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Evaluation of ultrafiltration and multimedia filtration as pretreatment process for forward osmosis

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ABSTRACT

In order to reduce scaling in a multistage flash (MSF) desalination plant, the brine reject can be diluted using forward osmosis (FO) before recycling. In this FO process, the brine is used as the draw solution (DS) and seawater is used as the feed solution (FS). However, the FO process suffers from low water flux owing to membrane fouling. The water flux in FO can be enhanced by reducing the foulant concentration in the FO feed solution (FS). Thus, in this paper seawater, multimedia sand filtered seawater, and ultrafiltrated seawater is being used as feed solution for the FO process. The flowrate of the feed solution was kept constant at 2.0 L/min. However, the flowrate of the draw solution (DS) were tested at 2.0 and 0.8 L/min. When the flowrate of the DS was 0.8 L/min, the highest initial flux of 44.1 L/m^2 h were obtained using ultrafiltrated seawater as FS. After the initial run, the membrane was cleaned and during the second run, 83% of the initial flux was recovered using the ultrafiltrated seawater as FS. For ultrafiltrated seawater, the water recovery rate and specific energy consumption was 36.2% and 0.065 kWh/m^3, respectively.

Keywords: Forward osmosis; Pretreatment; Ultrafiltration; Water flux; Sand filtration

1. Introduction

Multistage flash (MSF) and multi-effect distillation (MED) are the main thermal desalination technologies that have successfully met water demand in arid areas [1–4]. However, these technologies suffer from loss of efficiency due to scaling on the inner surface of the heat transferring equipment. For long, scaling has been reduced by adding antiscalants and regular maintenance of the equipment. However, these strategies are not sufficient as scale build up over time cannot be avoided [2,5–8]. In recent years, feed pretreatment methods are being investigated to reduce the concentration of scale causing divalent ions [9,10]. Hassan et al. [10] proposed the pretreatment of the feed to MSF using nano-filtration (NF). By utilizing NF, the concentration of divalent ions was reduced which reduced the energy consumption of the MSF process by 20%–30% [11–13]. However, nanofiltration is considered costly due to the required operating pressure [14]. By using NF, the water recovery rate of 65% has been achieved at a specific energy demand of 1 kWh/m^3 [15]. This extra energy demand increases the cost of water and makes NF impractical.

Unlike NF, which uses hydraulic pressure as the driving force, forward osmosis (FO) is a process that uses the osmotic pressure gradient between feed solution (FS) and draw solution (DS) as the driving force [16,17]. Thus,

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the operating cost of FO is expected to be lower than any other membrane-based pretreatment process. A simulation study by Altaee et al. [16] showed that major scaling ions in MED/MSF can be removed by diluting the recycle brine using FO. In the simulation, Altaee et al. [16] used brine reject as draw solution and seawater as feed solution. The results showed a 32% water recovery rate along with 62% reduction in Ca^{2+}, Mg^{2+}, and SO_4^{2-} ions [16]. Thabit et al. [17] used real seawater as feed solution and brine reject as draw solution in FO [17]. The results showed an average water flux of 16.9 L/m^2.h when the FO process was operated with DS and FS flowrates of 0.8 and 2.0 L/min, respectively. Moreover, by increasing the temperature of the draw solution to 40°C (from 25°C), the average water flux was improved to 22.3 L/m^2 h. Furthermore, the flux increased by 26% when the FO process was operated in pressure retarded osmosis (PRO) mode, where the active layer of the membrane faces the draw solution. In addition, it was found that the FO process was able to reduce the concentration of divalent ions in the draw solution (brine reject). However, one of the critical drawbacks that hamper the practical application of FO process is the low water flux due to membrane fouling [18–21]. Several researchers have investigated the reduction of fouling in FO process [18]. Zhao et al. [22] evaluated the effect of membrane operation mode on the performance of FO using synthetic seawater as draw solution (DS) and various saline waters as feed solutions (FS) [18]. The results showed that, when the FS has high fouling propensity, FO mode (i.e., feed solution facing active layer) is preferred. Whereas, when the FS has low fouling propensity, PRO mode (i.e., feed solution facing support layer) is preferred [18]. Sun et al. [19] suggested preconditioning of the FO membrane with polyaluminum chloride to reduce fouling in the FO membrane [19]. Balkenov et al. [20] doped the FO membrane with silver nanoparticle and was able to recover 100% of the flux after cleaning the membrane with distilled water. Ang et al. [21] suggested using a metal chelating agent and an anionic surfactant for cleaning the membrane in order to reduce fouling propensity during FO operation [21].

None of the previous studies have considered using ultrafiltration or sand filtration as a pretreatment process for FO in desalination application. So far FO has been used as a pretreatment process for desalination. However, the performance of the FO process can be further enhanced by reducing the foulants in the feed solution. In this paper sand filtration and ultrafiltration were evaluated as pretreatment processes for FO. In the FO Process, the draw solution was brine reject supplied from an MSF desalination plant in Qatar. And the feed solutions were seawater, sand filtered seawater, and ultrafiltrated seawater. The effect of feed solution and draw solution flowrates on the water flux and the water recovery rate were studied. In addition, the energy requirements for sand filtration and ultrafiltration were assessed.

