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# Rejection of nutrients contained in an anaerobic digestion effluent using a forward osmosis membrane

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ABSTRACT

The possibility of applying a forward osmosis (FO) membrane filtration process for the post-treatment of an anaerobic membrane bioreactor (AnMBR) was investigated in this study. The FO membrane filtration test, using a surrogate AnMBR effluent prepared by supernatant obtained from a real anaerobic digester, demonstrated excellent rejection of phosphate ions. On the other hand, the rejection of ammonium ions was moderately effective and depended heavily on the operating conditions of the FO membrane (e.g. orientation of the FO membrane) solute concentration in the draw solution (DS) and ammonium ion concentration in the feed solution (FS). The flux of ammonium ions across the FO membrane decreased as the solute concentration in the FS increased. The reverse solute flux from the DS to FS also increased as the solute concentration in the DS increased. The above-mentioned trend was particularly remarkable in the FO filtration with an active layer facing DS (AL-DS) orientation, in which the reverse solute flux was higher than that in the active layer facing FS (AL-FS) orientation. The relationship between the degree of reverse solute flux and flux of ammonium ion was further explained by the FO filtration test using different solute species in the DS. When we used the solutes with higher reverse solute flux than sodium chloride as DS, the flux of ammonium ion became smaller. On the basis of the results obtained in this study, it can be concluded that the reverse solute flux would have a positive influence on the rejection of ammonium ions.

*Keywords:* Forward osmosis; Rejection of nutrients; Solute diffusion; Anaerobic membrane bioreactor

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## 1. Introduction

Wastewater treatment is an essential part of maintaining public health and water quality surrounding a city. However, treating wastewater generally consumes a lot of energy [1]. From the viewpoint of sustainability, the development of wastewater treatment technologies that consume less energy is of great importance. Aerobic treatments, such as the conventional activated sludge treatment process, are the most preferred method of treatment of municipal wastewater. In these processes, the concentration of organic constituents is relatively low. Owing to the familiarity of the operation and maintenance of aerobic wastewater treatment technologies, its technical reliability is sufficiently high. However, the removal of organic constituents with the help of aerobic microorganisms consumes a lot of energy for the aeration of bioreactor to maintain dissolved oxygen concentration above a certain level. In general, 45–75% of the total operating costs of aerobic treatment processes are attributed to costs associated with aeration [2].

Recently, anaerobic wastewater treatment is gaining much attention in the field of municipal wastewater treatment [3,4]. In anaerobic treatment, the organic content of wastewater is converted into methane and carbon dioxide by anaerobic microorganisms [5,6]. In anaerobic treatment processes, aeration is not required, resulting in substantial reduction in energy consumption as compared to aerobic treatment processes. The additional advantages of anaerobic treatment include considerably less sludge production and energy recovery through the collection of biogas-containing methane generated during the treatment [7]. Therefore, anaerobic treatment for municipal wastewater would allow us to construct energy-independent or even producing wastewater treatment systems [8–10]. However, the growth rates of anaerobic microorganisms are generally low, indicating that the possibility of washout of microorganisms involved in anaerobic treatment is high. Therefore, membrane separation is used in anaerobic wastewater treatment (i.e. anaerobic membrane bioreactor (AnMBR)), since the membrane retains the anaerobic microorganisms. Recently, many researchers reported that an AnMBR can be successfully applied for the removal of organic constituents from municipal wastewater [11,12]. However, since an AnMBR does not have pathways for the removal of nitrogen and phosphorus, implementation of some post-treatment processes are necessary [13]. Post-treatment processes would increase the operation and maintenance costs of the whole treatment system. The development of low-cost and effective post-treatment techniques for the effective removal of nutrients in the effluent of an AnMBR would expand the possibility for the application of an AnMBR to municipal wastewater treatment. For this purpose, we focused on a forward osmosis (FO) membrane filtration process for polishing the AnMBR effluent.

Recently, FO has attracted attention as a low-energy membrane separation process [14]. In an FO membrane filtration process, water is spontaneously transferred across a semi-permeable membrane from the feed solution (FS) with lower osmotic pressure to draw solution (DS) with high osmotic pressure governed by the difference in osmotic pressure. Since the skin layer of an FO membrane is almost comparable to that of a reverse osmosis (RO) membrane, effective removal of the nutrients that may remain in the AnMBR effluent (e.g. ammonium and phosphate ions) by the FO membrane can be expected. However, in RO membrane filtrations [15], rejections of ions would differ depending on the ion species. In addition, the operating condition of the FO membrane process and property of membrane surface would also affect the degree of rejection [16,17]. Gaining such fundamental knowledge is necessary in designing a wastewater treatment system based on AnMBR and FO membrane filtration processes.

