Partially aerated submerged fixed-film bioreactor for simultaneous removal of carbon and nutrients from high-strength nitrogen wastewaters: effect of aeration rate and C:N:P ratio

Mojtaba Forouzesh, Ali Baradar Khoshfetrat and Salman Alizadeh Kordkandi

ABSTRACT

Influence of aeration rate and COD:N:P (C:N:P) ratio on the performance of an upflow partially aerated submerged fixed film (UP/ASFF) bioreactor for simultaneous carbon and nutrient removal from high-strength nitrogen wastewater was investigated during 6 months. Airflow rates at three levels of 1.5, 3, and 4.5 L/min and C:N:P ratios at four levels of 450:300:10, 450:150:10, 450:100:10, and 450:75:10 were selected as the two main input factors. All experiments were performed at constant chemical oxygen demand (COD), phosphorus (P) and hydraulic residence time of 450 mg COD/L, 10 mg PO₄³⁻/L and 7.3 h, respectively. The results showed when the airflow rate increased from 1.5 to 4.5 L/min, complete COD removal was achieved. At an airflow rate of 4.5 L/min, total nitrogen removal reached a maximum value of 75% for the C:N:P ratio of 450:75:10. A maximum value of 54% for total phosphorus removal, however, was obtained at an airflow rate of 3 L/min for the C:N:P ratio of 450:75:10. Analysis of variance for the obtained data revealed that aeration rate and nitrogen concentration had more impact on phosphorus removal than COD and nitrogen removal. The study demonstrated that the UP/ASFF system has considerable potential for use in simultaneous removal of carbon and nutrients for high-strength nitrogen wastewater.

Key words | COD removal, nitrogen removal, partially aerated submerged fixed-film bioreactor, phosphorus removal

INTRODUCTION

Wastewater reclamation is one of the major pathways to restore water to nature’s cycle. The main objective of wastewater reclamation and reuse development is to produce water with sufficient quality for all non-potable uses, such as irrigation purposes and industrial applications. Among the different types of wastewater (domestic wastewater, industrial wastewater, stormwater, leachate, septic tank wastewater), municipal wastewater is a main source of reusable water. Nitrogen, phosphorus, and organic chemical oxygen demand (COD) form the main composition of municipal wastewater streams. The wastewater quality, however, varies from region to region (Metcalf & Eddy 2003). Particularly, COD:N (C/N) of municipal wastewaters reduces to values less than 5 in the summer season (Metcalf & Eddy 2003). The release of large amounts of nutrients in natural water results in excessive growth of algae and consequently the eutrophication phenomenon, which disturbs aquatic plants and animal life by depleting dissolved oxygen (DO) in the water (Tay et al. 2003). On the other hand, more chlorine is required to disinfect the effluent in the presence of ammonia (Metcalf & Eddy 2003). To achieve a standard level of wastewater discharge, several types of biofilm bioreactor with various performances for nutrient and COD removal have been reported for municipal wastewater treatment and reuse (Xiang et al. 2014; Wang et al. 2015). Improved process stability, high sludge retention time, minimized need for settling capacity and small environmental footprint are several features of the biofilm process (Kordkandi & Berardi 2015). In addition, biofilm bioreactors with high sludge retention time and biomass concentration...
reduce sludge production. However, the process suffers from several drawbacks, such as requiring expert knowledge, the occurrence of clogging, and complexity of modeling studies due to mass-transport resistance, reaction kinetics, and flow hydrodynamics (Kordkandi & Ashiri 2015; Kordkandi & Berardi 2015; Kordkandi & Khoshfetrat 2015).

Most biological treatment of nitrogen involves a combination of two separated bioreactors under aerobic (aerated) and anoxic (non-aerated) conditions for nitrification and denitriﬁcation processes or bioreactors connected in series for an anaerobic/anoxic/aerobic (A2O) process, which increase operating costs and occupy more space than a single bioreactor (Galvez et al. 2003; Ryu et al. 2014). Some researchers reported that the denitriﬁcation process and total nitrogen (TN) removal would be inhibited due to the insufﬁcient carbon source when the C/N ratio is low (Li et al. 2016; Lin et al. 2016). Kuba et al. (1996a) suggested that extra COD should be added into the system when the inﬂuent C/N ratio is lower than 5.4. Therefore, it is essential to develop new bioreactors for treating wastewater with low C/N ratio.

