Optimization of Forward Osmosis System for the Utilization of Reverse Osmosis Brine

R.C. Eusebio[1,2]*, M.A. Promentilla[2] and H.S. Kim[1]

[1]Department of Environmental Engineering and Biotechnology, Myongji University, San 38-2, Namdong, Cheoingu, Yongin, Gyeonggido, 449-728, South Korea
[2]Center for Engineering and Sustainable Development Research, De La Salle University, Manila, 1004, Philippines

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*Email: rceusebio@gmail.com; Tel.: (+63)9175127338

Abstract

This research aims to utilize the concentrated brine by incorporating an FO system as a post-treatment in an RO plant. The objective of this study is to optimize the operating condition of an FO system suitable for energy recovery. Water flux and reverse solute flux were measured at different draw solution (DS) concentrations. Change in the salinity of the feed and permeate flux are the two parameters that were monitored and evaluated. To further optimize the process, membrane fouling was also investigated. Fouled membrane was subjected to scanning electron microscopy and energy dispersive x-ray analyses. Seawater was used as the feed while sodium chloride was used to simulate different brine concentrations. It was observed that increasing the concentration of brine enhances permeate flux. However, increase in reverse solute flux was also observed compensating the high water flux. Fouling in the support layer of FO membrane was evident at 200 g/L DS concentration. Whilst 100 g/L was found to be the most suitable for FO system with almost similar fouling propensity as compared to 50 g/L and 75 g/L. With lower internal concentration polarization and optimized operating condition, FO system could be efficiently used in utilizing brine for energy recovery.

Introduction

As early as 1970's, researchers have already been investigating the application of forward osmosis to produce drinking water [1]. However, the introduction of reverse osmosis (RO) process overshadowed the potential of forward osmosis (FO) for desalination. Nowadays, reverse osmosis is widely used in desalination for water purification. Though, the concentrated brine produced from the RO system is a huge challenge for waste disposal. Thus the utilization of RO concentrate should further be explored. Ng and Tang cited that forward osmosis could be used for drinking water industry and brine reclamation [2]. Integrating RO and FO processes is a promising combination to treat the RO brine prior to disposal. There are various ways to utilize the brine from the seawater reverse osmosis plant. One of those is to generate electricity from the salinity gradient using a pressure retarded osmosis process as reported by Yip and Elimelech [3]. In 2008, Skilhagen *et al.* mentioned that the osmotic power stands out as a promising and yet unexploited new and renewable energy resources [4]. In addition, Ahmad and Williams also presented their findings in recovering energy from brine prior to disposal [5]. However, these studies of recovering energy from RO brine using FO process should still be elucidated. It was believed that FO membranes are not easily fouled due to absence of external pressure as compared to RO process. But an important parameter is being neglected; the membrane fouling caused by internal concentration polarization. Internal fouling in FO membrane plays an important role in optimizing the operating condition of the FO system. Concentration polarization directly affects the permeate flux as well as the transport of solute into the membrane. Several studies were already conducted to show the relationship between water flux and reverse solute flux [6-7]. On the other hand, just few studies were conducted to investigate the effect of membrane fouling to the overall performance of the FO system, especially the utilization of brine using seawater as feed water. In 2006, McCuncheon did an experiment to explain the influence of concentration polarization to flux behaviour under a FO mode [8]. And recently, She *et al.* presented a research relating the reverse and forward diffusion of solute across the membrane [9]. However, further investigation on the effect of RO concentrate to membrane fouling using seawater as feed in harvesting energy for possible electricity generation is still needed. This research aims to utilize the concentrated brine by incorporating an FO system as a post-treatment in an RO plant. The objective of this study is to optimize the operating condition of an FO system by minimizing the effect of internal concentration polarization. The suitable condition could maximize the permeate flux while lowering the reverse solute flux, which can improve the system efficiency as well as prolonging the lifespan of the membrane.

Materials and Methods

Experimental Set-Up

The lab-scale FO system is composed of two closed loops, one for the feed solution and the other for the draw solution. Gear pumps, due to its stability and reading consistency, were used to inject the feed and draw solutions into the FO cell. Blue-White® flowmeters with an acrylic meter body and stainless steel floats were used to prevent scaling caused by high salt concentration. Cellulose acetate membrane from Hydration Technology Innovations (HTI) was utilized in this experiment with an effective area of 0.0065 m^2. To reduce the strain on the membrane, mesh spacers were installed at both sides of the membrane, which serves as a support, and promotes turbulence and mass transport. JSR Cire water bath maintains the temperature of both operating solutions. AND GF-4000 analytical balance recorded the change in mass of the draw solution to be used in the calculation of permeate flux. Thermo Scientific Cimarec magnetic stirrer was used to ensure that the reconstituted seawater is well mixed. The schematic diagram of the lab-scale FO system is illustrated in Figure A.1.

