

# **Anti-sized reed bed system for animal wastewater treatment: a comparative study**

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## **Abstract**

Two separate sets of reed bed systems were operated in parallel for the purpose to study a comparative behaviour of high strength animal wastewater treatment. Each system consisted of five-stage gravel-based reed beds. The only difference between the two systems lies in the gravel arrangement within the beds. One system employed single sized gravel as bed medium (termed as mono-sized bed) while the other used two layers of gravel with coarse grain as the upper layer (termed as anti-sized bed). It was demonstrated that both the systems have the strong capacity for animal wastewater treatment but no significant difference with regard to pollutants' removal efficiency. However, anti-sized system showed a clear advantage in its ability to retard the clogging phenomenon exhibited during the system operation and avoid the impairment of its long-term functioning and sustainability. Clogging development was monitored via daily record of evolution of water level after the reed bed fill-up step in tidal flow operation strategy. According to present study, anti-sized reed bed experienced more than 2-fold operating period without clogging as compared with mono-sized reed bed in their parallel operation. In addition, a conceptual model to predict the clogging time was attempted and its utility was demonstrated via the data of this study.

**Keywords:** biofilm; clogging; constructed wetlands; gravel; reed bed; suspended solids; tidal flow; wastewater treatment

## INTRODUCTION

With regard to the application of constructed wetlands, more commonly known as reed beds, for wastewater treatment, one of the most serious problems faced in practice is the clogging phenomenon of the bed medium [1,2]. When clogging occurs, it is the integrated effects that several processes involved the blockage of active void volume of the medium and resulted in the decrease of infiltration rate. This will then cause a reduced O<sub>2</sub> supply and finally lead to a rapid decrease of the treatment efficiency. In spite of the several processes contributed to clogging and unclear clogging mechanisms, it is generally accepted that accumulation of suspended solids (SS) by sedimentation and filtration in bed medium and biomass production due to growth of the microorganisms are the main contributions in most cases to clogging [3-7]. Furthermore, Langergraber et al. [2] declared that SS loading plays a key role on clogging. Comparing to SS accumulation, biomass growth has only a minor effect on clogging behaviour.

In order to eliminate or minimize the reverse effect of clogging on reed bed treatment system, alternative feed operation and bed resting strategy have been proposed and their utilities have been demonstrated [2,3,5,8-10]. As is known, the treatment efficiency of reed bed depends mainly on efficient bed medium aeration, which is achieved by mass transfer and diffusion of air-flow through the bed medium. It appears that maintaining the bed medium in aerobic conditions is a reasonable way to counteract the clogging. Hence, the intermittent pulse loading of reed bed especially for vertical flow type is adopted in early investigation of reed bed technology [11]. A recent year emerged alternative feed strategy in terms of “tidal flow” was therefore derived from the intermittent loading concept [12,13]. In addition, it has been demonstrated that resting of the beds is a favourable operating strategy to control clogging [2,9]. The main mechanism of resting lies in the improved decomposition of organic particles by microorganisms via the extra amount of O<sub>2</sub> under pulse loading, thus minimizing organic particles’ accumulation of clogging. Even so, clogging is still the major problem in practice and is subjected to research.

It was noted from literature that application of coarse grain medium was proposed in reed bed [2,3]. De Vries [11] reported that the O<sub>2</sub> concentrations in coarse sand returned to the starting values more quickly than in fine sand. Traditionally, dual or even multiple layers of medium are employed in the

reed bed where the medium was arranged with increased sizes from the top layer to the bottom layer. However, this arrangement of medium limited the solids-storage capacity of the upper layer, where the clogging most likely occurred [2,3,6,14]. On the other hand, O<sub>2</sub> mass transfer and diffusion functions depend mostly on hydraulic conductivity or drainage capacity of the top layer of the bed medium [8]. It is striking that conventional arrangement of multiple layers is against the O<sub>2</sub> mass transfer and diffusion mechanism.

In a previous study, a so-called “anti-sized” reed bed was preliminarily developed by the use of coarse grain as the upper layer of a gravel-based reed bed [15]. It has been demonstrated that the anti-sized reed bed has a clear ability to counteract the effect of bed clogging, which was evaluated by a specific clogging tendency rate ( $\psi$ ) defined as the relative development of evolution of water level in reed bed. Therefore, anti-sized reed bed can be considered to allow the top coarse layer to serve to remove part of the SS while the small-sized gravel polishes the effluent after the coarse layer so that a high quality effluent is obtained. In the anti-sized reed bed, solids can penetrate deeper since the void size of the top layer of gravel is larger than that of the lower layer. As a result, the solids-storage capacity of the bed is better utilized and thus the effective depth of the bed is increased.

In this study, two side-by-side experimental reed bed systems with five-stage reed beds in each system were operated to allow direct comparison of treatment efficiencies when a pig farm wastewater was tested. One system was the single sized gravel-based reed beds (termed as mono-sized reed beds) and the other was dual layer gravel-based reed beds with coarse grain gravel in the upper layer (termed as anti-sized reed beds). The study focused mainly on the clogging behaviour exhibited between the two systems during the animal wastewater treatment. Clogging behaviour was described by a mathematical prediction of clogging time, which was the maximum operational time (days) when clogging occurs. In addition, scanning electron micrographs (SEM) was used to provide the detailed observation of gravel surface before and after the biofilm formation.

## **MATERIALS AND METHODS**

## Reed bed systems

Two experimental reed bed systems are shown schematically in Fig. 1. Each system consists of five identical beds that were made of Perspex columns of 90 cm in height and 10 cm in diameter. Round gravel was employed as bed medium in both systems. However, anti-sized bed system employed two layers of gravel with coarse grain in the upper layer. Detailed composition of the two reed bed systems is given in Table 1. Gravel size distributions are presented in Fig. 2. The vertical axis of Fig. 2 represents a mass fraction of the total mass of each layer of gravel. Young *Phragmites australis*, bought from a commercial supplier was planted in the top layer of each bed. The two reed bed systems was supported firmly side-by-side with a constructed metal rig and fully sealed by a heavy-duty plastic curtain with overhead air extraction system in the sealed area.

