

Efficiency of Organic Draw Solutions in a Forward Osmosis Process Using Nano-filtration Flat Sheet Membrane

Saleh O Alaswad^{1*}, Sami Al-Aibi¹, E Alpay¹ and Adel O Sharif^{1,2}

¹Centre for Osmosis Research and Applications (CORA), Chemical and Process Engineering Department, University of Surrey, Guildford, UK

²Qatar Environment and Energy Research Institute, HBKU, Qatar Foundation, Doha, Qatar

*Corresponding author: Saleh O Alaswad, Centre for Osmosis Research and Applications (CORA), Chemical and Process Engineering Department, University of Surrey, Guildford, UK, Tel: +966114814116; E-mail: salaswad@kacst.edu.sa

Received date: December 11, 2017; Accepted date: January 06, 2018; Published date: January 16, 2018

Copyright: © 2018 Alaswad SO, et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Abstract

The aim of this study is to investigate the performance of specific organic osmotic agents, namely, Sucrose draw solution and Glucose draw solution against deionized water in a Forward Osmosis (FO) process using NF flat sheet membrane. The key parameters affecting the FO process studied were: temperature, flow rates of osmotic agent and feed water, and concentration of osmotic agent. The experimental results showed that increasing the concentration of osmotic agents yield lower water flux, recovery percentage and permeability, along with an apparent increase in the specific energy consumption. Although the findings indicated superior performance of Glucose over Sucrose as a better osmotic agent, it has to be emphasized that both organics were ineffective draw solutions against deionized water for the Nano-filtration (TFC-SR2) membrane used in this study and the given operating parameters.

Keywords: Sucrose; Glucose; Water flux; Water recovery; Specific energy consumption; NF membrane

Abbreviations:

Greek symbols	
$\Delta\pi$	Osmotic pressure gradient
η	Viscosity
Subscripts	
FO	Forward osmosis
ICP	Internal concentration polarization
ECP	External concentration polarization
FS	Feed solution
DS	Draw solution
AL	Active layer
SL	Support layer
°C	Degree Celsius
mg/l	Milligram per litre
NaCl	Sodium chloride
SDS	sucrose draw solution
GDS	glucose draw solution
NF	Nano Filtration

Introduction

Desalination technologies such as Reverse Osmosis (RO), thermal Multi-Stage-Filtration (MSF) and Multi Effect Distillation (MED) play a primary role in meeting the global fresh water demand. Unfortunately, these technologies are energy intensive, thus leading to high water production cost [1]. In recent years, FO has emerged as one of the low-cost alternative technologies in the water-treatment industry. As such, FO potentially can be used as an alternative for both traditional desalination and brine treatment technologies due to its lower energy requirements. Some researchers suggested that low energy consumption and suitable seawater desalination technologies need to be developed [2-9].

In FO process, net water movement occurs through a semi-permeable membrane from a low-concentration solution (feed) to a higher-concentration solution (DS) under the osmotic pressure gradient across the membrane [10]. Because of the higher osmotic pressure of the DS, water permeates from the feed stream across the membrane without the addition of external energy, thus making FO a relatively low-energy process. FO has been successfully used for the production of potable water by desalination (<200 mg/l) [4] and by treating wastewater [11,12]. FO has also been used to treat industrial wastewaters to concentrate landfill leachate by increasing water flux [13-16]. FO is also used to treat liquid foods in the food industry to increase concentration of sugar contents in smaller rather than bigger industries [17-25].

RO and other conventional water-treatment processes require more pressure than the FO process [26], while the removal of different types of contaminants is possible with lower membrane fouling [27,28]. The FO process requires an extra step to separate the water from the DS [29]. Although FO has many potential applications in osmotic

pressure-based separation, the quest to find the ideal DS remains a challenge. The desired properties of ideal DS/osmotic agents are (i) significantly higher osmotic pressure than the feed solution [30-32], (ii) easy separation from water [27,32], (iii) easy regeneration and reuse [27,33], (iv) non-toxic and membrane compatible and (v) solutes of high liquid diffusivity and low permeability across the membrane to minimize losses and fouling [27,28,34,35]. Another limiting factor of an FO process is the decline in the permeate flux due to concentration polarization. Previous studies on various FO processes indicated that measured fluxes were significantly lower than the theoretical values. The lower-than-expected flux is mainly due to internal and external concentration polarizations (ICP and ECP, respectively) during the mass transport process, which significantly reduce the available osmotic driving force [36]. Preparation of a suitable membrane that reduces the effect of concentration polarization, fouling and reverse-solute diffusion is also a challenge in FO processes.

Recent studies proposed several guidelines in selecting the optimal DS [27,37]. Three main criteria for optimal DS are (i) high osmotic pressure, (ii) ease of recovery with minimum cost and (iii) minimized ICP effect [10,27,32,37]. Nevertheless, the interrelation between these factors does not always make the choice of the solution easy. For example, Kerr and Reid, [38] and, Zhao and Zou [39] demonstrated that the DS's viscosity, diffusion coefficient, and ion/molecule size have a significant impact on ICP.

Past studies have also focused on the analyses of various DSs. Simple NaCl solution was quite popular among the researchers mainly due to being highly soluble, non-toxic at low concentrations and easy to re-concentrate [27,40-42]. Volatile gas DSs were used for the ability to separate or recover the DS, while sugars were preferred for the ability of their solutes to become easily re-concentrated at lower pressure levels.

A relatively novel approach to draw solutes was proposed by McCutcheon [31], who combined water-soluble NH₃ with CO₂ containing NH₄HCO₃. It was shown that the mixture is capable of providing higher water fluxes and only moderate heat (approximately 60°C) is required to recover the solute. The issue with this method, however, is the strong ammonia odour retained in the purified water [43]. Some other natural chemicals and even inorganics have been tested as the draw solutes [27]. However, according to Zhao [44], there is hardly a naturally existing chemical that can become a perfect draw solute.

The primary objective of this study was to investigate the performance of organic osmotic agents such as Sucrose and Glucose using an NF membrane to regenerate them. Special attention was given to the use of NF flat sheet membrane in the FO process. The effects of a wide range of operating parameters (such as the solutes' concentration, DS and feed water flow rates, DS and feed water temperatures) on the performance of the FO process were also considered.

Methodology

Materials

Sucrose powder (from Tate & Lyle) and Glucose (from Sigma-Aldrich) were used in this study. DSs at desired concentrations were then prepared by dissolving the organic powders in deionized water.

