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Clogging processes caused by biofilm growth and organic particle accumulation in lab-scale vertical flow constructed wetlands

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Abstract

The accumulation of organic matter in substratum pores is regarded as an important factor causing clogging separately in the subsurface flow constructed wetlands. In this study, the developing process of clogging caused by biofilm growth or organic particle accumulation instead of total organic matter accumulation was investigated in two groups of lab-scale vertical flow constructed wetlands (VFCWs), which were fed with glucose (dissolved organic matter) and starch (particulate organic matter) influent. Results showed that the growth of biofilms within the substratum pores certainly caused remarkable reduction of effective porosity, especially for the strong organic wastewater, whereas its influence on infiltration rate was negligible. It was implied that the most important contribution of biofilm growth to clogging was accelerating the occurrence of clogging. In comparison with biofilm growth, particles accumulation within pores could rapidly reduce infiltration rate besides effective porosity and the clogging occurred in the upper 0–15 cm layer. With approximately equal amount of accumulated organic matter, the effective porosity of the clogged layer in starch-fed systems was far less than that of glucose-fed systems, which indicated that composition and accumulation mode in addition to the amount of the accumulated organic matter played an important role in causing clogging.

Key words: clogging; constructed wetland; organic matter; particle accumulation; biofilms

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Introduction

Because of the advantage of low energy requirement, convenient operation and maintenance, constructed wetland (CW) is used as an alternative efficient means of wastewater treatment (Fabio and Nicola, 2007; Geary and Moore, 1999; Zhang *et al*., 2007; Healy *et al*., 2007; Molle *et al*., 2005). However, substratum clogging is one of the worst operational problems for the subsurface flow constructed wetlands (SSFCWs) (Geary and Moore, 1999; Platzer and Mauch, 1997; Siegrist, 1987). According to the investigation report of over 100 CWs from the United Stated Environmental Protection Agency (USEPA, 1993), clogging occurred in nearly half of the wetlands after running for five years. Once clogging occurs, the permanent ponding on the surface of substratum leads to anaerobic conditions within the CW systems and then further reduces the pollutants removal efficiency.

Clogging is a complex process and the mechanisms of clogging are not completely clear. At present, the total accumulated matter within CW systems which occupied pore volume is considered to be one of the major factors related to the clogging (Blazejewski and Murat-Blazejewska, 1997). Accordingly, it is readily to imagine that the organic composition in the total matter accumulated in pores play an important role in causing clogging since the CW systems are most commonly applied to strong organic wastewater treatment (Molle *et al*., 2005). This imagination can be confirmed by the interesting discovery: the infiltration rate of the clogged constructed wetlands almost rallied when the appropriate operation mode of feeding and rest was adopted. It is because the accumulated organic matters were mineralized by microorganisms on the reoxygenation condition of substratum (Platzer and Mauch, 1997).

However, the correlation between the organic matters (OM) accumulated within substratum and clogging is complicated. In a series of four gravel-bed CWs supplied with farm dairy wastewater which contain a excessive amount of OM, Tanner *et al*. (1998) and Nguyen (2000) found that there is a general reduction trend of infiltration rate with the increase of accumulated OM, however, this relationship between them is not linear. A similar conclusion was also drawn from the study of Caselles-Osorio *et al*. (2007) in six municipal wastewater treatment wetland systems. On the other hand, Platzer and Mauch (1997) found there was little association between substratum OM content and infiltration rate yet, and they considered that other factors such as form and distribution of OM in soil pores are more

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important to the infiltration rate than the total amount of OM.

Since the accumulated organic matter in substratum pores is mainly composed of biofilms and organic particles without being biodegraded timely, the respective influence of them on clogging should be paid more attention. The great contribution of accumulated organic particles to clogging was indubitable, whereas the viewpoint of effects of biofilms growth on clogging was controversial. Vandevivere and Baveye (1992) emphasized the influence of the microorganisms accumulation on the surface sealing. However, others believed that the biofilms growth had a minor effect on clogging (Healy *et al*., 2007; Zhao *et al*., 2007; Rodgers *et al*. 2004; Suliman *et al*., 2006). As biofilms are essential for CW systems to biodegrade the organic pollutants in wastewater, the understanding of the influence of biofilms on clogging was fairly significant.

In addition, many studies about clogging were carried out in clogged wetland systems (Tanner *et al*., 1998; Nguyen, 2000; Caselles-Osorio *et al*., 2007) and some conclusions were drawn from the comparing results of infiltration rate before and after clogging (Suliman *et al*., 2006). In order to get further understanding of the clogging mechanism and to adopt proper methods to prolong the lifetime of CW systems, the developing process of clogging separately caused by biofilms growth and particles accumulation instead of the total OM accumulation must be investigated.