2. Materials and setup

2.1. Feed solution and draw solution

The feed solution (FS) in the FO system was seawater. Seawater was collected from corniche beach located in Doha, Qatar. The draw solution in the FO system was brine reject (BR) collected from an MSF desalination plant located in the south of Doha. The characteristics of the seawater and the brine reject are summarized in Table 1.

2.1.1. Pretreatment of feed solution

Multimedia sand filtration and ultrafiltration have been used for pretreating the forward osmosis feed solution (i.e., seawater). Figs. 1a and b shows the schematic diagram of the multimedia sand filter and the ultrafiltration system, respectively.

The multimedia sand filter was manufactured by Atico (India). The filtration media consists of 10 cm of activated carbon (anthracite) (0.8–1.6 mm), 25 cm of coarse sand (0.71–1.18 mm), 25 cm of fine sand (0.4–0.8 mm), and 5 cm of gravel. The filter can operate in two modes the normal mode and the backwash mode. By controlling the turbid water valve and backwash water valve, the mode of operation can be switched. A domestic pump (CEAM 70/5, Lowara Co., Italy) was used to pump water into the system. Before running the multimedia filter, the system was backwashed using tap water for 20 min. Then the turbid water valve was opened to permit a constant seawater flow to the filter at a flowrate of 2.5 L/min and at a pressure of 0.5 bar. After the filtration stage, water was collected from the effluent sampling port and used as a feed solution for the forward osmosis.

For the ultrafiltration (UF) system, a CF042D crossflow cell assembly provided by Sterlitech was used. The cell dimensions were 12.7 cm × 8.3 cm × 10 cm with active inner dimensions of 4.6 cm × 9.2 cm and 0.23 cm slot depth. Two tanks were used to store the feed and the permeate solutions. A M-03S HYDRACELL pump (230 V, 50 Hz, 3 pH, and 6.7 L/min) was used to increase the pressure of the feed solution. A Concentrate/Backpressure control valve assembly was used to control water flow through the system and to regulate pressure inside the system. A flow meter (Sterlitech

Table 1
Characteristics of the feed solution (seawater) and the draw solution (brine)

Parameter (unit)	Seawater	Brine	Standard Method
pH	7.9	8.9	APHA 4500-H+ B. Electrometric Method
Temperature (°C)	25	40	APHA 2550 temperature
Turbidity (NTU)	20.1	1.45	APHA 2130 B. Nephelometric Method
Conductivity (mS/cm)	61.3	94.6	APHA 2510 B. Conductivity
TDS (g/L)	44.5	87.6	APHA 2540 C. Total dissolved solids dried at 180°C

