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Optimizing and real-time control of biofilm formation, growth and renewal in denitrifying biofilter

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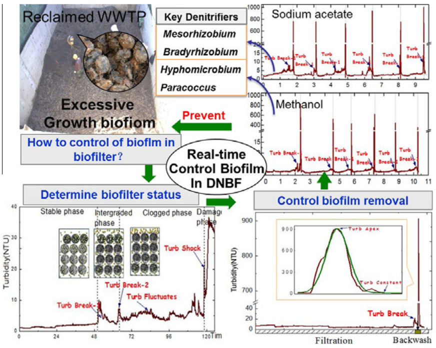
HIGHLIGHTS

- Optimizing and control of biofilm was studied in biofilter (600 m^3/d).
- Biofilm formation, growth and removal can be controlled using turbidity.
- The filter layer status can be indicated by Turb break points on turbidity profile.
- Filter layer clogging coefficient can be used to determine filter layer condition.

GRAPHICAL ABSTRACT



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ABSTRACT

A pilot-scale denitrifying biofilter (DNBF) with a treatment capacity of 600 m^3/d was used to study real-time control of biofilm formation, removal and renewal. The results showed biofilm formation, growth and removal can be well controlled using on-line monitored turbidity. The status of filter layer condition can be well indicated by Turb break points on turbidity profile. There was a very good linear relationship between biofilm growth degree (X_{biof}) and filter clogging degree (C_{filter}) with R^2 higher than 0.99. Filter layer clogging coefficient (Yc) lower than 0.27 can be used to determine stable filter layer condition. Since variations of turbidity during backwash well fitted normal distribution with R^2 higher than 0.96, biofilm removal during backwash also can be well optimized by turbidity. Although biofilm structure and *nirK*-coding denitrifying communities using different carbon sources were much more different, DNBF was still successfully and stably optimized and real-time controlled via on-line turbidity.

1. Introduction

Wastewater reclamation is one of the most effective ways to solve both water shortage and pollution problems. Many wastewater treatment plants in water deficient regions, especially large and medium-sized cities, have been up-graded to produce reclaimed water, and advanced nitrate removal is required. Because denitrifying biofilter (DNBF) has advantages of high treatment efficiency, small footprint, and low shock loading impact, it is widely used for advanced nitrate removal. However, because biofilm growth cannot be easily monitored, many biofilters do not provide stable performance. Moreover, some biofilters can not be normally operated due to frequent clogging (Leverenz et al., 2009; Snowball, 2006) (Fig. S1), which limits the engineering application and development of biofilter.

In fixed-film wastewater treatment systems (Corona et al., 2013; Ji et al., 2014; Wang et al., 2015), biofilm is used to remove pollutants in wastewater; whereas, in other fields including membrane treatment processes (Miura et al., 2006; Pang et al., 2005), drinking water or reclaimed water distribution systems (Mathieu et al.,

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2014; Yang et al., 2015), and food processing industry (Simões et al., 2010), biofilm formation is harmful and should be avoided. It was reported that biofilm formation comprised a series of complicated steps (Giaouris et al., 2014; Simões et al., 2010) including cell deposition, cell adsorption and/or desorption, cell–cell signaling and EPS production, replication and growth, secretion of biofilm matrix, and biofilm detachment or sloughing. To date, there is no effective method to accurately measure or determine biofilm growth condition in a biofilter, especially in a DNBF. Generally, during the start-up stage of a DNBF, biofilm was naturally cultivated with nitrate and organic carbon. However, since biofilm can not be practically monitored or measured during treatment, it is hard to determine the biofilter run time between backwashes (backwash cycle), the backwash strength and duration. This may result in over backwash and energy cost, or biofilter clogging if backwash is not performed in time. In the last decade, most studies on biofilter process were focused on optimizing backwash procedures (Amburgey and Amirtharajah, 2005; Slavik et al., 2013; Snowball, 2006), while limited studies have been conducted on optimizing the biofilter operation based on the extent of biofilm growth and removal.

Many on-line biofilm monitoring methods, such as differential turbidity measurement (Métadier and Bertrand-Krajewski, 2012), microwaves (Saber et al., 2013), multi-channel impedimetric and amperometric sensor (Pires et al., 2013) and thermal sensors (Reyes-Romero et al., 2014), have been used to monitor biofilm growth. Among these methods, turbidity is suitable for industrial applications. It was used to calculate urban storm water pollutant concentrations and loads (Métadier and Bertrand-Krajewski, 2012). Backwash is the key operational step to control biofilm growth, removal and renewal in treatment plants that employ biofilter/filter as major unit process. However, the effective method to monitor biofilm growth on-line in biofilter has not been well developed, and very limited studies have been conducted on real-time control and optimization of biofilter-based biofilm formation and growth.

