Nitrogen-removal efficiency in an upflow partially packed biological aerated filter (BAF) without backwashing process

Pramanik Biplob, Suja Fatihah, Zain Shahrom and ElShafie Ahmed

ABSTRACT

An upflow, partially packed biological aerated filter (BAF) reactor was used to remove nitrogen in the form of ammonia ions by a nitrification process that involves physical, chemical and biological phenomena governed by a variety of parameters such as dissolved oxygen concentration, pH and alkalinity. Dissolved oxygen (DO) and pH were shown to have effects on the nitrification process in this study. Three C:N ratios i.e., 10, 4 and 1 were compared during this study by varying the nitrogen loading while the carbon loading was kept constant at 0.405 ± 0.015 kg chemical oxygen demand m⁻³ d⁻¹. The removal efficiencies of ammonia linearly increase with a rise of the initial concentration of ammonia-nitrogen. The results of the 115 days’ operation of the BAF system showed that its overall NH₃-N performance was good, where a removal efficiency of 87.0 ± 2.9%, 89.2 ± 1.38% and 91.1 ± 0.7% and COD removal of 87.6 ± 2.9%, 86.4 ± 2.1% and 89.5 ± 2.6% were achieved for the C:N ratios of 10, 4 and 1, respectively on average, over 6 h hydraulic retention time (HRT). No clogging occurred throughout the period although backwashing was eliminated. It was concluded that the BAF system proposed in this study removed nitrogen by the nitrification process extremely well.

Key words | alkalinity, biological aerated filter (BAF), C:N ratio, DO, nitrification, pH

INTRODUCTION

Carbon and nitrogen are major pollution sources that contribute to environmental quality problems all over the world, especially those that mainly cater to treatment of wastewater. The most adverse environmental impacts associated with improper discharge of municipal wastewater containing significant amounts of organic matter (chemical oxygen demand, COD), nitrogen (N) and phosphorus (P) include promotion of eutrophication, toxicity to aquatic organisms and depletion of dissolved oxygen receiving streams (Klees & Silverstein 1992; Moosavi et al. 2005). Nitrate- and nitrite-contaminated water supplies are also related to several diseases such as methemoglobinemia in infants, also known as ‘blue baby disease’ (Doyle et al. 1985; Gálvez et al. 2005). Due to the adverse impacts, completed treatment of municipal wastewater before discharge is increasingly necessary.

Although conventional biological treatment processes are mostly reliable, well designed and tested, they present a number of drawbacks in terms of treatment capacity, efficiencies, stability and space requirements. Advanced biological treatment processes, developed to overcome these deficiencies, are now in increasing demand. One of the systems, the biological aerated filter (BAF), appears to be promising.

The application of a BAF in municipal and industrial wastewater treatment has increased significantly, first in Western Europe and then worldwide, as a novel wastewater-treatment system due to its advantages over other systems (Mann et al. 1998; Ryu et al. 2008). Due to the number of advantages of the BAF process, a space-saving layout that takes up only one-third of the footprint size of an activated sludge process can be achieved (Han et al. 2009).
BAF systems have also been shown to operate successfully at higher hydraulic and organic loading rates (OLR) than activated sludge systems (Mendoza-Espinosa & Stephenson 1999; Ryu et al. 2008). Peladan et al. (1997) reported OLR up to 18 kg COD m⁻³ day⁻¹ in high-water-velocity BAFs. Although the BAF system has many advantages, it has been difficult to apply for the treatment of raw wastewater, which contains a high concentration of suspended solids. Several researchers have tested the BAF for ammonia and nitrogen removal (Tay et al. 2003; Lee et al. 2005). A pilot scale fixed-film bioreactor system demonstrates greater waste degradation than traditional technology, e.g., the removal rates for COD were consistently between 80% and 90% at an empty bed HRT of 8 hours for the entire system (Jou & Huang 2003). In addition, successful nitrogen removal in high-strength wastewater was also investigated by Tay et al. (2003) using a single fixed-bed filter with anaerobic, anoxic and aerobic zones.