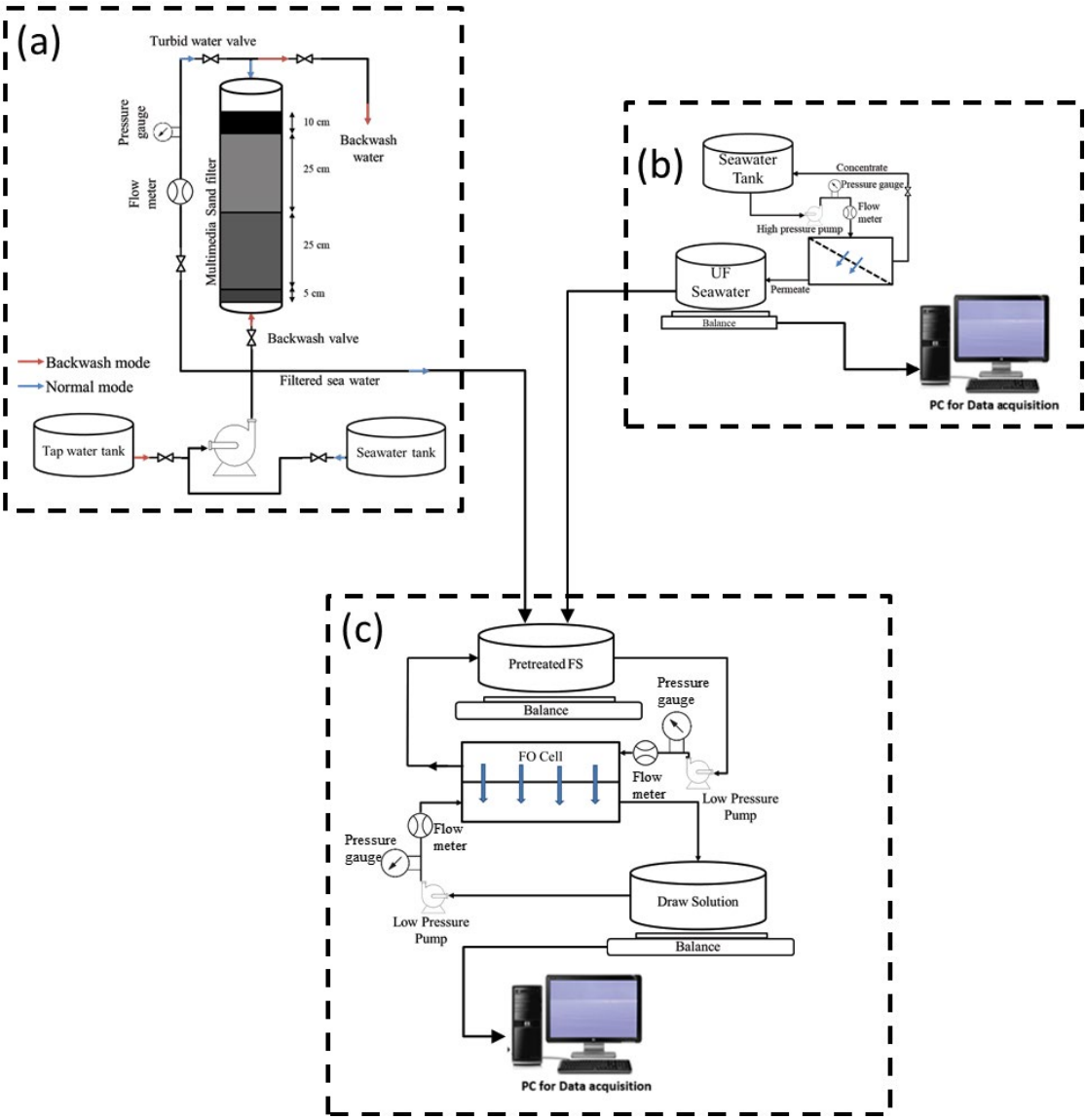

Fig. 1. Schematic diagram of (a) multimedia sand filter, (b) ultrafiltration, and (c) forward osmosis setup.

Site Read Panel Mount Flow Meter) was used to measure the flow rate of the feed solution. A digital balance (Mettler Toledo – ICS 241, Columbus, Ohio, United States) was connected to a computer to measure the weight of the permeate from the UF system. NADIR PM UP 150 membrane was used in the ultrafiltration process. The feed to ultrafiltration unit was pressurized to 3 bar. Before ultrafiltration, the membrane was washed for 30 min with distilled water for pre-conditioning and for removing any impurity from the surface. The characteristics of the treated seawater are summarized in Table 2.

2.2. Forward osmosis

The schematic diagram for the forward osmosis (FO) process is shown in Fig. 1c. In the FO system, a Sterlitech CF042 Delrin membrane cell was used. The cell dimensions were 12.7 cm × 8.3 cm × 10 cm with an active inner dimension of 4.6 cm × 9.2 cm and a slot depth of 0.23 cm. Two tanks with a capacity of 10 L each were used for storing the feed and the draw solutions. Two Cole-Parmer gear pumps (0.91 ml/rev) were used to circulate the feed and draw solutions through the membrane cell. Two flow meters (Sterlitech Site Read Panel Mount Flow Meter) were used to measure the flow rate of the feed and the draw solutions. A digital balance (EW-11017–04 Ohaus Ranger™ Scale) was used to measure the change of mass of the DS tank in order to calculate the water flux in the FO system. The volume of the feed and the draw solutions were 4.5 L at the beginning of each experiment. The solutions going out from the FO cell were recycled back into the same tanks. A thin film composite FO membrane (FTSH2O (USA)) was used for all the tests. The membrane was cut to be placed inside the cell with dimensions of 5.75 cm × 11.5 cm. Before carrying out FO, the membrane was washed for 20 min with distilled water for pre-conditioning and removal of any chemicals from its surface. A 1 mm Sepa CF high fouling spacer

Table 2
Characteristics of the pre-treated feed solution using sand-filtration and ultra-filtration

Parameter (unit)	Sand-filtration	Ultrafiltration	Standard Method
pH	7.9	7.6	APHA 4500-H+ B. Electrometric Method
Temperature (°C)	25	25	APHA 2550 temperature
Turbidity (NTU)	11	0	APHA 2130 B. Nephelometric Method
Conductivity (mS/cm)	61.4	60.6	APHA 2510 B. Conductivity
TDS (g/L)	44.7	44.3	APHA 2540 C. Total dissolved solids dried at 180°C

(8 cm × 3.5 cm) was placed on the support side of the FO membrane for mitigating the internal concentration polarization. The temperature of the draw solution and feed solutions were maintained at 40°C and 25°C, respectively. The FO process was run in PRO mode, where the active layer of the membrane was facing the draw solution. PRO mode was selected to be the mode of operation because, in our previous study, we found that PRO mode resulted in 30% higher water flux compared to FO mode [17]. The duration for all FO experiments was 1,400 min. In order to remove foulants and to retrieve the flux, the membrane was washed for 30 min using distilled water after each run.

2.3. Analytical methods

After the FO process, the used membranes were stored in an airtight container. The surface morphology of the membranes was analyzed by taking SEM images without washing the membranes. The SEM images of the used membranes were taken using a scanning electron microscopy (Field Electron and Ion Company Nova NanoSEM 450) purchased from ThermoFisher Scientific (Japan).