Membrane testing apparatus

Figure 1 shows a schematic diagram of the membrane cell containing a flat sheet NF membrane. The membrane cell unit consisted of a two-compartment FO flat sheet cell fabricated using Perspex, as shown in Figure 2. 10 L polyethylene tanks, equipped with an immersion heater, were used to store osmotic agents and feed water. Digital balances were used to compute fluid fluxes where weight differences of each polyethylene tanks were recorded during the course of test runs. Two small centrifugal pumps (capacity: 0-10 l/min) were used to pump the solutions into the FO cell. Inlet streams of the FO cells were monitored using a pressure gauge and Rotameter. Only PVC pipes, fittings and valves were used in these studies. A magnetic stirrer was used to mix and prepare osmotic solutions. OLI stream analyzer software was used to determine the osmotic pressure of Sucrose and Glucose solutions. A Mettler-Toledo conductivity meter and an HPLC instrument (Varian 385-LC ELSD with evaporative scattering detector column and with 80% Acetonitrile phase, flow rate 3.0 ml/min) were used to measure the conductivity and salinity of feed water and sugar solution, respectively. Finally, the unit was designed to recycle both the osmotic agent and feed water to their respective tanks.

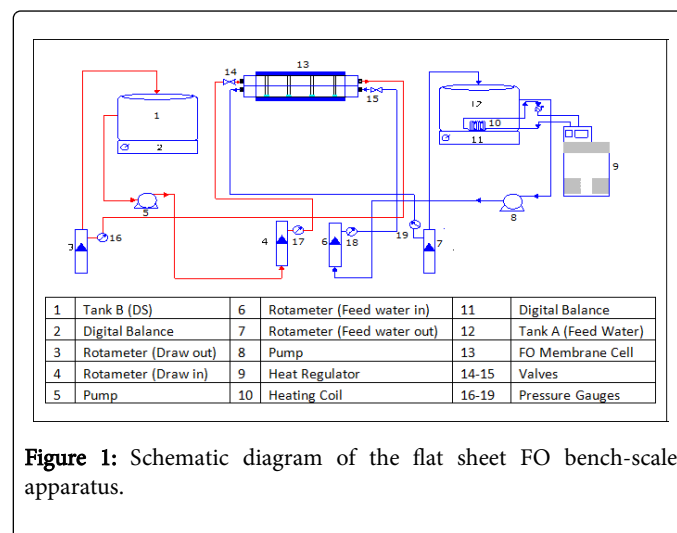


Figure 1: Schematic diagram of the flat sheet FO bench-scale apparatus.

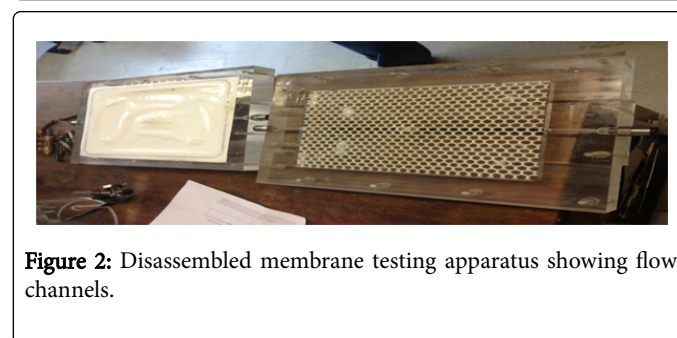


Figure 2: Disassembled membrane testing apparatus showing flow channels.

Process operation

The membrane test cell was configured for counter-current operation with a flow rate of 10 l/min for both feed and draw solutions. All of the experiments were performed using deionized water as FS and Sucrose or Glucose solutions as DSs. The specifications of the nanofiltration membrane (TFC-SR2) used in this work are shown in Table 1. The FS was pumped on the active layer while the DS flowed on the support layer. The flat sheet membrane was fixed between the two

compartments within the cell. The effect of DS concentration, flow rates of DS and feed water, and temperatures on water flux (J_w), water recovery percentage (%R), water permeability (A_w), specific energy consumption (SEC) and Sucrose and Glucose solute flux (J_s) were studied.

Type of membrane	Low pressure, selective rejection, NF element
Membrane chemistry	Proprietary TFC membrane
Typical operating pressure	3.45-7 bar
Maximum operating pressure	34.5 bar
Maximum operating temperature	45°C
Rejection % of Sucrose and Glucose	97.53
Flux (GFD)	57.2
Allowable pH-continuous operation	4-9

Table 1: TFC-SR2 specifications (Koch membrane systems Ltd, UK).

The various parameters in the FO process were calculated as summarized below.

Water flux (J_w): The water flux (J_w) of feed water through the membrane was estimated using the following equation.

$$JW = \frac{Q_{FWin} - Q_{FWout}}{A_m} \quad (1)$$

where, Q_{FWin} is the volumetric flow rate of feed water entering the membrane, Q_{FWout} is the volumetric flow rate of feed water leaving the membrane and A_m is the active surface area of membrane (m^2).

Water permeability (A_w): The water permeability (A_w) through the membrane in the FO process was estimated using the following equation.

$$A_w = \frac{J_w}{NDP} \quad (2)$$

where, J_w is the water flux (l) and NDP is the Net Driven Pressure (bar) across the membrane surface during the FO process.

Recovery percentage (%R): The recovery percentage (%R) of the feed water was estimated using the following equation.

$$\%R_{FW} = \frac{(Q_{FWin} - Q_{FWout})}{Q_{FWin}} \times 100 \quad (3)$$

where, Q_{FWin} is the quantity of feed water entering the membrane and the Q_{FWout} is the quantity of water leaving the membrane during the FO process.

Salt flux (J_s): The salt flux (J_s) of the diffused osmotic agent was calculated by the following equation.

$$J_s = \frac{(C_{FWout} - Q_{FWout}) - (C_{FWin} - Q_{FWin})}{A_m} \quad (4)$$

Where C_{FWout} is the concentration (mol/l) of feed water leaving the membrane, C_{FWin} is the volume in litres (l) of feed water leaving the membrane, C_{FWin} is the concentration (mol/l) of feed water entering the membrane and where, is the volume (l) of feed wter entering the membrane.

SEC: The SEC of the FO process (assuming 100% efficiency) was calculated using the following equation.

$$SEC = \frac{(P_{DSin} - Q_{DSin}) - (P_{DSin} - Q_{DSin})}{Q_{FWin} - Q_{FWout}} \quad (5)$$

Where, P_{FWin} is the pressure (bar) of the feed water entering the membrane, Q_{FWin} is volume (l) of feed water entering the membrane and Q_{FWout} is the volume (l) of feed water leaving the membrane during the FO process.

Osmotic agent concentration effect: Sucrose solutions of various concentrations ranging from 170-400 g/l were prepared and stored in the DS feed tank. On the other hand, the feed water tank was filled with deionized water (conductivity of 10-15 μ S/cm). Samples of solution were collected and the initial weights of DS and feed water tanks were recorded. DS and feed water were simultaneously pumped into the FO module at a rate of 1.5 l/min and 2.5 l/min, respectively. The temperature of both streams was kept at 25°C for the entire two hours of operation. At the end of the study, samples were collected again and the final weights of the tanks were recorded.

The above-mentioned procedure was repeated using Glucose solution of different concentrations ranging from 90-250 g/l. The concentrations of Sucrose and Glucose were determined using HPLC equipment and the results are presented in Figures 3-9.