A BAF consists of a medium that provides a large surface area per unit volume for biofilm development. The filter media play a significant role in wastewater treatment. The characteristics of the media are not only related to the initial capital outlay, process design and operation mode of BAFs, but also affect daily running costs like backwashing and air influx (Rozic et al. 2000; He et al. 2007). For the development of biofilm technologies, the BAF has been considered to be a system capable of enhanced biological carbon and nitrogen removal. But the average nitrification rate was reduced when weekly backwashing was applied due to a loss of autotrophic bacteria (Elenter et al. 2007). Most of the cost problems with the BAF are related to backwashing, media, aeration and sludge handling. A partially packed-bed BAF has a lower media cost, saves energy during aeration, requires a lower capital investment for pumping facilities and has a thinner and denser biofilm with better attachment of nitrifiers (Fatihah 2004). Studies on the effects of low C:N ratios on carbon and nitrogen removal in BAFs have been done to better understand removal behaviour as the ratio is decreased (Ryu et al. 2008). Fixed COD loading was applied to stimulate the growth of autotrophs as autotrophs decrease with the incremental increase of influent COD (Ni et al. 2008).

An understanding of the impact of C:N ratio on nitrogen removal wastewater is imperative for optimizing the biofilm reactor. A study by Fatihah (2004), at a C:N ratio of 24:1, showed that partial nitrogen removal occurred most probably because of a very low concentration of limiting carbon source due to high total organic carbon (TOC) removal efficiency of 92.1 ± 6.5% for full-bed BAF and 90.2 ± 6.3% in partial bed. However, information on the performance of the BAF under various operating and environmental conditions is still lacking.

For this purpose, the studies propose a partially packed upflow BAF process, within which nitrification steps were investigated. The main objective of this paper was to evaluate the effect of different low carbon–nitrogen ratios in synthetic wastewater to remove carbon and nitrogen using a partially packed biological aerated filter without any backwashing process at 30 ± 2°C and to investigate ammonia-nitrogen removal impacting nitrification parameters.

**MATERIALS AND METHODS**

**Synthetic wastewater**

A synthetic wastewater prepared in the laboratory was used to provide a consistent organic substrate for loading. The synthetic feed was formulated by considering the major nutritional requirements for microbial growth including sources of carbon, sources of energy, electron acceptors, nitrogen sources and sources of other major mineral nutrients like sulfur, phosphate, potassium, magnesium, calcium and trace-metal requirements. The composition of the synthetic wastewater, prepared with tap water, is shown in Table 1.

**Operation of BAF and experimental setup**

The BAF reactor used in this study was cylinders 1.5 m in height (0.65 m in attached growth zone and 0.85 m in suspended growth zone) and 0.15 m in diameter with a working volume of approximately 26 L. The reactor was partially packed with plastic media (Kaldnes K1, Sweden) and the system was operated at 30 ± 2°C. According to the mechanical and biological tests performed, plastic has the lowest weight loss and it can be considered as the most suitable medium for application in the pilot scale BAF.
(Farabegoli et al. 2003). The experimental equipment consisted of the partial-bed reactor, one feed tank, one effluent tank, an interconnecting pipe network, pumping facilities, diffuser and the sensors for ORP (RD1R5, Hach, USA), pH (PD1R1, Hach, USA) and DO (5540DOA, Hach, USA). Masterflex peristaltic pump (77200-60, USA) was used to supply the feed. A polypropylene mesh was positioned in between the suspended growth and attached growth zones to keep the medium in place. A schematic of the experimental set-up is shown in Figure 1.

Table 1 | Synthetic wastewater composition

<table>
<thead>
<tr>
<th>Source</th>
<th>Composition</th>
<th>Concentration (mg L⁻¹)</th>
<th>C:N 1</th>
<th>C:N 4</th>
<th>C:N 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>Glucose</td>
<td>1,000</td>
<td>13,000</td>
<td>13,000</td>
<td>13,000</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>NH₄Cl</td>
<td>600</td>
<td>13,000</td>
<td>3,250</td>
<td>1,296</td>
</tr>
<tr>
<td></td>
<td>KNO₃</td>
<td>50</td>
<td>650</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>KH₂PO₄</td>
<td>7.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Na₂HPO₄</td>
<td>944</td>
<td>129</td>
<td>129</td>
<td>129</td>
</tr>
<tr>
<td>Nutrient</td>
<td>MgCl₂ 6H₂O</td>
<td>100</td>
<td>1,300</td>
<td>1,300</td>
<td>1,300</td>
</tr>
<tr>
<td></td>
<td>MnCl₂ 4H₂O</td>
<td>0.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>FeCl₂ 6H₂O</td>
<td>0.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>CaCl₂ 2H₂O</td>
<td>7.5</td>
<td>97.5</td>
<td>97.5</td>
<td>97.5</td>
</tr>
</tbody>
</table>