In previous study, we found that the clogging occurred more easily in the vertical flow constructed wetland (VFCW) unit models fed with starch influent than with glucose influent (Tong *et al*., 2007). In this study, we further investigated the two types of clogging process in the identical VFCWs, glucose influent was fed as a soluble organic matter and starch influent was fed as a particulate organic matter. The purposes in this study were: (1) to investigate the different development of clogging processes caused by the biofilm growth and particle accumulation respectively, (2) to analyze the cause of the different clogging process, and (3) to provide theoretical recommendation for delaying the occurrence of clogging.

1 Materials and methods

1.1 Experimental setup

We used ten lab-scale VFCWs which were built nearby the Ancient Canal of Zhenjiang in Jiangsu Province, China. Each setup was made of sheet iron columns (lined with plastic film) of 80 cm in height and 30 cm in diameter. The height of the filter bed was 45 cm and coarse sand (d_{10} = 1 mm, the uniformity coefficient C_u = 4.4, the initial porosity was 36% and the initial infiltration rate $K_f = 4.85 \times 10^{-2}$ cm/s) was used as substratum material. Three sampling ports were installed at 15 cm, 30 cm and 45 cm from the top of the sand filter. The 5 cm of deep gravel (10–20 mm, diameter) was prepared at the bottom to support the sand filter and evenly distribute the treated wastewater. An overflow port was equipped near the top outside of column to keep a constant water head. A glass tube (1 m in length, 2 cm inner diameter) with scales was connected with the sampling port through a rubber tube when the infiltration rate was measured regularly. Tong *et al*. (2007) found that plant did not show significant effects on clogging during a short period (one or two months) in previous study. Moreover, this experiment was carried out in winter which is not growing season. Therefore, the experimental setups were unplanted. Figure 1 shows a schematic description of the experimental unit model.

Synthetic wastewater was continuously fed into each VFCW unit from a 60-L feed tank through a rubber hose with flow rate control valves and the synthetic influent was daily prepared. The feed tanks were placed in a higher position so that influents could flow automatically into the VFCWs. Treated wastewater drains through a drainage pipe at the bottom of the column near the outlet. According to the literature (Zhan *et al*., 2003a), the hydraulic loading of 0.85 $m^3/(m^2 \cdot d)$ was used through the experimental period.

1.2 Experimental influent

Two types of identical organic synthetic influents except organic carbon source were used in this study. For the two organic influents, major nutrients were supplied by adding KNO_3 and K_2HPO_4 to the tap water. Glucose and starch were added to the influents respectively as different organic carbon sources. Glucose ($C_6H_{12}O_6$) is a kind of soluble organic substrate and can be directly assimilated by microorganisms. The glucose-fed VFCWs were used to investigate the clogging process caused by the biofilm growth. Starch ($(C_6H_{11}O_5)_n$), as a kind of particulate organic substrate, must undergo cell external hydrolysis before it is available for biodegradation (Caselles-Osorio and Garcia, 2006). Therefore, starch-fed VFCWs were used to investigate the development process of clogging synthetically caused by biofilm growth and particle accumulation, especially for the latter. Comparing the difference of pore volume and infiltration rate of the VFCWs fed with glucose and starch influent, the clogging

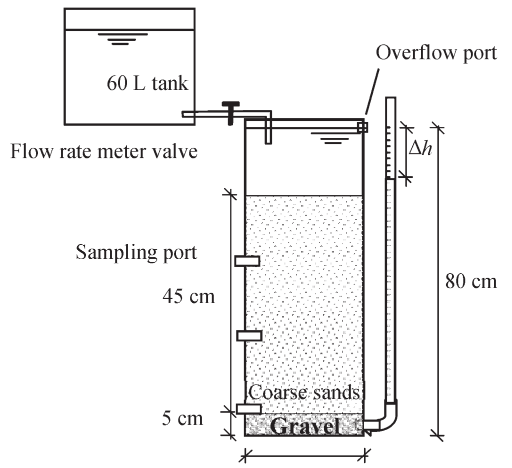

Fig. 1 Schematic description of the experimental vertical flow constructed wetland (VFCW) model.

characteristic of biofilm growth and particle accumulation was studied.

Organic loading rate is an important factor causing clogging of constructed wetland (Healy *et al*., 2007). In this study, the hydraulic loading was kept constant and the organic matter concentration in influent was changed. Constructed wetland has been used in treating organic wastewater with a wide range of organic matter concentration, such as for domestic wastewater and municipal wastewater, COD concentration is generally 250–400 mg/L, and in eutrophic river or lake water, COD concentration is generally about 4–15 mg/L. However, in China, many urban rivers have been seriously polluted and organic matter is always the main pollutant exceeding the water quality standard. According to our aperiodic water quality monitor of some polluted urban river water in Zhenjiang, the COD concentration reached 5–110 mg/L. In order to shorten the time required for clogging in the laboratory, higher organic matter concentration of 50–400 mg/L were adopted in this study. The water quality of the synthetic wastewater is listed in Table 1.