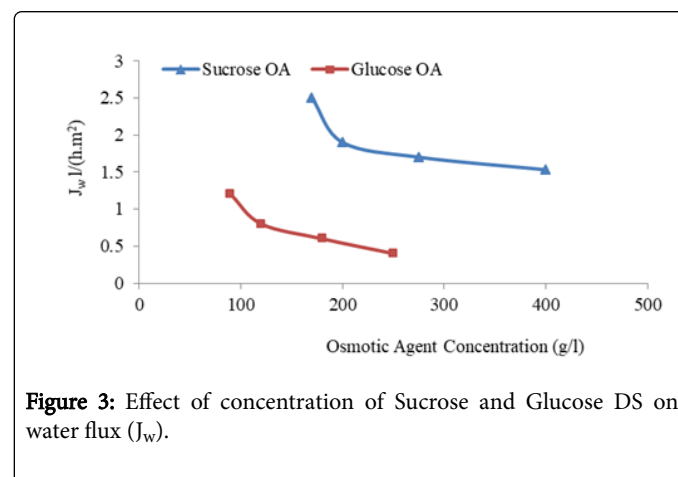


Figure 3: Effect of concentration of Sucrose and Glucose DS on water flux (J_w).

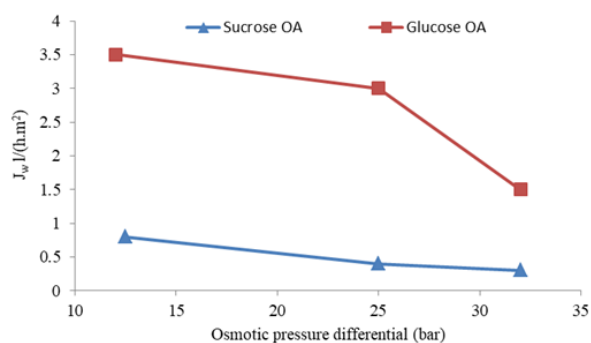


Figure 4: Effect of water flux (J_w) on osmotic pressure differential.

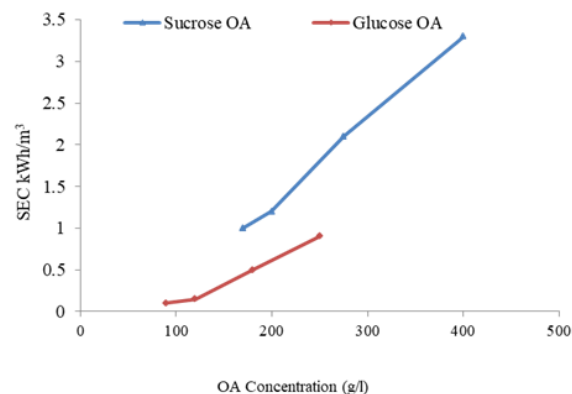


Figure 7: Effect of concentration of Sucrose and Glucose DS on SEC.

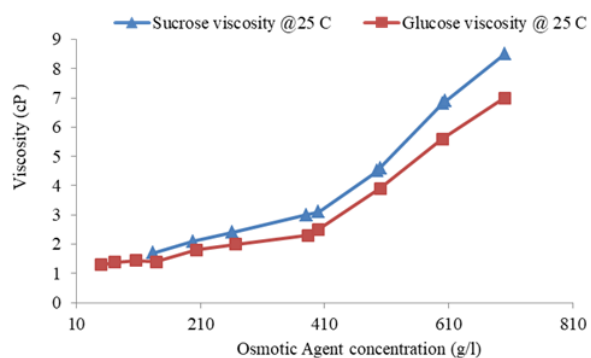


Figure 5: Effect of concentration of Sucrose and Glucose on viscosities at 25°C.

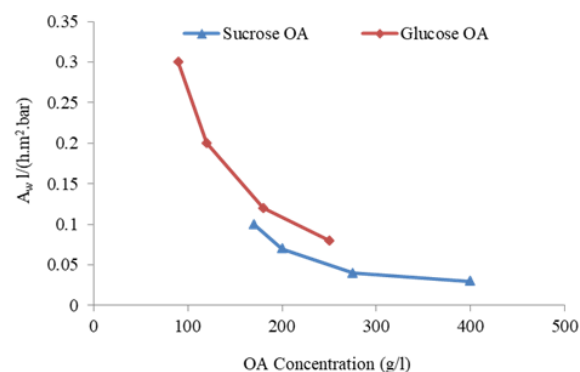


Figure 8: Effect of concentration of Sucrose and Glucose DS on water permeability.

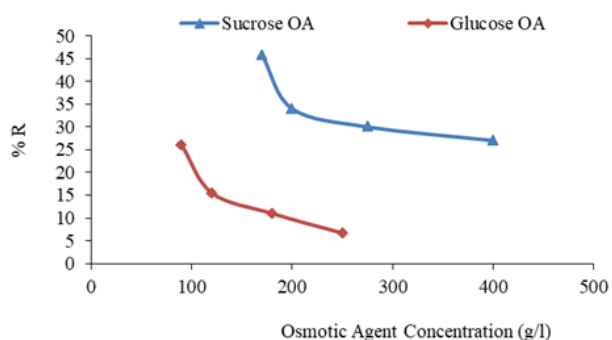


Figure 6: Effect of concentration of Sucrose and Glucose DS on water recovery rate using NF membrane.

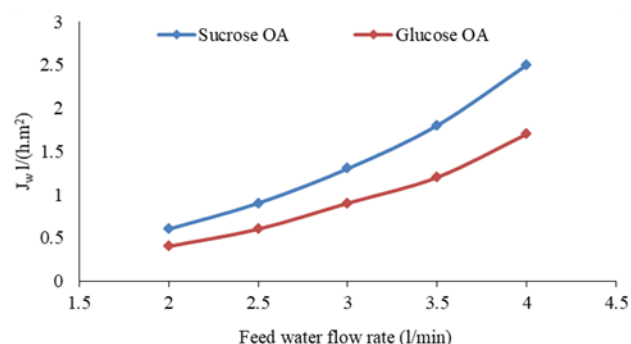


Figure 9: Effect of flow rate of feed water on water flux.

DS and feed water flow rate effect: Several experiments were carried out to evaluate the effect of different feed water flow rates (2-4 l/min) on various water flux, percent recovery, permeability, SEC and solute flux. The concentration of GDS (250 g/l) and the temperature (25°C) were kept constant.

To determine the feed water flow rate (2-4 l/min) effect on the FO parameters, the temperature (25°C) and the concentration of SDS (275 g/l) were kept constant during the experiment. The same set of experiments was repeated for each concentration of SDS varying from 170-400 g/l.

An experiment was run to evaluate the effect of GDS flow rates (2-4 l/min). The GDS of different concentrations (90-250 g/l) was prepared and pumped to the FO membrane. The feed water flow rate (1.5 l/min) was kept constant throughout these experiments.

In the feed water study, different feed water flow rates (2, 2.5, 3, 3.5, 4 l/min) were used. The concentration of GDS (250 g/l) and its flow rate (1.5 l/min) were kept constant. The above mentioned experiments were conducted at 25°C. The results are presented in Figures 10-15.

