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Investigating fertilizer drawn forward osmosis process for groundwater desalination for irrigation in Egypt

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ABSTRACT

Groundwater desalination could be a possible solution to Egypt's water scarcity problem through applying state-of-the-art desalination technologies. This work investigated a recently developed sustainable desalination technology which is fertilizer drawn forward osmosis (FDFO). In this work, ammonium sulfate was selected as a draw solution being a commercial, inexpensive, and efficient Egyptian fertilizer. Three commercially available Forward Osmosis (FO) membranes were tested for baseline flux. The best membrane was selected for further experimentation. A real Egyptian brackish groundwater sample from El Tor in Sinai was used as the feed solution. Performance has been assessed by the water flux, reverse permeation, and the forward rejection of the feed solutes. Porifera's commercial FO membrane proved to be the best membrane with respect to baseline flux. It was chosen for further experimentation. Water flux and ammonium sulfate concentration can be correlated logarithmically. Further increase in ammonium sulfate concentration decreases water flux gradually due to increased severity of concentration polarization effects that take place at high draw solution concentration. Specific Reverse Solute Flux (SRSF) values did not exceed 0.18 g/l for both NH_4^+ and SO_4^{2-} ions, indicating high membrane selectivity. At flux exceeding $20\,\text{L}\text{m}^{-2}\,\text{h}^{-1}$, NH_4^+ ion reported higher SRSF values than that of SO_4^{2-} ion, a phenomenon that could be attributed to thermodynamic influence. SRSF is almost constant irrespective of ammonium sulfate concentration. While increasing draw solution concentration lead to increasing Na^+ ion rejection, it caused a significant decline in Cl^- ion rejection. This phenomenon could be probably associated to an ion exchange mechanism and the membrane surface charge. In conclusion, the scheme studied showed that ammonium sulfate is an efficient draw solution for FDFO process using Porifera's commercial FO membrane exhibiting high osmotic pressure, low reverse solute permeation, and remarkable rejection of feed solute.

Keywords: Draw solution; Egypt; Fertigation; Fertilizer drawn forward osmosis; Flux; Forward osmosis; Groundwater; Irrigation; Rejection; Reverse solute flux

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1. Introduction

The production of fresh water from saline water is one of the most important challenges facing Egypt today, as the country is facing a serious water scarcity problem as well as an inevitable energy crisis. Water experts should be looking for alternative sustainable sources of water. The next alternative water source in Egypt is groundwater. More than half of Egypt's area has access to brackish groundwater, 47% of which has access to aquifers with moderate-to-high potential for development [1]. If low cost and sustainable desalination technology is available, large-scale desalination for irrigation could become inexpensive. It will be inevitably required to decrease the cost of irrigation water using state-of-the-art desalination technologies [2].

Forward osmosis (FO) is an emerging technology that is classified as an "osmotically driven membrane" process. This technology takes advantage of the osmotic pressure difference that is generated when a semipermeable membrane separates two solutions of differing concentrations [3,4]. By using the osmotic pressure difference to drive the permeation of water across the semipermeable membrane, FO may be capable of overcoming several of the limitations of hydraulically driven membrane processes, such as reverse osmosis (RO) [5]. Unlike RO, FO does not need a highly applied hydraulic pressure and exhibits a lower fouling tendency compared to FO thereby decreasing capital, operating, and energy costs [2,6].

FO has numerous applications [7,8], yet, one outstanding application is fertilizer drawn forward osmosis (FDFO), as per Fig. 1. In this process, concentrated (sometimes blended) fertilizer solution is used as the draw solute [9]. Two different solutions are used in the FDFO process: saline water (as the feed solution, FS) on one side of the membrane, and highly concentrated fertilizer solution (as the draw solution, DS) on the other side of the membrane. The two solutions are always kept in contact with the membrane through a countercurrent flow system, where fresh water flows from the saline feed solution toward the highly concentrated fertilizer draw solution. After extracting the water by the FO process, the fertilizer draw solution becomes diluted and thus can be used directly for fertigation, avoiding the need for separation and recovery of the DS [10]. The impact of such technology on the agriculture sector would be revolutionary for water scarce countries like Egypt, where saline water is abundant in the form of sea water along coastal areas and brackish groundwater in inland areas.

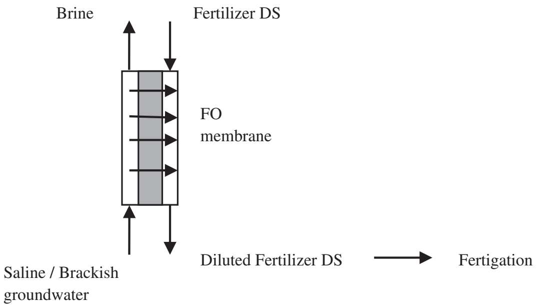

Fig. 1. Typical fertilizer drawn forward osmosis setup (adapted from [9]).