Operating Condition

The labscale FO system was operated in a counter-current flow. Reconstituted seawater was used as the feed solution while different sodium chloride concentrations served as draw solution. The brine is flowing on the permeate side and the seawater on the active layer side. Water flux and reverse salt flux (RSF) were measured at different draw solution concentrations to determine the most efficient operating concentrations for both feed and draw solution. Change in the salinity of the feed and permeate flux are the two parameters that were monitored and evaluated. The FO system was operated with a flowrate of 0.2 L/min for both feed and draw solution at a constant temperature of 25 ºC. Synthetic seawater was used as the feed while sodium chloride (NaCl) was used to simulate different brine concentrations: 50 g/L, 75 g/L, 100 g/L and 200 g/L. Operating parameters were summarized in Table A.1.

FO Membrane

The OsMemTM CTA-NW membrane from Hydration Technology Innovations (HTI) was used in the experiment. This FO membrane has a fouling resistant feature and casted on a weldable nonwoven support. The maximum operating temperature is 71 ºC and the pH range is 3 to 8 as provided by HTI.

Composition of Reconstituted Seawater

Reconstituted seawater was made using the Standard Method [10]. Composition of seawater is listed in Table A.1. The sequence of salt addition is an important factor that must be followed as well as the dissolution of each salt prior to the addition of the next one.

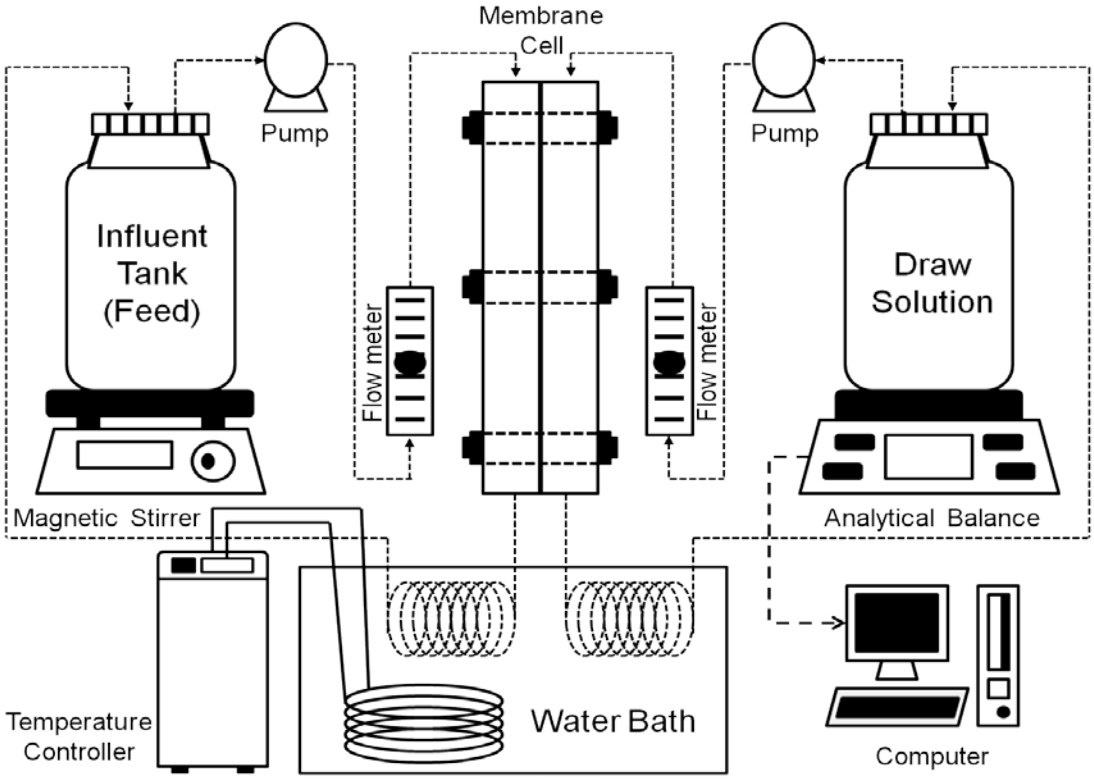


Fig. 1 Labscale forward osmosis system.

