Municipal wastewater treatment through an aerobic biofilm SBR integrated with a submerged filtration bed
Kai Yang, Jiajie He, Mark Dougherty, Xiaojun Yang and Lu Li

ABSTRACT

A biofilm reactor and a gravitational filtration bed were integrated as a sequencing batch reactor (SBR) to aerobically treat a municipal wastewater. Polyacrylonitrile balls (50 mm diameter, 90% porosity) were filled into the upper part of the SBR as biofilm attaching materials and anthracite coal (particle size ~1.17 mm) was placed into the lower part as filter media. The SBR was aerated during filling and reaction phases, followed by a 10 min discharge phase during which the wastewater went through the filtration bed without aeration. The SBR was tested with raw wastewater from a municipal WWTP in Wuhan, China from July 2006 to January 2007, during both a warm season and a cold season. The SBR showed a capability to accept COD and turbidity fluctuations in the receiving wastewater. Seasonal influence on COD and nitrogen removal by the biofilm reactor was significant. Nitrogen and phosphorus removals were limited by COD levels in the wastewater. The filtration process removed considerable COD, nitrogen, phosphorus, and turbidity. The overall SBR effluent quality consistently satisfied the national secondary effluent discharge standard of China, except for total phosphorus. An anaerobic phase before the aerobic reaction is proposed to improve phosphorus and nitrogen removal. The filter normally required a backwash every seven days and the water needed for backwash was less than 4% of the wastewater treated by the SBR. This experiment provides information needed for further investigation to improve performance of the SBR.

Key words | aerobic, biofilm, filtration, SBR, wastewater

INTRODUCTION

Sequencing batch reactor (SBR) is renowned for its capability to achieve different wastewater treatment effects with flexible controlling strategies (Irvine et al. 1997). Specific characteristics of biological nitrogen and phosphorus removals have been investigated in detail through bench scale tests (Ho et al. 1994; Keller et al. 1997; Keller & Yuan, 2002) and realized in numerous full and pilot scale wastewater treatment facilities (Tasli et al. 2001; Wu et al. 2001; Li et al. 2003; Lee et al. 2004; Puig et al. 2004; Kargi et al. 2005; Obaja et al. 2005).

Membrane technologies have been used as an effective filtration process to achieve high quality effluent (Lubbecke et al. 1995), but its application has been restrained by the high cost of membrane modules (Wang et al. 2006). Kiso et al. (2000) and Wang et al. (2006) studied the potential of using a mesh filter unit to replace the membrane unit in a conventional suspended activated sludge system and found a quickly reduced hydraulic permeability of the filter media due to excess growth/accumulation of suspended sludge. Trussell et al. (2005) rated high solid contents in the water detrimental to the membranes in municipal wastewater treatment.

Biofilm processes do not have the same sludge separation issue and can have a reliable organic carbon and nitrogen removal once the biofilm has ripened (Odegaard et al. 1994). Gupta & Gupta (2001) incorporated sulphur
oxidizing bacteria into a rotating biological contactor (RBC) and achieved simultaneous 90% COD removal and 44 ~ 63% nitrogen removal under aerobic conditions. Srivastava & Majumder (2007) anticipated that a three- to six-fold increase in biofilm treatment capacity can be achieved with the progress of genetic engineering and appropriate engineering combination.

In this study, the potential of combining a biofilm reactor and a gravitational filtration bed was tested on municipal wastewater treatment. A pilot scale SBR was divided into two layers. The upper layer was filled with immobilized porous media as a biofilm reactor and the bottom layer was filled with anthracite coal as a gravitational filtration bed. The idea is to rely on the upper biofilm reactor to provide most of COD and nutrient removal and allow the filtration bed to intercept leftover particles and provide a certain level of contaminant removal. The SBR was operated under aerobic conditions during filling and reaction phases with the assumption that an aerobic reaction plus filtration can effectively remove COD, TN, TP, and TSS from the testing wastewater to levels that meet national regulations. Also, a relatively higher system daily wastewater treatment capacity was anticipated as a trade-off for a lower effluent quality than provided by introducing an anaerobic reaction phase. The highest system operating water level was set 1 metre above the lowest operating water level, which is right on top of the biofilm reactor. The filtration (discharge) period was approximately 10 min (at 5 m/h filtration speed), leading to an approximately 27% volumetric exchange rate for the biofilm reactor. The system was tested in a WWTP with raw wastewater for five months. Contaminant removal as a function of duration of aerobic reaction phase and seasonal water temperature were evaluated. Advantages and limitations of the tested system are discussed with respect to experimental results.

