Optimization of operation conditions for domestic sewage treatment using a sequencing batch biofilm filter

Bin Ji, Taoyuan Wei, Wei Chen, Jie Fan, Jian Wang, Lei Zhu and Kai Yang

ABSTRACT

A sequencing batch biofilm filter (SBBF) was applied to treat domestic sewage. The bioreactor consisted of fibrous filler in the upper part and ceramsite filter media in the lower part. The impacts of the most important factors including dissolved oxygen (DO), water temperature and hydraulic retention time (HRT) were evaluated on contaminants removal during the operation of the SBBF. Changes in DO (1.5–4.0 mg/L) and water temperature (2–30 °C) had little effect on the removal of chemical oxygen demand (COD), but had a greater impact on the removal of total nitrogen (TN) and NH_4^+-N. Changes in HRT (8–14 h) had little effect on the removal of COD, but had a greater impact on the removal of TN, NH_4^+-N and total phosphorus. The optimal operating parameters for the SBBF were as follows: DO of 2–3 mg/L, water temperature above 10 °C, and HRT of 10–13 h. Furthermore, a simple kinetic model was developed, reflecting the relationship between COD and HRT.

Key words | domestic sewage, hydraulic residence time, kinetics model, operation parameters, sequencing batch biofilm filter

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INTRODUCTION

It is of great significance to explore new biological methods for wastewater treatment (Khouni *et al.* 2012). As a novel hybrid bioreactor, the sequencing batch biofilm filter (SBBF) is the combination of a sequencing batch biofilm reactor (SBBR) and a biological filter (Ji *et al.* 2015). Wastewater is treated by microorganisms growing on the media packed in the upper part, the filter media at the bottom is used to minimize the concentration of suspended solids in the effluent. The unique characteristic of a SBBF exists in quick filtration instead of the precipitation stage of a traditional SBBR, which may result in faster, more efficient and greater nutrients removal in wastewater treatment.

Dissolved oxygen (DO) concentration and water temperature are significant factors affecting the operation of a bioreactor, which can change the components of the microbial community. The impact of aeration on the competition between polyphosphate accumulating organisms and glycogen accumulating organisms has been reported (Carvalheira *et al.* 2014). Shifts in the microbial community in response to DO levels in activated sludge have been described (Yadav *et al.* 2014). The optimum temperatures for common bacterial activity in activated sludge processes are in the range between 25 °C and 35 °C (Krzeminski *et al.* 2012). The enzyme which promotes the degradation of organic matter only functions well at a certain temperature. Temperature may also affect the filtration of the activated sludge. Therefore, it is necessary to investigate the impacts of DO concentration and temperature on contaminants removal.

Hydraulic residence time (HRT) is another significant parameter in the disposal of wastewater (Wang *et al.* 2014). A low HRT enhances contaminants removal but the volume of the bioreactor must be increased, while a high HRT is not advantageous to ensure the water quality of the effluent. So it is necessary to determine an appropriate HRT for various wastewater treatment processes. When a filter process was used for contaminant disposal, HRT was often reported. Increasing the total HRT from 8 to 16 h significantly improved the chemical oxygen demand (COD) and biochemical oxygen demand (BOD) removal when an integrated anaerobic-aerobic system was used for domestic wastewater treatment (Tawfik *et al.* 2008). The best performance was obtained at a HRT of 12 h for an anoxic moving bed biofilm reactor–biological aerated filter (Zhuang *et al.* 2014).

The overall aim of the present study was to describe and evaluate the performance of a SBBF. The effects of key factors including DO, water temperature (working temperature) and HRT on the SBBF were reported systematically. The work was

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conducted in an actual wastewater treatment plant (WWTP) and will lay a foundation for further application of the technology.