The water flux (J_w) in the FO process was calculated using the following equation:

$$J_w = \left(\frac{V_p}{A_m \times t} \right) \tag{1}$$

Here, V_p is the volume of the permeate (L), A_m is the area of the membrane (m^2), t is the operating time (h). The water recovered rate (%R) has been calculated as [23]:

$$\%R = \left(\frac{V_P}{V_F} \right) \times 100\% \tag{2}$$

Here, V_P and V_F are the volume of permeate and feed, respectively. The flux recovery rate (R) was calculated as:

$$R_f(\%) = \left(\frac{\phi_{N_2}}{\phi_{N_1}} \right) \times 100\% \tag{3}$$

Here, ϕ is the average water flux from 1st (N_1) and 2nd (N_2) run. The specific power consumption during feed solution (FS) pretreatment was calculated as [24]:

$$E_s = \frac{P_f \times Q_f}{n \times Q_p} \tag{4}$$

Here, E_s is specific power consumption in (kWh/m^3), P_f is the feed pressure (bar), n is the pump efficiency (assumed 0.8), Q_f is the feed flow rate (L/h), and Q_p is the permeate flow rate (L/h).

2.4. Error estimation

All the experiments were repeated three times, the mean and standard deviation of the results were calculated as:

$$\bar{x} = \frac{\sum_1^N x_i}{N} \tag{5}$$

$$\text{SD} = \sqrt{\frac{\sum_1^N \left(x_i - \bar{x} \right)^2}{N}} \tag{6}$$

Here, x_i, $\bar{x}$, and N stands for the measured value, the mean of the three measured values and the number of replications. In this paper, the mean values of the experimental results are being reported along with error bars representing the standard deviation.

3. Results and discussion

3.1. Water flux

In Fig. 2a, the effect of different draw solutions (DS) on water flux of the forward osmosis (FO) process is shown at FS and DS flowrate of 2.0 L/min. When seawater is used as the feed solution, the initial water flux was 46 L/m^2 h. After 1,400 min of operation, the water flux declined and reached 11 L/m^2 h. Using sand filtered seawater as feed solution resulted in an initial flux of 57 L/m^2 h and after 1,400 min of operation, the flux declined to 11 L/m^2 h. Using ultrafiltered seawater as feed solution resulted in an initial water flux of 57 L/m^2 h and reached 15 L/m^2 h after 1,400 min of operation. Fig. 2b shows the effect of different DS on water flux for forward osmosis process with FS flowrate of 2.0 L/min and DS flowrate of 0.8 L/min. When seawater was used as FS, an initial permeation flux of 45 L/m^2 h was obtained. The water flux declined to 12 L/m^2 h after 1,400 min of operation. Using sand filtered seawater as FS resulted in an initial permeation flux of 57 L/m^2 h and reached 12 L/m^2 h after 1,400 mins of operation. An initial water flux of 57 L/m^2 h was achieved by using ultrafiltrated seawater as feed solution and the water flux declined to 15 L/m^2 h after 1,400 min of operation. For all the flowrates and feed solutions, the initial

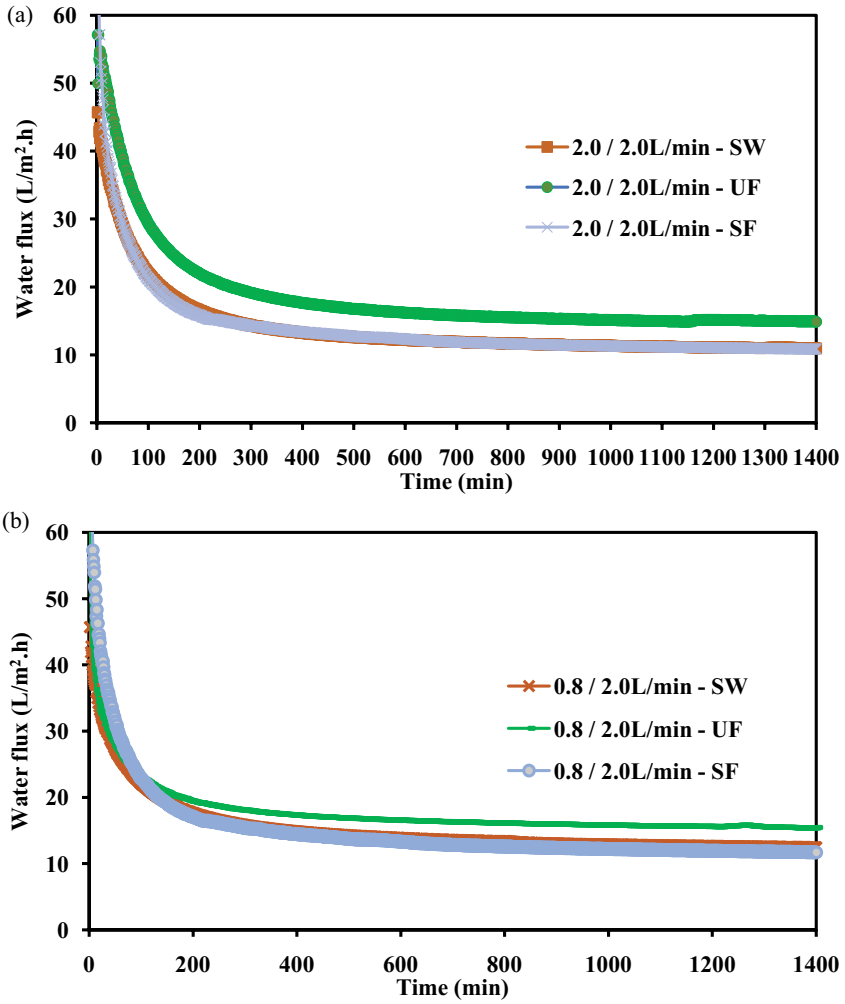

Fig. 2. Water flux obtained by using seawater, sand filtered seawater, and ultrafiltered seawater as FS at DS flowrate of (a) 2 L/min and (b) 0.8 L/min (FS flowrate = 2.0 L/min).

