers of the bed. Compared with a conventional mono-sized reed bed the anti-sized reed bed was more effective with regard to the removal of several major pollutants from a high strength piggery wastewater. In addition, the anti-sized reed bed showed a clear advantage that it had the ability to counteract the clogging of bed matrix by allowing the suspended solids to be filtered and deposited more uniformly inside the bed. A greater amount of suspended solids were removed in the anti-sized bed than in the mono-sized bed because the solid-storage capacity was more effectively utilized in the former. A specific clogging tendency rate was defined that may be used to quantitatively describe the time when clogging occurs in the reed beds. Calculated values of the clogging tendency rate showed that the anti-sized medium arrangement had prolonged the stable operational period of the beds.

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