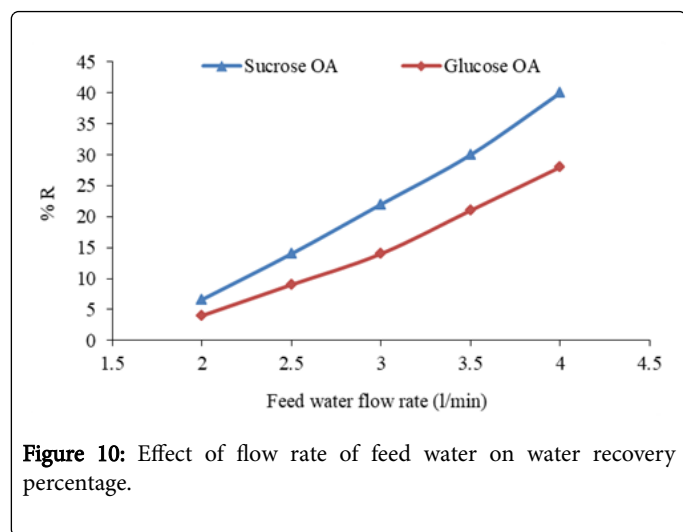


Figure 10: Effect of flow rate of feed water on water recovery percentage.

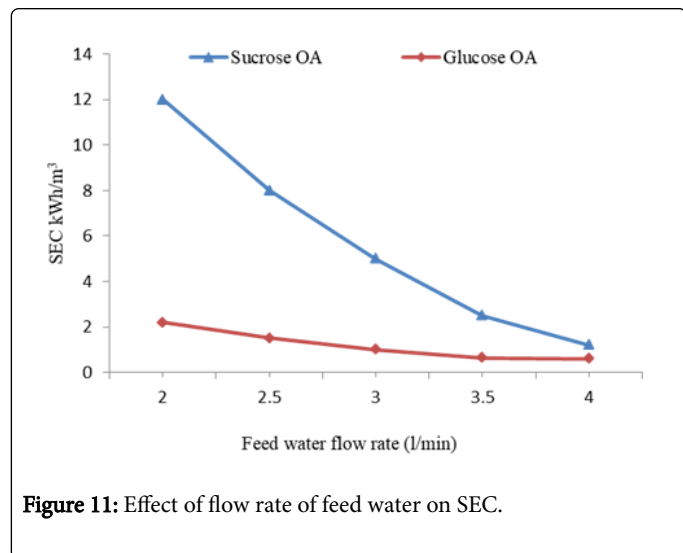


Figure 11: Effect of flow rate of feed water on SEC.

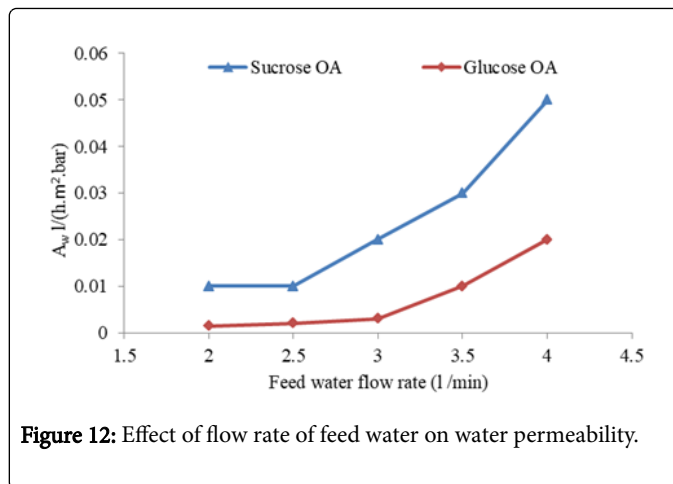


Figure 12: Effect of flow rate of feed water on water permeability.

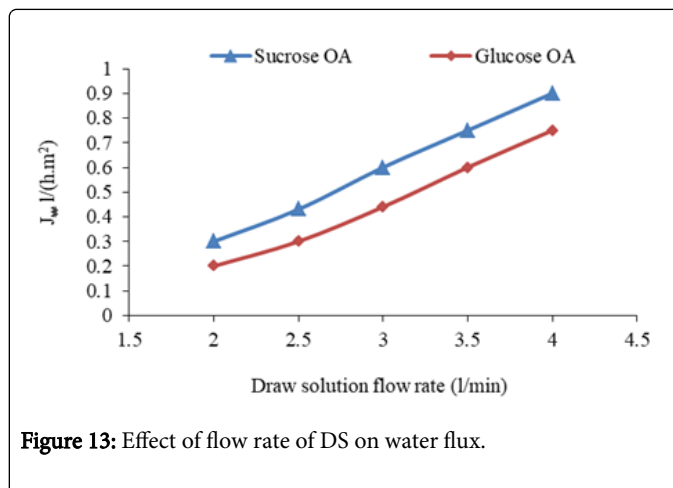


Figure 13: Effect of flow rate of DS on water flux.

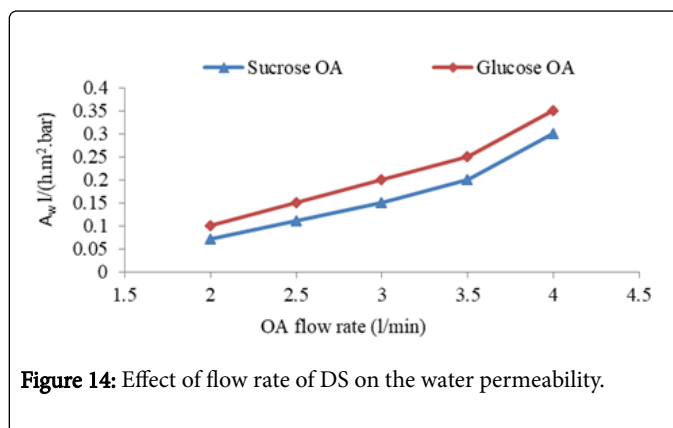


Figure 14: Effect of flow rate of DS on the water permeability.

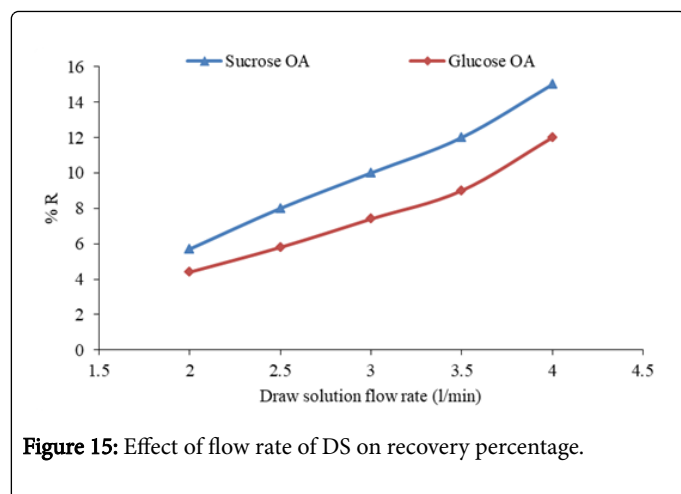


Figure 15: Effect of flow rate of DS on recovery percentage.