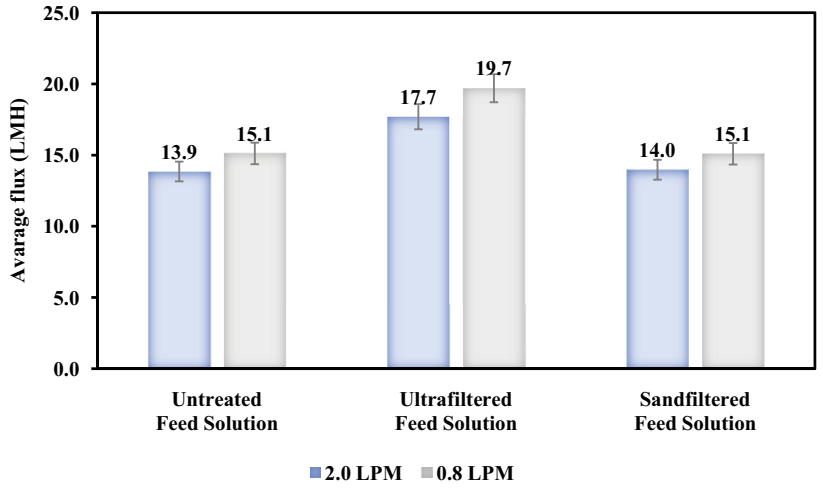

Fig. 3. Average FO water flux using different feed solutions in PRO mode at different DS flow rates (FS flowrate = 2.0 L/min).

water flux decreased rapidly until 300 min of FO operation. This was due to dilutive external concentration polarization occurring at the active layer facing the draw solution and concentrative internal concentration polarization occurring at the support layer facing the feed solution [25–28]. The improvement in water flux can be further verified by studying the average water flux for different feed solutions and draw solution flowrates.

Fig. 3 shows the average water flux for the FO process with seawater, sand filtered seawater, and ultrafiltered seawater as FS circulated at a flowrate of 2.0 L/min. The DS was circulated at flowrates of 2.0 and 0.8 L/min. When seawater was used as FS, DS flowrate of 2.0 L/min resulted in an average water flux of 13.9 L/m^2 h. Decreasing the DS flowrate to 0.8 L/min increased the average water flux to 15.1 L/m^2 h. While using sand filtered seawater as FS, the DS flowrate of 2.0 L/min resulted in an average water flux of 14.0 L/m^2 h and improved to 15.1 L/m^2 h when the DS flowrate was reduced to 0.8 L/min. Finally, when using ultrafiltered seawater as FS, the DS flowrate of 2.0 L/min resulted in an average water flux of 17.7 L/m^2 h and increased to 19.7 L/m^2.h when DS flowrate was decreased to 0.8 L/min. For all the feed solutions, decreasing draw solution flowrate enhanced water flux. This is because of the difference in FS and DS flowrate makes the FO process pressure assisted by inducing a positive hydraulic gradient of 0.5 bar [26,29,30]. This higher average flux is expected to promote concentration polarization. However, the improvement in water flux was more significant than the negative impact of concentration polarization [30]. The results show that, by using ultrafiltered seawater feed solution at a DS flowrate of 2.0 and 0.8 L/min, the average membrane flux in the FO process can be enhanced by 27.3% and 30.4%, respectively. However, sand filtered feed solution did not show significant improvement in terms of the average water flux in the FO process. This is because the turbidity of seawater and sand filtered seawaters were 20.1 and 11.0 NTU, respectively. When the turbidity is low, sand filtration cannot remove the suspended solids from the feed significantly. A previous study showed that, for FS with high turbidity (300 NTU), pretreatment using sand filtration enhances the average water flux by 64.3% [25]. The ultrafiltered seawater had a turbidity of 0 NTU. The lower turbidity of ultrafiltered seawater resulted in lower fouling of the membrane and resulted in higher average water flux. Moreover, ultrafiltration of the seawater also removed colloidal particles with a size ranging between 0.01 to 1.0 micron which results in reduced fouling at the membrane surface [31]. The fouling of the membrane surface can be seen in images from the SEM.

Fig. 4a shows the SEM image of the clean support layer, whereas Figs. 4b and c show the support layer after the FO process with seawater and ultrafiltrated seawater, respectively. In SEM analysis, seawater is showing increased fouling compared to ultrafiltrated seawater. This proves that pre-treatment of feed solution using ultrafiltration has reduced foulant concentration and enhanced the average water flux (as seen in Fig. 3).