1.3 Experimental strategies

From November 17, 2005 to January 16, 2006, glucose influent was continuously fed to the VFCWs. On account of unexpected damage of some experimental setup, the VFCWs fed with starch influents began running 8 d later and stopped after serious ponding.

Air temperature suddenly dropped to near 0°C since December 1, 2005 and did not rise again. Before this temperature drop, the average air temperature was around 10°C. In order to get a qualitative understanding of the influence of temperature on the two types of clogging process, heating rod was used to keep the influent temperature about 25°C from December 20 for glucose-fed systems and from December 9, 2005 for starch-fed systems. Total effective porosity, total infiltration rate and the effective porosity of each layer along the sand filter were measured regularly during the overall period. The infiltration rate and accumulated organic matter content of each layer were examined once at the end of experiment.

1.4 Sampling and analyzing

1.4.1 Effective porosity measurements

Under the condition of saturated sand filter, the drainage volume of the whole filter and each layer (upper layer 0–15 cm, middle layer 15–30 cm and bottom layer 30–45 cm) were measured every 6 d for glucose-fed VFCWs and 3 d for the starch-fed VFCWs. After the above drainage volumes were separately divided by the total volume and each layer volume of the filter without filling with sand, we could get the values of effective porosity of total filter and each layer.

Table 1 Water quality of the synthetic organic influent

	COD (mg/L)	TN (mg/L)	TP (mg/L)
Glucose influent	48.16 ± 5.44	10.14 ± 3.51	1.98 ± 0.58
	101.24 ± 11.52	10.22 ± 4.26	2.01 ± 0.47
	145.52 ± 14.21	10.03 ± 4.11	2.05 ± 0.35
	194.87 ± 20.45	10.45 ± 5.02	1.96 ± 0.22
	389.65 ± 8.63	10.28 ± 3.24	2.01 ± 0.36
Starch influent	50.29 ± 12.06	9.87 ± 2.16	2.13 ± 0.19
	112.05 ± 15.84	10.12 ± 1.21	1.85 ± 0.39
	143.11 ± 26.48	10.23 ± 2.11	2.04 ± 0.44
	226.84 ± 26.55	10.16 ± 1.14	2.19 ± 0.32
	403.59 ± 43.57	10.04 ± 3.24	2.21 ± 0.31

TN and TP refer to the concentration of total nitrogen and total phosphorus in the synthetic organic influent, respectively.

1.4.2 Infiltration rate measurements

The infiltration rate was measured every 6 and 3 d for the glucose-fed and starch-fed VFCWs, respectively. The measurement was based on the constant water head method of Standard for Soil Test Method (GB/T50123-1999). The glass tube was connected to one bottom sampling port and water would always overflow from the overflow hole to keep the water level constant. When the water level of the glass tube reached stable, the difference of water level between the glass tube and experimental column (Δh, Fig. 1) could be measured. With a graduated flask and a stopwatch, the infiltrated water volume over a period could be easily measured. Then the value of infiltration rate K_T (cm/s) could be calculated through the following modified Darcy's equation (Eq. (1)).

$$K_T = \frac{V \times L}{t \times \Delta h \times A} \quad (1)$$

where, V (cm^3) is infiltrated water volume, t (s) is infiltrated time, L (cm) is the length of the sand filter and it is 45 cm in this study. Δh (cm) is the difference of water level. A is surface area of the sand filter and is 706.5 cm^2 in this study.

In addition, the infiltration rate of each layer was measured at the end of experiment to understand the characteristic of spatial distribution within sand filter and the relationship between infiltration rates and accumulated organic matter.

1.4.3 Organic matter content accumulated in substratum

The loss on ignition (LOI) method (Tanner and Sukias, 1995) was used to calculate the OM content accumulated in substratum. At the end of experiments, three substratum samples of each layer were taken with self made sampler and mixed evenly. Some of the above mixed substratum were dried to constant weight in a forced air oven at 80°C and then were burnt at 550°C for 4 h. The weight difference before and after burning was estimated as OM content of substratum. The OM content was divided by the weight of substratum before ignition and then the percentage of OM content could be calculated.

2 Results

2.1 Clogging process of systems with different organic influent

Figure 2 shows the changes of infiltration rate with different organic matter concentration over time in starch-fed or glucose-fed systems. It can be found that the infiltration rates decreased more quickly in starch-fed system than that in glucose-fed system. In previous study, adopting the identical experimental setup, Tong *et al*. (2007) defined critical infiltration rate K_c of around 1.61×10^{-3} cm/s to quantify the occurrence of clogging. In this study, as can be seen from Fig. 2, the infiltration rates of all starch-fed systems with different COD concentrations decreased to K_c within 30 d and serious ponding phenomena were observed in the surface of substratum. However, none of the infiltration rate of the glucose-fed system dropped to K_c after running for 60 d.