In addition to water flux, investigating the efficiency of the process in terms of reverse permeation of draw solute from the DS into the FS could be a significant limitation to the practicality of FDFO process. Ideally, an FO membrane should prevent any dissolved draw solute from reaching the feed solution, yet this is not the case, as a small amount of dissolved solute will ultimately be transported across the membrane [11]. Reverse permeation has negative economic, technical, and environmental impacts. In case an expensive draw solute (fertilizer in case of FDFO) is utilized, the cost of restocking the draw solute that permeated in the feed solution could drive up the cost of FO and make it less attractive as an alternative desalination process. Reverse permeation eventually reduces the net osmotic driving force and increase the fouling potential of the FS by forming new compounds with the feed ions [7,12]. In addition, if reverse permeation is major when nitrogen- and phosphorus- containing DSs are used, eutrophication in the receiving water environment could take place [13]. Therefore, a careful assessment of reverse solute permeation is important to the effective development of FDFO.

It is worth mentioning that FDFO has some anticipated challenges. There is an ultimate limit to which the osmotic process can continue occurring as each DS can extract water only up to the "osmotic equilibrium," which is defined as "the concentration where the DS osmotic potential equals that of the feed water" [14]. Beyond this point, the DS cannot be further diluted. At this equilibrium point and depending on the feed salinity, the fertilizer concentration is still too high and thus exceeding the maximum limit that a crop can tolerate [10]. In case the nutrient concentration does not meet the fertigation standard, the DS must be further diluted to make the treated water fit for fertigation. Dilution is only achievable if there is access to a source of fresh water for irrigation. However, if this is not the case then this is a limitation. To achieve lower nutrient concentration in the final FDFO product water, possible options are pre-treatment or post-treatment of feed water, use of blended fertilizer, or hybrid FO system [13].

The aim of this work is to investigate the efficiency and performance of FDFO process by treating a real Egyptian groundwater sample using a commercially available nitrogenous-based draw solution. Three different FO membranes are tested and compared. Process efficiency is assessed by evaluating the water flux, reverse permeation of draw solute from the DS into the FS, and the forward rejections of the feed solutes.

2. Materials and methods

The experimental investigations in this work were performed using a bench-scale crossflow filtration unit (Fig. 2). The FO unit consists of a circular FO cell with diameter equal to 40 mm and an effective membrane area of 1.257×10^{-3} m^2. A flow channel is provided on each side of the membrane to allow feed water to flow on one side of the membrane and draw solution on the other side of the membrane. Both the feed loop and the draw loop follow the same water path. Circular rubber gaskets were used to support the membrane and provide adequate depth in each flow channel.

Experiments in this study were carried out at a crossflow rate of 0.22 l/min, which is equivalent to a crossflow velocity of 12.9 cm/s. The crossflows were operated in countercurrent flow directions using a double-headed peristaltic pump (Stenner, model 170DMP5, 25 psi, 1.7 bar, 50 Hz, USA). The temperature of all solutions was maintained at 25°C using a temperature water bath controlled by a heater/chiller (Polyscience temperature controller, model 9106A12E). The changes in the DS and FS volumes were recorded real-time by connecting the DS and FS to digital mass scales which are connected to a computer for online data logging every three minutes. Water flux across the membrane in the FO process was calculated from the change in the volume of the DS and the FS, where both fluxes are averaged for accuracy reasons. To consider mass balance, if (ΔFS–ΔDS) exceeded 5 g/d or if noticeable leakage is observed, the experiment is disregarded and repeated.

The initial volume of both the DS and FS (V_i) was 2.0 L each. The solutions after passing through the membrane were returned to their respective tanks (Fig. 2), which led to the continuous dilution of the DS and a continuous increase in the concentration of the FS. This resulted in a continuous decrease in water flux with time due to decline in effective osmotic