MATERIALS AND METHODS

Reactor operation

As shown in Figure 1, the bioreactor is a 4.0 m high column, with an inner diameter of 23.5 cm, made of polymethyl methacrylate. A long handle filter nozzle in the middle of the retainer plate with many holes with a diameter of 0.9 mm was at the bottom of the bioreactor. The upper part was filled with a depth of 0.3 m fibrous filler (1,512 kg/m^3 density, 0.4 mm diameter, 35–40 mm length, 90% porosity) while the lower part was filled with a depth of 1.0 m ceramsite filter media (1–2 mm diameter, 2,260 kg/m^3 density, non-uniform coefficient $K80 = d80/d10 < 2.0$). The highest water level (H1) and the lowest water level (H2) were controlled automatically by a floating ball valve, thus resulting in different HRTs.

The tests were operated outside under ambient climatic conditions. The raw wastewater was obtained from the outlet of the grit chamber of a typical urban domestic wastewater treatment plant named Erlangmiao in Wuhan, China. The influent characteristics are listed in Table 1. The bioreactor was operated automatically by the control cabinet with regard to the processes of influent, effluent and aeration as follows. Raw water was pumped into the reactor and mixed quickly, standing for 30 min. This was followed by the aeration stage, and the aeration time was 70 min. After settling for 10 min, the effluent was discharged from the SBBF with an initial filtration velocity of 5 m h^{-1}. Excess sludge was discharged from the bioreactor after backwashing in order to achieve the desired sludge retention time (SRT) of about 50 d. In order to obtain valid statistics, only one parameter was changed to alter one operating condition. Specifically, parameters of DO, water temperature and HRT ranged from 1.5–4.0 mg/L, 2–30 °C, and 8–14 h, respectively. These values were chosen based on the ambient climatic conditions in a real WWTP. Samples were tested at about 10 d after the changes when the system was stable.