Figure 1 | BAF reactor.
The pH, DO and ORP data were taken from pH (P33, Hach, USA), DO (D33, Hach, USA) and ORP (P33, Hach, USA) meters, respectively, during the off-line monitoring period of the BAF reactor. Due to the lack of on-line monitoring, pH, ORP and DO data were taken once a day. Aeration was supplied by a compressor into the air inlet pipe to the reactor. The air pump was connected to the air diffuser, which was placed at the bottom of the column to provide air to the reactor. The flow rate for the continuous aeration was determined by the air control meter (Model No 0Z0395F, Japan). During this study, air flow was set at 2.5 L min\(^{-1}\). Air delivered through this system had to provide adequate air supply for biological activity and for mixing within the reactor. Activated sludge from a biological nutrient-removal municipal wastewater-treatment plant was used as a seeding culture, in which the mixed-liquid suspended-solids (MLSS) value was approximately 2,500 mg L\(^{-1}\). Activated sludge was used for the seeding process because of its high suspended biomass concentration, which leads to rapid biofilm formation (Mann et al. 1999). In this seeding process, the activated sludge was fed daily batchwise with 0.405 ± 0.015 kg COD m\(^{-3}\) d\(^{-1}\) of synthetic wastewater until a high concentration of biomass was obtained and a biofilm was formed on the plastic particles. During the study period, the COD load was set at 0.405 ± 0.015 kg COD m\(^{-3}\) d\(^{-1}\) and the loads of ammonia were investigated based on different C:N ratios as shown in Table 2.

### RESULTS AND DISCUSSION

#### COD-removal performance

Organic matter, in terms of COD, is one concern in the treatment of wastewater. Therefore, its removal is the focus of a wastewater treatment facility. The removal process was carried out by the microorganisms that grow attached to the filter-packed media. In this study, the COD removal pattern is quite consistent with the loadings and COD-removal efficiency was high at 87.6 ± 2.9%, 86.4 ± 2.1% and 89.5 ± 2.6% with different C:N of 10, 4 and 1, respectively, at 6 h HRT. At a C:N ratio of 24, the carbon removal was also known to be high (TOC removal efficiency of 90.2 ± 6.3% in partial bed) (Fatihah 2004). For different C:N ratios, the COD removal efficiency did not vary significantly based on changes of the ratio. Sales & Shieh (2006) reported that for C:N ratios of 50 and 100 the COD removal efficiency (above 90%) was similar for both ratios for an A/O hybrid bioreactor. However, the COD removal was almost stable during the experimental period. This trend occurred because of the fully developed biofilm structure inside the reactor on the plastic media.

The high removal efficiency in the experiment was due to the efficient utilization of organic compounds in the aerobic process. In addition, the high removal rate could also be attributed to the complete particulate retention of suspended COD and BOD, high-molecular-weight organics and biomass (Stephenson et al. 2000). In this study, suspended solids was found to be high and this resulted in the depletion of COD and nitrogen removal due to competition for oxygen inside the reactor. The attached-growth system does not possess good settling characteristics. According to Ong et al. (2004), a shorter HRT would lead to more dispersed growth and therefore poorer suspended solids settling in the treated effluent. Furthermore, there was no biomass separation step in the BAF reactor. Most of the suspended solids, mainly from biofilm detachment, accumulated at the bottom of the reactor because of a lack of backwashing in this experiment. The nitrification process typically requires an MLSS concentration between 2,000

### ANALYSIS

Influent and effluent samples were collected each day from the influent tank and effluent pipe. The samples were analyzed for COD, NH\(_3\)-N, NO\(_3\)-N, alkalinity, suspended solids and MLSS. Chemical analyses were carried out according to standard methods (APHA 1998). DO, pH and ORP were measured using a DO probe meter, pH meter and ORP probe meter, respectively. All samples were analysed after being filtered through 0.45-μm pore size filter paper.