MATERIALS AND METHOD

Experiment apparatus

Experiment facilities are shown in Figure 1. A polymethyl methacrylate column of 5.5 m height and 23.5 cm inside diameter was used as a SBR. An air diffuser was put on the bottom of the column for aeration and water passage. The bottom 1.0 m of the column was designed to be used as a filtration bed and was filled with anthracite coal (particle size ~ 1.17 mm) as filter media. Starting from 10 cm above the top of the filtration bed, porous polyacrylonitrile balls (50 mm diameter, 90% porosity) were added to a depth of 3.0 m as growth materials for the biofilm reactor. Polyacrylonitrile balls within the biofilm reactor were immobilized with plastic screens placed above and below that section. Two water level sensors were placed 1.0 m apart along the column to control the water level (highest and lowest) inside the column, with the lowest water level (L) located at the top of the biofilm layer (Figure 1).

Sludge seeding, startup, and system operation

The inoculums were an aerobic sludge taken from the aeration pond in Wuhan ShaHu wastewater treatment plant. About 20 litres of aerobic sludge was inoculated into the test column and then the whole column was submerged into raw wastewater and aerated for 30 minutes to achieve complete mixing inside the column. After conditioned for 8 hours, wastewater in the column was emptied and fresh wastewater was continuously fed with

Figure 1 | Experiment facilities and specifics (not to scale).
the discharge line opened to maintain a steady state flow inside the column. Aeration was applied consistently from the bottom of the column. This process continued for about one week until biofilm removal rates of COD and NH$_3$-N were stabilized.

The operation cycle started with an aerated filling phase of 2 min to raise the water level from the lowest water level (L) to the highest water level (H), immediately followed by an aerobic reaction phase. During the filling and aerobic reaction phases, air was applied to the column from the air diffuser to maintain aerobic conditions in the biofilm reactor. The aeration rate was controlled to maintain a DO level of at least 2 mg/l at the top of the biofilm reactor. The required air flow rate during the experiment was approximately 0.2 m$^3$/h. During the discharge phase, the discharge line at the bottom of the column was opened and the wastewater went through the filtration bed at a speed of 5 m/h until the water level in the column dropped to the lowest water level (L). Under such operational scheme, with water volume deduction by biofilm growth in the porous medium neglected, the volumetric exchange rate of the biofilm reactor during each SBR operation cycle was estimated to be 27%. The whole operation cycle was controlled by a programmable logic controller (PLC). Water samples were taken at sampling points as indicated in Figure 1. The timing for sampling point A was: 1) right after a filling phase (for a homogeneous initial wastewater mixture); and 2) at the end of the aerobic reaction phase (for the treatment result of the biofilm reactor). Sampling point B was sampled during the middle of a filtration (for the final SBR effluent).

The system was operated consistently as a SBR with the preset filling/reaction/filtration procedure from July 2006 to January 2007, during which time the system experienced a warm season (water temperature $15.2 \sim 30.6^\circ$C) and a cold season (water temperature $11.2 \sim 16.4^\circ$C). Five aerobic reaction times (32, 40, 52, 60, 70 min) were tested during the warm season, and two aerobic reaction times (40 and 60 min) were tested during the cold season. The filtration water head loss was monitored by water pressure gauges deployed along the filtration column (Figure 1). When a filtration speed of 5 m/h could not be maintained at the maximum discharge line opening, the column was backwashed from the bottom with stored effluent water from previous SBR operation cycles at a loading rate of 6 l/m$^2$.s.

**Microfauna identification**

Biofilm was sampled regularly from the polyacrylonitrile balls during the experiment. Sequential dilution and agar plate isolation was applied to obtain typical single bacterial colonies that could be identified. The agar plate tests were nitrate reduction, glucose oxidation-fermentation, methyl red, Voges-Proskauer, indole production, gelatine hydrolysis, litmus milk reaction, catalase reaction, starch hydrolysis, lipid utilization, and citrate utilization. Fungus was identified with an OmniLog® ID System (Biolog, CA, USA). Protozoans, Metazoans, and Oligochaete were observed by an Olympus CX31 Microscope. All tests and observations were performed in the microbiology lab in the Department of Municipal Engineering, Wuhan University, China.