The upﬂow partially aerated submerged ﬁxed-ﬁlm (UP/ASFF) system can be considered as another candidate, which forms both an aerated and a non-aerated zone inside a single bioreactor using the aerators placed part way up the ﬂoating media (Tay et al. 2005; Albuquerque et al. 2012; Kordkandi & Khoshfetrat 2015). In the UP/ASFF system, energy can also be saved because of the denitriﬁcation process happening in the non-aerated (anoxic) zone (Espinosa & Stephenson 1999; Kordkandi & Khoshfetrat 2015). Moreover, simultaneous removal of carbon and nutrients in a single bioreactor can reduce the size of the treatment system in addition to operational costs. In our previous study (Kordkandi & Khoshfetrat 2013), the UP/ASFF system also showed an acceptable potential to treat high-ammonium municipal wastewaters. Another gap is insufﬁcient investigation of phosphorus removal in bioﬁlm bioreactors particularly the UP/ASFF system. Usually, the wastewater of Tabriz city has a C/N ratio lower than 5, particularly in the summer season (Forouzesh 2013). Therefore, the inﬂuence of aeration rate and C:N:P ratio on the UP/ASFF system performance was tested to evaluate the system’s economic potential for use in real high-nitrogen municipal wastewater treatment.

To the best of our knowledge, this is the ﬁrst report demonstrating the UP/ASFF performance evaluation of simultaneous removal of carbon, nitrogen and phosphorus for high ammonium-content wastewaters.

**MATERIALS AND METHODS**

**Bioreactor speciﬁcation**

Specifications of the bioreactor and its supporting media are presented in Table 1. The bioreactor was made of a cylindrical Plexiglas column with effective volume of 7.6 L, and was ﬁlled with polypropylene media as microorganism attaching support. Airﬂow was injected through a ﬁne-bubble diffuser from midway in the bioreactor to generate anoxic and aerobic zones inside the bioreactor with a volume ratio of aerobic to anoxic equal to 2.5. To supply produced nitrate in the aerobic compartment for denitriﬁers in the anoxic part as electron acceptors for denitriﬁcation and phosphorus removal, two zones were connected by an external loop of 2.5 cm in diameter. A schematic diagram of the experimental system is shown in Figure 1.

**Operational conditions and analytical procedures**

Initially, the bioreactor acclimatized with activated sludge mixed liquor provided from the wastewater treatment plant of Tabriz, Iran. The system was then operated under batch condition for 2 weeks with the real wastewater. After this step, synthetic wastewater was replaced and continuously fed into the bioreactor at the bottom part. Synthetic wastewater was prepared by adding CH3COONa, NH4Cl, and KH2PO4 as carbon, nitrogen, and phosphorus sources, respectively, and was continuously pumped into the bioreactor by a peristaltic pump with a ﬂow rate of 1 L/h at constant hydraulic residence time (HRT) of 7.3 h. The average DO concentration in the non-aerated zone was always less than 1 mg O2/L. An