Organic matter concentration showed some effects on the clogging process. The infiltration rates were lower for the systems fed with higher concentration influents (Fig. 2). For the glucose-fed system, infiltration rate of the system with influent of 400 mg/L was the lowest, but was even higher than K_c. For the starch-fed system with COD concentration of 50 mg/L, infiltration rate decreased to K_c after running for 30 d while the reaching time was shortened to 24 d when the organic concentration was higher than 100 mg/L.

Both biofilm growth and suspended solid accumulation could occupy the pore space and then reduce the pore size of the wetland systems. Figure 3 shows the changes over time of effective porosity in glucose-fed and starch-fed systems. The COD concentration had a significant influence on the effective porosity of glucose-fed systems. For instance, the effective porosity decreased from 17% to 11% when the COD concentration increased from 50 to 400 mg/L. Comparing the effective porosity of glucose-fed and starch-fed systems at the end of experiment, it can be found that the value of clogged starch-fed systems

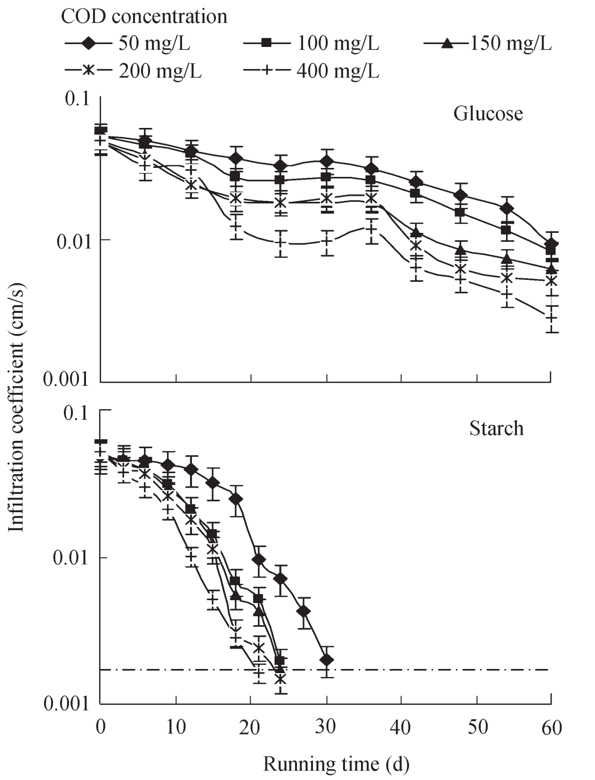

Fig. 2 Infiltration rate as a function of time in glucose-fed and starch-fed systems.

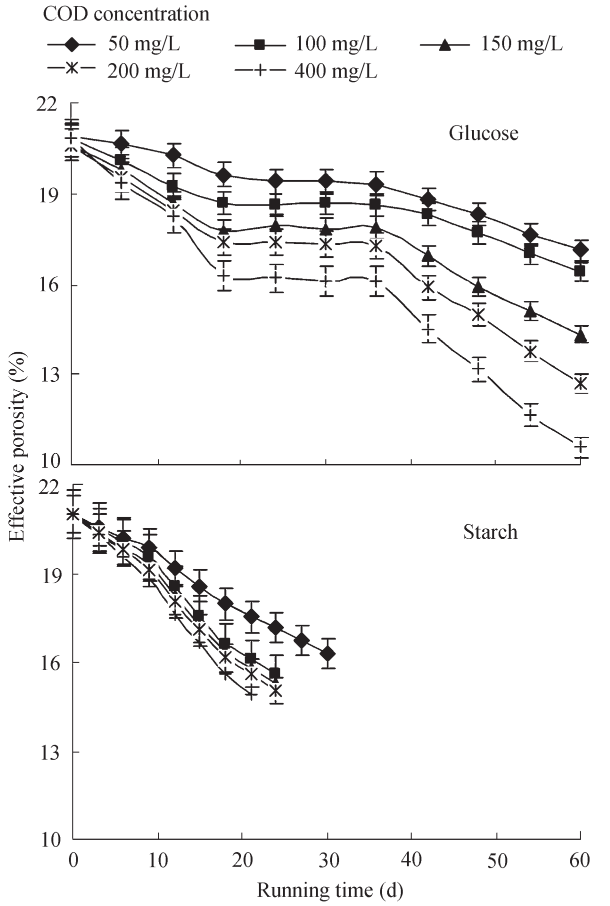

Fig. 3 Effective porosity as a function of time in glucose-fed and starch-fed systems.

was not less than that of glucose-fed systems. For example, the effective porosity of glucose-fed and starch-fed system with COD concentration of 50 mg/L was 17% and 16%, respectively (Fig. 3). As we have known that all glucose-fed systems were not clogged till the end of experiment (Fig. 2), it can be inferred that not only reduction of pore spaces, but also some other factors can affect the hydraulic conductivity.