**Water analysis**

Dissolved oxygen (DO) and water temperature were measured with an YSI DO meter (Model 52). Water pH was measured by an Orion pH meter (Model 828). Turbidity was measured by a Hach turbidity meter (Model 2100P). COD was measured by closed reflux method, total nitrogen (TN) was measured by persulfate method, and total phosphorus (TP) was measured by ascorbic acid method as given in *Standard Methods for Examination of Water and Wastewater* (1998). Ammonia nitrogen (NH$_3$-N) was measured by Nesslerization. These tests were performed in the water chemistry lab in the Department of Municipal Engineering, Wuhan University, China.

**Statistical analysis**

Analysis of variance (ANOVA) was conducted to compare the levels of COD, NH$_3$-N, TN, TP, and turbidity at each sampling point during the experiment. Duncan’s tests ($\alpha = 0.05$) were used to separate the differences indicated by ANOVA tests and to evaluate the influence of aerobic reaction time and seasonal water temperature on the target parameters (contaminants’ levels and removal rates).
RESULTS AND DISCUSSIONS

COD and nitrogen

COD levels at each sampling point during the two-season experiment are shown in Figure 2a. Duncan test results are listed in Table 1. Figure 2a shows that despite a significant COD fluctuation of the initial mixture, the biofilm reactor effluent remained at a fairly stable COD level. Results indicate that even though the COD level of the biofilm reactor effluent remained relatively stable within each season, a significantly lower COD level was observed in the warm season compared to the cold season. With DO level being maintained above 2 mg/l during the experiment, a prolonged aerobic reaction time showed no significant improvement on COD removal. These results indicate that the upper biofilm reactor can tolerate COD fluctuations in the receiving wastewater, and that water temperature impacts COD removal under tested aerobic condition. The COD removal of the filtration bed was at least 6-fold lower than that of the biofilm reactor, suggesting biological assimilation in the biofilm reactor was the main cause for COD attenuation in this system. As a result, the overall influence on final COD removal was pronounced from

Figure 2  |  COD, NH3-N, total nitrogen, and total phosphorus removal during the experiment. (a. COD levels at each sampling point; b. NH3-N levels at each sampling point; c. total nitrogen (TN) levels at each sampling point; d. TN removal rates within the biofilm reactor versus initial CODcr/TN; e. total phosphorus (TP) levels at each sampling point; f. TP removal rates within the biofilm reactor versus initial CODcr/TN).
Table 1 | Mean and standard deviation of measured contaminants’ levels during the experiment