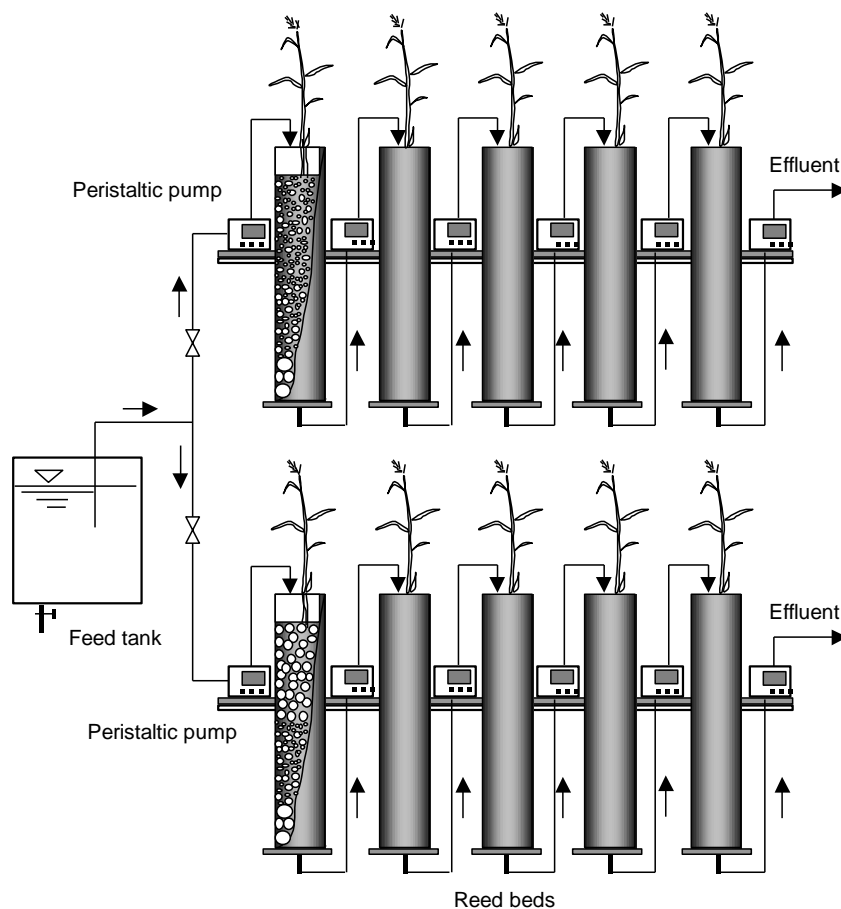


Fig. 1 Schematic description of experimental reed bed systems: mono-sized system (upper) and anti-sized system (lower)

Table 1 Characteristics of the two reed bed systems and operating conditions used in this study

Parameters	Anti-sized beds	Mono-sized beds
Reed bed height and diameter	90 cm × 10 cm	90 cm × 10 cm
Medium (gravel) (size/depth)		
Upper layer	9.8 ± 2.7 mm / 35 cm	4.4 ± 1.5 mm / 35 cm
Lower layer	4.4 ± 1.5 mm / 30 cm	4.4 ± 1.5 mm / 30 cm
Supporting layer (bottom)	26.4 ± 7.2 mm / 15 cm	26.4 ± 7.2 mm / 15 cm
Pump cycle operation (tidal flow operation)	every 4 hr@6 times/day	every 4 hr@6 times/day
Pump flow rate (ml/min)	56	56

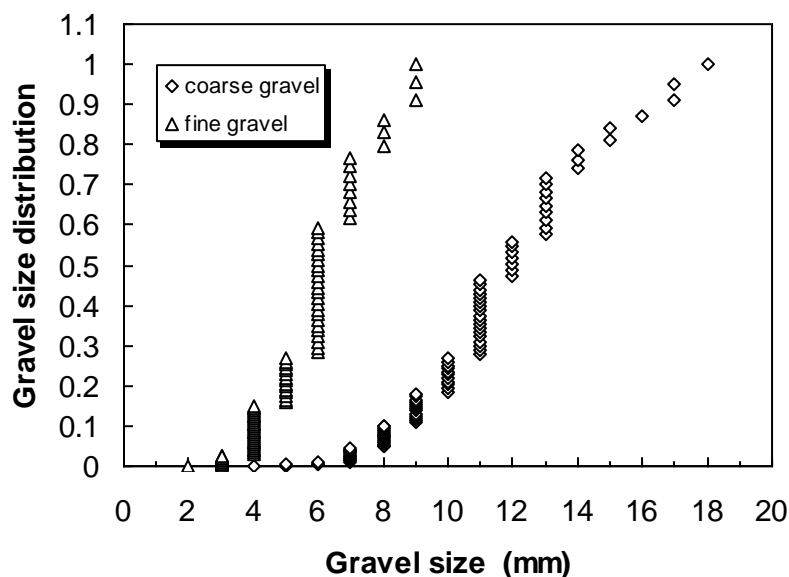


Fig. 2 Gravel size distribution of the two reed bed systems

### Experimental methodology

Prior to this study, the two reed bed systems underwent a start-up period of three months when the root systems of the reeds developed and colonies of microorganisms were established via batch operation with tap water and intermittent addition of a commercial liquid feed as a reed growing nutriment. During this study, the two systems were operated in parallel by introduction of animal wastewater via peristaltic pump. Wastewater was prepared by diluting raw slurry collected from a

pig farm. After collection, the raw pig 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. Table 2 summarizes the characteristics of diluted pig slurry used in this study. The two reed bed systems were actually operated with one week continuous tidal flow operation and another week for resting. In tidal flow operation period, prepared wastewater was pumped into the reed bed system from the 1<sup>st</sup> to 5<sup>th</sup> stages, while the “tide” of rhythmical completely filling and draining of the bed medium, was generated in each stage by peristaltic pump controlled by timer, as shown in Fig. 1. The ‘tides’ took place in a cycle of four hours and six times a day (see Table 1). The flow rate of all peristaltic pumps was set as 56 ml/min throughout the experiments; this provides a hydraulic loading of about 1.7 m<sup>3</sup>/m<sup>2</sup>·d for each bed.