2.2 Clogging characteristics within the systems

The developing process of clogging accompanied with the pollutants removal from wastewater. Since the pollutants in wastewater were mostly eliminated in the inlet part of the constructed wetland systems (Zhao *et al*., 2006; Zhao *et al*., 2007a), it is necessary to investigate the variations of pore spaces and infiltration rate in different depth of filter to deeply understand the clogging characteristics caused by biofilm growth and particle accumulation.

Figure 4 shows the effective porosity changes over time for each layer in VFCWs fed with glucose or starch influent. It can be found that the decreasing trend of the effective porosity in the glucose-fed systems was fairly different from that in the starch-fed systems. For the glucose-fed systems, the reduction of effective porosity of the upper and middle layer was significant and that of the bottom was slight. For the starch-fed systems, however, the effective porosity only dropped rapidly in the upper layer, and it did not decrease basically with time in the

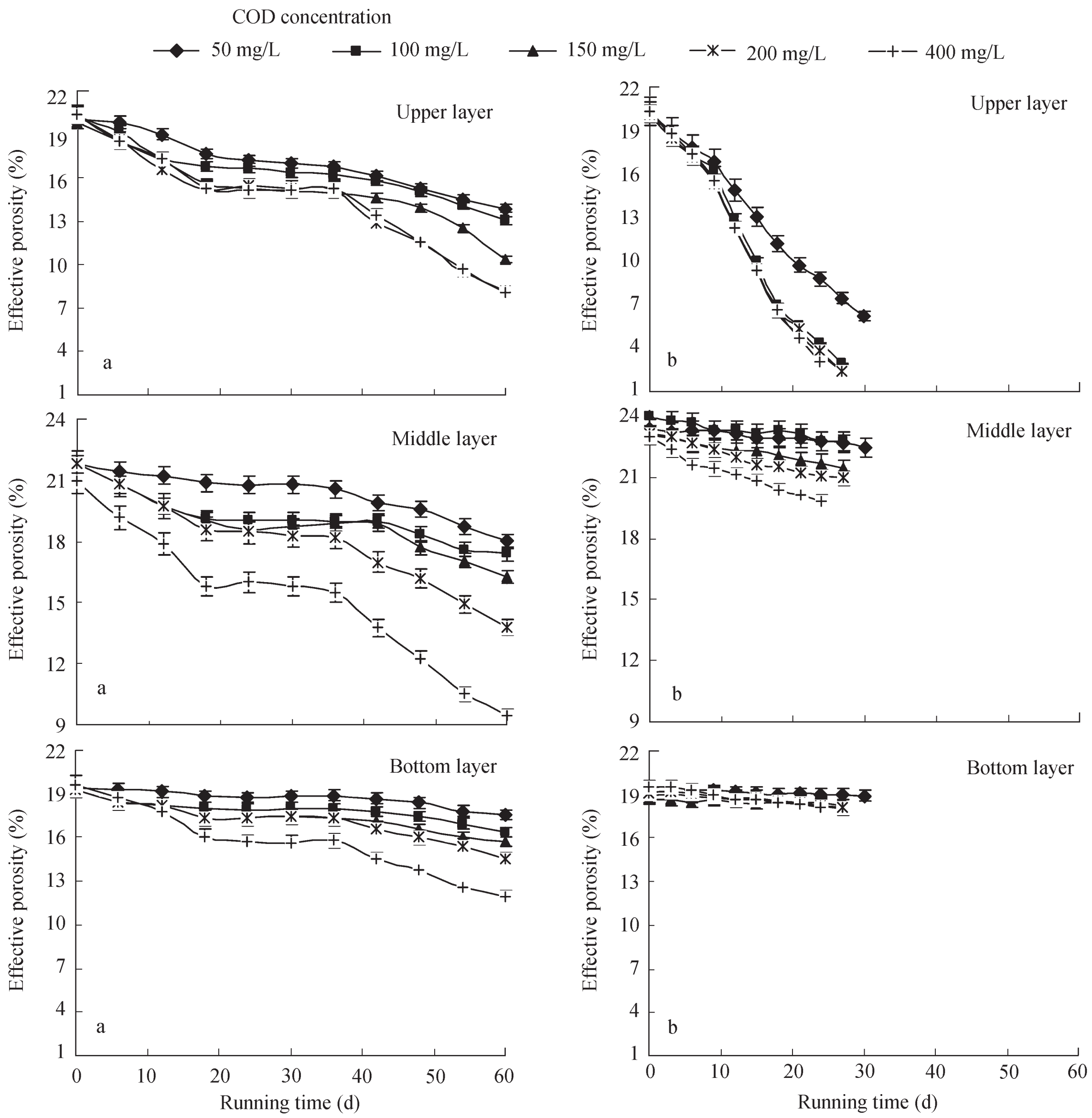

Fig. 4 Effective porosities of each layer as a function of time in glucose-fed (a) and starch-fed (b) systems.