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Bioreactor Total height, cm</td>
<td>90</td>
</tr>
<tr>
<td>Internal diameter, cm</td>
<td>11</td>
</tr>
<tr>
<td>Effective volume, L</td>
<td>7.6</td>
</tr>
<tr>
<td>Loop diameter, cm</td>
<td>2.5</td>
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<tr>
<td>Volume ratio of aerobic to anoxic compartment</td>
<td>2.5</td>
</tr>
<tr>
<td>Packing media Sizes (H × outer D × inner D), mm</td>
<td>18 × 16 × 1.5</td>
</tr>
<tr>
<td>Specific surface area, m²/m³</td>
<td>320</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>88</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>0.90</td>
</tr>
<tr>
<td>Dosage</td>
<td>830</td>
</tr>
</tbody>
</table>
A randomized one replication full factorial design was used to carry out the experiments and a test developed by Tukey \(^{1949}\) was used to analyze the obtained data statistically (Montgomery \(^{2001}\); Kordkandi & Forouzesh \(^{2014}\)). C:N:P ratios at four levels and aeration rate at three levels were selected. All experiments were performed at constant COD and TP concentrations of 450 mg COD/L \((1.46 \text{ kg COD/m}^3\cdot\text{d})\) and 10 mg PO\(_4^{3-}\)-P/L \((0.032 \text{ kg PO}_4^{3-}\text{-P/m}^3\cdot\text{d})\), respectively. The values were selected based on the average of COD and TP of Tabriz city wastewater in summer. A airflow rate was varied at three levels of 1.5, 3, and 4.5 L/min. Nitrogen loading rates were 300 mg NH\(_4^+\)-N/L \((0.96 \text{ kg N/m}^3\cdot\text{d})\), 150 mg NH\(_4^+\)-N/L \((0.48 \text{ kg N/m}^3\cdot\text{d})\), 100 mg NH\(_4^+\)-N/L \((0.32 \text{ kg N/m}^3\cdot\text{d})\), and 75 mg NH\(_4^+\)-N/L \((0.24 \text{ kg N/m}^3\cdot\text{d})\). Therefore, different C:N:P ratios were as follows: 450:300:10, 450:150:10, 450:100:10, and 450:75:10. Furthermore, the alkalinity and the pH of the influent were controlled at 800 mg CaCO\(_3\)/L and 7.5, respectively. All experiments were performed at ambient temperature \((25 \pm 3 \text{ °C})\). The experimental strategy of the present work is illustrated in Figure 2. To prevent clogging, the system was backwashed every 2 weeks. A UV/Vis Spectrophotometer (Merck, Model Pharo300) was used to measure the concentrations of COD, NO\(_2^-\)-N, NO\(_3^-\)-N, NH\(_4^+\)-N and PO\(_4^{3-}\)-P according to Standard Methods \(^{1998}\). DO and pH values were measured using a DO meter (Cyberscan DO 300, Eutech Instruments Pte Ltd) and a pH-meter (Metrohm). To evaluate the impact of the main factors on the output COD, TN, and TP, the F-test analysis of variance (ANOVA) with a 95% confidence interval was considered. The obtained data from the last 10 consecutive days were considered to calculate average values.
RESULTS AND DISCUSSION

System stability and performance examination

The system performance during the 204-day operational period is presented in Figure 3. New steady-state conditions due to the changes in operating conditions were reached after a week without any incident in the system. Under almost all operational conditions, COD removal values of over 90% were observed. Partial reduction of COD removal at the high influent nitrogen loading rate shows that the nitrogen concentration had a slight effect on COD removal; however, it was less affected by an increase in aeration rate. Unlike carbon, nitrogen removal illustrated considerable fluctuations. The highest influent nitrogen concentration applied between days 1 and 17, 69 and 85, and 137 and 153 led to the lowest nitrogen removal efficiency in these steps. Nitrogen elimination has been gradually improved by reducing the input nitrogen loading rate and increasing the aeration rate to supply more DO. Finally, 82% elimination was achieved on day 204. Irregular fluctuations in the elimination of phosphorus are related to the specific mechanism of phosphorus removal. This mechanism requires phosphorus-rich microorganisms and timely disposal by backwash (Morgenroth & Wilderer 1999). It is clear that ideal conditions such as DO abundance and adequate carbon and nutrient sources for full growth of microorganisms are necessary. At the airflow rate of 3 L/min, 62% phosphorus removal was obtained on day 132 due to the adequate DO and organic carbon for biofilm growth rate. In addition, the experimental data showed that a high nitrogen concentration affected phosphorus removal more than COD removal. In general, airflow rate increase has significant influence on COD, nitrogen and phosphorus removal as long as biofilm detachment does not occur.