<table>
<thead>
<tr>
<th>Load</th>
<th>C:N 1</th>
<th>C:N 4</th>
<th>C:N 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD (kg m(^{-3}) d(^{-1}))</td>
<td>0.405 ± 0.015</td>
<td>0.405 ± 0.015</td>
<td>0.405 ± 0.015</td>
</tr>
<tr>
<td>NH(_3)-N (kg m(^{-3}) d(^{-1}))</td>
<td>0.184 ± 0.001</td>
<td>0.046 ± 0.001</td>
<td>0.018 ± 0.001</td>
</tr>
</tbody>
</table>
and 3,500 mg L$^{-1}$. It was indicated that low MLSS concentrations do not provide for the establishment of an adequate population of nitrifying organisms to perform nitrification. High MLSS concentrations can result in unacceptable suspended solids concentrations in the effluent. The COD removal rate for BAF reactors was very high throughout the operation, and was unaffected by changes in the MLSS concentration. The results show that the partially packed upflow BAF reactor without backwashing was generally reliable and it had a better treatment capacity at a low C:N ratio with less HRT. Clogging did not occur also because of the low influent load and low sludge production during the operating period. Carbon-removal performance in this type of system showed improved carbon removal although the C:N ratio was low.

The relationship between the COD loading rate and COD removal is shown in Figure 2. A linear regression of the data indicated that COD removal rate had a linear relationship with loading rate ($R^2$) of 0.85. According to Farabegoli et al. (2005), a linear relationship between the COD loading rate and its removal efficiency was investigated in a downflow-submerged BAF with an $R^2$ of 0.6192. Westerman et al. (2000) also similarly obtained a linear relationship between the COD loading rate and its removal in an up-flow biological aerated filter with an $R^2$ of 0.92.

**Nitrogen-removal performance**

The variation of ammonium-nitrogen (NH$_3$-N) in BAF was observed according to the variation of influent of ammonium during the operation period. The average influent loading of ammonium was 0.182 kg NH$_3$-N m$^{-3}$ d$^{-1}$, 0.046 kg NH$_3$-N m$^{-3}$ d$^{-1}$ and 0.018 kg NH$_3$-N m$^{-3}$ d$^{-1}$ with a C:N of 10, 4 and 1, respectively. In this study, the removal of NH$_3$-N was 87.0 ± 2.9%, 89.2 ± 1.5% and 91.1 ± 0.7% with a C:N of 10, 4 and 1, respectively. The study done by Ryu et al. (2008) proposed a four-stage biological aerated filter system to treat low C:N ratio wastewater with a nitrogen removal of more than 95% for a ratio of TCOD:TKN of 4.3 ± 1.1. NH$_3$-N removal was relatively high over this time but stability of the removal rate was only achieved at a C:N of 1 during the study period, which may be due to variation of alkalinity consumption. The relationship between the ammonia loading rate and ammonia removal loading rate was linear with an $R^2$ of 0.97 (figure not shown here). On the other hand, there was no backwashing involved in this operation.

It was observed that ammonia decreased over time under aerobic conditions, and there was a corresponding increase of the nitrate concentration over time as ammonia was converted to nitrate through nitrification. Nitrate concentration rose as the aeration continued, indicating that the nitrite-oxidizers were present in the reactor, and that they were adjusting to the aerobic environment. The nitrification rate may have been limited by the biodegradable organic matter concentration or by the variation in oxygen concentration. Nitrate removal occurred at more than 70% when the DO was below 0.6 mg L$^{-1}$ and the anoxic phase was available at C:N 10 (Figure 3). If oxygen is properly supplied to the reactor with the inlet wastewater, biodegradable organic matter will be consumed in the process of oxygen respiration and thus reduce the amount available for denitrification. But under low DO conditions in the biofilm layer, nitrate also produced by the nitrification process was converted via nitrite to nitrogen gas, which was then evolved from the reactor. Therefore, removal of nitrate can be found in the process (Figure 3).