3.2. Water recovery from the feed solution

Fig. 5 shows the recovery rate for the FO process with seawater, sand filtered seawater and ultrafiltered seawater as FS with flowrate of 2.0 L/min and brine reject as DS with flowrates of 2.0 and 0.8 L/min. Using seawater as FS with DS flowrate of 2.0 L/min resulted in a recovery rate of 30.6% but increased to 34.5% when the flowrate of DS was reduced to 0.8 L/min. When sand filtered seawater was used as FS, DS flowrate of 2.0 L/min resulted in a water recovery rate of 33.1% but increased to 33.8% when DS flowrate was reduced to 0.8 L/min. Using ultra-filtered seawater as FS achieved a recovery rate of 39.6% when the DS flowrate was 2.0 L/min and increased to 44.1% when DS flowrate was reduced to 0.8 L/min. Using ultra-filtered seawater as FS with FS and DS flowrate of 2 L/min and 0.8 L/min demonstrated the highest recovery rate in the FO process compared to other FS and operating conditions. The recovery rate at this operating condition was the highest because the average water flux at this operating condition was also the highest (as seen in Fig. 3) [23].

3.3. Water flux recovery after cleaning

The results for water flux recovery are shown in Fig. 6. When seawater was used as FS and the DS flowrate was

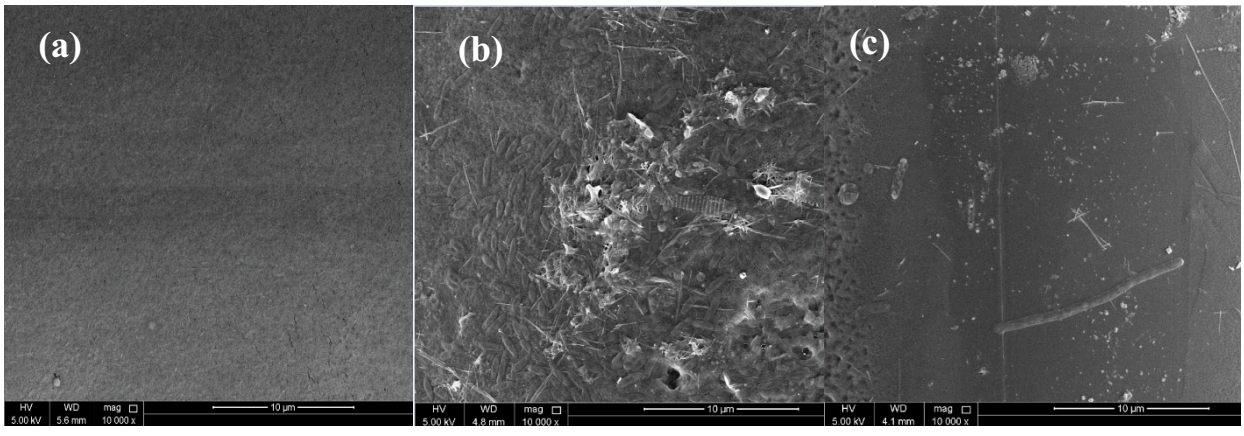

Fig. 4. SEM images of (a) clean support layer, (b) support layer after FO operation using seawater, and (c) support layer after FO using ultrafiltrated seawater as feed solution.

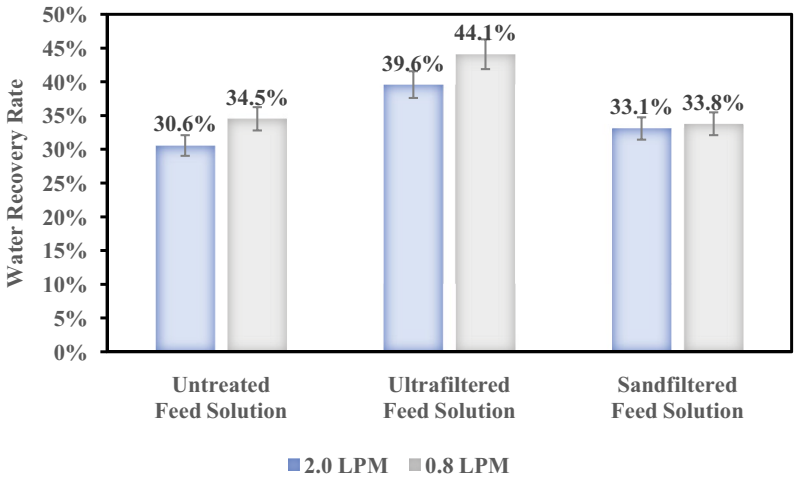

Fig. 5. Recovery rate using different feed solutions in PRO mode at different DS flow rates (FS flowrate = 2.0 L/min).

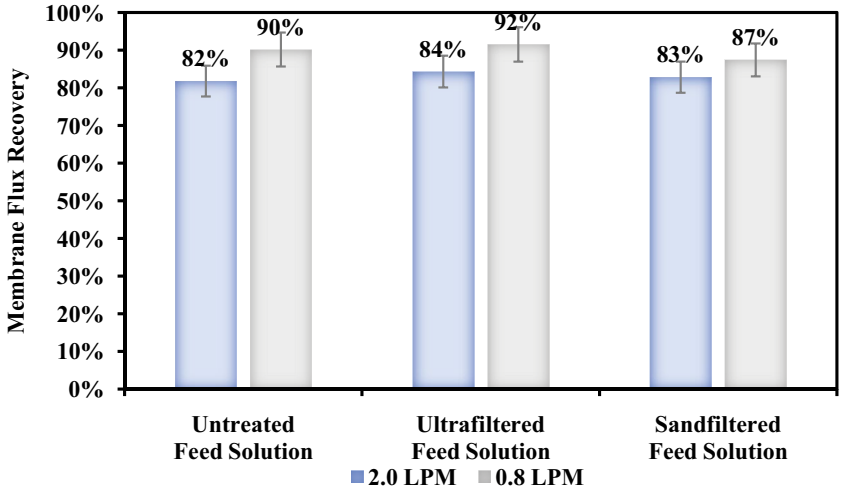

Fig. 6. Water flux recovery using different feed solutions in PRO mode at different DS flow rates (FS flowrate = 2.0 L/min).