COD removal

Figure 4(a)–4(c) show COD, TN and TP removals at different airflow rates and C:N:P ratios. The influent concentration was 450 mg COD/L. An increase in the airflow rate from 1.5 to 4.5 L/min led to more DO supply (from around 3 mg O2/L at the airflow rate of 1.5 L/min to 7 mg O2/L at the airflow rate of 4.5 L/min).
to Figure 4(a), a reduction in nitrogen loading rate from 300 to 75 mg NH\textsubscript{4}\textsuperscript{+}-N/L controls the competition between heterotrophic and autotrophic microorganisms for DO consumption as well as space within the biofilm. Therefore, the predominant species of bacteria growing within the biofilm were heterotrophic, which induced a higher degree of COD degradation. In addition, almost complete elimination of COD at the airflow rates of 3 and 4.5 L/min were observed, while at the lower aeration rate of 1.5 L/min, due to insufficient oxygen delivery to the microorganisms, the concentration of effluent COD reached 23 mg/L, revealing a COD removal efficiency of 95%. Han et al. (2009) reported that 90% COD removal could be achievable at a loading rate of 4.06 kg COD/m\textsuperscript{3}.d in an upflow anoxic-oxic bioreactor. Figure 4(a) shows that COD removal efficiency can be improved with increasing airflow rate and decreasing nitrogen concentration. Indeed, as reported in our previous study (Kordkandi & Khoshfetrat 2015) at constant HRT with decreasing C/N, the COD removal efficiency remained almost constant. Table 2 shows the ANOVA performed on the obtained data for the COD, TN, and TP removals. The \( P \)-value for the COD removal output in Table 2 indicates that both aeration rate and C:N:P ratios were significant (\( P < 0.05 \)), while there is no significant interaction between the two main factors (\( P > 0.05 \)). This implies that the effect of aeration rate on COD removal is independent of C:N:P levels in the selected range. The \( F \)-values for the aeration rate and C:N:P values were 15.07 and 13.67, respectively, indicating that both factors have almost equal importance. Previous studies (Khoshfetrat et al. 2011; Hosseini et al. 2013) have also confirmed the importance of nitrogen loading and aeration rates, as well as the lack of their interactions, on DO. However, the increase of airflow rate is effective before the start of biofilm detachment (Galvez et al. 2003).

Nitrogen removal

TN removal based on variation of aeration rates and C:N:P ratios is demonstrated in Figure 4(b). Accordingly, at the airflow rate of 1.5 L/min, the TN removal improvement could not exceed 20% except at the C:N:P ratio of 450:75:10, when it reached 67%. This shows that at higher nitrogen concentrations, oxygen limitation has a strong influence on nitrifier activity, and conversion of ammonium to nitrate has been limited by oxygen concentration. With increasing aeration rate, almost similar profiles for TN removals were observed versus various C:N:P ratios at the airflow rates of 3 and 4.5 L/min. Maximum nitrogen reduction of 75% observed at the airflow rate of 4.5 L/min and the C:N:P of 450:75:10 could be due to the relatively high DO concentration in the bioreactor for the nitrification process (DO value higher than 5 mg O\textsubscript{2}/L). This result coincided with a report by Albuquerquea et al. (2012), where the TN removal efficiency was 75% in a down flow biological aerated filter. Although different experimental conditions make comparison difficult, the results of the present study for COD and nitrogen removals showed considerable improvements compared with other reports for municipal wastewater treatment by biofilm systems (Tay et al. 2005; Albuquerquea et al. 2012; Fulazzaky et al. 2015).

