Nutrient removal in reverse osmosis concentrates using a biological aerated filter

H. J. Choi

ABSTRACT

The aim of this study is to employ a biological aerated filter (BAF) in the treatment of reverse osmosis (RO) concentrate received from reuse of treatment plant wastewater. Furthermore, the influence of chemical oxygen demand (COD)/N ratio on the nutrient removal was analyzed to find the detailed removal pathways of nutrients. The result was found to be high efficiency for biochemical oxygen demand removal (95.86%) compared to that of COD (88.95%) and suspended solids (81.12%). The total phosphorus (TP) (67.66%) and PO4-P (61.42%) removal efficiencies were relatively lower than that of total nitrogen (TN) (81.42%) and NO3-N (76.70%). This may be due to the fact that the biochemical oxygen demand (BOD)/TP ratio (8.01) was relatively low. Decreasing the COD/N ratio decreased TP and PO4-P removal efficiency. However, the removal efficiency of TN and NH4-N was increased from 47.60 to 64.54 and 54.17 to 73.72% with decreasing of COD/N ratio from 8.19 to 7.64, respectively. In addition, the denitrification rate and nitrification rate were increased from 211.8 to 301.0 mg/L d and 87.7 to 109.4 mg/L d, respectively, when COD/N ratios changed from 8.19 to 7.64. Therefore, in order to reuse the RO concentrate, the BAF process could effectively treat the RO concentrate.

Key words | biological aerated filter, COD/N ratio, industrial wastewater, nutrients removal, RO concentrate, wastewater reuse

INTRODUCTION

Water resources are under tremendous stress and found to be scarce in many areas of the world because of the increased and widespread demand. Reverse osmosis (RO) is a membrane-based technology widely applied in water desalination, production of potable water and more recently in the tertiary wastewater treatment process (Chelme-Ayala et al. 2009). In recent years, RO has also been applied to the treatment of secondary effluents of wastewater treatment plants (WTPs). The RO concentrates obtained from WTPs contained less salinity than the RO concentrates from desalination plants. However, they contained high content of organic matter along with persistent micro-pollutants (Pérez-González et al. 2011). Solly et al. (2010) reported that the level of contamination of RO concentrate is six to seven times higher than the usual wastewater contamination level. The advanced oxidation process (AOP) employed with sorbing resins has been shown to be a fairly a good treatment process for the treatment of RO concentrate along with the removal of persistent micro-pollutants. AOPs, such as ozonation, Fenton processes, photocatalysis and photooxidation, sonolysis and electrooxidation, are probably the most promising technologies to degrade and detoxify endocrine disrupting compounds (Pérez-González et al. 2011). However, high chemical dosage and high energy consumption of these technologies may limit their application (Bagastyo et al. 2011). Therefore specific treatment, such as the biological aerated filter (BAF) process, was proposed in order to reduce the pollutant load in the treatment of wastewaters.

The BAF process is ideal for reclamation and reuse of wastewater. The BAF process has several advantages which confer on it benefits in adaptation of this technology (Solly et al. 2010). The attached growth on an inert granular media in BAF allows for a much higher concentration of active biomass than a suspended growth activated sludge.
system, so that the size of the reactor can be reduced. In addition, suspended solids (SS) in the influent can be captured physically by the media and this eliminates the requirement for separate secondary clarification. Overall, these advantages result in a space-saving layout that uses only one-third of the footprint space of an activated sludge process (Wang et al. 2006).

The aim of this study is to optimize the treatment of RO concentrate obtained from reuse of WTP using the BAF process. Furthermore, the influence of the chemical oxygen demand (COD)/N ratio on the nutrient removal is studied so as to predict possible pathways of nutrient removal.

### MATERIALS AND METHODS

#### Characteristics of wastewater

The chemical characteristics of the wastewater and RO concentrate used for the present investigation are given in Table 1. A pilot scale plant is installed at an industrial WTP located in Ulsan city, Korea. This industrial wastewater contains more Na, Mg, Cl, Mn and Ba content but fewer nutrients compared to the municipal wastewater. The COD/N/P ratio is found to be 100/20/2 for the wastewater samples and is recommended for nutrient removal. The biochemical oxygen demand (BOD)/total phosphorus (TP) and BOD/PO₄ ratios for influent wastewater (10.34 and 12.34) are also found to be reasonably high compared to the RO concentrate (8.00 and 9.27). However, the PO₄/TP ratio has almost identical values for influent wastewater and RO concentrate, i.e. 0.84 and 0.86, respectively.