Temperature effect: Several experiments were carried out to evaluate the effect of different temperatures (25-35°C) of SDS on water flux, permeability, recovery percentage, SEC and solute flux. The temperature (25°C) and the flow rate (2 l/min) of feed water were kept constant. The concentration of SDS was 200 g/l and pumped into the membrane for 2 hours.

In addition, several experiments were carried out to evaluate the effect of different temperatures (25-35°C) of feed water on various FO parameters. The concentration of SDS (200 g/l) and the flow rate (2 l/min) were kept constant.

Similarly, numerous experiments were carried out to evaluate the effect of different temperatures (25-35°C) of GDS on water flux, permeability, recovery percentage, SEC and solute flux in the FO process. The temperature (25°C) and the flow rate (2 l/min) of feed water were kept constant. The concentration of GDS was 90 g/l and pumped into the membrane for 2 hours.

In addition several experiments were carried to evaluate the effect of different temperatures (25-35°C) of feed water on various FO parameters. The concentration of GDS (90 g/l) and the flow rate (2 l/min) were kept constant. The experimental results are presented in Figures 3-24.

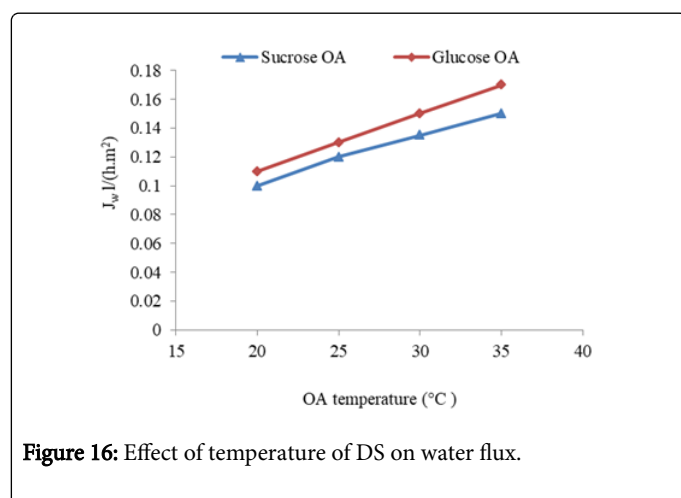


Figure 16: Effect of temperature of DS on water flux.

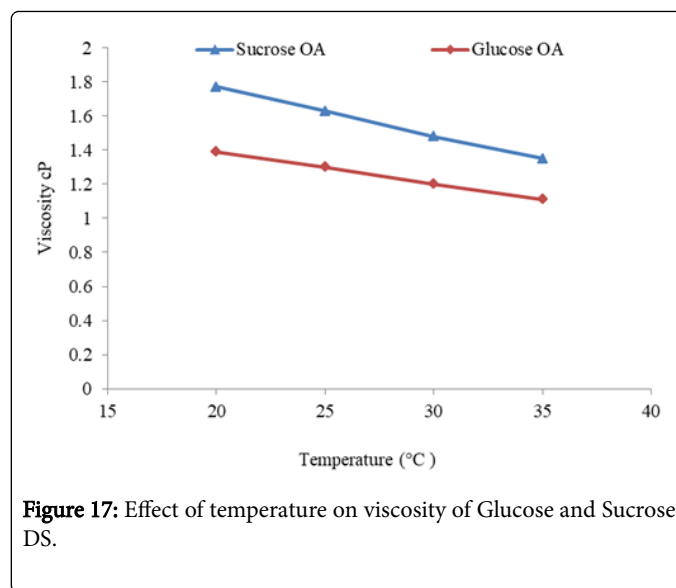


Figure 17: Effect of temperature on viscosity of Glucose and Sucrose DS.

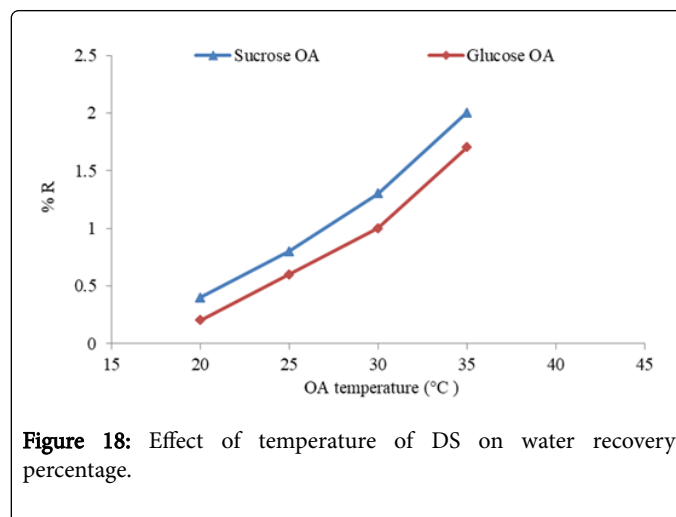


Figure 18: Effect of temperature of DS on water recovery percentage.

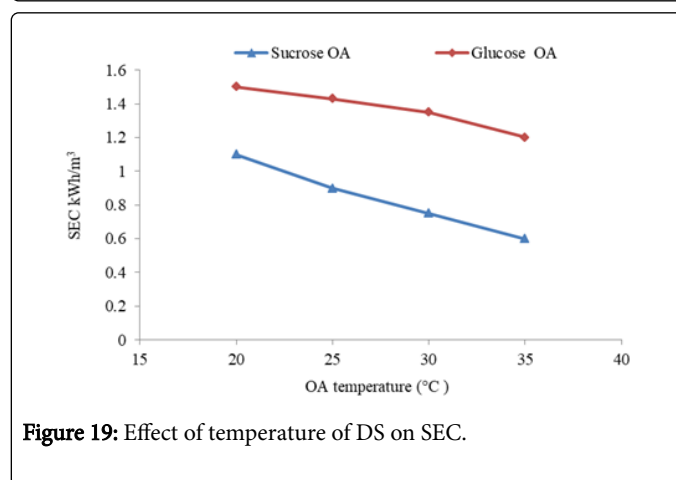


Figure 19: Effect of temperature of DS on SEC.

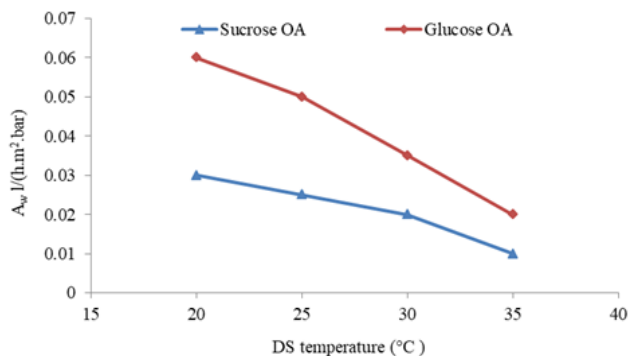


Figure 20: Effect of temperature of DS on water permeability.