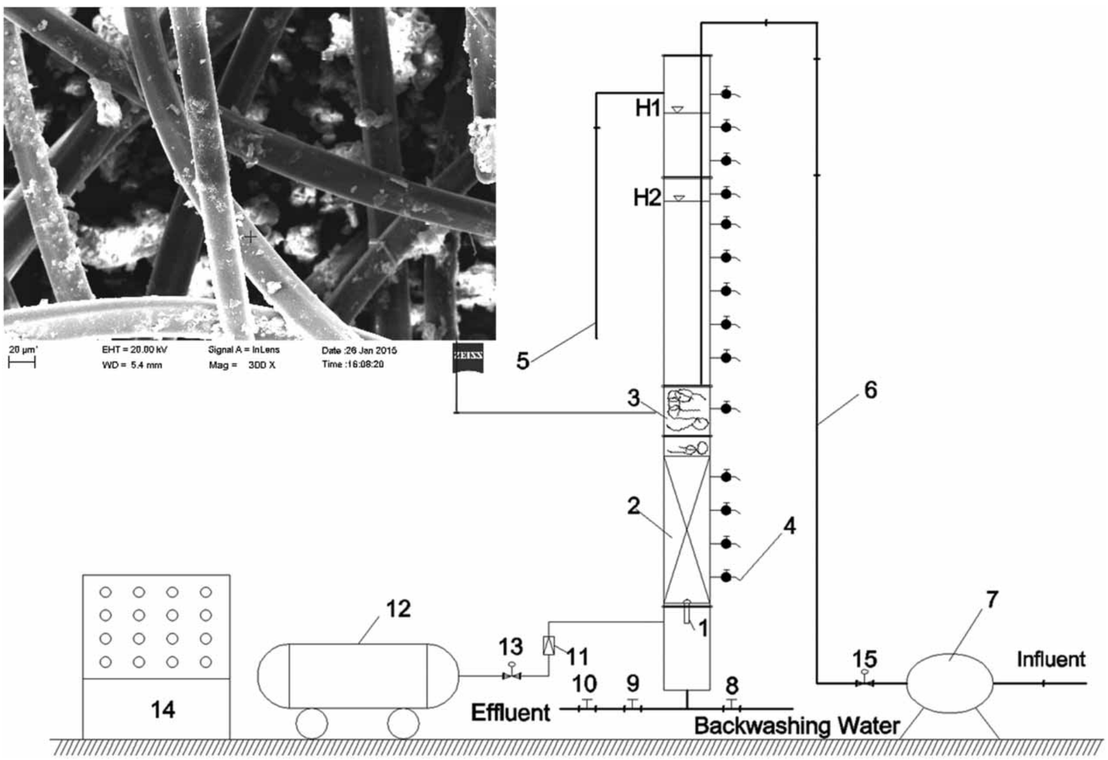

Figure 1 | Sketch of SBBF. 1, long handle filter nozzle; 2, ceramsite filter media; 3, fibrous filler; 4, sampling point; 5, overflow pipe; 6, intake pipe; 7, pipeline pump; 8, backwashing water valve; 9, effluent regulating valve; 10, effluent electronic valve; 11, gas flowmeter; 12, air compressor; 13, intake electromagnetic valve; 14, control cabinet; 15, influent electromagnetic valve; H1, highest water level; H2, lowest water level.

Table 1 | Characteristics of the raw water

Parameters	COD (mg/L)	NH_4^+-N (mg/L)	TN (mg/L)	TP (mg/L)	pH (−)
Range	66.8–203.9	10.7–23.8	12.4–26.7	1.3–4.3	6.4–7.8

The SBBF was inoculated with about 30 L activated sludge with a concentration of 3,000 mg/L, which was obtained from an aeration tank of Erlangmiao WWTP. Then the whole reactor was submerged in wastewater and aerated for 1 h to achieve complete mixing. After being conditioned for 10 h, the wastewater in the reactor was discharged entirely. Fresh influent was continuously injected into the reactor, with the discharge line opened to maintain a steady flow with aeration. This process continued for 15 days until attached biofilm could be found on the fibrous filler by microscopical examination (Figure 1). Then the reactor was operated as mentioned above. After 7 days, the removal of COD and total nitrogen (TN) were stabilized. The backwashing procedure was as follows: air scour for 2 min, combined air scour and water backwash for 2 min, and water backwash for 5 min. The backwash air and water velocities were 16 and 5 L/(m^2 s), respectively. The average operation before a backwash was 3 days.

Analysis methods

COD, ammonia nitrogen (NH_4^+-N), TN, total phosphorus (TP) and mixed liquor suspended solids (MLSS) of the samples were determined according to *Standard Methods* (APHA 2005). Water pH was measured by an 828 Orion pH meter. DO and water temperature were measured with a 52 YSI DO meter. Fibrous fillers were scanned by using a high resolution field emission scanning electron microscope (ZEISS, ΣIGMA HD/VP). Pretreatment was carried out as the procedures introduced in our previous paper (Ji *et al.* 2014).

RESULTS AND DISCUSSION

Effect of DO

Experimental results showed that DO concentrations did not significantly influence COD removal. Changes in COD removal rates were not obvious when the DO concentration varied from 1.5 to 4.0 mg/L (Figure 2A). Despite the COD fluctuation of the influent, the COD of the effluent was constantly below 25 mg/L. The SBBF could tolerate COD fluctuations in the wastewater due to the large population of microbes on the fibrous filler (Figure 1). Based on our previous report (Yang *et al.* 2014), the total biomass concentration in the reactor was over 4,000 mg/L constantly, and the biofilm had higher biomass concentrations. Numerous facultative aerobes attached on the surface or in the inner part of the fibrous filler could use organic compounds to metabolize and grow when the DO ranged from 1.5 to 4.0 mg/L. Moreover, the batch running mode could result in the dilution of the influent and alleviate the organic load for the next cycle.

NH_4^+-N removal increased dramatically when the DO concentration increased (Figure 2B). The reason lies in the fact that the process of ammonia oxidation is an aerobic reaction. More oxygen acts as electron acceptors, which is favorable to the process of nitrification. Moreover, the long SRT could benefit the growth of nitrifiers with long generation cycles (Dvok *et al.* 2013).