Recently, several researchers reported that 70–80% rejection of ammonium ion and almost complete rejection of phosphate ion can be achieved by FO membrane installed in AnMBR (i.e. anaerobic osmotic membrane bioreactor) [18]. Similar or more efficient rejections of these nutrients were also reported in osmotic membrane bioreactor (OMBR) operated under aerobic conditions [19,20]. However, when an FO membrane filtration process is incorporated in anaerobic wastewater treatment systems as a form of OMBR, in which FO membrane is utilized for withdrawing water molecules from a bioreactor, depending on operating conditions, accumulation of salts and potential toxicants may adversely affect the performance of microorganisms contained in bioreactor. On this basis, placing FO membrane filtration process outside the anaerobic bioreactor would also be reasonable selection. OMBRs used in the previous studies [19,20] were operated with mixed liquor suspension concentrations of 5.5–7.0 g/L. Since the existence of suspended solids may alter ion profiles in the vicinity of membrane surface, it is still unclear whether the findings obtained in the previous studies mentioned above can be directly applied to operations of FO membrane applied to a post-treatment of AnMBR. To obtain knowledge that can be used for designing post-treatment process of AnMBR using an FO membrane, rejections of nutrients contained in feedwater without suspended solids need to be investigated.

Valladares Linares et al. investigated the rejection of ammonium ion in both AL-FS and AL-DS orientations [21]. However, in their study, the effects of operating conditions of FO membrane other than membrane orientation on the rejection of ammonium ion were not investigated. On the basis of the information mentioned above, it can be said that limited information is currently available on the rejection of the nutrients by the FO membrane used as a post-treatment of effluent of AnMBR. Current understanding on nutrient rejection by FO membranes is still limited.

In this study, we investigated the potential of the FO membrane filtration process as a post-treatment technique of an AnMBR. To simulate AnMBR effluent, diluted anaerobic digestion sludge from full scale sewage treatment plant was prepared. Firstly, the rejection of ammonium and phosphate ions was evaluated using a surrogate AnMBR effluent comprising the supernatant of the real anaerobic digester. Subsequently, the effects of the operating conditions of the FO membrane (e.g. membrane orientation, solute concentration in DS, and solute species in DS) on rejection of nutrients were also investigated using artificial solutions prepared in our laboratory. On the basis of the experimental data obtained in this study, factors affecting the rejection of ammonium and phosphate ions are discussed.

## 2. Materials and Methods

### 2.1. Feed and draw solutions

A surrogate AnMBR effluent and artificial solutions prepared with commercially available chemical reagents were used as the FS. The surrogate AnMBR effluent has been prepared using anaerobically digested sludge obtained from the Higashinada Sewage Treatment Plant in Kobe, Japan. The anaerobic digester at the facility was fed with excess sludge generated from real municipal wastewater in Kobe City. To simulate the AnMBR effluent, suspended solids in the sludge collected were removed by centrifugation (15,000 rpm, 3 min) followed by membrane filtration using polytetrafluoroethylene (PTFE) membrane with a nominal pore size of 0.22 μm. To adjust the nitrogen concentration to the typical concentration of the AnMBR effluent [22], the filtrate was diluted 50-fold by an aerobic MBR effluent obtained from the pilot-scale MBR operated at the Port Island Sewage Treatment Plant in Kobe, Japan. An aerobic MBR effluent was selected as the diluent to keep the salt concentration at the same level as real wastewater. Artificial solutions have been prepared to evaluate factors affecting the rejection of ammonium and phosphate ions. The sources of ammonium and phosphate ions in these solutions were $NH_4Cl$ and $NaH_2PO_4$, respectively, and 0.6 M NaCl solution was used as the DS. The salt concentration in the DS was selected in the simulation of the typical salt concentration of seawater. To evaluate the effect of variation in the solute species in the DS on the rejections of target nutrients, the DSs containing LiCl, glucose, and $MgSO_4$ were also used in the FO filtration tests. The detailed compositions of FS and DS are summarized in Table 1. In the solute concentration designated in Table 1, the water fluxes in the FO membrane filtration were almost the same (approximately 8 $L/m^2/h$ in initial water flux).