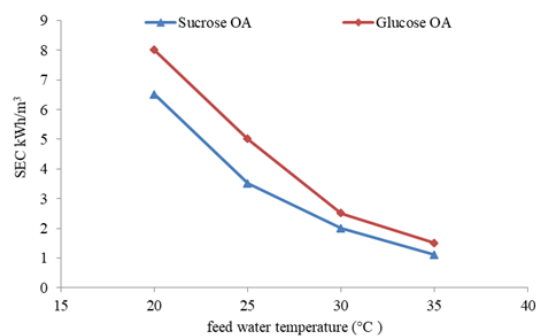


Figure 23: Effect of temperature of feed water on SEC.

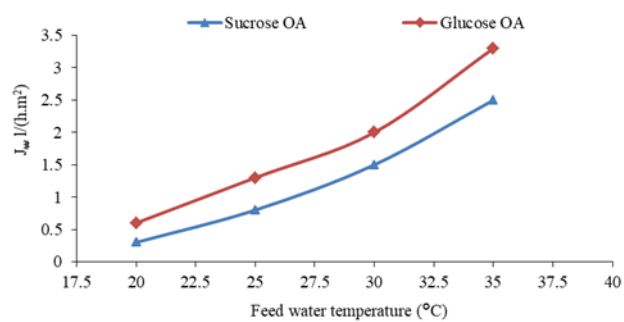


Figure 21: Effect of temperature of feed water on water flux.

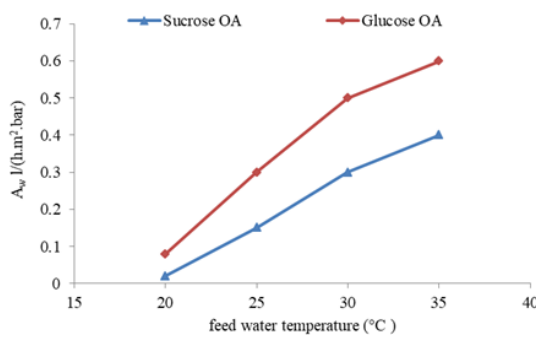


Figure 24: Effect of temperature of feed water on water permeability.

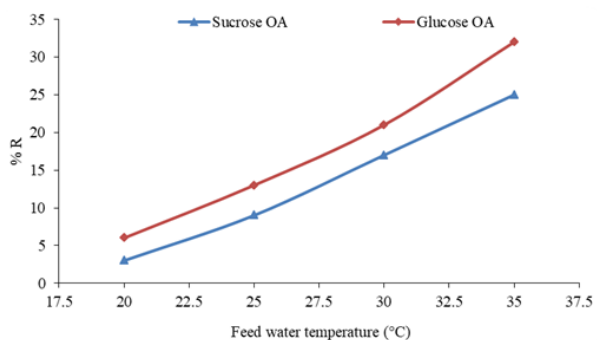


Figure 22: Effect of temperature of feed water on water recovery percentage.

Results and Discussion

DS concentration effect

A number of experiments were carried out to investigate the effect the draw solution concentration and the results are presented in terms of flux, viscosity and recovery rate. Figure 3 shows that the water flux declined from 1.40-0.5 l/(m².h) on increasing the Glucose concentration from 90-250 g/l. A similar trend was observed when operating the FO module with SDS. This could be due to the fact that these osmotic agents are less viscous at higher osmotic potential differential (Figure 4). In addition, the water flux decreased from 2.75-1.75 l/(h.m²) with increased SDS concentration from 170-400 g/l. This might be due to a decrease in the viscosity of Sucrose and Glucose with increasing concentration, as shown in Figure 5. The decrease in viscosity resulted in a lower pressure differential across the membrane surface, thus causing decreased water flux. In addition, the ICP on the membrane surface caused low water flux.

Figure 6 shows a decreasing trend of water recovery percentage from 45-30% as Sucrose concentration increased from 170-400 g/l, whereas water recovery percentage decreased from 25%-5% with the increase in Glucose concentration from 90-250 g/l. This clearly indicates that both flux and recovery percentage of deionized water decreased at higher osmotic concentration. This decrease in both of these parameters may be due to higher ICP on the active layer of the membrane than the ECP.

Figure 7 shows that the increasing trend in SEC was linear with an increase in the concentration of osmotic agents. The decrease in SEC was from 3.25-1.0 kWh/m³ and 0.75-0.1 kWh/m³ using SDS and GDS, respectively. From the results in the Figure 7, it seems that using Glucose as DS agent consumed lower energy than Sucrose in NF membrane. Figure 8 shows that water permeability (A_w) decreased from 0.3-0.09 l/(h.m².bar) using Glucose as DS, while a decrease from 1.0-0.02 l/(h.m².bar) was observed in the Sucrose-related studies, although the overall A_w was lower for Sucrose. It is important to notice that, at higher osmotic concentration, the decline is not as rapid as in the Glucose test.

Flow rate study effect

Feed water flow rate: The data in Figure 9 shows that the water flux increased from 0.6-2.5 l/(h.m²) and from 0.4-1.55 l/(h.m²) for Sucrose and Glucose DS, respectively, on increasing the feed water flow rate from 2-4 l/min. Data in Figure 10 indicates that water recovery rate (%R) increased from 5-40% and 3.0-30% for SDS and GDS, respectively, with increasing the feed water flow rate from 2-4 l/min. This indicates that the water flux and water recovery percentage increase with increasing the feed water flow rate. However, SDS exhibited higher water flux than GDS at the same osmotic pressure. This may be attributed to the difference in viscosity between these two DSs at the same concentration. In addition, an increase in the feed water flow rate may have reduced the osmotic pressure on the active layer of the membrane more than on the support layer. From the data in Figure 11, it can be seen that the SEC decreased from 12-1.8 kWh/m³ when the feed water flow rate was increased from 2-4 l/min using SDS. In addition, it decreased from 2.2-0.8 kWh/m³ on increasing the water flow rate from 2-4 l/min for GDS. This may be due to an increase in the fluxes with increasing feed water flow rate. The experimental data shows almost the same value of solute flux i.e., 2.6 l/(h.m²) from DS side to feed water side using the NF membrane. Figure 12 shows that water permeability (A_w) increased from 0.005-0.02 l/(h.m².bar) using GDS and 0.01-0.05 l/(h.m².bar) using SDS. Overall, it was observed that for both of the DSs (Sucrose and Glucose), water permeability increased constantly with increasing the feed water flow rate. This increase may be due to increased osmotic pressure resulting from high feed water flow rate from active layer to support layer of the membrane.

DS flow rate: From Figure 13, it can be seen that the water flux increased from 0.2-0.9 l/(h.m²) and 0.2-0.7 l/(h.m²) for SDS and GDS, respectively, on increasing the flow rate from 2-4 l/min. This increase in water flux may be due to increased osmotic pressure across the membrane surface with increasing DS flow rate.