Table 2 Characteristics of diluted pig slurry used in this study

Parameters	Values
SS (mg/l)	133 ~ 1402
COD (mg/l)	888 ~ 4728
BOD <sub>5</sub> (mg/l)	441 ~ 3150
Ammoniacal-nitrogen, NH <sub>4</sub> -N (mg/l)	28.2 ~ 159.2
Nitrite-nitrogen, NO <sub>2</sub> -N (mg/l)	0 ~ 6.0
Nitrate-nitrogen, NO <sub>3</sub> -N (mg/l)	0 ~ 4.2
Phosphorus (P) (mg/l)	13.5 ~ 60.5
pH	6.7 ~ 7.2
Temperature (°C)	17 ~ 22

### Sampling and measurements

Samples of influent and effluent from each stage of the two reed bed systems were collected individually and analysed on the same day of collection for SS, COD, BOD<sub>5</sub>, NH<sub>4</sub>-N, NO<sub>2</sub>-N, NO<sub>3</sub>-N, phosphorus (P) and pH. A Piccolo II portable pH meter was used for the pH analysis. BOD<sub>5</sub> was determined using a BODTrack apparatus (CAMLAB Ltd., UK). NH<sub>4</sub>-N was tested with a Sension II pH/ISE meter and an ammonia electrode, and the remaining parameters were analysed using a HACH DR2010 Colorimeter (CAMLAB Ltd, UK) according to its manual. In addition, the water level of the bed after the fill-up step (in tidal flow operation) was recorded daily during the bed performance for the purpose of monitoring the development of the bed medium clogging.

### **Scanning electron micrographs**

In order to observe the biofilm attachment on gravel, selected gravel samples 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. Samples were then observed using a JEOL JSM 6400 Scanning Electron Microscope.

## **RESULTS**

### **Carbonaceous substrate removal**

The purification capacity of mono- and anti-sized reed bed systems was monitored and expressed in terms of influent and effluent concentrations of COD and BOD<sub>5</sub> throughout the systems. The results were illustrated in Fig. 3 and 4. In general, it is noted that a striking reduction of COD and BOD<sub>5</sub> was observed in both the systems. However, considering the difference between influent and effluent, the removal rates of anti-sized system exceeded those of mono-sized system, although the difference was slight (Table 3). During the study period, the average COD and BOD<sub>5</sub> removal rates for anti-sized system was respectively 73.9% and 66.6% while corresponding removal rate of COD and BOD<sub>5</sub> for mono-sized system of 71.1% and 66.3% was obtained, as shown in Table 3. With regard to the comparison of carbonaceous substrate removal of each stage in the two reed bed systems, Fig. 5 illustrated the percentage of COD or BOD<sub>5</sub> removal of individual stage in total COD and BOD<sub>5</sub> removal over the system. It is seen from Fig. 5 that, in both the systems, the first stage plays a key role in the reduction of carbonaceous substrate, especially for anti-sized reed bed system where the first stage undertakes 61.7% of COD and 47.4% of BOD<sub>5</sub> of their total reduction over the system. In addition, for anti-sized system, the fourth stage appears to undertake relative high fraction of carbonaceous substrate removal while the fifth stage serves as polishing for the final effluent. In contrast, the second and third stages in mono-sized system served as second level while the fourth and fifth stages served as third level for the reduction of carbonaceous substrate (Fig. 5).

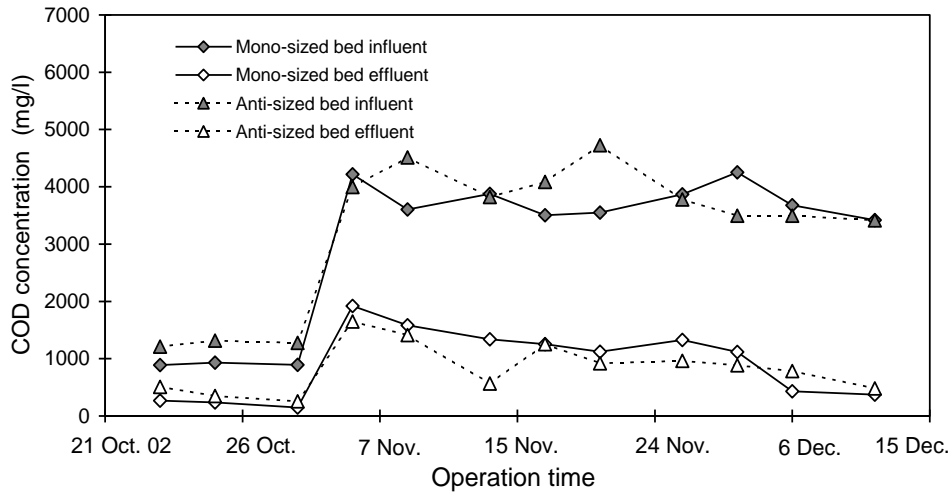


Fig. 3 Variation of COD in the two reed bed systems

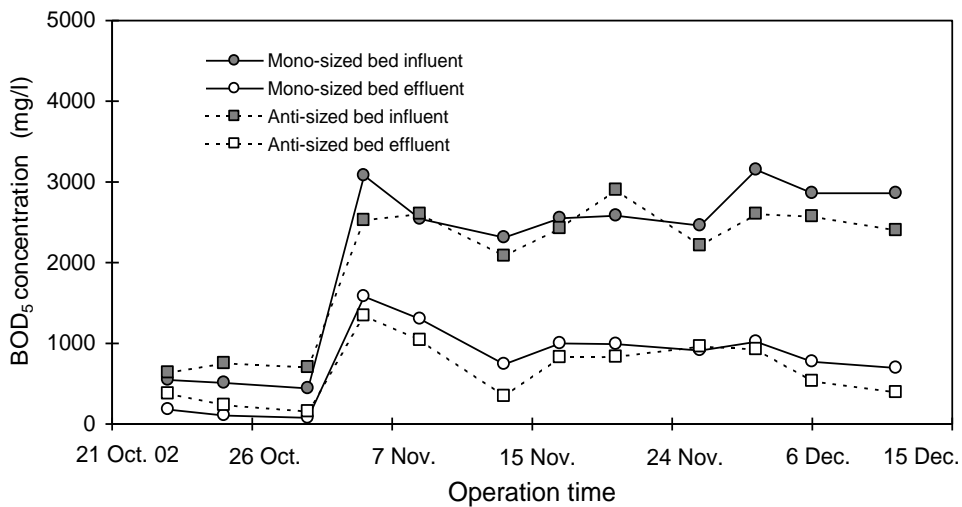


Fig. 4 Variation of BOD<sub>5</sub> in the two reed bed systems

Table 3 Treatment efficiencies of COD and BOD<sub>5</sub> of the two reed bed systems (mean±SD/(min-max))

Parameters	Mono-sized reed bed system	Anti-sized reed bed system
COD (%)	71.1 ± 11.3/(54.4 – 89.1)	73.9 ± 9.0/(58.1 – 85.9)
BOD <sub>5</sub> (%)	66.3 ± 10.6/(48.7 – 82.3)	66.6 ± 13.8/(40.7 – 83.8)