Table 1. FO system operating parameters.

Parameter	Description
Membrane	Cellulose Triacetate
Feed Solution	Seawater
Draw Solution	NaCl
Influent flowrate (L/min)	0.2
Temperature (ºC)	25

Table 2. Composition of reconstituted seawater.

Compound in Order of Addition	Final Concentration (mg/L)
NaF	3
$SrCl_2 \cdot 6H_2O$	20
H_3BO_3	30
KBr	100
KCl	700
$CaCl_2 \cdot 2H_2O$	1470
Na_2SO_4	4000
$MgCl_2 \cdot 6H_2O$	10780
NaCl	23500
$Na_2SiO_3 \cdot 9H_2O$	20
Na_4EDTA	1
$NaHCO_3$	200

Analytical Methods

To further optimize the FO process, concentration polarization on and within the membrane was investigated, an index in assessing the intensity of membrane fouling that could affect the efficiency of the system. Fouled membrane was subjected to scanning electron microscopy (SEM) and energy dispersive x-ray (EDX) analyses. To further increase the efficiency of FO system, the effect of membrane fouling on both permeate flux and RSF were investigated by evaluating the results of EDX and elucidating the SEM images of the fouled membrane. Thermo Scientific Orion Star A222 measured the increase in the salinity of the feed solution, which was use in calculating reverse solute flux.

Results and Discussions

Batch experiments were conducted at different brine concentrations to determine the effect of increasing draw solution concentration to permeate flux. The FO system was operated for 3 hours for each DS concentration. The change in mass of the draw solution was recorded every 60 seconds using a digital top loading balance. The computed difference in mass as well as the effective area of the membrane was used to calculated the permeate flux. The data gathered from batch experiments were plotted to visualize the flux trend for each DS concentration as illustrated in Figure A.2. Even though the graph shows a scattered plot, an evident linear trend is clearly observed. The average flux was computed for each DS concentration. As expected, increasing DS concentration enhances permeate flux due to the high osmotic difference across the membrane. The draw solution with a concentration of 200 g/L recorded the highest permeate flux of 6.24 LMH, while 50 g/L DS concentration recorded the lowest with 1.07 LMH. The average flux for each DS concentration is plotted in Figure A.3. A logarithmic increase of permeate flux was observed at increasing draw solution concentration. The graph generated an equation of $y = 3.7668 \ln(x) – 13.805$, wherein the change in permeate flux decreases as the DS concentration increases. This could be attributed to the tendency of the membrane to be fouled at high DS concentration resulting to an increase in internal concentration polarization. The salts deposited onto the membrane blocking the pathway where the permeate passes through.

Solutes from the draw solution have a tendency to penetrate the membrane to the feed side. It was found that increasing the DS concentration increases the permeate flux, however, the increase in DS concentration also increases the transport of solute across the membrane. The increase in the salinity of the feed solution is illustrated in Figure 4. The highest salinity of 0.23 ppt was obtained at the highest DS concentration of 200 g/L. To further evaluate the rate of transport of solutes from the draw solution side to the feed solution side, the graph of the reverse solute flux at different DS concentrations was generated. A logarithmic pattern was observed with an equation of $y = 0.2406 \ln(x) - 0.8697$. At low DS concentration, solutes from the draw solution could enter to the pores of the membrane's support layer and easily diffuse back to the draw solution side. In contrast, at high DS concentration, deposition of salts in the support layer could be severe, making it difficult for the solutes to diffuse back to the draw solution side, which also blocks the passage of the water from the feed side.