An appropriate DO value was important for TN removal and it proved to be 2–3 mg/L according to Figure 2C. A too low DO value could not trigger nitrification while a too high DO value hindered the denitrification process. Simultaneous nitrification and denitrification could happen in the SBBF (Rahimi *et al.* 2011). The growth of nitrifiers on the surface of the biofilm could degrade ammonia to nitrate or nitrite, while the denitrifiers in the inner part of the biofilm conducted the denitrification process.

It seemed that TP removal did not depend on DO concentrations in a range from 1.5 to 4.0 mg/L (Figure 2D). The disposal of phosphorus was mainly ascribed to the growth of biomass and the discharge of excess sludge. The two main factors affecting biological phosphorus removal were the organic matter concentration of the influent and the SRT value (Yoon *et al.* 2004). The low C/N ratio, organic loading rate variation and long SRT contribute to the weakness of phosphorus removal by the SBBF.

Effect of water temperature

Biological treatment of wastewater is the application of enzymatic reactions in microbes, and biological enzyme activity is greatly affected by temperature. So the bioreactor must be operated over a certain range of temperature. The study of the effect of temperature change on the treatment efficiency of the reactor is one of the key issues in the research into biological treatment technology. Since the SBBF system is operated in the wastewater plant under ambient climatic conditions, the water temperature is largely determined by the changes of season and weather.