#### Process of BAF

A schematic diagram of the BAF process and BAF media to treat RO concentrate is shown in Figure 1. The operation period of the pilot plant is fixed at 150 days.

### Table 1 | Characteristics of the influent wastewater and reverse osmosis concentrate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influent (wastewater) (mg/L)</th>
<th>RO concentrate (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD(Cr)</td>
<td>227.73 (90.52–500.45)</td>
<td>364.55 (130.78–740.54)</td>
</tr>
<tr>
<td>BOD</td>
<td>22.34 (10.91–40.54)</td>
<td>48.30 (11.14–127.16)</td>
</tr>
<tr>
<td>SS</td>
<td>38.42 (23.62–56.45)</td>
<td>98.95 (28.57–210.23)</td>
</tr>
<tr>
<td>TN</td>
<td>12.15 (2.57–20.32)</td>
<td>44.50 (17.34–58.61)</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>1.49 (0.98–2.15)</td>
<td>16.19 (12.47–20.54)</td>
</tr>
<tr>
<td>TP</td>
<td>2.16 (0.84–3.17)</td>
<td>6.03 (3.14–7.51)</td>
</tr>
<tr>
<td>PO₄-P</td>
<td>1.81 (0.41–2.26)</td>
<td>5.21 (2.73–5.92)</td>
</tr>
</tbody>
</table>

**Figure 1** | A schematic diagram of the BAF process.
In this experiment, the BAF is an upflow and biological wastewater treatment system with floating media. The process is capable of removing nutrients from the wastewater. The BAF technology relies on the suspension (fluidization) of small particles flowing upward in the wastewater. The BAF process was operated at 4 m³/day of flux and was prepared with a total volume of 0.4 m³ (media 2.5 m) and 0.2 m³ (media 1.5 m) for the denitrification (DN) phase and nitrification (N) phase, respectively (Figure 1). The used RO is the skid block type having a capacity of 0.83 l/hour. It consists of one vessel and one element made of polyamide.

The operating parameters of the BAF plant are represented in Table 2. Experiments were performed in two steps, the DN phase and N phase, at different linear velocities (LVs) and empty bed contact times (EBCTs). The used floating media in the experiment was 2–3 mm in diameter, 0.07–0.08 media g/cm³ density, 1,000–1,350 m²/m³ specific surface area and 2.5 kg/cm² compressive strength, and was made of polypropylene. Using the media with its adsorption capacity, an approach to the integration of biological removal and adsorption was possible.

### Table 2 | Operating parameters of the biological aerated filter plant

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DN phase</th>
<th>N phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>4 m³/day</td>
<td>4 m³/day</td>
</tr>
<tr>
<td>Size</td>
<td>0.35 (D) * 4.5 (H) (floating media 2.5)</td>
<td>0.25 (D) * 3.5 (H) (floating media 1.5)</td>
</tr>
<tr>
<td>LV</td>
<td>1.8/hour</td>
<td>3.40/hour</td>
</tr>
<tr>
<td>EBCT</td>
<td>1.5 hour</td>
<td>0.5 hour</td>
</tr>
</tbody>
</table>

### Table 3 | Summary of the removal efficiency of nutrient in the reverse osmosis concentrate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DN phase (RO concentrate) (mg/L)</th>
<th>N phase (mg/L)</th>
<th>Effluent (mg/L)</th>
<th>Average removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD(Cr)</td>
<td>364.55</td>
<td>178.18 ± 5.35</td>
<td>40.27 ± 1.21</td>
<td>88.95 ± 2.67</td>
</tr>
<tr>
<td>BOD</td>
<td>48.30</td>
<td>25.62 ± 0.77</td>
<td>2.00 ± 0.06</td>
<td>95.86 ± 2.87</td>
</tr>
<tr>
<td>SS</td>
<td>98.95</td>
<td>88.73 ± 2.66</td>
<td>18.68 ± 0.56</td>
<td>81.12 ± 2.43</td>
</tr>
<tr>
<td>TN</td>
<td>44.50</td>
<td>23.32 ± 0.70</td>
<td>8.27 ± 0.25</td>
<td>81.42 ± 2.44</td>
</tr>
<tr>
<td>NO₃-N</td>
<td>27.12</td>
<td>14.09 ± 0.43</td>
<td>6.12 ± 0.18</td>
<td>76.70 ± 2.30</td>
</tr>
<tr>
<td>NH₄-N</td>
<td>16.19</td>
<td>7.42 ± 0.22</td>
<td>1.95 ± 0.06</td>
<td>87.96 ± 2.64</td>
</tr>
<tr>
<td>TP</td>
<td>16.19</td>
<td>3.09 ± 0.09</td>
<td>1.95 ± 0.05</td>
<td>67.66 ± 2.03</td>
</tr>
<tr>
<td>PO₄-P</td>
<td>5.21</td>
<td>3.01 ± 0.08</td>
<td>2.01 ± 0.06</td>
<td>61.42 ± 1.84</td>
</tr>
</tbody>
</table>