### 2.2. FO filtration setup

A schematic representation of the lab-scale FO filtration unit used in this work is depicted in Fig. 1. The filtration experiment was continued for 10 h. A cellulose-based flat-sheet asymmetric membrane (CTA-ES, Hydration Technology Innovations (HTI), Albany, OR, USA) was used in the FO filtration tests. The effective membrane surface area in the FO filtration unit was 29.75 $cm^2$. The cross-flow velocity was set at 13.84 m/h using a tubing pump (MP-1000, Eyela, Tokyo, Japan). A counter-flow pattern was selected because stable osmotic pressure difference between FS and DS can be generated in this arrangement [23]. The initial volumes of FS and DS were 1 L. To evaluate the effect of membrane orientation on the rejection of ammonium and phosphate ions, the FO filtration test was carried out under two conditions: active layer facing FS (AL-FS) and active layer facing DS (AL-DS). The DS tank was located on an electronic balance (FX-5000i, A&D, Tokyo, Japan), and the change of weight was measured every 10 min. The FO membrane filtration was continues for 10 h. Since the focus of this study is evaluating rejections of nutrients by an FO membrane which is currently available in the market, alteration of membrane properties should be avoided as much as possible. Therefore, we decided to perform short-term FO operation in this study. In order to confirm the reproducibility, the experiments were performed three times under each condition.

### 2.3. Water quality analysis

Concentrations of ammonium, lithium, and magnesium ions were determined by an ion chromatograph (HIC-SP, Shimadzu, Kyoto, Japan) equipped with a cation analysis column (Shim-pack IC-C4, Shimadzu,

Table 1
Feed and draw solution using experiments

| | Solute | Concentration |
|---|---|---|
| Feed solution | Surrogate AnMBR effluent | 8.8 mg-C/L |
| | | 28.2 mg-N/L |
| | | 7.1 mg-P/L |
| | $NH_3Cl$ | 10, 30 mg-N/L |
| | $NaH_2PO_4$ | 5.0 mg-P/L |
| Draw solution | NaCl | 0.6 M |
| | LiCl | 0.6 M |
| | Glucose | 1.2 M |
| | $MgSO_4$ | 1.2 M |

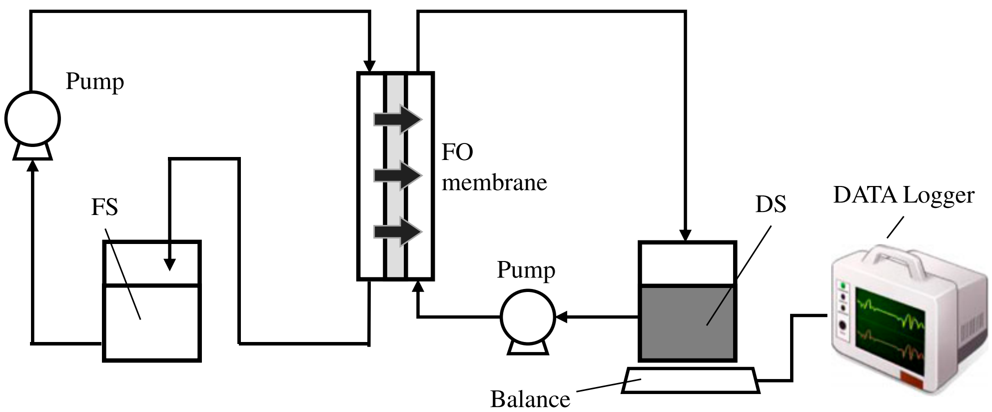


Fig. 1. Schematic representation of the lab-scale FO filtration unit.

Kyoto, Japan). The glucose concentration was evaluated as the total organic carbon (TOC) concentration determined using a TOC analyzer (TOC-VCSH, Shimadzu, Kyoto, Japan). The phosphate ion concentration was determined by the molybdenum blue method [24].

### 2.4. Calculation

The rejection of any dissolved components (ammonium and phosphate ions in this study) is calculated by following equation:

$$R_{\text{solute}}(\%) = \left(1 - \frac{J_{\text{solute}}/J_{\text{w}}}{C_{\text{FS}-\text{solute}}}\right) \times 100 \quad (1)$$

where $J_{\text{w}}$ is the water flux across the FO membrane [$L/m^2/h$], $J_{\text{solute}}$ is the flux of ammonium or phosphate ion across the FO membrane [$mmol/m^2/h$], $C_{\text{FS}-\text{solute}}$ is the initial ammonium or phosphate ion concentration in the FS [mol/L].

$J_{\text{w}}$ and $J_{\text{solute}}$ are calculated by the following equations:

$$J_{\text{w}} = \frac{V}{S\,t} \quad (2)$$

$$J_{\text{solute}} = \frac{C_{\text{FS}-\text{solute}}\,V_0 - C_{\text{FS}-\text{solute}'}(V_0 - V)}{St} \quad (3)$$

where $V$ is the volume of water transferred [L], $V_0$ is the initial volume of the FS [L] (1 L), $S$ is the effective membrane surface area [$m^2$] (0.002975 $m^2$), $t$ is the operating time [h] (10 h), $C_{\text{FS}-\text{solute}'}$ is the final concentration of ammonium or phosphate ion [mol/L].