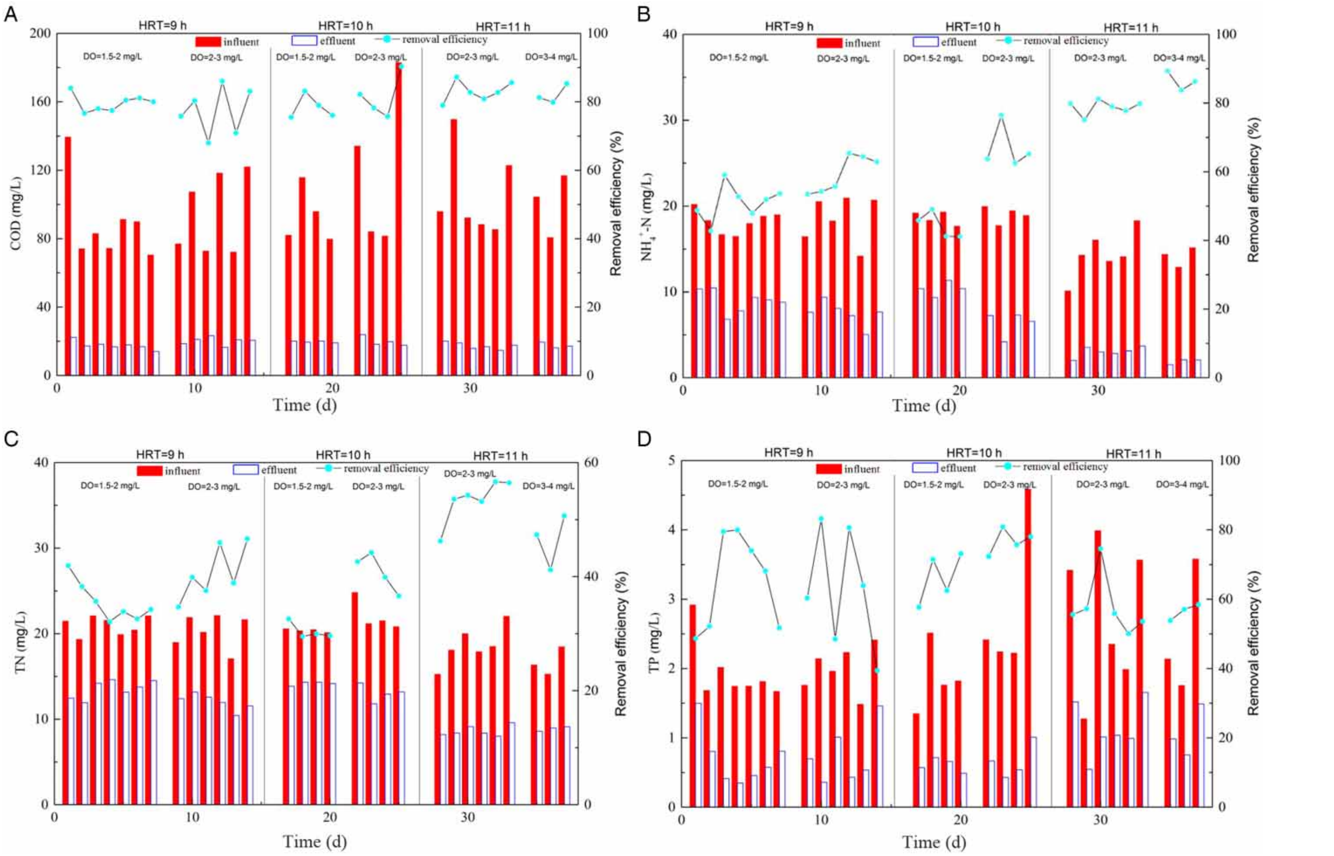

Figure 2 | Impact of DO; A: Variations of COD; B: Variations of NH_4^+-N; C: Variations of TN; D: Variations of TP.

Three ranges of temperature were investigated, which were 2–9 °C, 11–24 °C and 16–30 °C, respectively.

In the experiment, COD removal was slightly affected by temperature which ranged from 2 to 30 °C (Figure 3A). This may be caused by large populations of various species of microbes on the fibrous filler. Some species of bacteria could grow well in cold conditions (Akratos & Tsihrintzis 2007).

Water temperature can have dramatic impacts on the removal of nitrogen including NH_4^+-N and TN. When the temperature varied from 2 to 9 °C, the removal efficiencies of NH_4^+-N and TN were only 29.1% and 22.7%. When the temperature ranged from 16 to 30 °C, the average removal rates of NH_4^+-N and TN were 74.5% and 56.6%, respectively (Figure 3B and C). This showed that the activities of nitrifiers and denitrifiers were significantly affected by temperature.

The increase of water temperature might increase the phosphorus removal slightly but the enhancement is not obvious. The mechanisms of phosphorus removal in the SBBF were assimilation and denitrifying phosphorus removal (Ji *et al.* 2015). In cold conditions, some bacteria in the bioreactor could grow and absorb phosphorus. *Acinetobacter tjernbergiae* and *Acinetobacter lwoffii* were dominant species in the SBBF (Ji *et al.* 2015). It has been proven that the genus *Acinetobacter* is able to complete denitrifying phosphorus removal (Liu *et al.* 2014) at low temperatures. Despite the low removal efficiency of phosphorus in the SBBF, it was fairly stable over the range of temperature investigated (Figure 3D).

In summary, a variation of water temperature from 2 to 30 °C has a slight impact on COD and phosphorus removal. In order to obtain significant nitrogen removal, the water temperature should be above 10 °C. Moreover, the SBBF could achieve partial contaminants removal even at low temperatures.

Effect of HRT

The average COD removal efficiencies of the SBBF were 79.1%, 80.4%, 82.8%, 83.3%, 84.0%, 84.1% and 85.0% when the HRT was 8 h, 9 h, 10 h, 11 h, 12 h, 13 h and 14 h, respectively. This demonstrated that the HRT had little influence on COD removal, as shown in Figure 4A, COD varied from 66.8 to 203.9 mg/l in the influent and from 12.4 to