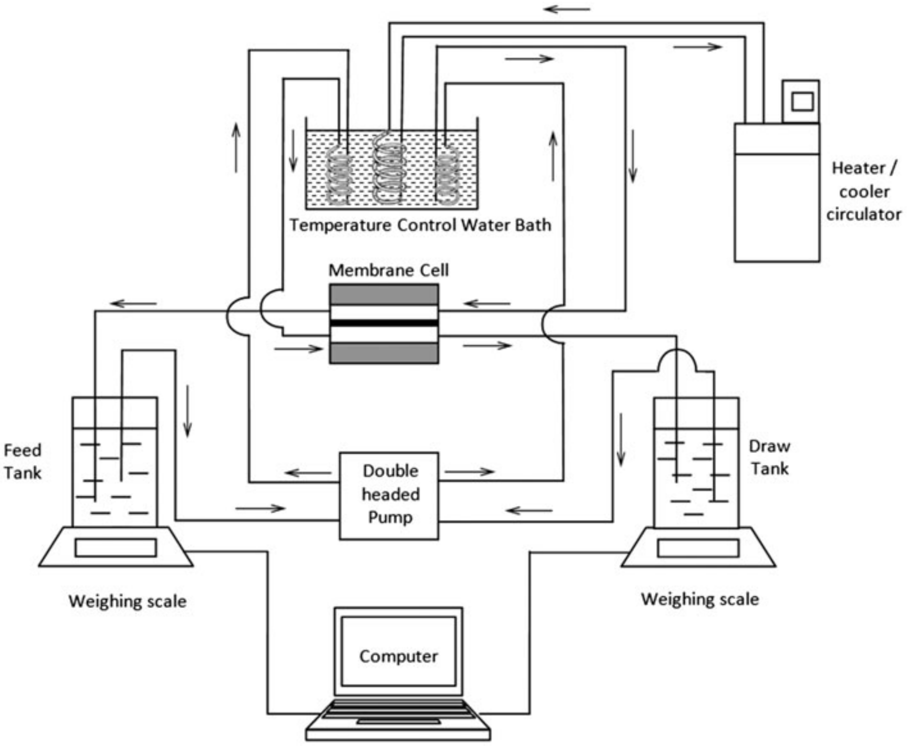

Fig. 2. Schematic of setup used.

pressure. However, the water flux was selected from the point at which a stable flux was observed from the plot of flux vs. time, which usually happened within the first 60 min of operation. All the experiments were carried out for a duration of 24 h for adequate diffusion of draw solutes. Both the FS and DS containers were tightly covered using parafilm to avoid evaporation losses during the experiment.

The general equation describing water transport in FO is given by the following basic equation [15]:

$$J_{\mathrm{w}} = A\ \sigma\ (\pi_{\mathrm{DS}} - \pi_{\mathrm{FS}}) \tag{1}$$

where J_{w} is the pure water flux, A is the pure water permeability coefficient of the membrane, σ is the reflection coefficient, usually assumed to be unity, indicating complete rejection of solute π_{DS} is bulk osmotic pressure of the draw solution (DS) π_{FS} is bulk osmotic pressure of the feed solution (FS).

The Reverse Solute Flux (RSF or J_{s}) of an individual solute through any semi-permeable membrane is governed by concentration gradients between the two solutions (i.e. $J_{\mathrm{s}}\ \alpha\ f\ (\Delta C)$) and can be calculated as follows:

$$\mathrm{RSF} = J_{\mathrm{s}} = \frac{(V_{\mathrm{i}} - \Delta V)\ \times\ C_{\mathrm{s}}}{\text{membrane area}\ \times\ \text{time}} \tag{2}$$

where V_{i} is the initial volume of FS, ΔV is the total volume of water that enters the DS from the FS, and C_{s} is the concentration of the draw solutes in the FS at the end of the experiment.

RSF in Eq. (2) does not account for the amount of pure water transferred through the membrane. That is why; Specific Reverse Solute Flux (SRSF) is introduced to relate the amount of draw solutes lost by reverse diffusion per unit volume of water extracted from the FS [11]. SRSF can be calculated using the following relation:

$$\mathrm{SRSF} = \frac{J_{\mathrm{s}}}{J_{\mathrm{w}}} \tag{3}$$

A higher SRSF value denotes a lower membrane selectivity and poorer FO efficiency. SRSF relates to the selectivity of the active layer of the membrane and is independent of the DS concentration and membrane support structure, as will be shown later [11,16].

The forward rejection of the feed solutes can be calculated using the following relation:

$$\mathrm{Re}\ (\%) = \left(\frac{C_{\mathrm{i}} - C_{\mathrm{p}}}{C_{\mathrm{i}}}\right)\ \times\ 100 \tag{4}$$

where C_{i} is initial concentration of the ion in FS C_{p} is final concentration of the ion in permeate, which is equal to $\left(\frac{C_{\mathrm{p,D}}\ (V_{\mathrm{i}}+\Delta V)}{\Delta V}\right)$, where $C_{\mathrm{p,D}}$ is the measured concentration of the ion in DS.

2.1. FO membranes

Three different membrane samples were tested using the above described setup. The three membranes tested were CTA from Hydration Technology Innovations (HTI), TFC from Woongjin Chemicals, Korea, and Porifera's commercial FO membranes. Table 1 summarizes the different membrane properties.

CTA structure is quite different from any typical RO membrane. While a typical RO membrane has a thin active layer with a thick porous fabric support layer, CTA membrane has an embedded polyester mesh which provides mechanical support to the membrane. TFC membrane structure consists of a selective active layer on top of a polysulfone support layer manufactured by phase separation onto a thin polyester non-woven fabric [17].

The three membranes were tested for baseline flux in FO mode using NaCl as DS and DI water as FS. The membrane that exhibited the highest water flux in baseline experiments was selected for the next set of experiments (using the real groundwater as FS).