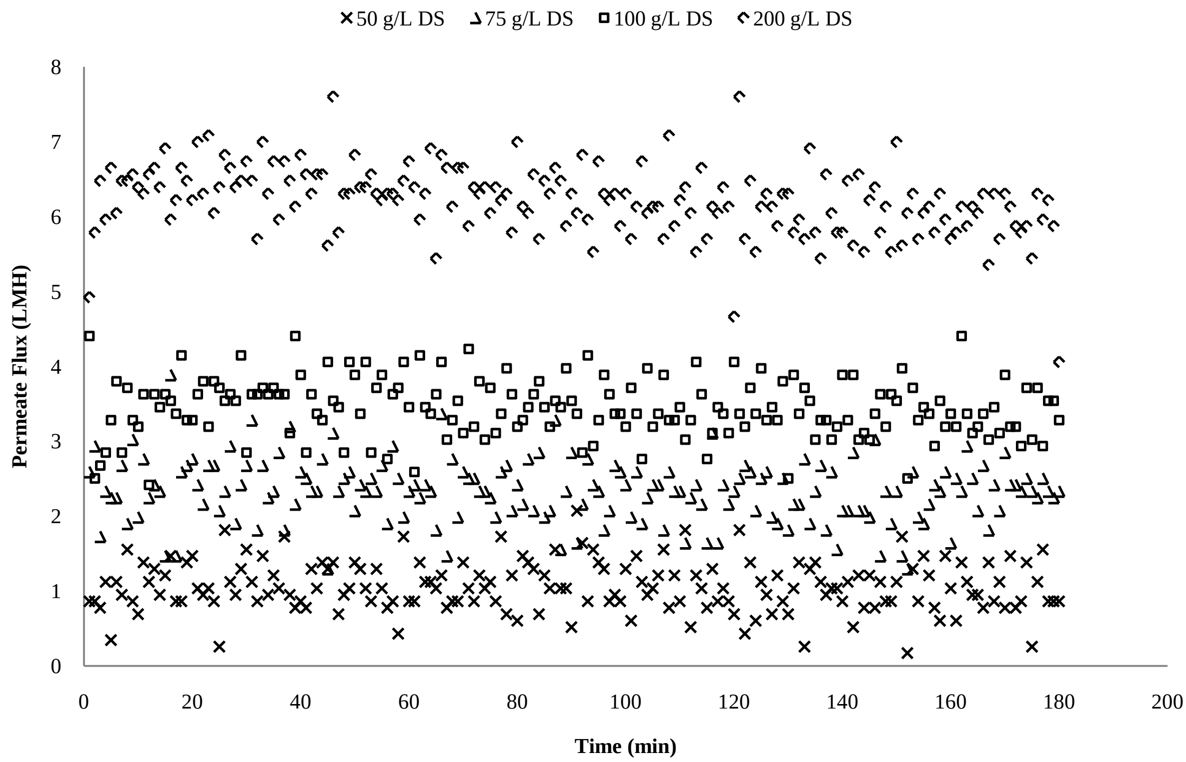


Fig. 2 Comparison of fluxes at different draw solution concentrations.

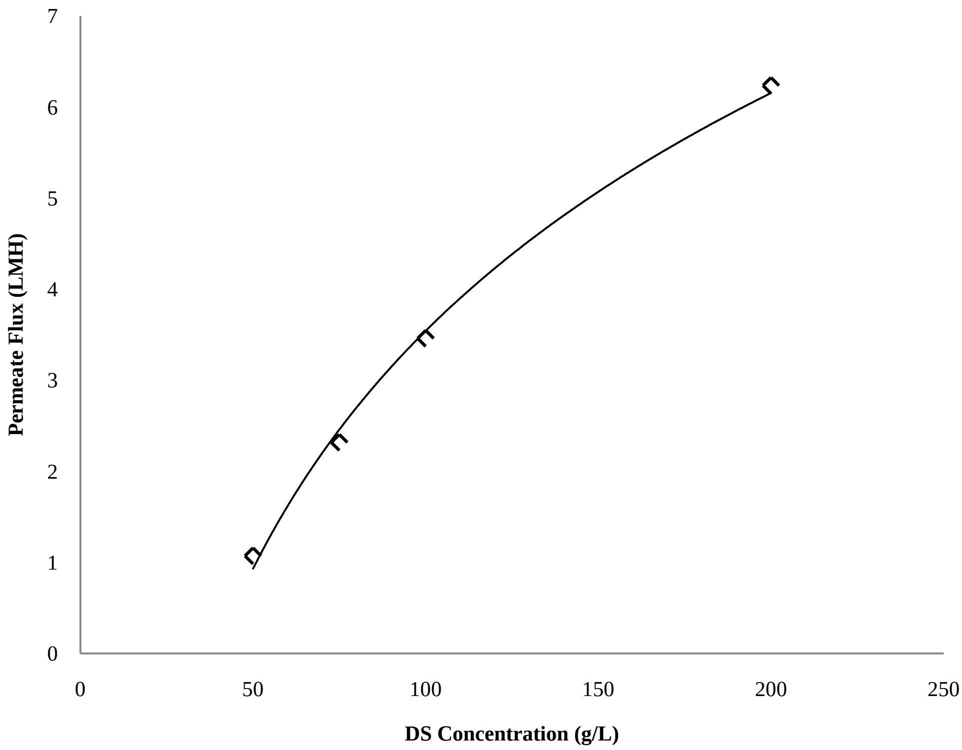


Fig. 3 Average flux at different draw solution concentrations.