The reverse solute flux from the DS to FS $J_{\text{S}}$ [$mmol/m^2/h$] is calculated by the following equation:

$$J_{\text{S}} = \frac{C_{\text{FS}'}(V_0 - V)}{St} \quad (4)$$

where $C_{\text{FS}'}$ is the final draw solute concentration in the FS [mol/L].

## 3. Results and discussion

### 3.1. FO experiment using the surrogate AnMBR effluent

Rejection of ammonium and phosphate ions in the FO filtration test, using a surrogate AnMBR effluent as FS, is shown in Fig. 2. About 10–15% of flux decline was observed while 10 h filtration using both surrogate AnMBR effluent. Irrespective of the membrane orientation, more than 95% of phosphate ions were rejected by the FO membrane. This result suggests that FO membrane filtration is a suitable technique for removing phosphorus from the AnMBR effluent. On the other hand, rejection of ammonium ions by the FO membrane was relatively poor, and was significantly dependent upon membrane orientation: 48% in the AL-FS orientation and 59% in AL-DS the orientation. Considering the typical nitrogen concentration in the AnMBR effluent (around 30 mg-N/L [22]), a further improvement in the process through increased ammonium ion rejections is clearly necessary. As shown in Fig. 2, the rejection of ammonium ions by FO membrane depends heavily on its operating conditions; therefore, selection of appropriate operating conditions is a crucial factor in FO membrane filtration process. Further, to be able to select appropriate operating conditions, an understanding of the factors affecting the rejection of ammonium ions is important. Therefore, we investigated the effect of key parameters, i.e. ammonium concentration in FS, solute concentration, and species in DS, on the rejection of ammonium ions.

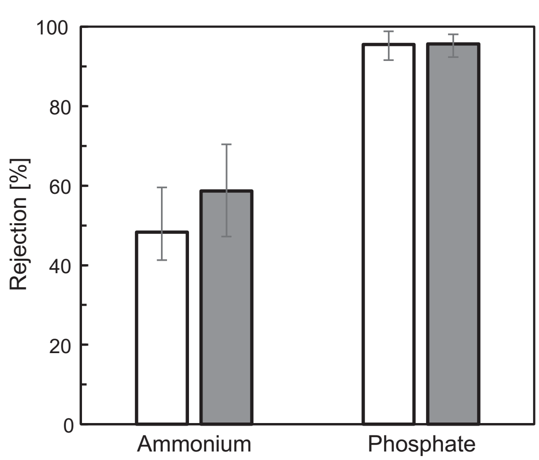


Fig. 2. Rejection of ammonium and phosphate ions using the surrogate AnMBR effluent.
Notes: 0.6 M NaCl solution was used as the DS. White bars represent the result in AL-FS and gray bars represent the result in AL-DS.

### 3.2. Rejection of ammonium ions

#### 3.2.1. Effect of FS concentration on the rejection of ammonium ion and reverse solute flux

To investigate the effect of ammonium concentration in FS on the rejection of ammonium ions by FO membrane, filtration tests using artificial FS with different ammonium concentrations were conducted. In addition, in the experiment using artificial FS, during the FO operation, water flux decreased approximately 10–15%. There is no clear difference of degree of water flux decline between artificial FSs and surrogate AnMBR effluent, it can be said that development of membrane fouling was negligible in all of the experiments carried out in this study. Rather, the decreases in water fluxes were likely to be attributed to dilution of DS. The results are shown in Fig. 3. For each different ammonium ion concentration, the FO membrane demonstrated relatively high rejection of ammonium ions with the AL-DS orientation, whereas the rejection decreased sharply when it had the AL-FS orientation. This trend was generally in accordance with that obtained in the experiment using the surrogate AnMBR effluent (Fig. 2), suggesting that the experiment using artificial solutions partially reproduced the phenomenon exhibited by the experiment that used the surrogate AnMBR effluent.