The membrane orientation used in this investigation was FO mode, where FS faces the membrane active layer and the DS faces the porous support layer. In this setup, concentrative external concentration polarization occurs on the membrane active layer, while dilutive internal concentration polarization (DICP) takes place inside the membrane support layer [18].

2.2. Draw solution (DS)

A nitrogenous-based fertilizer is chosen to be the DS for this study as nitrogenous fertilizers are by far the most common type of fertilizers in Egypt [19]. Fig. 3 demonstrates a price comparison of the four common nitrogenous-based fertilizers in Egypt, which are ammonium nitrate, calcium nitrate, urea, and ammonium sulfate. As each fertilizer contains a different amount of nitrogen content, comparison is carried out based on per kg of nitrogen. Ammonium sulfate was selected as the DS for this investigation. Reasons for this selection are discussed in the next few paragraphs.

Ammonium sulfate is a commercially available inexpensive nitrogenous fertilizer in the Egyptian market (Fig. 3). It is considered the third most used

Table 1
Membrane properties—as provided by manufacturer and from literature [17]

	CTA	TFC	Porifera
Manufacturer	Hydration technology innovations (HTI), Inc.	Woongjin chemicals, Korea	Porifera Inc.
Model	Cartridge	Hand casted	Roll-to-roll
Pure water permeability coefficient, A (Lm^{-2} h^{-1} bar^{-1})	1.02 ± 0.03	5.25 ± 0.51	2.2 ± 0.01
Salt permeability coefficient of active layer, B (m/s)	9.8×10^{-7}	N/A	1.6×10^{-7}
Total membrane thickness (μm)	93 ± 3	147 ± 16	70 ± 10
Structural parameter, S (μm)	595 ± 114	N/A	215 ± 30
Material of active layer	Cellulose tri acetate	Polyamide (PA)	Polyamide (PA)
Material of support layer	Polyester mesh embedded	TFC polysulfone	Porous hydrophilic polymer

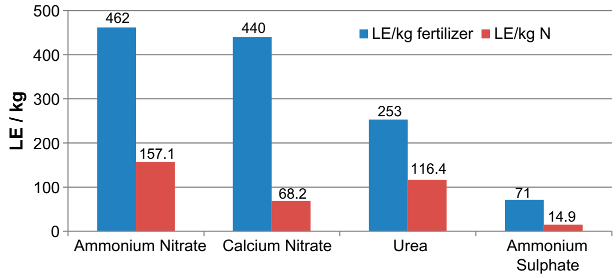

Fig. 3. Price comparison of four selected fertilizers (LE is Egyptian currency).

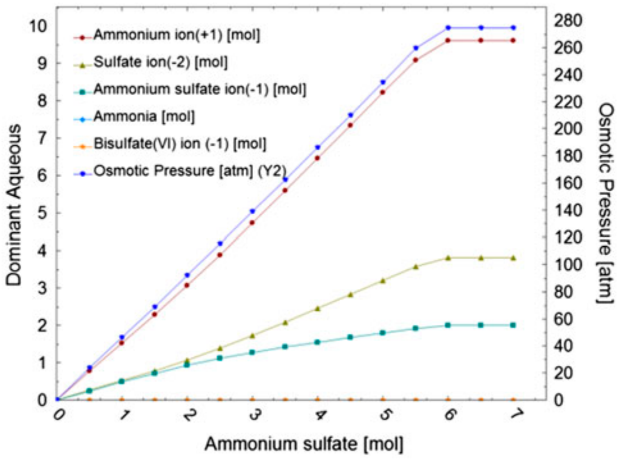

Fig. 4. Major species formed in the solution and osmotic pressure of ammonium sulphate. Analysis carried out using OLI stream Analyzer 9.1 at 25°C and 1 atm pressure [29].

fertilizer in Egypt after urea and ammonium nitrate [19]. It has been used in Egypt a long time ago and it is produced locally by numerous fertilizer factories [20]. Although domestic demand for the granular ammonium sulfate is low, the crystal form is popular in Egypt since it is relatively cheap [21]. It is reported that Egyptian market consumed 140,000 ton of ammonium sulfate in 2012 [22]. Cost of ammonium sulfate is not affected by the fluctuating costs of natural gas because it is a by-product of other industries such as steel and polyester compounds. Certain by-products that contain ammonia or sulfuric acid are commonly converted to ammonium sulfate for use in agriculture [23,24].