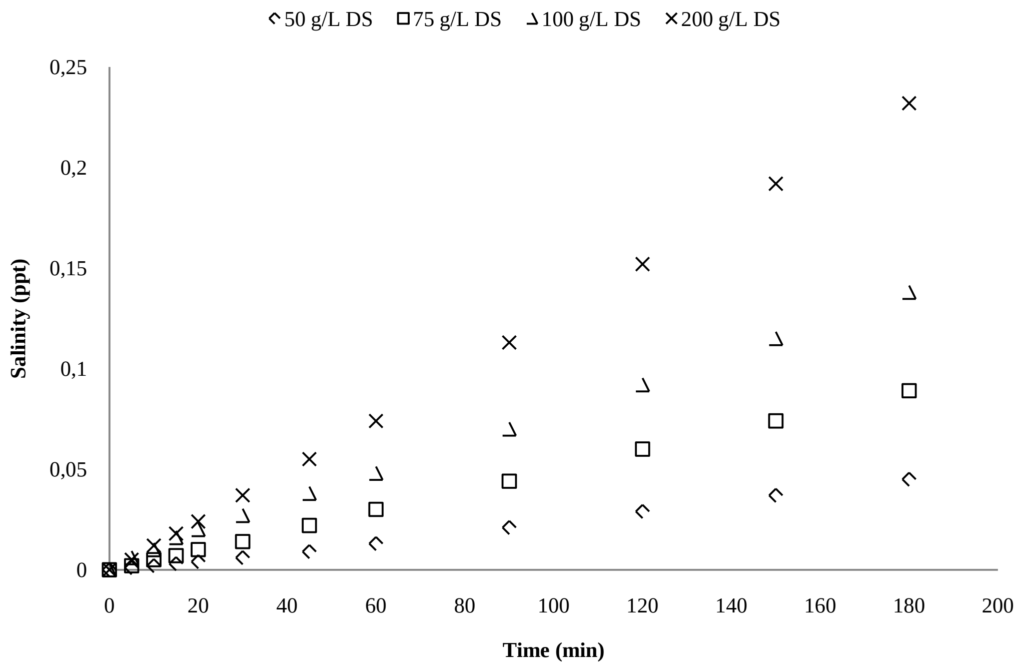


Fig. 4 Increase in salinity at different draw solution concentrations.