Table 2 | ANOVA for COD, TN, and TP removals

<table>
<thead>
<tr>
<th>Output variables</th>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>Mean square</th>
<th>( F )_0</th>
<th>( P )-value</th>
</tr>
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<tr>
<td>COD removal (%)</td>
<td>Aeration rate (A)</td>
<td>9.50</td>
<td>2</td>
<td>4.75</td>
<td>15.07</td>
<td>0.0076</td>
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<tr>
<td></td>
<td>C:N:P (B)</td>
<td>12.92</td>
<td>5</td>
<td>4.31</td>
<td>13.67</td>
<td>0.0076</td>
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<td>Nonadditivity (A,B)</td>
<td>0.26</td>
<td>1</td>
<td>0.26</td>
<td>0.82</td>
<td>0.4068</td>
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<tr>
<td></td>
<td>Error</td>
<td>1.58</td>
<td>5</td>
<td>0.32</td>
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<tr>
<td></td>
<td>Total</td>
<td>24.25</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TN removal (%)</td>
<td>Aeration rate (A)</td>
<td>841.17</td>
<td>2</td>
<td>420.59</td>
<td>5.65</td>
<td>0.0500</td>
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<td></td>
<td>C:N:P (B)</td>
<td>5.186</td>
<td>3</td>
<td>1,728.67</td>
<td>23.21</td>
<td>0.0023</td>
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<td>Nonadditivity (A,B)</td>
<td>1.05</td>
<td>1</td>
<td>1.05</td>
<td>0.02</td>
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<tr>
<td></td>
<td>Error</td>
<td>372.45</td>
<td>5</td>
<td>74.49</td>
<td></td>
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<tr>
<td></td>
<td>Total</td>
<td>6,400.67</td>
<td>11</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TP removal (%)</td>
<td>Aeration rate (A)</td>
<td>610.17</td>
<td>2</td>
<td>305.08</td>
<td>49.67</td>
<td>0.0005</td>
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<tr>
<td></td>
<td>C:N:P (B)</td>
<td>740.25</td>
<td>3</td>
<td>246.75</td>
<td>40.18</td>
<td>0.0006</td>
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<td>Nonadditivity (A,B)</td>
<td>171.79</td>
<td>1</td>
<td>171.79</td>
<td>27.97</td>
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</tr>
<tr>
<td></td>
<td>Error</td>
<td>30.71</td>
<td>5</td>
<td>6.14</td>
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<tr>
<td></td>
<td>Total</td>
<td>1,552.92</td>
<td>11</td>
<td></td>
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</table>
A high level of accessible DO moderates the competition between heterotrophic and autotrophic organisms. It is clear that TN removal can be improved with an increase in DO and carbon to nitrogen ratio owing to the better conditions for more nitrite and nitrate generation. Moreover, increasing the airflow rate above a certain value provides strong shear stress, biofilm washing out and disrupts the performances of denitrifier bacteria in the anoxic zone, resulting in a reduction in TN removal efficiency (Galvez et al. 2005). Obviously, insufficient carbon and oxygen at high levels of influent nitrogen concentration (over 150 mg NH₄-N/L) can lead to poor performances of the nitrifier and denitrifier for simultaneous removal of TN and COD, as reported in the literature (Chen et al. 2015). As can be seen in our recent work (Kordkandi & Khoshfetrat 2015), it was found that an increase in the non-aerated/aerated zone could improve nitrogen removal efficiency without any considerable change in COD removal efficiency. Based on the ANOVA for nitrogen removals in Table 2, both factors were effective; however, the C:N:P ratio affected nitrogen removal four times more than the aeration rate (F₀ values of 23.21 and 5.65, respectively). In addition, their interaction was not important (P-value greater than 0.05). The ANOVA was also in accordance with the obtained results, demonstrating that TN removal can be improved by increasing the C/N ratio and DO because of the favorable conditions for more nitrite and nitrate production.

**Phosphorus removal**

Figure 4(c) reveals the results observed for TP removal at various C:N:P and aeration rates. As shown, the TP removal showed a slight increase from 15% to 28% when the C:N:P values changed from 450:300:10 to 450:75:10 at the airflow rate of 1.5 L/min. With increasing the aeration rate to 3 L/min, the TP removal went up considerably, particularly when the nitrogen concentration decreased at the influent stream, reaching 54% at the C:N:P of 450:75:10. The TP removal decreased, however, when the aeration rate increased to 4.5 L/min. The values for TP removal increased from 22% to 33% with a change in the C:N:P values from 450:300:10 to 450:75:10 at the airflow rate of 4.5 L/min.

Nitrite and nitrate produced during the nitrification process enter the anoxic zone of the bioreactor through recirculation in the present study. Kuba et al. (1996b) showed that nitrite concentrations less than 4–5 mg NO₂-N/L are not a confounding factor for anoxic phosphorus removal, but higher concentrations of more than 8 mg NO₂-N/L could thoroughly stop the process. Measurements of our study showed that the concentration of DO in the anoxic zone (non-aerated) was less than 1 mg O₂/L. Thus, the condition for anoxic phosphorus removal using nitrite and nitrate as final electron acceptors was provided inside the non-aerated area of the UP/ASFF system.