<table>
<thead>
<tr>
<th>Aerobic reaction time (min)</th>
<th>COD</th>
<th>Biofilm Effluent (mg/l)</th>
<th>Turbidity Biofilm Effluent (mg/l)</th>
<th>Filtration</th>
<th>Biofilm Effluent (mg/l)</th>
<th>Filtration</th>
<th>Biofilm Effluent (mg/l)</th>
<th>Filtration</th>
<th>Biofilm Effluent (mg/l)</th>
<th>Filtration</th>
<th>Biofilm Effluent (mg/l)</th>
<th>Filtration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial mixture (mg/l)</td>
<td>Effluent (mg/l)</td>
<td>Removal rate (%)</td>
<td>Effluent (mg/l)</td>
<td>Removal rate (%)</td>
<td>Effluent (mg/l)</td>
<td>Removal rate (%)</td>
<td>Effluent (mg/l)</td>
<td>Removal rate (%)</td>
<td>Effluent (mg/l)</td>
<td>Removal rate (%)</td>
</tr>
<tr>
<td>Warm Season: 15.2 – 30.6°C</td>
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<td></td>
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</tr>
<tr>
<td>32</td>
<td>N/A</td>
<td>19.60 ± 4.88a</td>
<td>65.09 ± 10.13ab</td>
<td>14.90 ± 3.28ab</td>
<td>8.47 ± 4.61a</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>40</td>
<td>N/A</td>
<td>22.43 ± 10.10ab</td>
<td>62.41 ± 13.09b</td>
<td>13.48 ± 3.68ab</td>
<td>14.38 ± 8.81a</td>
<td>14.13 ± 1.52a</td>
<td>7.79 ± 2.54a</td>
<td>45.17 ± 15.96ab</td>
<td>4.79 ± 2.04a</td>
<td>25.91 ± 9.72a</td>
<td>21.42 ± 10.23b</td>
<td>21.19 ± 10.18a</td>
</tr>
<tr>
<td>52</td>
<td>N/A</td>
<td>21.80 ± 10.68a</td>
<td>71.52 ± 16.01ab</td>
<td>13.90 ± 6.01a</td>
<td>10.21 ± 6.53a</td>
<td>14.13 ± 2.01a</td>
<td>7.35 ± 1.20a</td>
<td>47.56 ± 8.74a</td>
<td>3.65 ± 2.19a</td>
<td>27.52 ± 14.76a</td>
<td>3.32 ± 1.18b</td>
<td>24.43 ± 11.15a</td>
</tr>
<tr>
<td>60</td>
<td>N/A</td>
<td>21.69 ± 4.19ab</td>
<td>75.01 ± 8.05a</td>
<td>10.59 ± 2.63a</td>
<td>15.22 ± 4.86a</td>
<td>15.57 ± 1.69b</td>
<td>7.70 ± 0.84a</td>
<td>50.29 ± 5.62a</td>
<td>4.37 ± 1.07a</td>
<td>20.47 ± 7.58a</td>
<td>3.26 ± 1.04b</td>
<td>20.12 ± 7.34a</td>
</tr>
<tr>
<td>70</td>
<td>N/A</td>
<td>18.00 ± 6.66a</td>
<td>73.54 ± 4.48a</td>
<td>12.20 ± 4.21a</td>
<td>8.51 ± 2.94a</td>
<td>13.77 ± 0.32a</td>
<td>7.18 ± 0.77a</td>
<td>47.81 ± 5.70a</td>
<td>3.82 ± 1.18a</td>
<td>24.43 ± 11.15a</td>
<td>2.67 ± 0.75b</td>
<td>13.19 ± 6.02a</td>
</tr>
<tr>
<td>Cold Season: 11.2 – 16.4°C</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>40</td>
<td>N/A</td>
<td>19.11 ± 3.94c</td>
<td>63.23 ± 10.77b</td>
<td>20.11 ± 2.02b</td>
<td>13.27 ± 6.95a</td>
<td>13.35 ± 0.72a</td>
<td>9.64 ± 0.66b</td>
<td>27.68 ± 3.62c</td>
<td>6.96 ± 1.57b</td>
<td>20.22 ± 11.00a</td>
<td>3.45 ± 1.18b</td>
<td>13.39 ± 6.02a</td>
</tr>
<tr>
<td>60</td>
<td>N/A</td>
<td>34.70 ± 36.31c</td>
<td>69.65 ± 7.34ab</td>
<td>27.30 ± 10.04c</td>
<td>6.86 ± 4.41a</td>
<td>13.79 ± 0.25a</td>
<td>8.58 ± 0.70bc</td>
<td>37.78 ± 4.67b</td>
<td>7.14 ± 0.69b</td>
<td>10.41 ± 5.23b</td>
<td>2.87 ± 0.75b</td>
<td>14.56 ± 6.02a</td>
</tr>
</tbody>
</table>

1 The contaminant removal rates under biofilm and filtration are calculated by dividing the removed contaminants in each section (biofilm or filtration) by their levels in the initial mixture.

2 Duncan tests are applied for each contaminant level at each sampling point under all the tested aerobic reaction times at α = .05. Different letters in each column, including both warm and cold seasons, indicate that means are significantly different at the 95% confident level.
seasonal water temperature changes. The seasonal influence on COD removal from the biofilm reactor can be ascribed to the relatively higher COD and relatively lower bacterial activity during the cold season. Overall COD removal rate of the SBR varied 73.65% - 88.20%. Final SBR effluent maintained at a COD level less than 30 mg/l in the warm season and less than 40 mg/l in the cold season. The corresponding national secondary effluent discharge standard of China for COD is 60 mg/l.