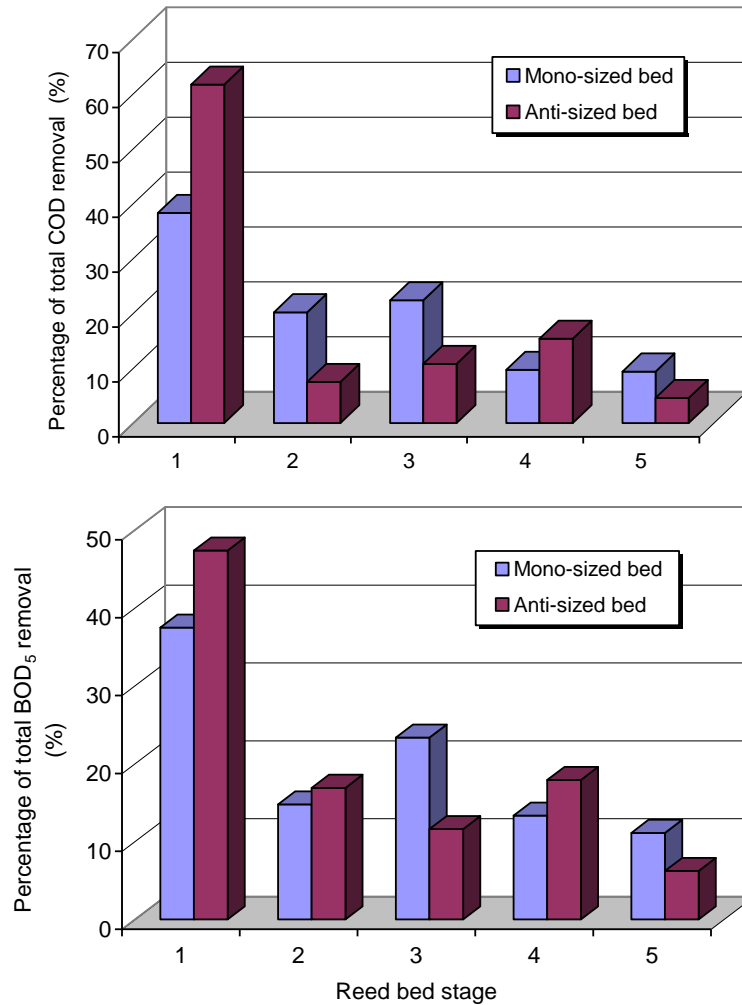


Fig. 5 Removal portions of individual stages in total removal over the systems: COD profile (above); BOD<sub>5</sub> profile (bottom)

### Nutrients removal

The reduction in the concentration of NH<sub>4</sub>-N and P over the two reed bed systems is illustrated in Fig. 6 and 7, respectively. Calculated removal rates are given in Table 4. Removal of nutrient in terms of NH<sub>4</sub>-N and P is generally not significantly different from anti- and mono-sized systems. Based upon the total reduction in mass of NH<sub>4</sub>-N and P, Fig. 8 provides the profile of individual stage removal fraction expressed in percentage of total removal over the system. It is shown clearly that reduction of NH<sub>4</sub>-N in mono-sized system takes place mainly in second and third stages while this reduction occurs significantly in first stage in anti-sized system. The reason is not clear but at least with something linked with the strong O<sub>2</sub> supply in anti-sized system. It should be noted that

there is no significant amount of the  $\text{NO}_2\text{-N}$  and  $\text{NO}_3\text{-N}$  in the effluent of both the reed bed systems, indicating the incomplete of nitrification and denitrification. For this reason, data of the  $\text{NO}_2\text{-N}$  and  $\text{NO}_3\text{-N}$  are not presented here. With concern about P reduction, both the reed bed systems have the similar pattern, i.e. the first stage undertakes about 40% (50%) reduction of P in mono-sized (anti-sized) system while the rest of the stages maintain sustained reduction of P in almost equal rate (Fig. 8).

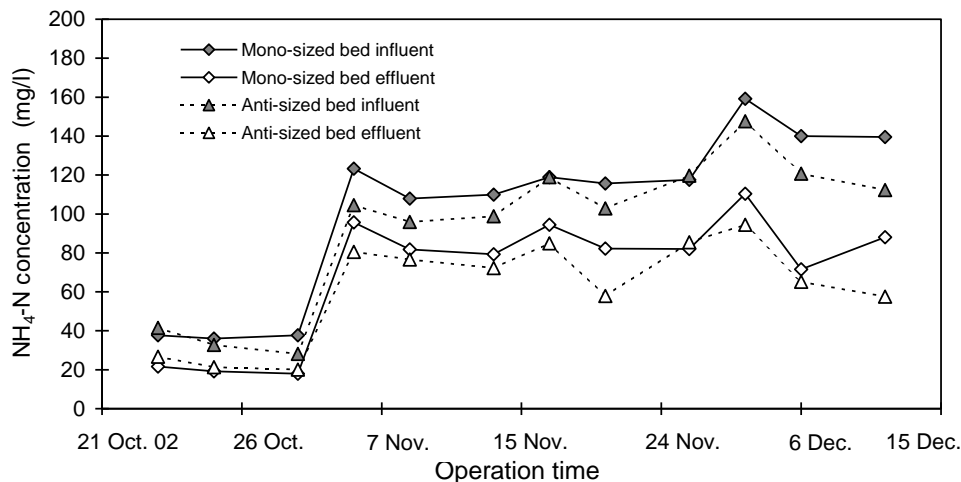


Fig. 6 Variation of  $\text{NH}_4\text{-N}$  in the two reed bed systems

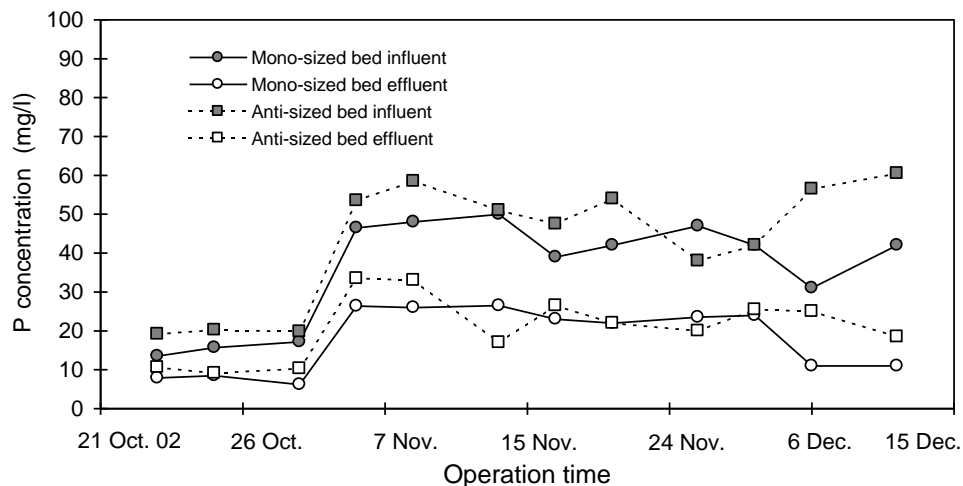


Fig. 7 Variation of P in the two reed bed systems

Table 4 Treatment efficiencies of NH<sub>4</sub>-N and P of the two reed bed systems (mean±SD/(min-max))