From a technical point of view, ammonium sulfate exhibits a high osmotic pressure due to the formation of a large number of species when aqueous (Fig. 4). At a 2 M concentration, osmotic pressure of ammonium sulfate is estimated to be 92.1 atm, which is comparatively high to that of seawater (~28 atm). In addition, ammonium sulfate provides the plant with nitrogen and sulfur at the same time as it contains approximately 21% nitrogen and 24% sulfur, promoting plant growth and crop yield. Because ammonium sulfate contains mainly ammonium nitrogen, it secures a lasting and sustainable nitrogen source. In the meantime, it minimizes nitrogen washing out from the soil. Also, ammonium sulfate promotes the availability of secondary nutrients like manganese, iron, and boron in the soil [25,26]. Ammonium sulfate is not hygroscopic (tendency to absorb moisture from the air), thus long storage duration is possible [27]. Compared to urea, ammonium sulfate is more resistant to valorization. While ammonium sulfate is the preferred fertilizer for flood irrigation used for rice production in Egypt, nitrate-based fertilizers are a poor choice due to denitrification losses [27]. Ammonium sulfate exhibits moderate final nitrogen concentration in product water when compared to other nitrogenous-based fertilizers, so it can easily meet irrigation water quality [9].

The speciation and the osmotic potential of ammonium sulfate were predicted using OLI Stream Analyzer 9.1 software (Fig. 4), which uses thermodynamic modeling based on published experimental data to predict properties of solutions over a wide range of molar concentrations [28]. These results indicate the selected fertilizer generates osmotic pressure that is much higher than seawater or brackish groundwater, indicating its suitability for use as an osmotic DS.

2.3. Feed solution (FS)

A real Egyptian brackish groundwater sample was selected for the experiments. Location of the well from which the sample was collected is El Tor, capital of South Sinai. A previous study [2] states that Sinai is a promising area for FDFO application due to high irrigation water demand, availability of arable lands, and ease of brine disposal. Most likely, the extracted water has been obtained from the Nubian Sandstone Aquifer or the Fissured Carbonate Aquifer, both of which have huge exploitable volumes [1,30,31] emphasizing the sustainability of groundwater in the area.

The groundwater sample is categorized as brackish, as its TDS fall in the range of 1–10 g/l [32,33]. Sample was extracted from a deep well at a 150 m depth. The sample was pre-treated using ultra-filtration to remove unneeded suspended solids that might damage the FO membrane fabric. The GW sample properties, past ultra-filtration and prior FO process, are presented in Table 2. The sample's EC, TDS, and SAR are 7.32 mS/cm, 3.66 g/l, and 33.9, respectively, classifying it as water that is unsuitable for irrigation and with a remarkably high sodium hazard [34]. A water of such quality and high SAR value, if used without proper treatment will cause sodium toxicity and loss of soil structure which will eventually lead to soil degradation and poor crop yield [35].

2.4. Experimental plan

Six baseline experiments (BL) were run using different concentrations of NaCl as DS and DI water as FS for each membrane sample. Importance of baseline experiments is that they report the flux in the absence of concentration polarization [36]. NaCl DS was used in these experiments because it is highly soluble in water and its properties in solution are well characterized. Based on that, the membrane that performed best in terms of flux was selected for further experimentation using ammonium sulfate. Six different concentrations of ammonium sulfate DS were investigated: 0.5, 1, 1.5, 2, 2.5, and 3 M.

Table 2
Raw GW sample characteristic (past ultra-filtration) in El Tor, Sinai

Ion	Concentration
Na^+	669.99 mg/l
Cl^-	1,041.25 mg/l
NH_4^+	2.1 mg/l
SO_4^{2-}	2,224.8 mg/l
Ca^{2+}	564.8 mg/l
Mg^{2+}	215.4 mg/l
K^+	41.73 mg/l
Fe^{3+}	0.036 mg/l
Mn^{2+}	0.016 mg/l
NO_3	29.75 mg/l
HCO_3^-	17.08 mg/l
CO_3^{2-}	0 mg/l
EC	7.32 mS/cm
TDS	3.66 g/l
pH	6.5

The DS was prepared by dissolving the salts in DI water with the help of magnetic stirrer (Lab Companion, HP-2000) at 200–300 rpm for at least 15 min to ensure that the salt was fully dissolved and uniformly mixed before starting the experiments. Reagent grade NaCl and $(NH_4)_2SO_4$ were used in this investigation and were supplied by Biostain Ready Reagents, UK.

When DI water was used as the FS in the baseline experiments, the RSF and SRSF were determined by measuring TDS using a portable TDS and EC meter (Hach, model 44600 Conductivity/TDS meter). However, when the FS was the GW sample, the draw solute concentration in the FS and feed solute concentration in the DS were measured using inductively coupled spectrometry (Ultima 2—Jobin Yvon). The concentrations of feed solutes were significantly lower in comparison to that of the DS. Each sample was analyzed a number of times using several dilution factors for accuracy purposes.

In addition, salt rejection was investigated being an important parameter in FO processes. In this study, the forward rejections of the feed solutes were measured by taking the DS sample at the end of each experiment and analyzing it for Na^+ and Cl^- ions. Eq. (4) was used to calculate Na^+ and Cl^- ions Rejection.