Ammonia nitrogen (NH$_3$-N) and total nitrogen (TN) levels at each sampling point during the experiment are shown in Figures 2b, 2c. Results shown in Table 1 indicate that NH$_3$-N and TN levels in the initial mixture were fairly stable during the experiment. However, a significant seasonal fluctuation of NH$_3$-N and TN in the effluents of the biofilm reactor and the filtration bed was observed, with lower warm season levels than the cold season. This phenomenon may be ascribed to the temperature sensitivity of the nitrifying bacteria in the biofilm reactor. The detected microorganisms from the ripen biofilm are listed in Table 2.

As for nitrification, *Nitrosomonas* sp. responsible for NH$_3$-N oxidation were more commonly detected than *Nitrobacter* sp. which are responsible for nitrite oxidation. As for *Pseudomonas* sp., although this study did not attempt to isolate specific strains, their nitrifying capabilities were also recognized in wastewater treatment (Su et al. 2006). Wu et al. (2007) observed a pronounced selection between ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB) between 20 to 28°C, with AOB more sensitive to temperature fluctuations. Madoni et al. (1993) found that the presence of protozoan species are usually an indicator of low NH$_3$-N and high DO for a suspended activated sludge system. The presence of shelled amoebae also indicates a fully nitrified effluent (Poole, 1984; Madoni et al. 1993). In the present study, the relative abundance of *Nitrosomonas* sp. and *Pseudomonas* sp., together with the presence of protozoans and metazoans, indicates the wastewater was fully nitrified within the capabilities of the AOB. The seasonally changing nitrogen and COD removal was mainly the result of the ambient temperature related bacterial activity on the biofilm.

Also from Table 1, aerobic reaction time showed no significant influence on NH$_3$-N and TN removal within either season. Aerobic conditions maintained inside the SBR during the reaction phase potentially made carbon a deficient element for biological nitrogen removal. The TN removal rate of the biofilm reactor versus the COD/TN ratio of the initial mixture is shown in Figure 2d. From the figure, a trend of increased TN removal rate with increasing COD/TN ratio is observed and a seasonal difference in TN removal rate versus COD/TN ratio is also manifested. It is recognized that the C/N ratio of a wastewater is a limiting factor for biological nitrogen removal (Seixo et al. 2004). A C/N ratio of 20 to 30 is commonly found as necessary for effective microorganism utilization (Fontenot et al. 2007). Gupta & Gupta (2001) used biologically efficient sulfur oxidizing bacteria to simultaneously removal carbon and nitrogen under aerobic conditions and still required a C/N ratio of at least 12. Obaja et al. (2005) achieved a maximum of 99.8% nitrogen removal and 97.8% phosphate removal for a piggery wastewater in a SBR by adding additional wastewater at the beginning of the de-nitrification process to supply carbon source. Most municipal wastewater have a C/N ratio of around 6 (Choi et al. 1995). The C/N ratio of

<table>
<thead>
<tr>
<th>Genus</th>
<th>Species</th>
<th>Detection frequency (times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria</td>
<td><em>Sphaeratilus natans</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Zoogloea ramigera</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Leptothrix</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Alcaligenes</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Pseudomonas</em> sp.</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><em>Coliform</em> sp.</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><em>Nitrosomonas</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Nitrobacter</em> sp.</td>
<td>2</td>
</tr>
<tr>
<td>Fungus</td>
<td><em>Penicillium</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Geotrichum</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Trichosporon</em> sp.</td>
<td>2</td>
</tr>
<tr>
<td>Protozoans</td>
<td><em>Amoeba</em> sp.$^2$</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><em>Epistyliis</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Vorticella microstoma</em></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><em>Paramecium bursaria</em></td>
<td>10</td>
</tr>
<tr>
<td>Metazoans</td>
<td><em>Rotaria</em> sp.</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td><em>Philodina</em> sp.</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td><em>Nemathelminth</em> sp.</td>
<td>2</td>
</tr>
<tr>
<td>Oligochaete</td>
<td><em>Nais</em> sp.</td>
<td>10</td>
</tr>
</tbody>
</table>

$^1$A total of ten observations were taken during the experiment;

$^2$Both naked amoeba and shelled amoeba were detected.
the initial mixture in this experiment (COD level was converted into carbon level by COD × 16/32) was below 6 at all times. Above results suggest that the tested SBR reached its treatment limits under aerobic conditions. Aerobic biological nitrogen removal within the biofilm reactor can be improved with a proper increase of COD in the initial mixture to improve the COD/TN ratio.