middle and bottom layers. That a large number of starch particles in influents were mostly detained in the upper layer and then accumulated within the pore spaces was the main reason. For the dissolved glucose influent, biofilms could grow anywhere the organic influent flow across and then reduced the effective porosity there. As the amount of the biomass is positively related to the organic matter content in influent, the glucose-fed system with COD concentration of 400 mg/L has great reduction of effective porosity in each layer and the others has reduction only in upper and middle layers.

Figure 5 shows the accumulated OM content within the substratum in each layer at the end of experiments. The contents in the upper layer were only slightly higher for the glucose-fed systems, whereas they were far higher for the starch-fed systems, which was in accordance with larger drop in the effective porosities (Fig. 4). In addition, the OM contents increased with the increase of influent organic matter concentration.

Figure 6 shows the distribution of infiltration rates of each layer at the end of the experiment. In general, the infiltration rates were lower in the upper layer. Especially for the starch-fed systems, the values of the infiltration rate of the upper layer all declined to K_c. Considering the distribution of OM content along the depth of filter (Fig. 5), the infiltration rate was negatively related to the accumulated OM content, which confirmed that the accumulation of OM within substratum was one of the main reasons to the substratum clogging. This result was in accord with the research conclusions by Platzer and Mauch (1997) and Zhan *et al*. (2003).

3 Discussion

(1) Temperature is one of the important factors in clogging (Platzer and Mauch, 1997). Higher temperatures result in a higher biological activity and higher growth rates. This results in a quicker degradation of the organic matter accumulated in pores, as well as that the pores are filled by a higher content of biomass. On the contrary, low

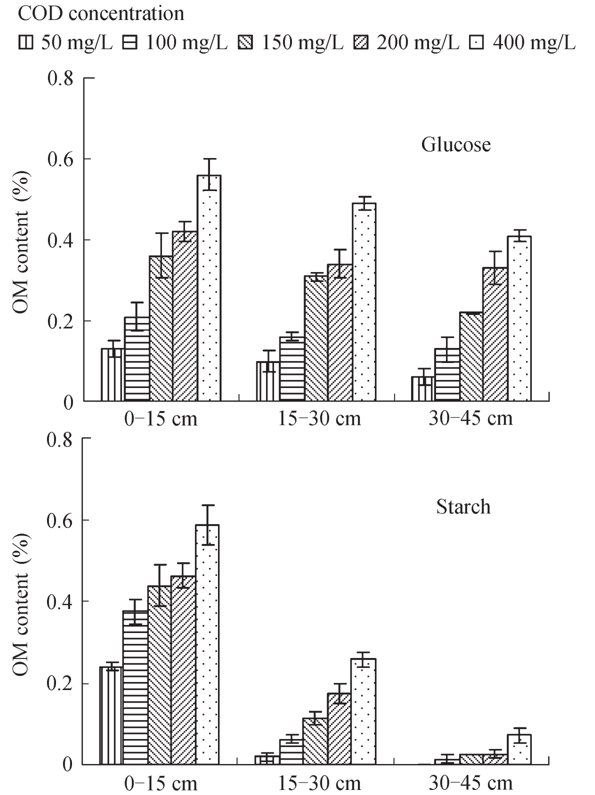

Fig. 5 Accumulated organic matter (OM) contents in each layer of glucose-fed and starch-fed systems.