3. Results and analysis

3.1. Flux

Fig. 5 compares the baseline water flux for the three membranes tested. For these three types, flux and DS

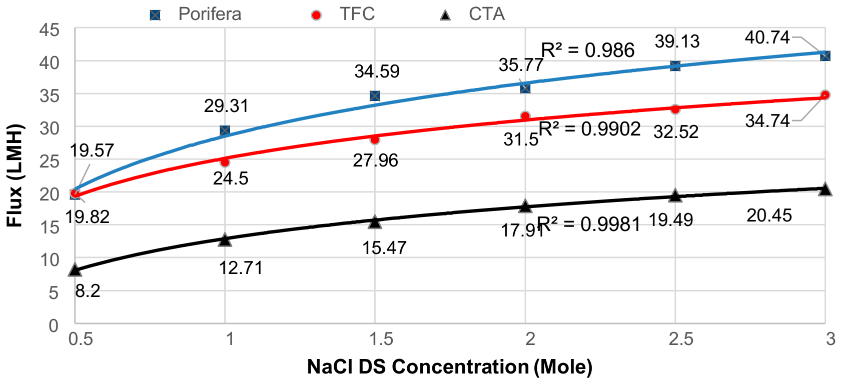

Fig. 5. Baseline water flux comparison for three different types of FO membranes using NaCl as DS and DI as FS.

concentration can be correlated logarithmically, with a correlation coefficient more than 98% indicating goodness of fit. Porifera membrane exhibited the highest flux at the same DS concentration compared to other TFC and CTA membrane. For example, at 1 M NaCl DS concentration, Porifera membrane reported 57 and 16% higher flux than that of CTA and TFC membranes, respectively. Thus, Porifera membrane proved to perform better in terms of flux for same DS concentration. Although Porifera's membrane possesses a moderate Pure Water Permeability Coefficient (A) in comparison to the other two membranes (Table 1), its significantly small structural parameter leads to the highest flux. Despite further increase in DS concentration, rate of water flux increase decreases gradually. The incremental increase in J_w for Porifera membrane for a 0.5 M increase in NaCl DS concentration projected by the logarithmic correlation is 8.1, 4.7, 3.3, 2.6, and 2.1 LMH, respectively. After each experiment, baseline flux is re-checked to make sure that no scaling is taking place on the membrane material. Fig. 6 shows flux of baseline experiments for Porifera membrane where DI was used as FS and NaCl with different concentration as DS. As can be seen from Fig. 6, as DS concentration increases, osmotic pressure increases and thus flux increases.

When $(NH_4)_2SO_4$ was used as the DS, water flux increased at higher molar concentrations of the DS. In almost all experiments, flux stabilized after the passage of around 60 min. The correlation between molar concentration and water fluxes was non-linear unlike osmotic pressure where the correlation with DS concentration was observed to be fairly linear up to 5.5 M $(NH_4)_2SO_4$ (Fig. 4). A logarithmic correlation was observed between DS concentration and the water flux (Fig. 7) and similar observation was reported in other

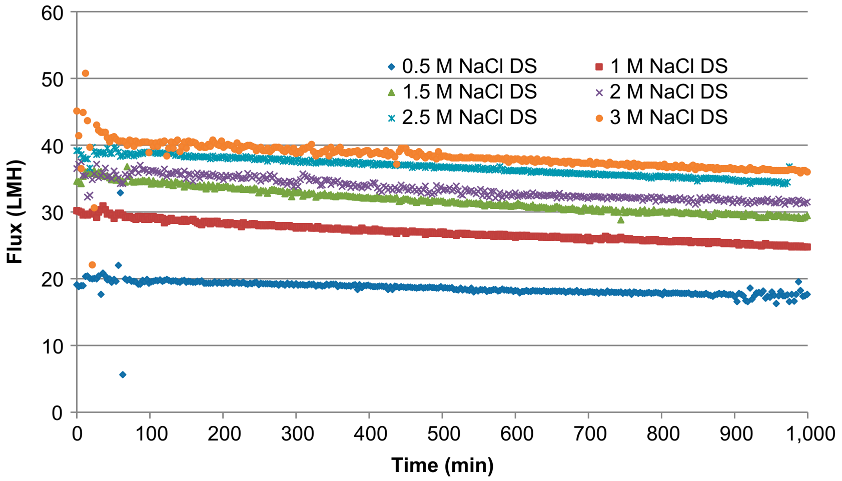

Fig. 6. Baseline flux using porifera membrane (DI as FS and NaCl with different concentration as DS).