From the data in Figure 14, it was observed that the NF membrane is more permeable using the GDS than using SDS. In addition, when the flow rate was increased from 2-4 l/min, the water permeability of both the Sucrose and Glucose DS increased from 0.05-0.3 l/(h.m².bar) and 0.1-0.35 l/(h.m².bar), respectively. As mentioned previously, the increase in permeability may be due to increased osmotic pressure across the membrane surface when the flow rate was increased from 2-4 l/min in the FO process. It was also observed from Figure 15 that recovery percentage showed an increasing trend from 5.5-15.5% and 4-12% for SDS and GDS, respectively, on increasing the flow rate from 2-4 l/min. This increase in recovery percentage may be due to increased pressure across the membrane with increasing flow rate, thus enhancing the water recovery percentage using the NF membrane.

Temperature effect

DS temperature: Analysis of the data in Figure 16 reveals that the water flux showed an increasing trend from 0.1-0.15 l/(h.m²) for SDS and 0.15-0.17 l/(h.m²) for GDS with increasing the temperature from 20-35°C. This may be due to a decrease in the viscosity of the Sucrose and the Glucose, as shown in Figure 17. This is because a decrease in viscosity might have increased the movement and speed of water molecules and the rate of diffusion across the membrane surface, thus causing high water flux. In addition, the GDS exhibited higher water flux than SDS. From the data in Figure 18, the water recovery percentage (%R) increased from 0.4-2% for SDS and from 0.2-1.7% for GDS on increasing the temperature from 20-35°C. This may be due to the decrease in the viscosity of both the Sucrose and Glucose DS with increasing temperature. It is obvious from the above results that water recovery percentage increased on increasing the temperature of both the DSs. In addition, the increase in temperature affects the movement and speed of water molecules, and the rate of diffusion of water molecules on the membrane surface. However, from Figure 19, it is evident that the SEC decreased slightly from 1.1-0.6 kWh/m³ for SDS and from 1.5-1.3 kWh/m³ for GDS on increasing the temperature from 20-25°C. This may be due to increased water flux on increasing the temperature of the DS, because lower viscosity at higher temperature promotes rate of diffusion of water molecules and increases the movement of water molecules across the membrane surface. Moreover, the GDS consumed less energy than the SDS being more viscous when compared to GDS.

From the study data, it is evident that the Sucrose and Glucose DSs exhibited constant solute flux i.e., 2.6 g/(h.m²) from the DS side to the feed water side on increasing the temperature from 20-25°C.

From the data in Figure 20, it appears that the water permeability decreased from 0.06-0.02 l/(h.m².bar) for GDS and 0.03-0.01 l/(h.m².bar) for SDS on increasing the temperature from 20-35°C.

Feed water temperature: It is evident from Figure 21 that the water flux increased from 0.2-0.8 l/(h.m²) for SDS and 0.5-1.1 l/(h.m²) for GDS with the increase in the feed water temperature from 20-35°C. This indicates that water flux increases with increasing feed water temperature. This may be due to a decrease in the viscosity of water and an increase in the membrane permeability on increasing the temperature. This is because lower viscosity promotes diffusion of water molecules and increases the movement of water molecules across the membrane surface.

From the data in Figure 22, the water recovery increased from 3.0-25% and 6-30% for SDS and GDS, respectively, on increasing the temperature from 20-35°C. This indicates that the water recovery percentage increases on increasing the feed water temperature. In contrast, from Figure 23, it is evident that SEC decreased from 6.5-1.0 kWh/m³ and 8-1.5 kWh/m³ for SDS and GDS, respectively, with increasing the temperature from 20-35 °C. This may be due to an increase in water flux on increasing the feed water temperature. The permeability of feed water increased from 0.1-0.6 l/(m².h.bar) and 0.05-0.4 l/(m².h.bar) for GDS and SDS, respectively, on increasing the temperature from 20-35°C (Figure 24). In addition, the NF membrane, being a loose membrane, showed higher permeability using GDS than SDS.

Conclusion

- With increasing the concentration of Glucose and Sucrose draw solutions, the water flux, water recovery percentage and water permeability decreased and the specific energy consumption increased.
- When the feed water flow rate increased at constant other parameters (concentration, temperature), the water flux, recovery percentage and water permeability increased, while the specific energy consumption decreased.
- When the draw solution flow rate increased, the water flux and water recovery percentage increased, while the specific energy consumption decreased on increasing the flow rate from 2-4 l/min for Glucose and Sucrose draw solutions.
- With increasing osmotic agent temperature, the water flux and water recovery percentage increased, while the specific energy consumption decreased and the solute flux did not show any effect with increasing the temperature of draw solutions from 20-35°C.
- The water flux, water recovery percentage and water permeability increased while the specific energy consumption showed a reduction on increasing the feed water temperature from 20-35°C. The permeability of feed water increased for both Glucose and Sucrose draw solutions on increasing the temperature from 20-35°C. In addition, the NF membrane showed higher permeability using GDS than SDS.
- The GDS showed higher efficacy than SDS using the NF membrane in all the FO parameters (water flux, percent recovery, permeability, specific energy consumption) in this work. The experimental results showed that both the Sucrose and Glucose may not be suitable draw solutions for the FO process. Because these draw solutions are more viscous as compared to other draw solutions such as NaCl.
- It is also pointed out that in all of the experiments involving concentration, temperature and flow rate of both the draw solutions did not affect the solute flux. Therefore, the data are not presented in this paper.

Acknowledgements

The authors acknowledge the support by King Abdul-Aziz City for Science and Technology (KACST), National Centre for Irradiation Technology (NCIT), Atomic Energy Research Institute (AERI), Kingdom of Saudi Arabia-Riyadh.