### Analyzed methods

The BOD, SS and COD are analyzed using an ion chromatograph (Dionex ISP 2000, Dinox, Sunnyvale, California), according to Standard Methods (APHA 1995) in the certified laboratory. The TP, PO₄-P, total nitrogen (TN), NO₃-N and NH₄-N are obtained photometrically using a spectrophotometer (UV–Vis 1240, Tecator Co., Germany).

### RESULTS AND DISCUSSION

**Removal of nutrients in the BAF process**

The results obtained in the removal of various nutrients in the RO concentrate are represented in Table 3. The results clearly demonstrated that BAF treatment for RO concentrate significantly reduces the BOD content and the percentage removal is as high as 95.86%. However, the removal percentage of COD (88.95%) and SS (81.12%) were relatively low compared to that of BOD. The high BOD removal efficiency is due to the complete oxidation of organic matter which often comes from the food to microorganism (F/M) ratio (0.48 BOD/kg MLSS·day) of the influent.

The TN and NH₄-N removal efficiencies were found to be 81.42 and 87.96%, respectively, with average effluent concentrations of 8.27 and 1.95 mg/L, respectively. These data indicated that about 6.12 mg/L NO₃-N remained in the treated samples, implying that DN was not accomplished fully. Similarly, results suggested that the removal efficiencies of TP and PO₄-P were not as good as TN and
NH$_4$N. It was assumed that organic matter in the influent was consumed to remove nitrogen by DN rather than the PO$_4$P removal. TP and PO$_4$P removal efficiencies were relatively low at 67.66 and 61.42%, respectively.

Chang et al. (2002) reported 99% BOD, 92% COD and 74% SS removal efficiency while treating the wastewater in a BAF with zeolite media. A relatively low efficiency of COD removal was obtained, i.e. in the range of 61.52 to 69.2% while treating the domestic wastewater using the BAF process, as reported by Wang et al. (2006). Hsieh & Davis (2005) used mulch for nitrate and nitrogen removal from wastewater in biological processing. They found that mulch had 60% nitrate and 72% nitrogen removal efficiency. The COD and SS removal efficiencies achieved in this study were found to be slightly higher compared to the studies demonstrated elsewhere for different systems. Fu et al. (2009) found relatively higher PO$_4$P removal (87.805%) having a COD/N ratio of 9.3 in a BAF process with wallstonite treating high strength wastewater. However, limerock, peat and sand could remove 41.40, 44 and 41.40% of P, respectively. It can be concluded that wallstonite is effective in phosphorus removal because it contains calcium and ferrous ions. The proposed media is perhaps cost effective compared to other conventional methods based on activated carbon. Moreover, the activated carbons need to be replaced every 6 months of operation, which causes an additional input cost of operation. However, it is almost comparable with zeolitic media (EPA 1999). Further, the operation of the proposed BAF system is feasible and quite versatile for the scaling up of the cost effectiveness to a larger extent.

Effect of COD/N ratio on nitrification and DN

The COD/N ratio of the influent is one of the most critical parameters for the wastewater nitrogen removal process, because it directly affects the functional microorganism populations, including autotrophic ammonium (NH$_4$N) oxidized bacteria, NO$_2$N oxidized bacteria and heterotrophic denitrifiers. Theoretically, the stoichiometric requirement for DN was 2.86 COD/g N, considering the electron transferring balance between organic substrate and NO$_2$N (Meng et al. 2008). The dependence of nitrification rates and DN rates on the COD/N ratio was examined with data from NH$_4$N removal and TN removal, respectively. The nitrification rate and DN rate were calculated according to Equations (1) and (2), respectively,

$$
\Gamma_{\text{nitrification}} = \frac{Q_{\text{in}}(\text{NH}_4^+\text{N}_{\text{influent}} - \text{NH}_4^+\text{N}_{\text{effluent}})}{V_{\text{reactor}}}
$$

(1)

$$
\Gamma_{\text{denitrification}} = \frac{Q_{\text{in}}(\text{TN}_{\text{influent}} - \text{TN}_{\text{effluent}})}{V_{\text{reactor}}}
$$