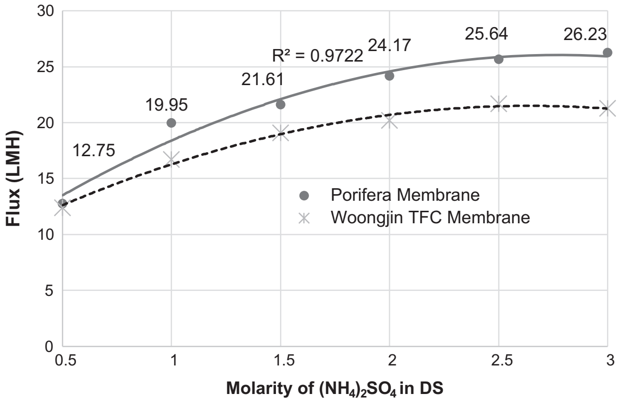

Fig. 7. Comparison of pure water flux for $(NH_4)_2SO_4$ draw solution at different molar concentrations using different membranes. The solid line indicates flux from Porifera membrane and the dotted line indicates flux from Woongjin TFC membrane.

studies [16,37]. Although the water flux increased with the increase in DS concentrations, the increase in water flux at higher DS concentrations were not proportional to the increased osmotic pressure at some point almost flattening at high concentration. This flattening of the water flux at higher DS concentration is a result of the high severity of DICP effects at higher osmotic pressure, as reported in previous studies [12,28,38,39]. While increasing the molar concentration of $(NH_4)_2SO_4$ from 0.5 to 1 M increased water flux by 36%, increasing the molar concentration of $(NH_4)_2SO_4$ from 2.5 to 3 M increased water flux by only 2.2%. As DS concentration increases, the net osmotic pressure increases, yielding short-term higher water fluxes, causing DICP to surge within the membrane, resulting in less water permeation [14].

The experimental flux obtained from this study is compared to flux from TFC membrane provided by Woongjin Chemicals (Korea) using same DS and FS. Results are presented in Fig. 7. Porifera membrane exhibited higher pure flux than that of Woongjin Chemicals membrane. The difference in flux was clear at higher DS concentration, indicating the severity of DICP at higher osmotic pressure, as discussed previously.

3.2. *Reverse permeation*

SRSF results can be summarized in Fig. 8 below. The general trend of the readings indicates that for all the experiments SRSF was noted to be a small value, which implies high membrane selectivity. All SRSF values ranged between 0 and 0.18 g/l. In comparison, a previous study reports that reverse permeation of urea may reach up to 29.2 g/l [9]. The effective diameter of the hydrated NH_4^+ and SO_4^{2-} ions are 250×10^{-12}–400×10^{-12} m, respectively. These diameters are considered large compared to other fertilizer species [38]. Thus, ammonium sulfate is expected to perform well in terms of RSF [13].

The SRSF value for NH_4^+ ion was noted to be slightly higher than that of SO_4^{2-} ion, especially at flux more than 20 Lm^{-2} h^{-1}, which is in agreement without previous investigations [40]. This phenomenon could probably be justified thermodynamically by factors related to ion exchange mechanism and speciation. While NH_4^+ ion in DS is attracted to the Cl^- ion in FS, SO_4^{2-} ions of DS is attracted to the Na^+ ions of FS. Depending on pH, NH_4^+ ion is in equilibrium with NH_3. As NH_4^+ ion is positively charged, it will have good rejection and high membrane selectivity. Yet, as NH_3 is not charged, it will be poorly rejected. Hence,

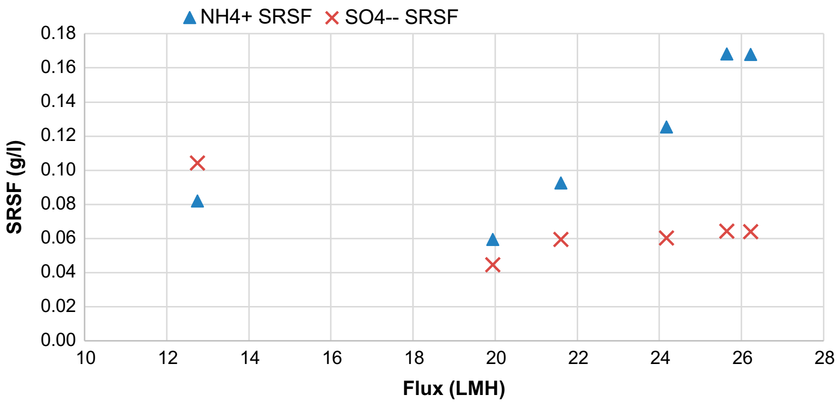

Fig. 8. NH_4^+ and SO_4^{2-} SRSF vs. flux.

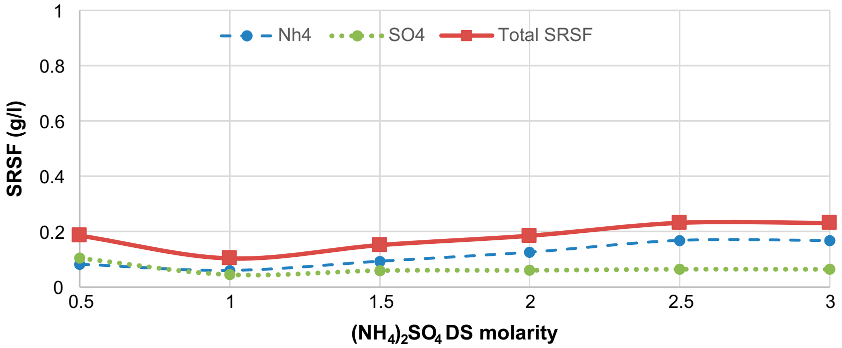

Fig. 9. NH_4^+ and SO_4^{2-} SRSF vs. $(NH_4)_2SO_4$ DS molarity.

the measured SRSF of NH_4^+ ion can be artificially high because of the permeation of NH_3.