2.0 L/min, the water flux recovery rate was 82%. Decreasing the DS flowrate to 0.8 L/min increased the water flux recovery rate to 90%. With sand filtered seawater as FS and DS flowrate of 2.0 L/min, the membrane flux recovery rate reached 83%. The membrane flux recovery rate increased to 87% when the DS flowrate was reduced to 0.8 L/min. Using ultra-filtered seawater as FS at DS flowrate of 2.0 L/min resulted in a water flux recovery rate of 84%. When the DS flowrate was reduced to 0.8 L/min, the water flux recovery rate reached 92%. The highest recovery rate was 92% achieved by using ultra-filtrated feed solution at draw solution flowrate of 0.8 L/min. This is because, at this condition, reduced fouling occurs at the membrane surface and it has been confirmed by SEM images shown in Fig. 4.

3.4. Energy consumption

Fig. 7 shows the overall energy consumptions of the pre-treatment and forward osmosis processes. According to Fig. 7, the total specific energy consumption of the FO process with a non-treated feed solution is 0.010 kWh/m^3. Combining the FO process with sand filtration increases energy consumption by 0.07 kWh/m^3. Combining the FO process with ultrafiltration increases energy consumption by 0.055 kWh/m^3. Since ultrafiltration is a pressure-driven process, the specific energy demand is higher. Although the energy demand is higher for ultrafiltration, the average water flux and the water recovery rate in the FO process increased by 27.9% and 10.3%, respectively. In addition, the energy demand of the UF-FO pretreatment process is 15 times lower than seawater pretreatment using NF alone [15].

4. Conclusions

The results showed that, for all feed solutions, the average water flux was higher when DS flowrate was 0.8 L/min due to the development of a small positive hydraulic pressure gradient in the direction of water flux. The highest average water flux of 19.7 L/m^2 h was obtained by using the ultra-filtered feed solution. At similar operating conditions, the water flux recovery rate and water recovery rate were 82% and 34.2%, respectively. The

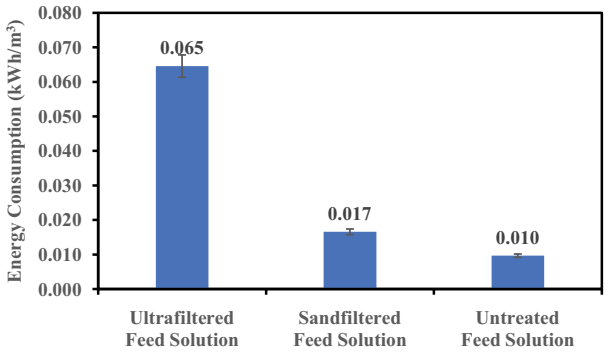

Fig. 7. Combined energy consumption of the pretreatment and forward osmosis process at FS flowrate of 2.0 L/min and DS flowrate of 0.8 L/min.

specific energy consumption during ultrafiltration was 0.065 kWh/m^3. Ultra-filtrated seawater as feed solution, improved the average water flux and water recovery rate in the FO process by 27.9% and 10.3%, respectively. Based on the results of this study, ultra-filtrated seawater is being recommended as the feed solution for the FO process.