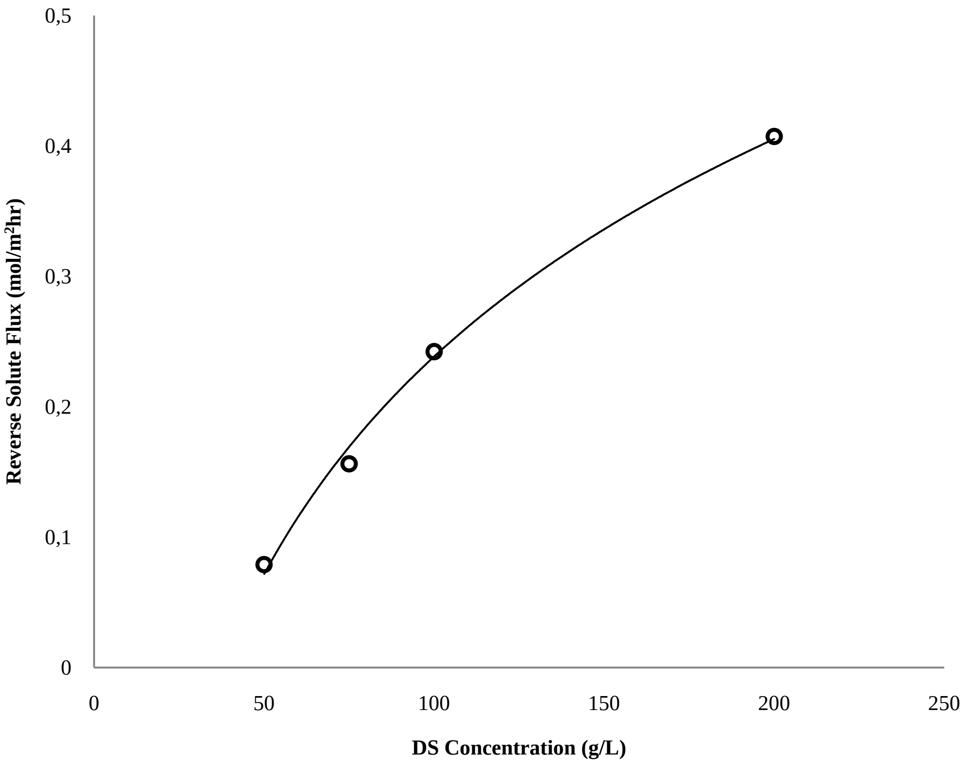


Fig 5 Comparison of reverse solute flux at different draw solution concentrations.

Table 3. EDX analysis of the fouled membrane at different draw solution concentrations.

Draw Solution Concentration (g/L)	Element (Composition, %)			
	C	O	Na	Cl
50	53.23	38.12	3.29	5.36
75	53.86	35.30	3.91	6.94
100	53.22	34.93	4.16	7.70
200	52.88	34.07	4.54	8.52

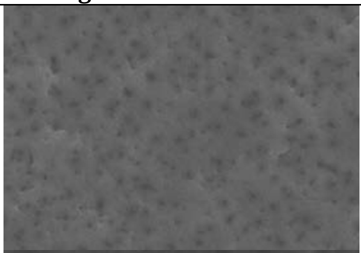
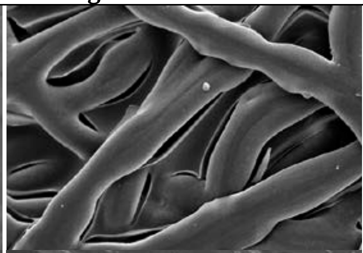
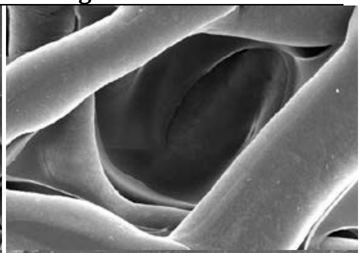
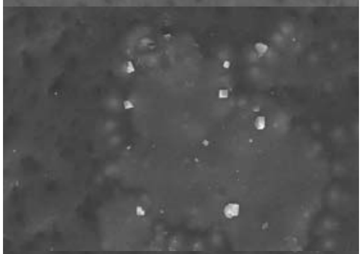
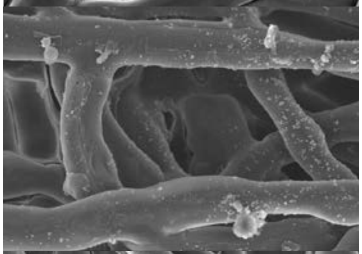
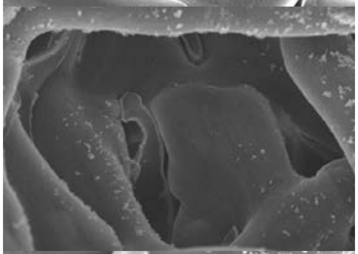
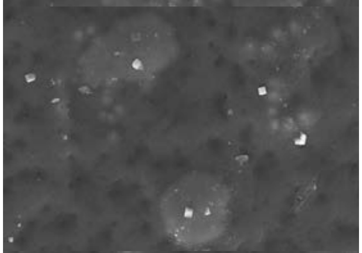
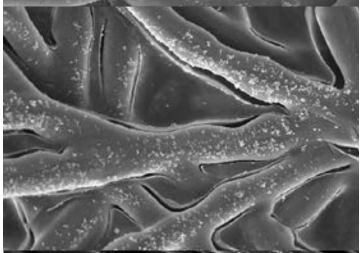
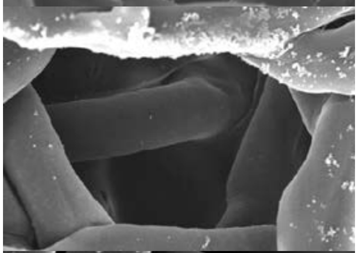
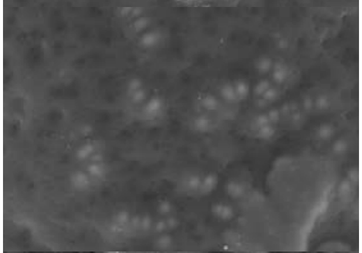
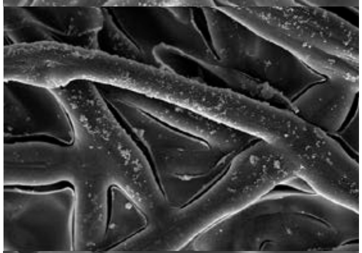
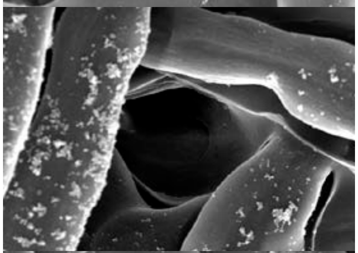
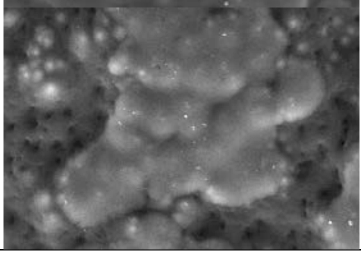
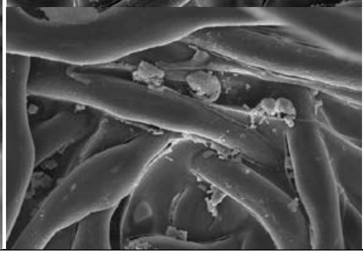
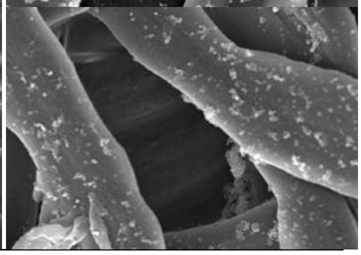
Deposition of salts in the membrane was quantitatively analyzed by EDX. The percent composition of the foulants was enumerated in Table A.3. The elements C and O came from the material used for membrane fabrication. As seen in the table, the % composition of Na and Cl increases as the draw solution concentration increases. This can be attributed to the deposition of salts at high DS concentration. It was proven that the composition of foulants at elevated salt concentration triggers pore blocking that prevents passage of water from the feed side to the draw solution side.