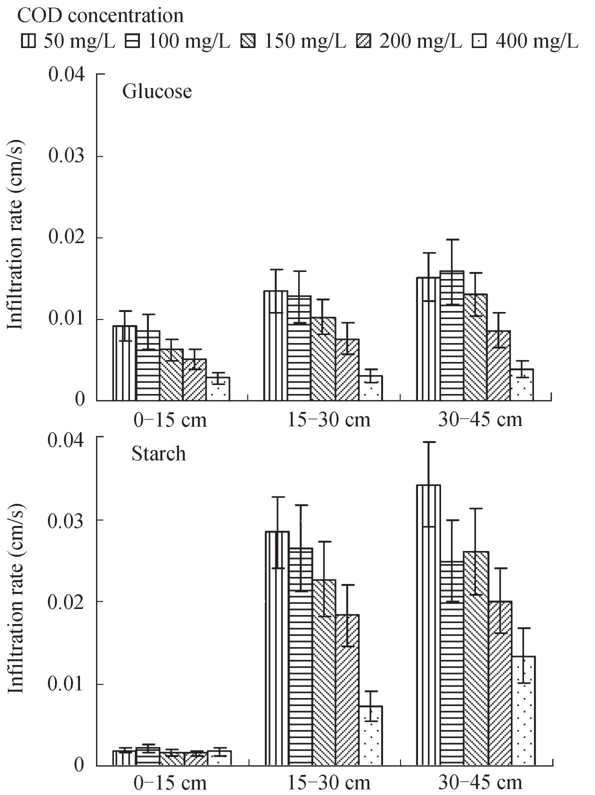

Fig. 6 Infiltration rates in each layer of systems fed with different organic influents.

temperatures will easily lead to organic particle clogging. In this study, we observed temperature changes influenced clogging caused by biofilm growth and particles accumulation (Fig. 2).

(2) Organic loading is generally regarded as one of the main factors resulting in clogging of substratum. In this study, hydraulic loading was constant (0.85 $m^3/(m^2 \cdot d)$) and the organic loading in influent was controlled by changing organic matter concentration. The effective porosity and infiltration rate of the highest loaded VFCE unit were markedly reduced compared to that in the lowest loaded unit. However, for the glucose-fed system with 400 mg/L COD, serious ponding did not appear during 60 d running time. For the starch-fed system with 50 mg/L COD, infiltration rate dropped to K_c and serious ponding occurred at day 30. This implied that except for organic loading, suspended solids (SS) content in the influent should also be paid attention in clogging, especially for the wastewater containing a large amount of particles. Winter and Goetz (2003) suggested that the average concentration of TSS in the inflow should not exceed 100 mg/L and the TSS loading should not exceed 5 $g/(m^2 \cdot d)$. In the study of Fu *et al*. (2004), no clogging was observed in the integrated vertical-flow constructed wetland after running for 52 months when SS loading was 11 $g/(m^2 \cdot d)$. In this study, due to the high hydraulic loading rate, the SS loading of the starch-fed system with 50 mg/L COD was more than 40 $g/(m^2 \cdot d)$, which may be the main reason for the occurrence of clogging within 30 d.

(3) Reduction of pore spaces within substratum will increase the resistance of water flow. Organic matter accumulation was regarded as one of main reasons for occupying pore spaces. Consequently, to further understand the different developing processes of clogging separately caused by the biofilm growth and particle accumulation, the correlations between infiltration rate and effective porosity, and effective porosity and accumulated OM content should be analyzed.

Figure 7 shows that the relationship between infiltration rate and effective porosity is positive, which confirmed the reduction of pore spaces increased the water flow resistance. However, the relationship is different in case of glucose-fed system and starch-fed system. When the effective porosity was more than 17%, the decreasing rate of infiltration rate with the reduction of effective porosity was approximately equal for those two groups of systems. Nevertheless, when the effective porosity was less than 17%, a slight decrease of effective porosity could result in a sharp decline of infiltration rate for starch-fed system, which is different from the case of glucose-fed system. For the starch-fed system, the reduction of the infiltration rate was 5.5×10^{-3} cm/s when the effective porosity decreased from 17% to 15%. For the glucose-fed system, the reduction was only about 6.0×10^{-3} cm/s when the effective porosity sharply decreased from 17% to 11%. Suliman *et al*. (2006) also observed that biological growth caused a pronounced reduction in drainable porosity and its effect on infiltration rate was negligible. This result indicated that besides the pore spaces of substratum, other factors such as the composition of organic influent might affect the infiltration rate. When the effective porosity was down to a certain degree, the diameter of starch particles

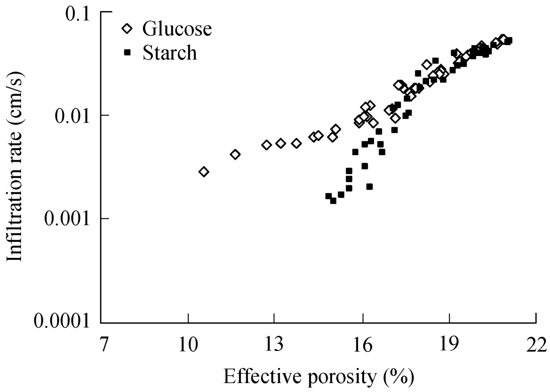

Fig. 7 Correlation between infiltration rate and effective porosity.