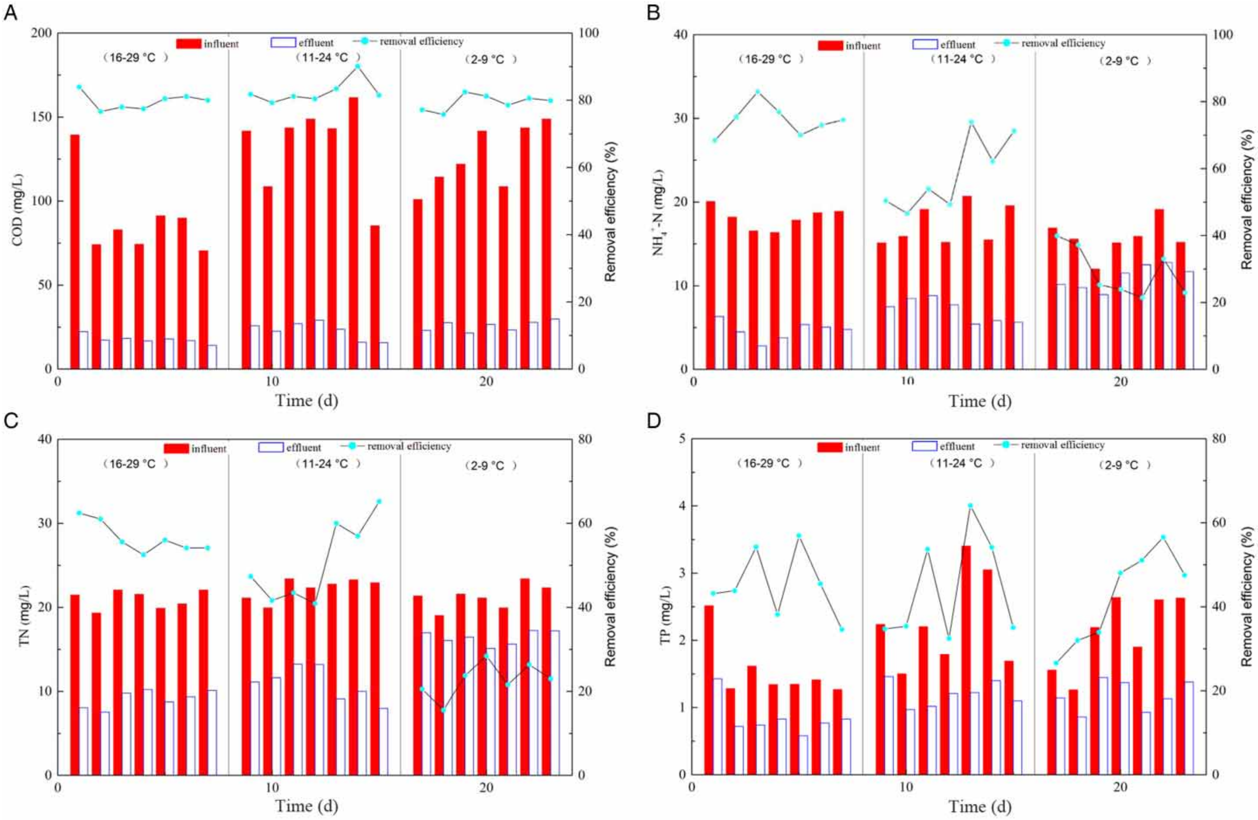

Figure 3 | Impact of water temperature. A: Variations of COD; B: Variations of NH_4^+-N; C: Variations of TN; D: Variations of TP.

23.9 mg/l in the effluent. This indicated that the SBBF can tolerate COD fluctuations in the wastewater.

The removal of NH_4^+-N increased with the increase in HRT (Figure 4B). Ammonium can be used as a nitrogen source for the growth of biomass. The growth of numbers of nitrifying microorganisms that adhered onto the large surface area of the fibrous filler contributed to the transformation of NH_4^+ to NO_3^-. A higher HRT could allow more time for the nitrifiers to degrade ammonia. With the increase in HRT, the removal of TN first increased and then decreased (Figure 4C). Experimental results demonstrated that a too high HRT of 14 h can slightly inhibit TN removal. This can be ascribed to the fact that denitrifiers grow slowly at low carbon concentrations which leads to insufficient organics being available as electron donors. Similar results were reported in a pilot-scale sequencing anoxic/anaerobic membrane bioreactor (Song *et al.* 2010).