Parameters	Mono-sized reed bed system	Anti-sized reed bed system
NH <sub>4</sub> -N (%)	34.4 ± 10.9/(20.6 – 52.4)	33.4 ± 9.1/(20.1 – 48.8)
P (%)	50.6 ± 10.7/(41.0 – 73.8)	50.9 ± 10.3/(37.4 – 69.4)

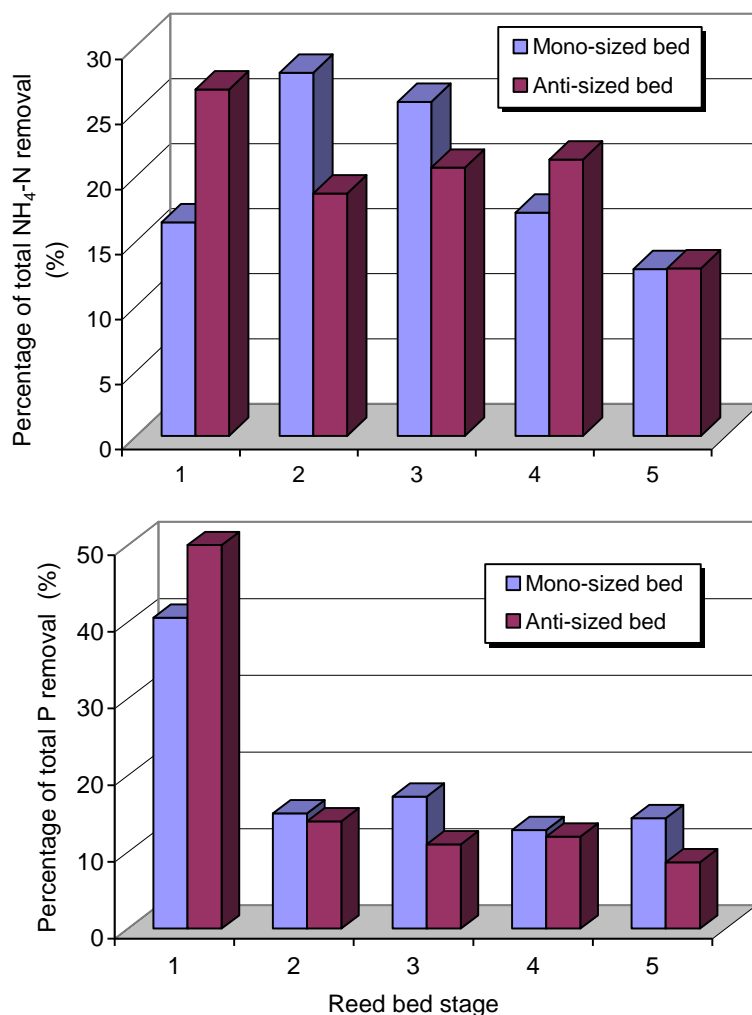


Fig. 8 Removal portions of individual stages in total removal over the systems: NH<sub>4</sub>-N profile (above); P profile (bottom)

### **SEM observation**

Fig. 9 and 10 present respectively SEM observation of the gravel surface in upper section of gravel layer in the first stages of the two systems. At first sight, there is no significant difference of the SEM images between the gravels taken from the anti- and mono-sized system. However, by comparison of the images in each figure, the development of the biofilm is clearly identified since the gravel surface was observed to be fully covered by the thick slimes, indicating the growth and considerable activities of the microorganisms.

Fig. 9 SEM images (3300 × magnification) of gravel surface of upper layer of anti-sized reed bed: before biofilm formation (left) and after biofilm formation (right)

Fig. 10 SEM images (3300 × magnification) of gravel surface of upper section of mono-sized reed bed: before biofilm formation (left) and after biofilm formation (right)

### **Clogging phenomenon**

During the systems' operation, it was observed visually that both the systems experienced clogging phenomenon since the blockage of pore volume of gravel by visible particles and some unidentified substances linked with heavy slimes was observed. Such clogging phenomenon was most serious in the first two stages of both the systems especially in the mono-sized reed bed system. Due to the lack of proper method to describe the clogging phenomenon, the water level after the bed fill-up step of tidal flow operation strategy was daily recorded for the purpose of used as a clue to gauge the clogging tendency. It was observed that the water level rose gradually with the system steady operation. In particular, the first stage of the mono-sized bed system exhibits the first increase of the water level on 6<sup>th</sup> day from the start of the operation. Initially, the water level is the exact level in which the bed medium is fully saturated by the influent after the formation of "tides" when the experiment was initially set up. Clearly, the evolution of this water level is an indication of enhanced resistance to filtration and is derived from the decrease of pore space inside the bed

medium. The cause of the congested pore space may be contributed to the removal of the SS from the influent, i.e. the trap of SS in bed medium. Table 5 presents the averaged data of SS removal and the removal fraction of the individual stages of the two reed bed systems. It is noted from Table 5 that over 65% of SS was removed in both the systems in spite of the high SS level in the influent. In particular, anti-sized system shows a bit better performance in SS removal. Moreover, the first stages of both the systems undertake around 50% SS removal of the total removal of each system, suggesting the significant accumulation of SS in first stages compared with that in other stages of the systems.