References

1. Farooque AM, Jamaluddin ATM, Al-Reweli AR, Jalaluddin PAM, Al-Marwani SM, et al. (2008) Parametric Analyses of Energy Consumption and Losses in SWCCSWRO Plants Utilizing Energy Recovery Devices. *Desalination* 219: 137-159.
2. Jeffery R, Robert L, Menachem E (2005) A novel ammonia-carbon dioxide forward (direct) osmosis desalination process. *Desalination* 174: 1-11.
3. Heather C, Peter HG, Wolff G (2006) *Desalination with a Grain of Salt*. Alonzo Printing Co. Inc., pp. 9.
4. Thompson NA, Nicoll PG (2011) Forward osmosis desalination: A commercial reality. IDA World Congress at Perth, Australia.
5. Ge J, Peng Y, Li Z, Chen P, Wang S (2014) Membrane fouling and wetting in a DCMD process for RO brine concentration. *Desalination* 344: 97-107.
6. Helfer F, Lemckert C, Anissimov YG (2014) Osmotic power with Pressure Retarded Osmosis: Theory, performance and trends- A Review. *J Membr Sci* 453: 337-358.
7. Holloway RW, Regnery J, Nghiem LD, Cath TY (2014) Removal of Trace Organic Chemicals and Performance of a Novel Hybrid Ultrafiltration-Osmotic Membrane Bioreactor. *Environ Sci Technol* 48: 10859-10868.
8. Han G, Zhang S, Li X, Chung TS (2015) Progress in Pressure Retarded Osmosis (PRO) membranes for osmotic power generation. *Prog Polym Sci* 51: 1-27.
9. Le NL, Nunes SP (2016) Materials and membrane technologies for water and energy sustainability. *Sustainable Materials and Technologies* 7: 1-2.
10. Cath TY, Childress AE, Elimelech M (2006) Forward osmosis: Principles, applications, and recent developments. *Journal of Membrane Science* 281: 70-87.
11. Cartinella J, Cath T, Flynn M, Miller G, Hunter K, et al. (2006) Removal of Natural Steroid Hormones from Wastewater Using Membrane Contactor Processes. *Environmental Science & Technology* 40: 7381-7386.
12. Chung TS, Zhang S, Wang KY, Su J, Ling MM (2012) Forward osmosis processes: Yesterday, today and tomorrow. *Desalination* 287: 78-81.
13. Beaudry EG, Herron JR (1997) Direct osmosis for concentrating wastewater. In: *Proceedings of the 27th International Conference on Environmental Systems, Lake Tahoe, NV*.
14. Osmotek Inc (2003) Landfill leachate treatment.
15. York RJ, Thiel RS, Beaudry EG (1999) Full-Scale Experience of Direct Osmosis Concentration Applied to Leachate Management. 2: 359-366.
16. Moody C, Kessler J (1976) Forward osmosis extractors. *Desalination* 18: 283-295.
17. Beaudry EG, Lampi KA (1990) Membrane technology for direct osmosis concentration of fruit juices. *Food Technology* 44: 121.
18. Dova MI, Petrotos KB, Lazarides HN (2007) On the direct osmotic concentration of liquid foods. Part I. Impact of process parameters on process performance. *Journal of Food Engineering* 78: 422-430.
19. Dova MI, Petrotos KB, Lazarides HN (2007) On the direct osmotic concentration of liquid foods. Part II. Development of a generalized model. *Journal of Food Engineering* 78: 431-439.
20. Jiao B, Cassano A, Drioli E (2004) Recent advances on membrane processes for the concentration of fruit juices: A Review. *Journal of Food Engineering* 63: 303-324.
21. Petrotos KB, Lazarides HN (2001) Osmotic concentration of liquid foods. *Journal of Food Engineering* 49: 201-206.
22. Petrotos KB, Quantick PC, Petropakis H (1998) A study of the direct osmotic concentration of tomato juice in tubular membrane-module configuration. I. The effect of certain basic process parameters on the process performance. *Journal of Membrane Science* 150: 99-110.
23. Petrotos KB, Quantick PC, Petropakis H (1999) Direct osmotic concentration of tomato juice in tubular membrane-module configuration. II. The effect of using clarified tomato juice on the process performance. *Journal of Membrane Science* 160: 171-177.
24. Popper K, Camirand WM, Nury F, Stanley WL (1966) Dialyzer concentrates beverages. *Food Eng* 38: 102-104.
25. Wrolstad RE, McDaniel MR, Durst RW, Micheals N, Lampi KA, et al. (1993) Composition And Sensory Characterization Of Red Raspberry Juice Concentrated By Direct-Osmosis Or Evaporation. *Journal of Food Science* 58: 633-637.
26. Jeffery R, Robert L, Menachem E (2006) Desalination by ammonia-carbon dioxide forward osmosis: Influence of draw and feed solution concentration on process performance. *Journal of Membrane Science* 278: 114-123.
27. Achilli A, Cath TY, Childress AE (2010) Selection of inorganic-based draw solutions for forward osmosis applications. *Journal of Membrane Science* 364: 233-241.
28. Lee S, Boo C, Elimelech M, Hong S (2010) Comparison of fouling behavior in Forward Osmosis (FO) and Reverse Osmosis (RO). *Journal of Membrane Science* 365: 34-39.

29. McCormick P, Pellegrino J, Mantovani F, Sarti G (2008) Water, salt, and ethanol diffusion through membranes for water recovery by forward (direct) osmosis processes. *Journal of Membrane Science* 325: 467-478.
30. Al-Mayahi AK, Sharif AO (2004) Solvent Removal Method, US Patent No. US 7,879,243; European Patent No. EP 1,651,570.
31. McCutcheon JR, Elimelech M (2006) Influence of concentrative and dilutive internal concentration polarization on flux behavior in forward osmosis. *Journal of Membrane Science* 284: 237-247.
32. Yen SK, Haja NFM, Su M, Wang KY, Chung TS (2010) Study of draw solutes using 2-methylimidazole-based compounds in forward osmosis. *Journal of Membrane Science* 364: 242-252.
33. Ling MM, Chung TS (2011) Novel dual-stage FO system for sustainable protein enrichment using nanoparticles as intermediate draw solutes. *Journal of Membrane Science* 372: 201-209.
34. Changwei Z, Peisheng MA (2003) Measurement and correlation of viscosity and apparent molar volume of ternary systems for L-ascorbic acid in aqueous D-glucose and sucrose solutions. *Chinese J Chem Eng* 11: 185-190.
35. Galmarini MV, Baeza R, Sanchez V, Zamora MC, Chirife J (2011) Comparison of the viscosity of trehalose and sucrose solutions at various temperatures: Effect of guar gum addition. *LWT-Food Science and Technology* 44: 186-190.
36. Altaee A (2012) Forward Osmosis: Potential use in Desalination and Water Reuse. *Journal of Membrane and Separation Technology* 1: 79-93.
37. Kim T, Kim Y, Yun C, Jang H, Kim W, et al. (2012) Systematic approach for draw solute selection and optimal system design for forward osmosis desalination. *Desalination* 284: 253-260.
38. Kerr WL, Reid DS (1994) Temperature dependence of the viscosity of sugar and maltodextrin solutions in coexistence with ice. *LWT-Food Science and Technology* 27: 225-231.
39. Zhao S, Zou L (2011) Relating solution physicochemical properties to internal concentration polarization in forward osmosis. *Journal of Membrane Science* 379: 459-467.
40. Cath TY, Gormly S, Beaudry EG, Adams VD, Childress AE (2005) Membrane contactor processes for wastewater reclamation in space. Part I. Direct osmotic concentration as pretreatment for reverse osmosis. *J Membr Sci* 257: 85-98.
41. Holloway RW, Cath TY, Dennett KE, Childress AE (2005) Forward osmosis for concentration of anaerobic digester centrate. In: *Proceedings of the AWWA Membrane Technology Conference and Exposition, Phoenix, USA* 41: 4005-4014.
42. Martinetti C, Childress A, Cath T (2009) High recovery of concentrated RO brines using forward osmosis and membrane distillation. *Journal of Membrane Science* 331: 31-39.
43. Miller JE, Evans LR (2006) Forward Osmosis: A New Approach to Water Purification and Desalination. Sandia Report, pp. 1-51.
44. Zhao S, Zou L, Tang C, Mulcahy D (2012) Recent developments in forward osmosis: Opportunities and challenges. *Journal of Membrane Science* 396: 1-21.