Another method to improve nitrogen removal is to introduce a denitrification process into the SBR operation. The 10 min filtration time without aeration could potentially provide a certain level of denitrification, but the time is not long enough for a measureable denitrification effect to occur. Based on available reports, the time required for effective denitrification after an aerobic reaction is usually at least 1 hour (Obaja et al. 2005; Wu et al. 2007). Furthermore, denitrification requires that a carbon source be supplied, so the denitrification rate is directly related to the C/N ratio (Aesoy et al. 1998). It requires further investigation to study whether or not an effective denitrification process can exist under the tested low COD/TN ratio municipal wastewater within this tested SBR. Nevertheless, Marsili-Libelli (2006) through fuzzy modeling demonstrated that full denitrification can occur in less than 30 min by placing the denitrification process before an aerobic/anoxic phase when COD is relatively abundant. Since nitrification is fully achieved during this experiment, there are two likely methods to improve nitrogen removal. One, adjust the current 27% volumetric exchange rate to a C/N ratio optimized for nitrification under current aerobic operation configuration. Two, stop aeration during the filling phase and create a prolonged anaerobic phase for denitrification, which will also assist phosphorus removal as well (Puig et al. 2004; Kargi et al. 2005; Marsili-Libelli, 2006).

A trade-off between environment protection and economical operation has to be made based on the local socioeconomic situation. The biofilm reactor effluent had a NH3-N level less than 10 mg/l and a TN level less than 14 mg/l during the experiment. The final filtration effluent can provide a NH3-N level less than 10 mg/l and a TN level less than 13 mg/l. The current U.S. EPA standard for nitrate (NO3-) is 10 mg/l, while the current national secondary effluent disposal standard of China only places a requirement for NH3-N (< 25 mg/l), not including nitrate. During the experiment, the differences between TN and NH3-N in the final effluent were below 10 mg/l, indicating the final nitrate levels were always lower than the U.S. EPA regulation.

Total phosphorus (TP)

The TP levels at each sampling point during the experiment are shown in Figure 2e. It is observed that most of the TP was removed during the filtration process, but not through biological assimilation in the biofilm reactor. The results in Table 1 indicate a pronounced TP fluctuation in the biofilm reactor effluent that follows the trend of TP fluctuation in the initial mixture. This result indicates that the biofilm reactor had limited biological TP removal efficiency that led to a poor tolerance for TP fluctuation in the receiving wastewater. Also, water temperature and aerobic reaction time did not significantly influence TP removal within the biofilm reactor, suggesting the biofilm reactor reached its TP removal limit under experimental conditions. In the filtration bed, the amount of TP removed was found higher than that of the biofilm reactor. However, no significant influence on TP removal was observed as a result of water temperature or aerobic reaction time. This result indicates the filtration bed is the main phosphorus remove process in this system, so alternatives should be sought to increase the phosphorus removal rate in the biofilm reactor. The national secondary effluent disposal standard of China requires that final discharged TP levels should be less than 1.0 mg/l. However, the TP level in the final effluent in the tested SBR can only meet this standard for about 24% of the time, a major deficiency of the tested SBR.