Table 5 SS removal over the systems and the removal percentage of the individual stages

	Influent	Effluent	Total removal (%)	Removal percentage of total removal (%)				
				1 <sup>st</sup> stage	2 <sup>nd</sup> stage	3 <sup>rd</sup> stage	4 <sup>th</sup> stage	5 <sup>th</sup> stage
Anti-sized system	543.5 ± 240.7	168.7 ± 94.0	69.0 ± 11.6	56.3 ± 17.7	18.6 ± 12.2	11.4 ± 8.5	8.4 ± 8.1	5.3 ± 2.1
Mono-sized system	614.8 ± 278.7	232.4 ± 118.8	64.6 ± 12.8	45.0 ± 17.9	19.6 ± 4.3	12.4 ± 7.1	10.9 ± 5.5	12.1 ± 11.5

Table 6 presents the experimental observation of clogging time. It was gauged by the evolution of the water level when it started to increase and reached the maximum level, respectively. Here, the maximum water level in the bed refers the situation in which the water level reached the top edge of the Perspex column, as shown in Fig. 1. It can be seen from Table 6 that the anti-sized beds do have the function to delay the clogging phenomenon as compared with the clogging occurred in mono-sized beds. It is noted in Table 6 that the first stage of the mono-sized system started the increase of water level on 6<sup>th</sup> day. It followed on 7<sup>th</sup> day and then the bed was due for resting for 7 days. After resting, the bed was kept normal operation and the water level started rising on 17<sup>th</sup> day and finally reached the maximum level on 19<sup>th</sup> day. This reflects the role of resting on clogging relieve.

Table 6 Observed clogging time gauged by the water level in the beds

Clogging time (day)	Mono-sized bed system		Anti-sized bed system	
	1 <sup>st</sup> stage	2 <sup>nd</sup> stage	1 <sup>st</sup> stage	2 <sup>nd</sup> stage
Gauged by the starting rise of water level	6	30	17	43
Gauged by the maximum water level	19	35	21	49

### Modelling approach of clogging time

During continuous tidal flow operation, wastewater was filtered by the bed medium and the carbonaceous substrates were then decomposed by the microorganisms within the bed. Here, only the SS loading was considered for the following theoretical calculation of the clogging time since the biomass growth plays a minor role compared to the SS load for the bed medium clogging [2]. Assuming the bed initial void volume (at  $t = 0$ ) is  $V_0$ ,  $V_0 = \varepsilon h A$ , where  $\varepsilon$ ,  $h$  and  $A$  represent respectively the bed medium porosity, depth of clogging layer (cm) and bed surface area ( $\text{cm}^2$ ). During the bed performance,  $V_0$  will be congested gradually by the SS. The wet volume ( $V_{t,s}$ ) of the captured SS during  $t$  days' operation can be expressed as [3]

$$V_{t,s} = \frac{Q(C_0 - C_e)}{\rho_s(1 - MC)} \cdot t \quad (1)$$

where,  $Q$  is flow rate (l/day);  $C_0$  and  $C_e$  are concentrations of SS in the influent and effluent of the bed, respectively;  $\rho_s$  and  $MC$  are respectively the density of SS ( $\text{g/cm}^3$ ) and moisture content of SS (%);  $t$  is the bed operating time (day). Here, assuming 50% of the SS from the influent was decomposed by the biological activity during bed operation; the available void volume at  $t$  day ( $V_t$ ) can then be expressed as

$$V_t = V_0 - \frac{1}{2} V_{t,s} \quad (2)$$

that is:

$$V_t = \varepsilon \cdot h \cdot A - \frac{1}{2} \frac{Q(C_0 - C_e)}{\rho_s(1 - MC)} \cdot t \quad (3)$$

When clogging occurs, there is no available void volume in the bed, i.e.  $V_t=0$  in Eq. (3). The clogging time ( $t_c$ ) can thus be calculated as

$$t_c = 2 \cdot \varepsilon \cdot h \cdot A \frac{\rho_s(1 - MC)}{Q(C_0 - C_e)} \quad (4)$$

During reed bed resting period, there is no SS loading. The reed bed experiences biodecomposing process, which leads to the recovery of available void volume for the next period of operation. The recovery of the void volume can be expressed as

$$V_{t,s}' = k_1 \cdot k_2 \cdot V_{t,s} \quad (5)$$

where,  $k_1$  refers to the fraction of organic substrate of SS;  $k_2$  represents the fraction of biodegradable organic substrates. After the resting period, the initial available void volume for the following operation period is

$$V_{01} = V_0 - V_{t,s}(1 - k_1 \cdot k_2) \quad (6)$$

By substitution  $V_0$  in Eq.(2) with  $V_{01}$  and carrying out the calculation in Eq.(3) and Eq.(4), the clogging time can be predicted. If more resting periods were experienced in the bed operation, the repeated procedure of calculations from Eq.(2) to Eq.(4) should be carried out. If the bed clogging occurs in the first operating period, i.e. the  $V_{t,s}=V_0$  in Eq.(6), the initial available void volume for the second run of operation after the bed resting period will be

$$V_{01} = k_1 \cdot k_2 \cdot V_0 \quad (7)$$

The application of the modelling approach for predicting the clogging time of this study is shown in Fig. 11 while the employed parameters involved in the model are listed in Table 7. The comparison of the clogging time between predicted time and observed time of the first two stages during the experimental operation of the systems is illustrated in Fig. 12. It can be seen from Fig. 11 that anti-sized system has clear advantage to prolong system steady operation and counteract the clogging of the system. It is also interesting to see from Fig. 12 that there is good agreement between the predicted clogging time and the observed clogging time in both the mono- and anti-sized bed systems, indicating the utility of the above conceptual model. It should be noted that the observed clogging time plotted in Fig. 12 is a range of time from the start of the increase of water level to the maximum water level to be reached, as shown in Table 6.