Fig. 9 shows SRSF as a function of DS concentration. It can be concluded that SRSF is almost constant irrespective of DS concentration, which is in agreement with a previous study [11], stating that the SRSF is independent of both bulk draw solution concentration and of membrane structural parameter (S). A high concentration of draw solute at the support/active layer interface is needed to create a large osmotic gradient, causing a high water flux. However, this high concentration of draw solute also magnifies the concentration gradient across the active layer, thus amplifying the RSF [11]. That is why, for an ideal solution the osmotic gradient should be proportional to the concentration gradient, and, therefore, the ratio of the two quantities is to remain uniform.

3.3. Rejection

Eq. (4) was used to calculate Na^+ and Cl^- ions rejection in this investigation. Feed solutes rejection is illustrated in Fig. 10. While rejection values of Na^+ ion ranged between 76 and 99%, that of Cl^- ion ranged between 72 and 25%. Typically, rejection increases with the increase in the driving force, which is directly related to the molar concentration of the DS. This proved to be true for Na^+ ion but not for Cl^- ion, a phenomenon which required further investigation.

As can be seen from Fig. 10, the membrane exhibited higher Na^+ ion rejection than for Cl^-, especially at high DS concentrations. Increasing DS concentration leads to increasing Na^+ ion rejection but at the same time leads to decreasing Cl^- ion rejection. This phenomenon could be probably attributed to the membrane surface charge. Originally, this membrane type possesses a negatively charged surface. As DS molarity increases (from 0.5 to 3 M), pH decreases, rendering the solution more acidic. The H^+ ion fully consumes the negative charge on the membrane surface and the surplus H^+ ion leaves the membrane surface positively charged. Thus, it seems that the membrane surface charge reverses from being originally negative to positive, repelling Na^+ ion and attracting Cl^- ion, so more Cl^- ions leave the FS and find its way to the DS than does the Na^+ ion.

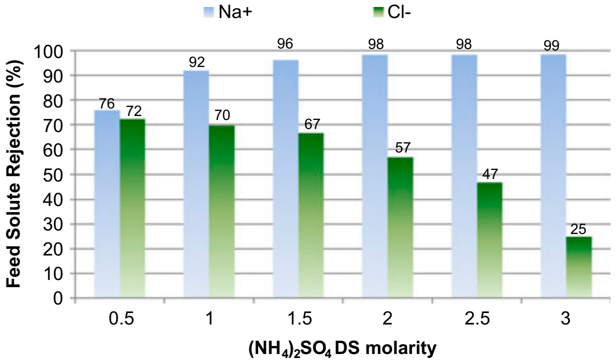

Fig. 10. Forward rejection of Na^+ and Cl^- ions operated at different DS concentrations.

4. Conclusion

This study investigated the performance of a selected nitrogenous-based fertilizer to be used as a draw solution in a typical FDFO process to be possibly used to desalinate Egyptian groundwater for irrigation purposes. After screening different available fertilizers, ammonium sulfate was used as a DS. Three FO membranes were tested for maximum baseline flux. The best membrane was used to desalinate a real brackish groundwater sample using ammonium sulfate as a draw solution, being a commercial inexpensive Egyptian fertilizer. Performance has been assessed by determining the pure water flux, reverse permeation of draw solute and the forward rejections of the feed solutes.

Porifera's commercial FO membrane proved to be the best membrane with respect to baseline flux. It was chosen for further experimentation. Water flux and ammonium sulfate concentration can be correlated logarithmically. Further increase in ammonium sulfate concentration decreases water flux gradually due to increased severity of DICP effects.

SRSF values did not exceed 0.18 g/l for both NH_4^+ and SO_4^{2-} ions, indicating high membrane selectivity. At flux exceeding 20 $Lm^{-2}\,h^{-1}$, NH_4^+ ion reported higher SRSF values than that of SO_4^{2-} ion, a phenomenon that could be attributed to thermodynamic influence. SRSF is almost constant irrespective of ammonium sulfate concentration.

While increasing DS concentration leads to increasing Na^+ ion rejection, it caused a significant decline in Cl^- ion rejection. This phenomenon could be probably associated to an ion exchange mechanism and membrane surface charge.

In conclusion, the scheme studied showed that ammonium sulfate is an efficient DS for FDFO process using Porifera's commercial FO membrane exhibiting high osmotic pressure, low reverse solute permeation, and remarkable rejection of feed solute.

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