To further investigate the salt deposition on and within the membrane, SEM analysis was conducted. Table A.4 shows the images of the active layer (membrane surface) and the support layer at different draw solution concentrations. The first row of micrographs shows the images of the virgin membrane, which sets as basis for comparison. For the active layer, increasing the DS concentration increases the amount of foulant on the membrane surface. It can be observed that the membrane surface was severely fouled at 200 g/L DS concentration, while the other three DS concentrations have almost similar amount of foulants. It was also found that the foulants adhered on the surface of the membrane can be easily removed by physical washing. On the other hand, adhesion of salts in the support layer was clearly seen in the SEM images magnified at 500X. Solutes were predominant at the outer part of the support layer. However, for the 200 g/L DS concentration, solutes penetrated the pores of the support layer as seen in the photo magnified at 1000X, thus increasing the deposits of salts in the membrane. This deposit causes internal concentration polarization that lowers the transport of water across the membrane and increasing the diffusion of salts to the feed side, which resulted to the low change in permeate flux and high reverse solute flux.

Conclusion

Performance of the labscale FO system was evaluated by investigating three important parameters: permeate flux, reverse solute flux and membrane fouling. Increasing the draw solution concentration increases permeate flux, which compensates the increase in reverse solute flux. Highest permeate flux was recorded at the highest DS concentration but recorded the lowest rate of water transport or the change of permeate flux with respect to DS concentration, which was caused by high internal concentration polarization at elevated salt concentration. Membrane fouling was severe at 200 g/L DS concentration, while the others showed similar fouling propensity. Thus, 100 g/L was the most suitable DS concentration that can be used in FO process to minimize internal concentration polarization with an optimized permeate flux and reverse solute flux of 3.46 LMH and 0.24 mol/m^2hr, respectively.

Table 4 SEM images of the fouled membrane at different DS concentrations.

	Active Layer	**Support Layer**	
	magnification: 1000X	**magnification: 500X**	**magnification: 1000X**
Virgin Membrane			
50 g/L DS			
75 g/L DS			
100 g/L DS			
200 g/L DS			

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