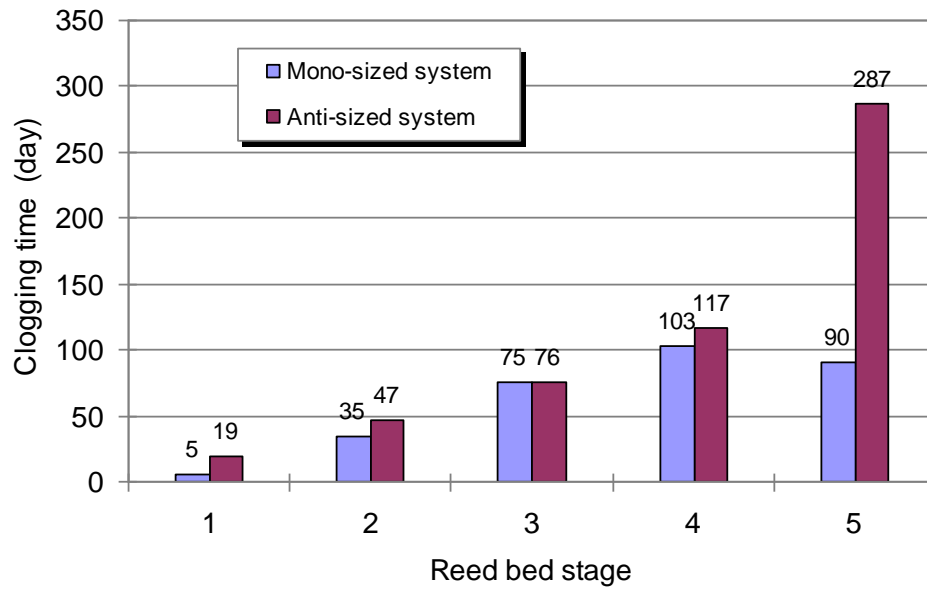


Fig. 11 Calculated clogging time of each stage of the two reed bed systems

Table 7 Values of parameters to predict clogging time used in this study

Parameters	Unit	Values		Reference
		Anti-sized system	Mono-sized system	
Porosity of gravel, ( $\epsilon$ )	%	35.8	32.6	Measured in this study
Depth of clogging layer, (h)	cm	30	20	[2, 3, 6]
Reed bed surface area, (A)	cm <sup>2</sup>	78.5	78.5	Measured in this study
Density of SS, ( $\rho_s$ )	mg/cm <sup>3</sup>	105	105	[3]
Moisture content of SS, (MC)	%	94	94	[3]
Flow rate, (Q)	ml/min	56	56	Measured in this study
k <sub>1</sub>	%	80	80	[2, 4, 16]
k <sub>2</sub>	%	90	90	[2, 6]

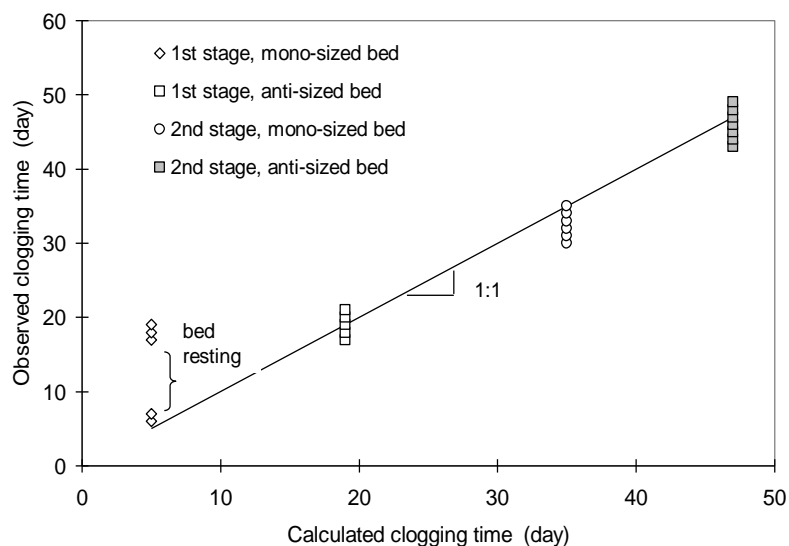


Fig. 12 Comparison of the clogging time between predicted time and observed time during the experimental operation of the two reed bed systems.

## DISCUSSION

It has been demonstrated in this study that anti-sized reed bed system remained high pollutants' removal with average efficiencies of nearly 74 % and 67 % for COD and BOD<sub>5</sub> and over 33 % and 50 % for NH<sub>4</sub>-N and P, respectively (see Table 3 and 4). Interestingly, these treatment efficiencies are more or less high than that of mono-sized system. This reflected the fundamental utility of anti-sized reed bed system. Samples taken across the treatment stages in anti-sized system revealed that the first bed played a key role in the system, not only decomposing the carbonaceous substrates but also treating nutrients. Large amounts of attached biomass were observed via SEM in the first bed (see Fig. 9). Compared to the first stage in the anti-sized system, the remaining stages in turn undertook less fraction of removal. In particular, the last bed essentially provided a "polishing" step for the final effluent. As such, it is recommended that it is wiser to employ a reed bed system with four stages in total. The similar treatment profile over the mono-sized system was obtained. Here, it should be noted that nitrification is not the predominant process in both the reed bed systems. Although there are strong O<sub>2</sub> supply via tidal flow operation strategy and even more possible O<sub>2</sub> diffusion via relatively open pore space in anti-sized system, it is reasonable to believe that most of

the available  $O_2$  is consumed by the decomposition of carbonaceous substrates due to the high strength influent. By dealing with agricultural wastewater treatment with reed bed system, Gray et al.[17] and Sun et al. [9] reported that significant nitrification does not take place until the  $BOD_5$  was reduced to 200 mg/l or even well below this level. Hence, the removal of  $NH_4-N$  in this study may possibly be attributed to the assimilation process of biomass growth with a large amount of reduction of carbonaceous substrates.

By inspecting the SS removal of the individual stages across the systems it is realized that the first stages can be characterized by significantly high SS removal as compared with all other stages (see Table 5). More significantly, anti-sized system shows a better performance with regard to the SS reduction. This may be attributed to the sedimentation function in the relative more open space within the upper layer bed medium of anti-sized system plus the polishing filtration in lower layer of the system. In order to provide the further understanding of SS removal, particle size distribution was examined via Galai-CIS-1 analyser. The results of the samples of influent and effluent of the first stages of the mono- and anti-sized bed are jointly illustrated in Fig. 13. Fig. 13 shows clearly a significant variation of particle size distribution. Particles in the influent with wide range of size were trapped (say filtered, settled and absorbed etc.) by the bed medium and the effluent exhibited a quite narrow range in particle size with small sized particle as the maximum fraction. Furthermore, it is seen from Fig. 13 that the effluent from anti-sized bed shows a bit smaller particle as its maximum fraction and more narrow range of particle size distribution as compared with the effluent from mono-sized bed. This implies that anti-sized bed can produce higher quality effluent with regard to the SS reduction. In other words, more SS was captured within the anti-sized bed. This leads to the following discussion on bed medium clogging phenomenon exhibited during the system operation. By the way, due to the large amount of SS accumulated in the first stage of the system, it is recommended that such the reed bed system should have spare first stage for alternative operation.