The results presented in Fig. 3 revealed that the rejection of ammonium ions for the AL-DS orientation

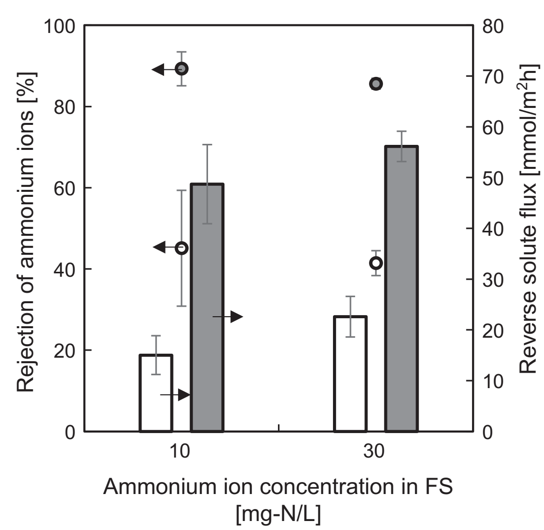


Fig. 3. Rejection of ammonium ions and reverse solute flux at different FS concentrations.
Notes: 0.6 M NaCl solution was used as the DS. Circles represent rejection of ammonium ions and bars represent reverse solute flux. White bars and circles represent the results in AL-FS and gray bars and circles represent the results in AL-DS.

is consistently higher than that in the AL-FS orientation, irrespective of the ammonium ion concentration in FS. One of the possible reasons for the higher rejection of ammonium ions in the AL-DS orientation might be due to a high water flux; the water flux typically becomes higher when an FO membrane is operated with the AL-DS orientation [25]. The increase in water flux is likely to have a positive effect on the apparent rejections because the proportion of water among the molecules transported from FS to DS increases. In other words, even flux of ammonium ion is constant, if the water flux increases, ammonia concentration of permeate decreases, and rejection of ammonium ion is higher (refer to Eqs. (1) and (3)). This phenomenon also occurs in RO membrane [26]. To investigate whether the mechanism mentioned above was involved in the increased ammonium rejections observed in the experiment with AL-DS orientation, we calculated the flux of ammonium ion across the FO membrane based on the data obtained in the FO membrane filtration test.

Water flux across the FO membrane and flux of ammonium determined in the FO filtration tests carried out at different FS concentrations are shown in Fig. 4 (a) and (b), respectively. As shown in Fig. 4 (a), water flux across the FO membrane recorded with the AL-DS orientation was slightly higher than that recorded with the AL-FS orientation for all different FS concentrations. This trend is in accordance with the previous findings [27], according to which the difference in water flux is thought to be caused by the difference in effective osmotic pressure achieved for the FO operation with the AL-DS and AL-FS orientations due to the effect of internal concentration polarization [28]. However, the difference in water flux associated with the difference in FO membrane orientation was not substantial enough to explain the large difference in the rejection of ammonium ions, as shown in Fig. 3. This in turn suggests the possibility of other mechanisms being involved in the increased rejection of ammonium ions in FO filtration with AL-DS orientation. With regard to the changes in ammonium ion concentration in FS, the results presented in Fig. 4 (b) revealed that the flux of ammonium ion clearly decreased when the FO membrane was operated with the AL-DS orientation. This result indicates that the improvement in the rejection of ammonium ions with the AL-DS orientation is mainly attributed to the reduction in ammonium flux rather than the increased water flux. On the basis of the findings stated above, the investigation on factors affecting flux of ammonium ion would be important for improving rejection of ammonium ion. This will be discussed in the following sections.

The reverse solute flux from the DS to FS is also presented in Fig. 3. As can be observed, reverse salt diffusion was apparently more pronounced in the FO operation with the AL-DS orientation. Xie et al. reported that the rejection of selected organic micro pollutants by FO membrane increased as the reverse solute flux increased [16], which serves as a good explanation for the improved rejection of ammonium ions in our experiments with an AL-DS orientation. Therefore, we investigated the effect of reverse solute rejection on the rejection of ammonium ions by changing the solute concentration and species in DS. The results will be presented in the following sections.

### 3.2.2. Effect of solute concentration and species in the DS on rejection of ammonium ions

The degrees of flux of ammonium ion and reverse solute flux determined in the FO filtration test with