The importance of an anaerobic phase for phosphorus removal in SBR was emphasized by Puig et al. (2004). Biological phosphorus removal requires an anaerobic phase for phosphorus release and then an aerobic phase for luxury phosphorus uptake. Different engineering combinations have been carried out to improve phosphorus removal based on this principle. Li et al. (2005) demonstrated a 90% phosphorus removal by alternating anaerobic and aerobic processes in a SBR. Kargi et al. (2005) achieved over 95% phosphorus removal in a SBR operated with anaerobic/anoxic/oxic phases. Cassidy & Belia (2005) obtained 98% phosphorus removal and 97% nitrogen removal by alternating anaerobic and aerobic conditions in a SBR treating an abattoir wastewater with granulated aerobic sludge.
Carbon source is also important for biological phosphorus removal. A higher COD at the beginning will result in a quicker phosphorus release, a more rapid phosphorus uptake, and a lower TP in the final effluent (Li et al. 2003). Also, the biodegradable substance level in a wastewater is positively related to biological phosphorus removal (Puig et al. 2007). The TP removal rate of the biofilm reactor versus initial COD/TN ratio during the experiment is shown Figure 2f. Similar to nitrogen removal, an increase in COD/TN ratio will yield an increased TP removal rate, which demonstrates that limited biological nitrogen assimilation will also limit biological phosphorus uptake. However, the differences between the warm and cold season are not significant, which corroborates the results in Table 1 that indicate no seasonal difference in TP removal from the biofilm reactor. These results suggest that if an anaerobic phase is needed for an improved phosphorus or nitrogen removal, it will be a practical option to place it right after or integrated with the filling phase, when COD is relatively higher and more biodegradable substrates are available.

Filtration performance

The turbidity levels at each sampling point during the experiment are shown in Figure 3. The biofilm reactor removed more turbidity than the filtration bed did and effluent remained at fairly stable turbidity levels even there was a significant turbidity fluctuation in the initial mixture during the experiment. Based on the Table 1 results, no influence on turbidity removal was observed as a result of either water temperature or aerobic reaction time. This indicates that the biofilm reactor did have an effective turbidity removal capability. The final filtration effluent maintained its turbidity less than 5 NTU for almost 77% of the time and the turbidity fluctuation from the biofilm reactor effluent was reduced further. In general, the whole SBR can accept a significant turbidity fluctuation from the receiving wastewater and provides a consistent turbidity removal.

As a common filtration bed, the tested gravitational filtration bed regularly needs backwash to maintain efficient hydraulic performance. During this experiment, the entire SBR column was backwashed when the filtration speed could not be maintained at 5 m/h at the maximum opening of the discharge line. Throughout the experiment (data not shown), the average filtration bed operation time before a backwash was 7 days and the maximum time was 14 days. A backwash loading rate of 6 l/m².s was tested sufficient to expand the filtration bed to fill the 10 cm space between the filtration bed and the biofilm reactor, corresponding to a 10% expansion rate. The water for backwash was from a reservoir where treated wastewater from previous treatment cycles was stored. The turbidity in the backwash effluent was reduced from 1600 NTU and stabilized around 20 NTU.
in less than 18 min. No significant improvement on backwash effluent turbidity was observed as backwash time was prolonged (data not shown).

Assuming it takes 60 min for the SBR to finish one operational cycle and the SBR can operate consistently for 7 days before a backwash is needed, at a volumetric exchange rate of 27% the total volume of treated wastewater will be around 29,000 L. The water needed for a backwash at a loading rate of 6 l/m².s for 18 min is approximately 1,100 L, which is less than 4% of the total treated wastewater.

CONCLUSIONS

A biofilm reactor integrated with a submerged gravitational filtration bed was operated as a SBR and tested with raw wastewater for five months which included both a warm and cold season. The SBR showed a capability to accept significant COD and turbidity fluctuations from the receiving wastewater. The biofilm reactor performance with regard to COD and nitrogen removal was affected by seasonal wastewater temperature. Aside from its original purpose to intercept solids, the filtration bed was proven a critical component of the SBR for COD and nutrient removal. The overall SBR effluent quality was consistent and, except for total phosphorus (TP), satisfied the national secondary effluent discharge standard of China. Biological nitrogen and phosphorus removal was limited by relatively low COD levels in the receiving water. A 30 min aerobic reaction time was found sufficient for the biofilm reactor to complete contaminant removal. The filtration bed was operated continuously for at least 7 days before a backwash was needed, with less than 4% of treated wastewater used for a backwash.

An anaerobic phase before the aerobic reaction phase was proposed as a practical method to improve phosphorus and nitrogen removal. Also, adjustment of the current 27% volumetric exchange rate may produce an improved COD/TN ratio that can help increase nitrogen and phosphorus removal under the current aerobic operation configuration. Further investigations are needed to test these concepts for improving the performance of the SBR in this study.

REFERENCES