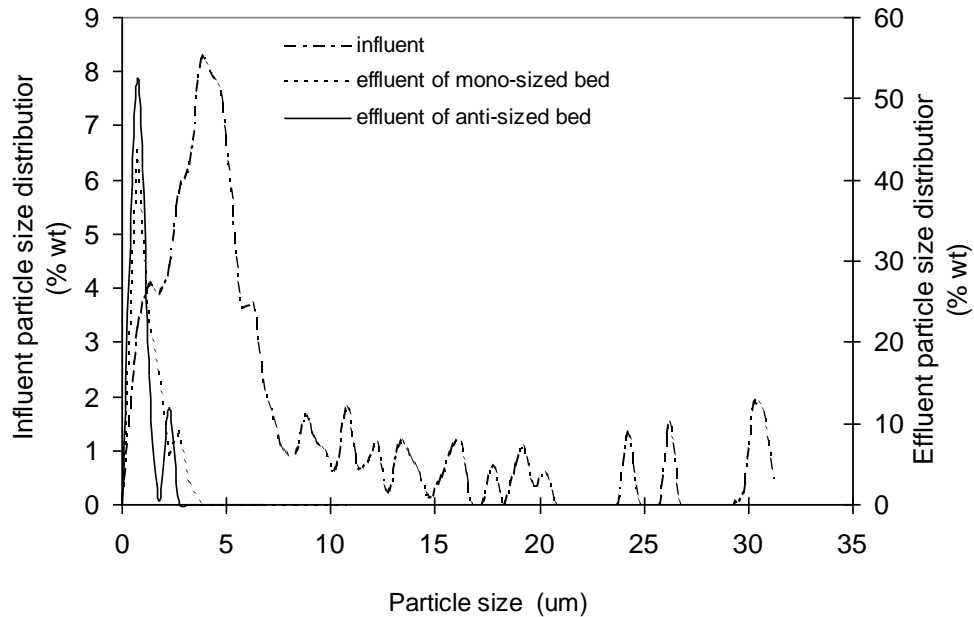


Fig. 13 Particle size distribution of the influent and the effluent from the first stages of the mono- and anti-sized bed, respectively

Previous studies have suggested that clogging is generally accelerated under increasing hydraulic loading rates, or under increasing concentrations of organic matter and SS at a given hydraulic loading rate [18]. As is widely accepted, accumulation of SS in the bed medium is one of the main contributions to medium clogging [2,3,8,14]. More likely, it may be the most important contribution leading to clogging phenomenon [2]. In spite of the fact that: (1) both the systems examined in this study experienced the clogging phenomenon; (2) more SS was captured in the first stage of the anti-sized system in comparison with the first bed of the mono-sized system, it was demonstrated that anti-sized beds could be operated with longer period when clogging occurred (see Table 6). Accordingly, it is reasonable to speculate that the controlling factors behind the clogging phenomenon in anti-sized beds are the clogging depth and the decomposition rate of the organic SS. Compared with the mono-sized beds, anti-sized beds make it possible that SS can penetrate deeper via the relative open pore space in upper layer, thus the bed solids-storage capacity being better utilized. Therefore, the clogging will then be delayed. More importantly, coarse grain of the upper layer in anti-sized beds can provide relative wide pore channels to allow the rapid and strong  $O_2$  diffusion during the tidal flow operation strategy. This strong  $O_2$  flux may enhance the

biodecomposition process of the captured organic SS and make the pore space available for further acceptance of the coming SS. As a result, clogging is then relieved. However, at a minimum, the mineral content of the trapped SS contributes to the permanent pore blockage. Nevertheless, it is the function to counteract the bed medium clogging that make the worth of the development of anti-sized reed bed system.

It was demonstrated that clogging development was significantly correlated with the cumulative mass of SS. Resting of the beds is a useful operating strategy and has been demonstrated to counteract the clogging. By the effort to consider the integrated effects of SS accumulation in bed operation and the organic SS decomposition during bed resting, a conceptual model was developed to predict the clogging time. Although a number of parameters was involved in the model and several assumptions were made for the model development, it is demonstrated that the model can be used to describe the clogging behaviour by predicting clogging time (see Fig. 12). However, it should be pointed out that the assumption of 50% SS from the influent being decomposed or becoming soluble in any way during the beds' daily operation is questionable. In fact, clogging behaviour is not as simple as only SS accumulation being considered. Detailed mechanism of the clogging is still unclear. Nevertheless, it is satisfactory that the experimental data match the conceptual model to certain degree.

## **CONCLUSIONS**

Subsurface-flow reed beds are susceptible to clogging when treating wastewaters containing high levels SS. If clogging happened, the treatment system will face the threat of its long-term functioning and sustainability. This study was conducted for the comparison between two reed bed systems for high strength animal wastewater treatment. From then, the utility of the development of so-called anti-sized reed bed system was demonstrated. The principal conclusions emanating from this study may be listed as follows:

- With regard to the pollutants' removal, anti-sized reed bed system is comparable with mono-sized system. Removal efficiencies from anti-sized system are more or less high than that from mono-sized system. Due to the high strength wastewater tested in this study, nitrification process is not complete in both the treatment systems.

- In the first stages the removal efficiency were always significantly higher than in all the remaining stages. Relatively, the fifth stages essentially provided a “polishing” step for effluents. For this reason fifth stages could be omitted from the systems.
- At a mean, 69% and 65% of the SS from the influent were removed (say filtered, settled and absorbed etc.) by the anti- and mono-sized reed bed system, respectively. Among these, 67% and 45% of the total removal were undertaken by the first stages of anti-and mono-sized system, respectively. Accordingly, the trapped SS led to the bed medium clogging especially in the first beds of both the systems. However, anti-sized system showed a clear advantage to counteract the clogging as compared with mono-sized system. This forms the main concern of the development of anti-sized reed bed system.
- The counteraction of clogging by anti-sized bed may attributed to the two reasons: (1) Anti-sized bed can allow SS to penetrate deeper via the relative open pore space in upper layer medium, thus the effective depth of the bed being increased and bed solids-storage capacity being better utilized; (2) Coarse grain of the upper layer in anti-sized beds can provide relative wide pore channels to allow the rapid and strong O<sub>2</sub> diffusion during the tidal flow operation strategy. This strong O<sub>2</sub> flux may enhance the biodecomposition process of the captured organic SS and make the pore space available for further acceptance of the coming SS.
- A conceptual model developed in this study can be used to quantitatively describe the clogging behaviour. In spite of some questionable assumption in the model development, a good consistent between predicted clogging time and experimental observed clogging time was obtained.

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