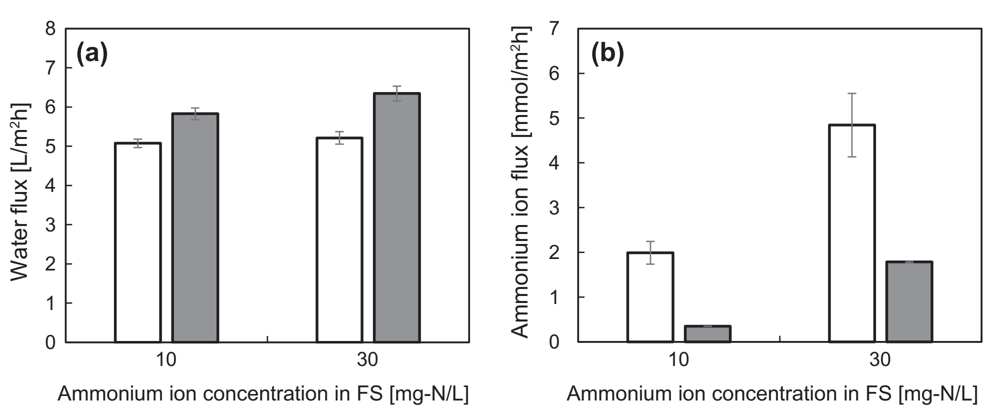


Fig. 4. Water flux and ammonium ion flux at different FS concentration (DS: 0.6 M NaCl); (a) comparison of water flux and (b) comparison of ammonium ion flux.
Notes: 0.6 M NaCl solution was used as the DS. White bars represent the result in AL-FS and gray bars represent the result in AL-DS.

different solute concentrations and solute species are shown in Figs. 5 and 6. With regard to the effect of solute concentration in the FS, flux of ammonium ion sharply decreased when the solute concentration of DS was set at 1.2 M. The decrease in flux of ammonium ion was particularly pronounced in the FO filtration with the AL-DS orientation. The trend in decrease in flux of ammonium ion is generally in accordance with the trend in increase in the degree of reverse solute flux; reverse solute flux increased as solute concentration in the DS increased and this propensity was particularly pronounced in the FO filtration process with the AL-DS orientation.

The relationship between flux of ammonium ion and reverse solute flux was further confirmed in the FO filtration test using DSs containing different solute species (Figs. 5 (b) and 6 (b)). Lithium chloride exhibited higher degree of reverse solute flux. Rejection of ammonium ion was also high in the FO filtration process when a DS containing lithium chloride was used. In contrast, when the DS contained solutes with low reverse solute flux propensities, such as magnesium sulfate and glucose, the flux of ammonium ion was higher than that when the DS contained sodium chloride. Based on the experimental results presented in Fig. 6, the effect of the degree of reverse solute flux on the rejection of ammonium ion was likely to be different depending on membrane orientation; the rejection of ammonium ion in AL-DS mode of operation was much more sensitive than that in AL-FS mode of operation. This fact implies that the rejection of ammonium ion is not directly affected by the degree of reverse solute flux. A possible explanation on the difference in sensitivity of rejection of ammonium ion to degree of reverse solute flux might be the difference in solute profile caused by the difference in membrane orientation. In AL-DS mode of operation, the solutes diffused from DS tend to be accumulated in the support layer of the FO membrane, whereas such solute would immediately be diffused into FS in AL-FS mode of operation. The elevated solute concentration created as a result of such accumulation may have some preventive effect for ions being transported (e.g. decrease in their activity). In previous report, it has been reported that approximately 90% rejection of ammonium ion can be achieved in OMBR operated with AL-FS mode [19]. In OMBR, due to high suspended solid concentration, formation of sludge cake layer on the surface of FO membrane is likely to be much more significant than the FO membrane filtration experiments carried out in this study. Taking the fact that cake layer formation on the membrane surface also accelerates the accumulation of solute diffused from DS into consideration, the results obtained in this study is thought to be in agreement with the previous findings obtained in the investigation on OMBR.

These results, again, suggest that increasing reverse solute diffusion has a positive influence on ammonia removal by the FO membrane. A similar phenomenon has been reported in a previous study by Phillip et al. [28]. However, the detailed mechanism of this phenomenon is not clear. It is well known that membrane surface properties such as surface charge affect rejection of ions by an FO membrane [29]. However, this might not be a good explanation on the difference in rejection of ammonium ion in each experiment carried out in this study. This is because, in all of the experiments carried out in this study, pH values of both DS and FS were in the range of 5.5–8, which was apparently higher than the isoelectric point of cellulose acetate membranes [30,31]. In addition, FO