**Figure 2** | Relationship between COD loading and removal.

**Figure 3** | Nitrate removal at different C/N.
The removal efficiency of ammonia-nitrogen linearly increased with the decrease of COD/NH₃-N. The study shows that the NH₃-N removal percentages of 91.1, 89.2 and 87.0% were achieved for the COD/NH₃-N of 2.2, 8.8 and 22.5, respectively (Figure 4). Ahmed et al. (2007) also found that for the influent COD/NH₄ of 7.2, 9.9 and 14.7, the removal efficiencies in the combined system were 88, 80 and 69%, respectively. Therefore, the results suggest that the nitrification efficiency may have also been inhibited by substrate (ammonia) concentration, because an increase in ammonia loading led to an increase in nitrification rate.

Free ammonia concentration

pH, temperature and ammonium concentration are the most important parameters that can influence the equilibrium controlling the free ammonia concentration (Farabegoli et al. 2004). Temperature influences bacterial kinetics of the nitrification process in the biofilter operation. The study was only performed at 30 ± 2°C and the NH₃-N removal was 87.0, 89.2 and 91.1% with the C:N ratios of 10, 4 and 1, respectively. When experimental temperature varied between 21°C and 31°C, higher temperature greatly improved the nitrification and COD reduction gradually went up from 73 to 86% (Li & Zheng 2004).

Figure 5 shows the concentration of the free ammonia in the BAF reactor after the start-up, calculated by Equations (1) and (2), was introduced in this study. The maximum levels of free ammonia are found at the bottom of the reactor since they decrease as the height increases (Fdz-Polanco et al. 1994). Figure 5 shows that at the bottom of the filter pH increase brings about an increase of free ammonia concentration at 30 ± 2°C according to Equation (1). Values of free ammonia concentration were 0.02 mg L⁻¹, 0.124 mg L⁻¹ and 0.176 mg L⁻¹ with respect to the C:N ratios of 10, 4 and 1, respectively. The free ammonia concentration was always in the range of 0.1–1 mg NH₃free-N L⁻¹ from 55 cm to the bottom of the filter (Farabegoli et al. 2004). High free ammonia (NH₃-N) inhibited not only nitrite oxidizing bacteria (NOB) but also ammonia oxidizing bacteria (AOB) (Kim et al. 2006). Furthermore, very little is known about the effects of different growth environments on nitrifying bacteria communities. Finally, the discussion of the concentration of free ammonia was carried out based on results from the lower part of the BAF reactor.

Free ammonia concentration depends heavily on pH based on the following equation:

\[ [\text{NH}_3\text{-N}]_{\text{free}} = \frac{[\text{NH}_4\text{-N}] \times 10 \text{pH}}{(K_a / K_w) + 10 \text{pH}} \]  

(1)

where \( K_a \) is the ammonia constant and \( K_w \) is the water ionization constant. The hydrolysis of ammonia reaction constant is dependent on temperature:

\[ K_a / K_w = \exp \left( \frac{6.354}{273 + T} \right) \]  

(2)

Effect of DO, pH and alkalinity on nitrification

DO profile

DO concentrations have a direct effect on the growth rates of nitrifying bacteria. In the presence of low dissolved oxygen,
incomplete nitrification occurred, which led to a build-up of ammonium within the BAF (due to the insufficient aeration time to convert the ammonia to nitrate). Zhu & Chen (2002) reported that it was more important to maintain sufficient DO in the fixed film process than in the suspended growth processes due to the nature of diffusion transport with fixed film.

Figure 6 shows that the nitrification rate increased along with a rise of DO concentration. The influence of DO on the nitrification process indicated that for 1 mg L\(^{-1}\) changes in DO in an aerobic reactor 10% removal of ammonia-nitrogen was achieved when the DO range was 0.48–0.98 mg L\(^{-1}\) in this study. According to the results, the nitrification rate improved with an increase of DO up to 3.7 mg L\(^{-1}\) and decreased above 4.0 mg L\(^{-1}\), which shows that over-aeration leads to a reduction in the nitrification efficiency because of detachment of the biofilm from the plastic media. In order to achieve an NH\(_4\)-N removal of above 60%, the dissolved oxygen concentration in the aerobic system should be maintained above 1 mg L\(^{-1}\) (Hsu & Chiang 1997). It is generally known that a DO concentration above 1 mg L\(^{-1}\) is essential for nitrification; if the DO level is lower, oxygen becomes the limiting factor and nitrification slows. Since DO acts as an electron acceptor in the biochemical reaction, its concentration is necessary in the reactor at the time of the nitrification process. Based on the available information, a suitable range of DO concentrations required to reliably achieve nitrification is between 2 and 4 mg L\(^{-1}\) in order to prevent the possibility of oxygen limitation and to enhance ammonia removal.