Phosphorus can be removed either by chemical precipitation of phosphate ions or by a biological process (Morgenroth & Wilderer 1999). In biological phosphorus removal, three phenomena can be studied: (i) normal absorption of phosphorus into the biomass, (ii) deposition by adding metallic salts to the biological process, and (iii) enhanced biological phosphorus uptake into the biomass (Rittmann & McCarty 2001). In the first method, phosphorus is used for the microorganism cell structure, thus phosphate ion concentration in the bulk phase is reduced (Morgenroth & Wilderer 1999). Advanced methods for phosphorus removal are based on the rich phosphorus accumulating organisms. For this purpose, microorganisms should be exposed to aerobic and anaerobic conditions, periodically (Morgenroth & Wilderer 1999). Ahn et al. (2001) and Hu et al. (2003), using different experiments, showed that oxygen, nitrite and nitrate could be used successfully as terminal electron acceptors for anoxic phosphorus removal. This is very important, because in biological treatment systems the nitrification process leads to production of large quantities of nitrite and nitrate ions. Air supply, therefore, can be reduced by using nitrite and nitrate instead of oxygen.

As stated by Rittmann & McCarty (2001), phosphorus removal is proportional to the biomass growth rate; therefore, the results of this research on phosphorus removal are related to normal absorbance of phosphorus into the biomass and denitrifying phosphorus removal. Espinosa & Stephenson (1999) reported that in biofilm systems, normal phosphorus removal of up to 35% is achievable. Based on Figure 4(c), the influent TP concentration was 10 mg PO₄-P/L. In the first stage, at an airflow rate of 1.5 L/min and a C:N:P ratio of 450:300:10, a high nitrogen loading rate and low DO in the aerobic zone (less than 3 mg O₂/L) led to a weak nitrification process and production of small amounts of nitrite and nitrate. Some of the nitrates are used for the denitrification process and some for denitrifying phosphorus removal. By reducing the influent nitrogen loading rate, nitrification performance was improved; however, the unsuitable biomass growth rate due to insufficient DO resulted in an average 28% phosphorus removal at an airflow rate of 1.5 L/min and a C:N:P ratio of 450:75:10. Maximum effluent phosphorus was 8.5 mg PO₄-P/L for
the C:N:P ratio of 450:300:10, which was only 15% TP removal. The best performance was obtained at an airflow rate of 3 L/min and a DO value of approximately 4.5 mg O₂/L in the aerobic zone. Under these conditions, sufficient concentration of DO led to a successful nitrification process in which 54% phosphorus removal was achieved. There is also light shear stress intensity, which can minimize biomass detachment. An increase in the airflow rate to 4.5 L/min led to an increase in shear stress and finally biomass detachment, influencing the nitrification process. Reduced oxygen consumption in the aerated zone increases DO concentration in the non-aerated zone, reducing denitrifying phosphorus activity owing to usage of oxygen instead of nitrate as the electron acceptor. Finally, 33% of phosphorus activity owing to usage of oxygen instead of nitrate was removed at a C:N:P ratio of 450:75:10. As Tay et al. (2003) reported, removal of phosphorus was more affected by influent COD, nitrogen, and phosphorus than nitrogen removal. From Table 2, comparison of F₀ for C:N:P effect on TN removal (23.21) and TP removal (40.18) confirms similar results. The obtained P-value from Table 2 reveals that both main factors and their interaction have significant effect on TP removal. This means that there is a mutual relationship between aeration rate and the level of the C:N:P ratio.

**CONCLUSIONS**

An upflow partially aerated submerged fixed film bioreactor with different aeration rates and C:N:P ratios was examined to remove carbon and nutrients simultaneously from high-nitrogen wastewater. Based on the results presented herein, the aeration rate was identified as the predominant factor, which had a major effect on COD, TN, and TP removals. In addition, according to the ANOVA, the aeration rate and nitrogen concentration had more impact on phosphorus removal than COD and nitrogen removals. TN removal efficiency increased gradually with the increase in aeration rate and C:N:P ratio, and higher phosphorus removal was achieved due to the denitrifying phosphorus removal promotion. Maximum performance of the UP/ASFF system for simultaneous removal of COD, nitrogen and phosphorus was observed as 99%, 67% and 54%, respectively, at the airflow rate of 3 L/min and the C:N:P value of 450:75:10. Interestingly, the removals for the C:N:P value of 450:100:10 at the aeration rate of 3 L/min showed similar results. The results revealed that the UP/ASFF system can be used for simultaneous removal of carbon and nutrients from high-strength nitrogen wastewater (C/N of less than 5) although the non-aerated zone size should be increased to increase TN and TP removals when the C/N of wastewater approaches values less than 5.

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