A higher HRT favored phosphorus removal as indicated in Figure 4D. Unlike nitrogen and organic matter, phosphorus can only be removed by sludge discharge after backwashing in the SBBF. A higher HRT meant a reduced volume of influent and less phosphorus fed into the system during each cycle. So the polyphosphate-accumulating microorganisms could metabolize more effectively and conduct phosphorus assimilation.

In general, the optimal operating parameters for the SBBF were determined as follows: DO 2–3 mg/L, water temperature above 10 °C, and HRT 10–13 h. The SBBF could achieve over 80% COD removal, 50% TN removal, 70% NH_4^+-N removal and 40% TP removal under 0.160–0.489 kg COD/(m^3 d) organic loading rate.

The SBBF is the combination of a SBBR and a biological filter. The HRT of the SBBF was shorter, and the effluent contained fewer suspended solids compared to a SBBR and a biological filter. The novel bioreactor demonstrated effective pollutant removal from domestic sewage, especially for nitrogen removal. Another main technical advantage of the SBBF lies in the fact that it can tolerate COD fluctuations in the feed wastewater and has excellent ability to resist shock loads. However, the phosphorus removal of SBBF should be improved.

Kinetics modeling of the SBBF

The established kinetics model reflects the relationship between COD and HRT. The SBBF is a completely mixed