**Alkalinity and pH profile**

Alkalinity is important not only for nitrification but also to indicate system stability. The decrease in pH is caused by the removal of ammonia from the system, and ammonia was also strongly correlated to the alkalinity of the wastewater. The end of alkalinity consumption in the wastewater was indicated by the complete removal of ammonia. The relationship between alkalinity (total alkalinity, in CaCO\(_3\)) and the NH\(_3\)-N removal efficiency is shown in Figure 7. It can be seen that the nitrogen removal rate was enhanced with an increase of alkalinity. The alkalinity affecting nitrification and the nitrogen removal rate improved with an increase of alkalinity when the wastewater’s alkalinity to NH\(_3\)-N ratio is less than 8.85 (Sakairi et al. 1996); however, this study shows the average ratio to be 2.10. Gujer & Boller (1986) also reported that in nitrifying biofilters used in municipal wastewater treatment, an alkalinity level of at least 75 mg L\(^{-1}\) was needed to maintain maximum nitrification rate. The result shows that the average alkalinity concentration was 93 mg L\(^{-1}\) during the entire period of this study. Therefore, sufficient alkalinity must be available in order to achieve complete nitrification, and operators must continuously monitor this parameter to achieve at least 100 mg L\(^{-1}\) of alkalinity in the wastewater effluent.

The impact of alkalinity on the nitrification rate is related to the pH. It has been reported that the pH of wastewater should be maintained between 6 and 9 to protect organisms (Akpor et al. 2008). In a study on the pH effect upon the nitrification efficiency in an upflow biofilter, it was reported that nitrification efficiency showed a linear increase of 13% per unit pH increase from pH 5.0 to 8.5 (Villaverde et al. 1997). The study also showed that the ammonia-nitrogen removal increased linearly with the raise of pH value with an \(R^2\) of 0.72 (data not shown here). Figure 8 shows the NH\(_3\)-N removal increasing from...
81.6 to 92.3% when there is a change of pH value from 4.7 to 6.4. While it was indicated that pH 6.45 to 8.95 had no effect on nitrification, a pH lower than 6.45 and over 8.95 completely inhibited the nitrification process (Jianlong & Ning 2004). After all, nitrification was not consistent due to the instability of the pH of the system. Thus, pH control was required for the reactor to complete nitrification and enhance nitrogen removal.

CONCLUSIONS

The up-flow partially packed BAF system with plastic media was evaluated for enhancing nitrogen removal in the treatment of low C:N ratio synthetic wastewaters. The study shows that NH$_3$-N removal efficiencies increased as the carbon-nitrogen ratio decreased but COD removal was not really affected by the C:N ratio. It was highly affected by the pH and dissolved oxygen (DO) on the nitrification process. The nitrification rate improved with an increase of DO up to 3.7 mg L$^{-1}$ and decreased at above 4.0 mg L$^{-1}$, while the ammonia-nitrogen removal increased from 81.6 to 92.5% when there was a change of pH value from 4.7 to 6.4. The results demonstrated that an up-flow partially packed BAF can be operated at an HRT of 6 h, where NH$_3$-N removal efficiency of 87.0 ± 2.9%, 89.2 ± 1.3% and 91.1 ± 0.78% and COD removal of 87.6 ± 2.9%, 86.4 ± 2.1% and 89.5 ± 2.6% were achieved for the C:N ratios of 10, 4 and 1, respectively. This study demonstrates that partially aerated BAF systems can be operated at a low HRT and can be used as a compact system for small communities to treat wastewater for NH$_3$-N removal. Future work will be directed at online control and monitoring of the biological aerated filter to enhance nitrogen removal.

ACKNOWLEDGEMENTS

This research was funded by the University Kebangsaan Malaysia (UKM-ASPL-07-05-020).

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