(2)

where $Q_{\text{in}}$ was the influent flux (L/d) and $V_{\text{reactor}}$ was the volume of the reactor (L). The nitrification capacity was influenced by influent COD/N. It was increased from 87.7 to 109.4 mg/L d, when COD/N ratios decreased from 8.19 to 7.64, respectively. Some researchers reported that the oxygen saturation coefficients of Monod kinetics for the nitrifying bacteria were higher than those of the heterotrophic bacteria (Itokawa et al. 2001; Xiao et al. 2007). Hence, dissolved oxygen would be utilized primarily by heterotrophic bacteria, rather than nitrifying bacteria. With the decrease of COD/N level, substrate concentration for NH$_4$N oxidation bacteria increased, which stimulated the growth of biomass (Fu et al. 2009). Therefore, the nitrification capacity was enhanced.

Denitrification rate was calculated according to Equation (2). The DN rate was increased from 211.8 to 301.0 mg/L d, when COD/N ratios changed from 8.19 to 7.64, respectively. Results showed that the DN rate was significantly increased. However, the TN removal efficiency was not increased due to the increase of NH$_4$N-volume loading. Furthermore, the nitrification and DN rate were increased from 2.42 to 2.75 times, respectively, implying that more oxidized nitrogen remained in the reactor. Results showed that DN was the rate limiting step in the total process of TN removal. It was speculated that the DN inefficiency was due to insufficient availability of electron donor substances since it was composed of the anoxic removal of influent organic materials.

Figure 2 shows the removal efficiencies of TN, NO$_3$N and NH$_4$N for different COD/N ratios. The removal efficiencies of TN and NH$_4$N were increased from 47.60 to 64.54 and 54.17 to 73.72% with decrease of the COD/N ratio from 8.19 to 7.64, respectively. The nitrification activity was increased gradually and attained a constant value between 75 and 150 day, with an average NH$_4$N removal
efficiency of 73.72%. The average effluent concentrations of NH$_4$-N and TN were 1.95 and 8.27 mg/L, respectively. These data demonstrated that about 6.32 mg/L NO$_x$-N remained, which implied that DN had not occurred completely.

**Effect of COD/N ratio on TP and PO$_4$-P removal**

The COD/N ratio was decreased from 8.19 to 7.64 to decrease the removal efficiency of PO$_4$-P and TP from 42.23 to 33.22% and from 48.76 to 36.89%, respectively. Moreover, the NO$_3$-N/PO$_4$-P ratio was decreased from 5.21 to 4.68 for a similar increase in COD/N ratio from 8.19 to 7.64. It was speculated that reduced NO$_3$-N/PO$_4$-P ratio in the reactor had induced sufficient available substrate for biological PO$_4$-P removal, which resulted in perfect PO$_4$-P removal. Figure 3 presents TP and PO$_4$-P removal efficiency during whole operation period. Having the COD/N ratio of 7.64, the PO$_4$-P and the TP concentrations were decreased insignificantly and average TP and PO$_4$-P removal efficiencies were lower than that for a COD/N ratio of 8.19. The phenomena showed that the PO$_4$-P and TP removal process might undergo rapid conversion, which was speculated to be due to the decrease of polyphosphate-accumulating organisms PAOs. Choi et al. (2008) reported that a logical selection would be a classic N, P process. For each gram of COD consumed, 0.05 and 0.01 mg of N and P was assimilated in the biomass. With decrease of the COD/N ratio, the excess of N was increased in the reactor. This excess N was basically what interrupted the TP and PO$_4$-P removal.

**CONCLUSIONS**

This study was about treatment of RO concentrate, which usually comes from reuse of wastewater treatment, using BAF. The higher BOD (95.86%) removal efficiency than COD (88.95%) and SS (81.12%) is due to the most complete oxidation of organic matter from the F/M ratio (0.48 BOD/ kg MLSS-day) of the influent. The TP (67.66%) and PO$_4$-P (61.42%) removal efficiencies were relatively lower than TN (81.42%) and NO$_3$-N (76.70%). This is due to the low value of the BOD/TP ratio (8.01). Decreasing the COD/N ratio caused the TP and PO$_4$-P removal efficiency to decrease. However, the removal efficiency of TN and NH$_4$-N was increased from 47.60 to 64.54 and 54.17 to 73.72% respectively with decrease of COD/N ratio from 8.19 to 7.64, respectively. In addition, the DN rate and nitrification rate were increased from 211.8 to 301.0 mg/L d and 87.7 to 109.4 mg/L d, respectively, when COD/N ratios changed from 8.19 to 7.64.

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REFERENCES


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