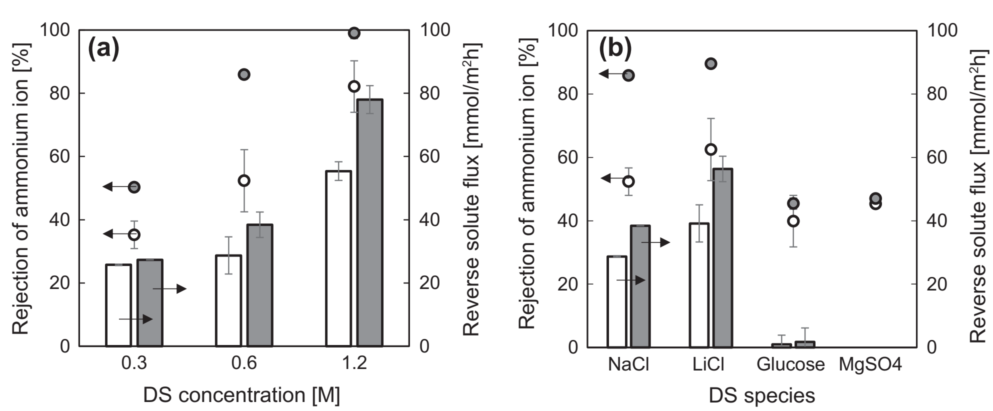


Fig. 5. Relationship between rejection of ammonium ions and reverse solute flux: (a) different DS concentrations and (b) different solute of DS species.
Notes: 30 mg-N/L $NH_4Cl$ solution was used as the FS. Circles represent rejection of ammonium ions and bars represent reverse solute flux. White bars and circles represent the results in AL-FS and gray bars and circles represent the results in AL-DS.

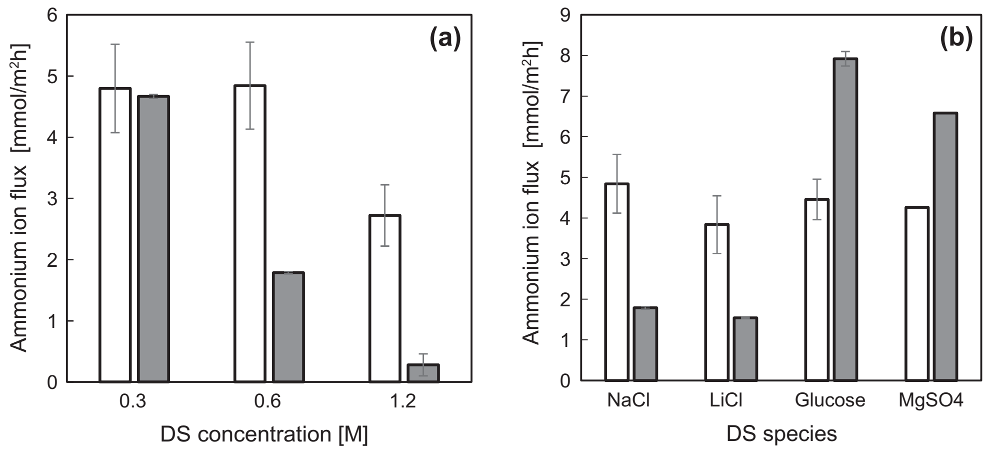


Fig. 6. Comparison of ammonium ion flux: (a) different DS concentrations and (b) different solute of DS species.
Notes: 30 mg-N/L $NH_4Cl$ solution was used as the FS. White bars represent the result in AL-FS and gray bars represent the result in AL-DS.

membranes made by CTA is known to have no functional group that dissociate under the pH range of the experiments carried out in this study [32]. On the basis of the discussion mentioned above, it is very likely that the difference in rejection of ammonium flux found in this study was not attributed to the difference in membrane surface properties. Elucidating the dominant phenomena affecting rejection of ammonium ion is an important subject to be explored in terms of improvement in the membrane performance.

### 3.3. FO membrane process as a post-treatment of the AnMBR

The results obtained in this study revealed that FO membrane filtration process could be a suitable technique for the post-treatment of AnMBR. Taking typical concentrations of ammonium-nitrogen (approximately 30 mg/L) and phosphorus (3–4 mg/L) into consideration, the virtual concentrations of nitrogen and phosphorus in the permeate of the FO membrane (excluding the effect of dilution by DS) can be lowered up to around 10–15 mg/L for nitrogen (when operated with the AL-DS orientation) and less than 0.5 mg/L for phosphorus. The phosphorus concentration in the permeate was lower than the wastewater discharge standard in Europe (1 mg-P/L), but the nitrogen concentration in the permeate exceeded this standard (10 mg-N/L) in our experiments. In future, as the FO membrane performance improves, the nitrogen concentration in the permeate can also be lowered than the standard value.