Acknowledgments

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References

[1] P. Budhiraja, A.A. Fares, Studies of scale formation and optimization of antiscalant dosing in multi-effect thermal desalination units, Desalination, 220 (2008) 313–325.
[2] S. Ghani, N.S. Al-Deffeeri, Impacts of different antiscalant dosing rates and their thermal performance in multi stage flash (MSF) distiller in Kuwait, Desalination, 250(2010) 463–472.
[3] A.M.S. El Din, R.A. Mohammed, Brine and scale chemistry in MSF distillers, Desalination, 99 (1994) 73–111.
[4] A.T. Yasir, F. Eljack, M.-K. Kazi, Synthesis of water capture technologies for gas fired power plants in Qatar, Chem. Eng. Res. Des., 154 (2020) 171–181.
[5] L.D. Tijing, Y.C. Woo, J.-S. Choi, S. Lee, S.-H. Kim, H.K. Shon, Fouling and its control in membrane distillation—a review, J. Membr. Sci., 475 (2015) 215–244.
[6] Z. Amjad, Calcium sulfate dihydrate (gypsum) scale formation on heat exchanger surfaces: the influence of scale inhibitors, J. Colloid Interface Sci., 123 (1988) 523–536.
[7] E. Lyster, M.-m. Kim, J. Au, Y. Cohen, A method for evaluating antiscalant retardation of crystal nucleation and growth on RO membranes, J. Membr. Sci., 364 (2010) 122–131.
[8] D.M. Warsinger, J. Swaminathan, E. Guillen-Burrieza, H.A. Arafat, J.H. Lienhard V, Scaling and fouling in membrane distillation for desalination applications: a review, Desalination, 356 (2015) 294–313.
[9] P. Nicoll, Forward Osmosis as a Pre-treatment to Reverse Osmosis, In: The International Desalination Association World Congress on Desalination and Water Reuse, Tianjin, China, 2013.
[10] A.M. Hassan, M.A.K. Al-Sofi, A.S. Al-Amoudi, A.T.M. Jamaluddin, A.M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G.M. Mustafa, I.A.R. Al-Tisan, A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes (Part 1), Desalination, 118 (1998) 35–51.
[11] A. Altaee, Forward osmosis: potential use in desalination and water reuse, J. Membr. Sep. Technol., 1 (2012) 79–93.
[12] P. Eriksson, M. Kyburz, W. Pergande, NF membrane characteristics and evaluation for sea water processing applications, Desalination, 184 (2005) 281–294.
[13] T. Mezher, H. Fath, Z. Abbas, A. Khaled, Techno-economic assessment and environmental impacts of desalination technologies, Desalination, 266 (2011) 263–273.
[14] D. Zhou, L. Zhu, Y. Fu, M. Zhu, L. Xue, Development of lower cost seawater desalination processes using nanofiltration technologies — a review, Desalination, 376 (2015) 109–116.
[15] A. Altaee, A. Mabrouk, K. Bourouni, P. Palenzuela, Forward osmosis pretreatment of seawater to thermal desalination: high temperature FO-MSF/MED hybrid system, Desalination, 339 (2014) 18–25.
[16] A. Altaee, A. Mabrouk, K. Bourouni, A novel Forward osmosis membrane pretreatment of seawater for thermal desalination processes, Desalination, 326 (2013) 19–29.
[17] M.S Thabit, A. Al Hawari, M. Hafez Ammar, J. Zaidi, G. Zaragoza, A. Altaee, Evaluation of forward osmosis as a pretreatment process for multi stage flash seawater desalination, Desalination, 461 (2019) 22–29.
[18] Q.V. Ly, Y. Hu, J. Li, J. Cho, J. Hur, Characteristics and influencing factors of organic fouling in forward osmosis operation for wastewater applications: a comprehensive review, Environ. Int., 129 (2019) 164–184.
[19] F. Sun, D. Lu, J.S. Ho, T.H. Chong, Y. Zhou, Mitigation of membrane fouling in a seawater-driven forward osmosis system for waste activated sludge thickening, J. Cleaner Prod., 241 (2019) 118373.
[20] A. Balkenov, A. Anuarbek, A. Satayeva, J. Kim, V. Inglezakis, E. Arkhangelsky, Complex organic fouling and effect of silver nanoparticles on aquaporin forward osmosis membranes, J. Water Process Eng., 34 (2020) 101177.
[21] W.S. Ang, S. Lee, M. Elimelech, Chemical and physical aspects of cleaning of organic-fouled reverse osmosis membranes, J. Membr. Sci., 272 (2006) 198–210.
[22] S. Zhao, L. Zou, D. Mulcahy, Effects of membrane orientation on process performance in forward osmosis applications, J. Membr. Sci., 382 (2011) 308–315.
[23] N. Singh, S. Dhiman, S. Basu, M. Balakrishnan, I. Petrinic, C. Helix-Nielsen, Dewatering of sewage for nutrients and water recovery by forward osmosis (FO) using divalent draw solution, J. Water Process Eng., 31 (2019) 100853.
[24] A. Altaee, G.J. Millar, A.O. Sharif, G. Zaragoza, Forward osmosis process for supply of fertilizer solutions from seawater using a mixture of draw solutions, Desal. Water Treat., 57 (2016) 28025–28041.
[25] A.H. Hawari, A. Al-Qahoumi, A. Ltaief, S. Zaidi, A. Altaee, Dilution of seawater using dewatered construction water in a hybrid forward osmosis system, J. Cleaner Prod., 195 (2018) 365–373.
[26] M.A. Hafiz, A.H. Hawari, A. Altaee, A hybrid forward osmosis/reverse osmosis process for the supply of fertilizing solution from treated wastewater, J. Water Process Eng., 32 (2019) 100975.
[27] V. Parida, H.Y. Ng, Forward osmosis organic fouling: effects of organic loading, calcium and membrane orientation, Desalination, 312 (2013) 88–98.
[28] C.Y. Tang, Q. She, W.C.L. Lay, R. Wang, A.G. Fane, Coupled effects of internal concentration polarization and fouling on flux behavior of forward osmosis membranes during humic acid filtration, J. Membr. Sci., 354 (2010) 123–133.

[29] A.H. Hawari, N. Kamal, A. Altaee, Combined influence of temperature and flow rate of feeds on the performance of forward osmosis, Desalination, 398 (2016) 98–105.
[30] J.R. McCutcheon, M. Elimelech, Influence of concentrative and dilutive internal concentration polarization on flux behavior in forward osmosis, J. Membr. Sci., 284 (2006) 237–247.
[31] V. Lahoussine-Turcaud, M.R. Wiesner, J.-Y. Bottero, Fouling in tangential-flow ultrafiltration: the effect of colloid size and coagulation pretreatment, J. Membr. Sci., 52 (1990) 173–190.