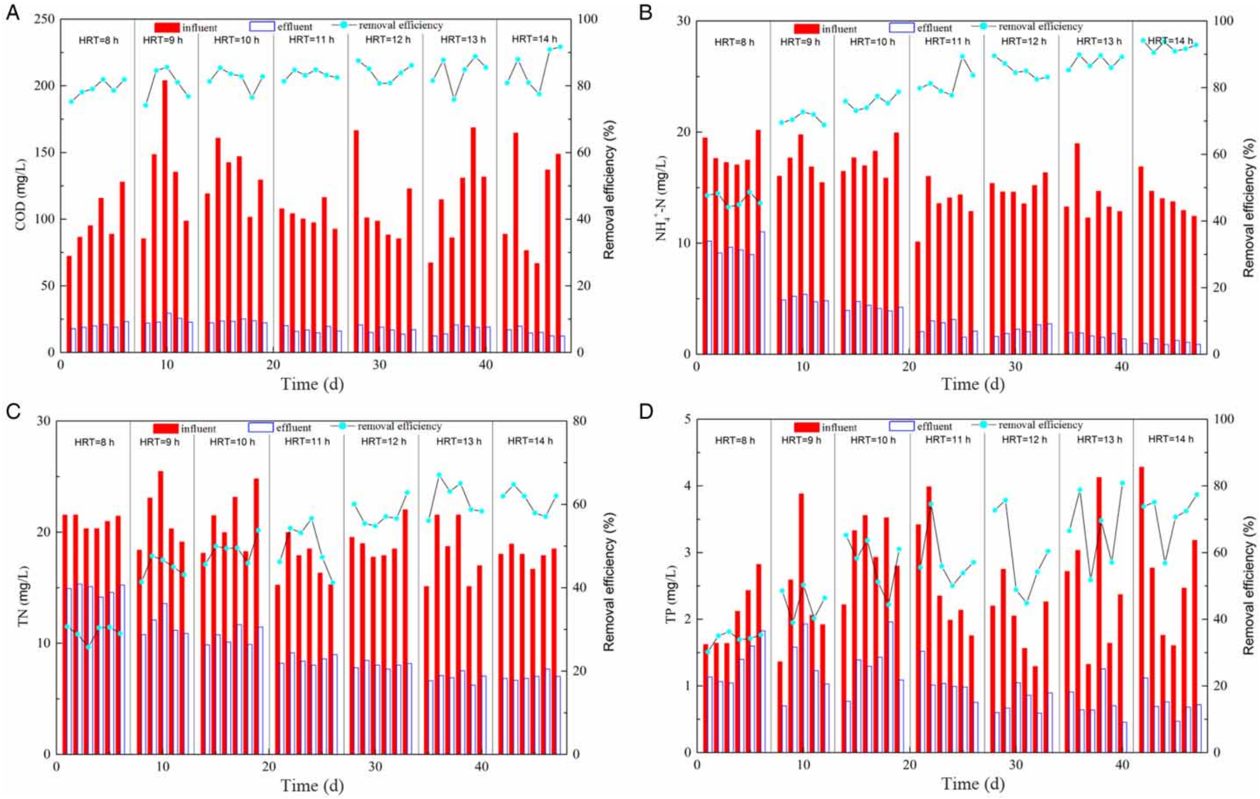

Figure 4 | Impact of HRT. A: Variations of COD; B: Variations of NH_4^+-N; C: Variations of TN; D: Variations of TP.

batch reactor. The overall reaction rate for substrate utilization can be described as a first order reaction (Wang *et al.* 2006). Based on Monod's Equation and mathematical deduction (Abu Hasan *et al.* 2014), the kinetics model can described as follows: $S = S_0\exp(-k\ t)$, where S_0 is the COD concentration of the influent, S is the COD concentration of the SBBF effluent, t is the hydraulic retention time and k is the reaction rate constant.

Taking S_0/S as the dependent variable, and t as the independent variable, according to the principle of least squares method, the kinetic constant K can be obtained (Table 2). The fitted result of kinetics modeling is shown in Figure 5. The fitted curve shows a close approximation to the kinetics model, which is $S_0/S = 2.985\ \exp(0.064\ t)$ ($R^2 = 0.9779$). Kinetics modeling of the SBBF indicates the relationship between COD and HRT and provides a fundamental reference for practical application.

Table 2 | Calibration of the kinetics model

t (h)	S_0(COD) average value (mg/L)	*S*(COD) average value (mg/L)	S_0/S
8	97.68	19.97	4.89
9	134.36	24.58	5.47
10	133.38	23.45	5.69
11	103.05	17.25	5.97
12	110.39	17.09	6.46
13	116.52	17.49	6.66
14	113.72	15.23	7.47

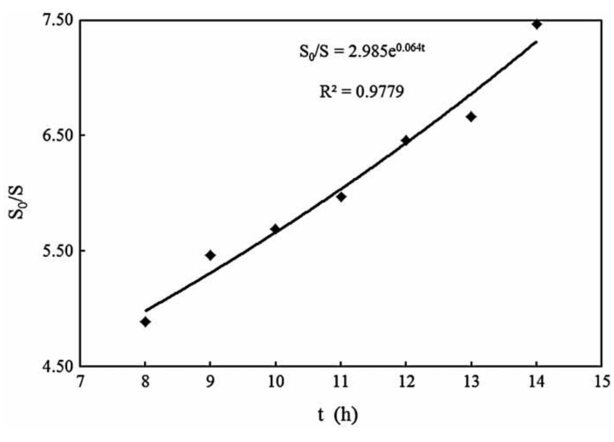

Figure 5 | Correlation curve of kinetics model.

CONCLUSION

The impacts of important factors including DO, water temperature and HRT on contaminants removal of a SBBF are described in detail. An excessive DO concentration was unfavorable for nitrate removal. Water temperature mainly affected nitrogen removal significantly. When the HRT ranged from 8 to 12 h, a higher HRT value favored contaminants removal. In order to achieve considerable organics and nutrients removal, the parameters should be controlled as follows: DO 2–3 mg/L, water temperature above 10 °C, and HRT 10–13 h. Kinetics modeling of the SBBF, reflecting the relationship between COD and HRT, was developed.

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