Among the nutrients in the effluent of an AnMBR, phosphorus is likely to be removed well, irrespective of the operating conditions. On the other hand, the removal of ammonium ions will depend heavily on operating conditions of the FO membrane filtration process, suggesting that an FO membrane filtration unit intended to be used for post-treatment should be designed for maximizing the removal of ammonia rather than phosphorus. On the basis of the above-mentioned results, increase in reverse solute flux form the DS to the FS is likely to have positive influence on the rejection of ammonium ions by the FO membrane. However, there might be several practical concerns regarding the AL-DS orientation, when actually designing the FO membrane filtration facility. Firstly, membrane fouling tends to be more significant when an FO membrane is operated with the AL-DS orientation [33]. Since the AnMBR effluent would typically have a high fouling potential, achieving stable FO membrane filtration with the AL-DS orientation is thought to be challenging. In addition, high reverse solute flux would also be a problem for effective operation of the FO membrane filtration process to be used as a post-treatment of AnMBR. Reverse solute flux results in an increase in the osmotic pressure of the FS, which in turn reduces the effective osmotic pressure difference between the FS and the DS.

Based on the discussion above, further improvement in the FO membrane filtration process is needed for (1) improving the ammonium rejection with the AL-FS orientation, and (2) achieving stable FO filtration with the AL-DS orientation. One of the probable approaches for overcoming the above-mentioned issues would be to achieve improved membrane performance. Specifically, development of membranes with high rejection of ammonium ions with an AL-FS orientation or resistant to membrane fouling in the FO filtration process with the AL-DS orientation are important topics for future research. The findings obtained in this study would be useful for elucidating the mechanisms by which rejection of ammonium ion is affected, and therefore, also useful for establishing countermeasures stated above.

### 3.4. Treatment of concentrate discharged from FO membrane post-treatment

Apart from the quality of treated water (i.e. permeate of FO membrane), an appropriate treatment of concentrate discharged from FO membrane filtration unit is of great importance for proposing wastewater treatment systems based on AnMBR and FO membrane filtration processes. The results obtained in this study suggested that the rejections of ammonium and phosphate ions are approximately 60 and 95%, respectively. Assuming that the concentrations of ammonium and phosphate ions in an effluent of AnMBR are 30 and 3.5 mg/L, respectively [22], concentrations of these ions in a concentrate from FO membrane filtration unit can be estimated as approximately 90 mg/L for ammonium ion and 15 mg/L for phosphate ion. Unfortunately, these concentrations may not be sufficiently high for recovering these nutrients through crystallization of magnesium ammonium phosphate [34]. For phosphorus recovery, the hydroxyapatite crystallization process could be applied, since this process functions successfully in solution containing phosphorus in relatively low concentration (e.g. 3.5 mg/L) [35] though controlling the scaling comprised of calcium phosphate would be an additional issue in this application. Recent advancement in phosphorus adsorbent [36,37] may give us further opportunities for efficiently recovering phosphorus from concentrate discharged from FO membrane filtration units.

On the other hand, recovering ammonia from an FO concentrate is likely to be more difficult. Taking into account that the economic value of ammonia is smaller than that of phosphorus, it can be thought that ammonium-nitrogen needs to be "removed" rather than "recovered." Since large portion of organic matter is removed in AnMBR, the carbon-to-nitrogen (C/N) ratio in a concentrate discharged from FO membrane filtration unit installed after AnMBR is expected to be low. Adding external carbon source would be required for successful removal of nitrogen through conventional nitrification/denitrification process. Another possible measure for treating concentrated ammonium ion might be anammox. According to the work performed by Furukawa et al. [38], successful operation of anammox reactor incorporating partial nitrification can be achieved with an ammonia concentration in influent of 100 mg/L. Further improvement in rejection of ammonium ion by an FO membrane would allow us to apply more efficient treatment methods for concentrate discharged from FO membrane filtration units.

## 4. Conclusions

In this study, we investigated the possibility of applying an FO membrane filtration process for the post-treatment of an AnMBR. The results of an FO membrane filtration test using a surrogate AnMBR effluent prepared by supernatant obtained from a real anaerobic digester revealed that the FO membrane demonstrated excellent rejection of phosphate ions, whereas the rejection of ammonium ions was moderate and depended heavily on the orientation of the FO membrane. The flux of ammonium ions across the FO membrane decreased as the solute concentration in the FS increased. In the FO filtration experiment using the DS with a high solute concentration, the reverse solute flux from the DS to FS increased. The above-mentioned trend was particularly remarkable in the FO filtration with the AL-DS orientation, in which the reverse solute flux was higher than that in the other membrane orientation. The relationship between the degree of reverse solute flux and flux of ammonium ion was confirmed by the FO filtration test using different solute species in the DS. When lithium chloride, which had a high reverse solute flux than sodium chloride, was used for preparing the DS, the flux of ammonium ion decreased. On the other hand, a higher flux of ammonium ion was observed in the FO filtration using the DS-containing solutes with less reverse flux, such as magnesium sulfate or glucose. On the basis of the results obtained in this study, it can be concluded that reverse solute flux has a positive influence on the rejection of ammonium ions.

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