Therefore, this study aimed to: (a) determine the relationship between biofilm formation and turbidity variation during the biofilm cultivation stage of a DNBF; (b) control and optimize biofilm growth, removal and renewal during filtration and backwash processes in the DNBF via on-line monitored turbidity; (c) test the stability of real-time control of biofilm growth, removal and renewal in the DNBF using different typical carbon sources.

2. Methods

2.1. Pilot-scale and lab-scale DNBF

A pilot-scale DNBF located at Beijing Gaobeidian Municipal Wastewater Treatment Plant (WWTP) with a maximum treatment capacity of 600 m^3/d was used in this study. The DNBF was packed with expanded clay particles (4–6 mm) at a bed depth of 2.5 m (Table S1). The pilot-scale treatment system consisted of a DNBF reactor, a carbon dosage system, and a backwash system (Fig. S2).

The control consists of four parts: detectors, a computer, interface cards and control units. Nitrate (NO_3^-), turbidity, pH, dissolved oxygen (DO) and pressure sensors were installed in the top section and the bottom of DNBF reactor, respectively. The values of the NO_3^-, turbidity, pH, and DO were recorded every 0.5–10 min and then transferred to a programmable logic controller (PLC) and process control system (PCS). PCS was programmed according to the control logic.

A lab-scale DNBF with a total volume of 30 L and filter media height of 1.1 m was used to study biofilm formation further. Except for volume and media height, the lab-scale DNBF was the same as the pilot-scale DNBF.

2.2. Secondary effluent composition

The secondary effluent of Gaobeidian municipal WWTP that employs an anoxic/oxic (A/O) process was continuously fed to the DNBF. The concentrations of the soluble chemical oxygen demand (SCOD), NH_4^+-N, NO_3^--N, turbidity, and SS in the secondary effluent were in the range of 23.28–76.03 mg/L, 0.33–2.36 mg/L, 20.40–34.12 mg/L, 0.48–13.10 NTU, and 1.33–16.15 mg/L, respectively.

2.3. Experimental design

Experiments were conducted for 210 days, which was divided into 3 phases. Experimental procedures, parameters, aims, and backwash operation were shown in Tables 1 and S2. In the first phase, the natural biofilm cultivation method was used in the pilot-scale and lab-scale DNBF. Since biofilm formation in the pilot-scale DNBF was only operated for one time and the filter media is difficultly taken out to observation, the lab-scale DNBF was operated with Filtration velocity (FV) of 2.38 m/h only to further confirm the results obtained in the pilot-scale DNBF. In the second phase, DNBF was firstly operated for 40 days to establish backwash strength. Thereafter, variations of the effluent turbidity during long-term filtration and backwash operation were studied on the following 38 days and 33 days, respectively. In the third phase, the stability of long-term operation of DNBF with real-time control using turbidity as parameter was tested using two typical carbon sources. When carbon source changed from sodium acetate to methanol, nitrate removal efficiency of DNBF was recovered for 30 days.

Table 1
Experimental procedure and aims.

Phases	Duration (days)	Operation and main parameters	Aims
1st	6/15[*]	CS: sodium acetate FV: 4.76 m/h; FV: 2.38 m/h[*]	• Determine correlation between biofilm formation and turbidity during the start-up of the pilot-scale and lab-scale DNBF
2nd	9–120	CS: sodium acetate; FV: 4.76 m/h	• Effects of backwash on DNBF operation and establish backwash strength
	(40)	Fixed time backwash cycle (48 h)	• Determine the possibility of using turbidity as control parameter to indicate biofilm growth and filter layer condition during long-term filtration
	(38)	Long-term filtration: Three times (Each time: filtration 5-6 days and recovery 5 days)	• Establish the methods of determining filter layer clogging degree • The correlation between the variations of the effluent turbidity and backwash
	(33)	Backwash cycle: Turb break-1 point (FV: 4.76-8.79 m/h)	
3rd	121–210	FV = 8.79 m/h	• Establish the real-time control approach of biofilm growth, removal and renewal in DNBF via on-line monitoring turbidity
	(30)	CS: sodium acetate; Real-time control	
		CS: methanol;	• Test the stability of the real-time control approach using two typical carbon sources
	(30)	Recovery stage	• Analyze biofilm structure and diversity of denitrifying bacteria
	(30)	Real-time control	

[*] In the lab-scale DNBF; CS–Carbon source; Real-time control–backwash was controlled via turbidity.