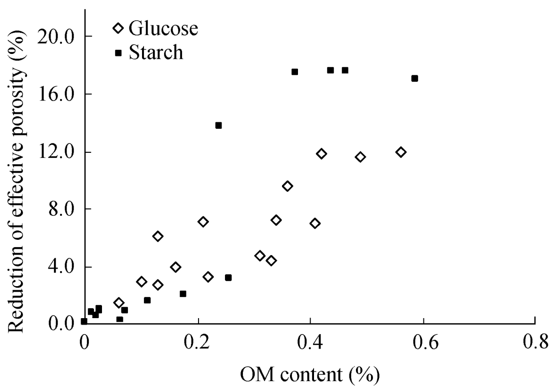

Fig. 8 Correlation between reduction of effective porosity and accumulated organic matter (OM) content.

could not be neglected and the starch particles could directly block the pores within substratum and led to rapid clogging phenomena. In the study of Winter and Goetz (2003), the content of SS, especially with particles > 50 μm are considered to play a key role in causing clogging, because these particles are of the same size as the pores of the substratum.

It is true that the amount of OM accumulated in the substratum has a great influence on pore size. The form of the accumulated OM and accumulation mode also has some effects on effective porosity. Figure 8 shows the relationship between the accumulated OM content and reduction of effective porosity at the end of experiment in the case of glucose and starch influent. For the glucose-fed system, the effective porosities decreased evenly with the increase of accumulated OM content. For the unclogged layer of starch-fed system, the relationship between the reduction of effective porosity and OM content also showed a positive trend. However, the effective porosities in the clogged upper layer of starch-fed system showed no correlation with the accumulated OM content and they all had a significant decline. Compared with the effective porosity of glucose-fed system under the condition of similar OM content, the reduction of clogged layer in starch-fed system was greater. As discussed above, the main composition of accumulated OM within substratum were biofilms for the glucose-fed system and detained starch particles for the upper layer of starch-fed system. Thullner *et al.* (2002) and Liu *et al.* (2003) thought biological growth forms continuous and uniform biofilm which covers the wall of each pore leading to reduction in the pore diameter, and Caselles-Osorio *et al.* (2007) considered the particles interstitially accumulated in the pores. According to these previous studies, we can infer that the accumulated solids could reduce the pore spaces more rapidly than the biofilms could under the experimental conditions.

In this study, we used glucose influent to simulate the clogging process of substratum caused by biofilm growth. Although the influence of biofilm growth on infiltration rate was not as significant as that of starch particles, biofilm grow could pronouncedly reduce the effective porosity of substratum, especially with high organic influent. Since the particles could directly block small pores when the pores size declined to a certain value, we can deduce that the important contribution of the biofilm growth to clogging in practice is accelerating the occurrence of clogging.

(4) According to the clogging caused by organic matter accumulation, we could adopt some methods to prolong the lifetime of the constructed wetland or to prevent clogging. For example, appropriate organic loading and SS loading, especially the latter, should be controlled in the influent to avoid excessive growth of biofilms and accumulation of particles. Adopting multiple physical-chemical pretreatment method to effectively remove the solids from the wastewater is very important. Appropriate feeding-resting operation mode for the constructed wetland should be determined. The length of the required resting period must be long enough to supply a sufficient oxygen amount to oxidize the accumulated organic particles and the resting period allow the thick biofilm lose water to increase the effective porosity.

(5) It should be noted that the above conclusions was drawn without considering the influence of plants on clogging. In fact, plant plays an important and complicated role (Liénard *et al.*, 2006). Tanner and Sukias (1995) found that the planted wetlands retained higher apparent gravel porosity in comparison with the unplanted wetlands, despite great accumulations of organic matter. Fu *et al.* (2004) also indicated that the infiltration rate of the upper layer was slightly higher than that of the middle layer due to the existence of plant roots within surface layer. Plant roots provide a large number of surface area for microorganisms settling, which will improve the degradation rate of organic matter and promote the growth of biofilms and then have some influence upon clogging process. The effects of plants on clogging process separately caused by biofilms growth and organic particles accumulation will be further investigated.

4 Conclusions

Both biofilm growth and particle accumulation within substratum could reduce the effective porosity and infiltration rate of the constructed wetland system. The contribution of the accumulated organic particles to the process of clogging was greater than that of biofilm growth and the clogging mainly occurred in the upper 0–15 cm layer in this case.

The biofilm growth surely remarkably reduced the effective porosity, especially for the strong organic wastewater, and its influence on infiltration rate was negligible. Biofilm growth contributed mostly to accelerate the occurrence of clogging.

Except for the amount, the composition and accumulation mode of the accumulated organic matter also played important roles in causing clogging. When the pores size of the substratum was small enough, the interstitially accumulated solids could reduce the pore spaces more rapidly than the biofilms. This might be the reason for that the effective porosity of the clogged layer in starch-fed systems was less than that of glucose-fed systems with approximately equal amount of accumulated organic matter.

Acknowledgments

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