Performance Of Novel Draw Solutions In Brackish Water Desalination Using Forward Osmosis

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The main goal of the present study is to examine the performance of novel draw solutions to extract high-quality water from simulated brackish water. Three different types of draw solutions namely L-ascorbic acid, L-aspartic acid, and thiourea. The current draw solutions' performance was measured in terms of average water flux (LMH) and average reverse solute flux (g/m^2h). The impact of several parameters on FO desalination performance, such as draw solution type, feed water concentration, draw solution concentration, and membrane orientation mode, was investigated. Ascorbic acid (vitamin C) was shown to have better FO performance in terms of high water flow up to 7.5 LMH and negligible reverse solute flux among the various types of draw solutions studied. The suggested FO technique can extract clean water to dilute the vitamin C draw solution up to the daily vitamin C in drinking water dose limit. Immune system deficits, cardiovascular illness, maternal health difficulties, eye disease, and even skin wrinkling may be protected by the supplemented vitamin C drinking water created. Some specialists recently recommended taking 200 mg of vitamin C daily for COVID-19 prophylaxis or 1-2 grams for COVID-19 treatment, according to some experts.

Keywords: Forward osmosis; Desalination; Brackish water; Draw solutions; Membrane technology

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1. Introduction

The world's population is quickly growing and concerns like freshwater, food, and energy are having a major influence on global economies. As one of three factors in the energy-water-food nexus, clean water shortage has long been a major problem for many communities. Today, over two billion people lack access to safe and clean water [1]. Egypt presently has a water shortage of around 13.5 billion m3/y, which is likely to grow in the coming years [2]. Desalination and water reuse are gaining popularity as solutions to this problem and to fulfill the rising demand for clean water. Reverse osmosis (RO) and thermal processes are two of the current desalination technologies. Around the world, there are over 18,000 desalination plants in operation, with a total output capacity of 38 billion m^3/year, which is anticipated to rise by 2030 [3]. On the other hand, conventional desalination methods are believed to be energy-intensive, with energy consumption accounting for 50-60% of overall water production costs [3]. Forward osmosis (FO), a relatively new membrane-based desalination method, utilizes a highly concentrated draw solution (DS) to pull water from a feed solution (FS) via a semi-permeable membrane [4]. Forward osmosis (FO) is an innovative membrane technology that recieved a lot of attention in the recent decade since it is a low-energy desalination method. The availability of efficient draw solutions

(DS), which must offer high osmosis pressure and minimal reverse solute flux, is one of the most critical difficulties facing FO. FO uses less energy, has a better antifouling capability, and recovers more water than RO [4]. DS is important to the FO process since it is the major source of net driving force across the membrane. High solubility, high osmotic pressure, low molecular weight (MW), low cost of regeneration, good membrane compatibility, minimal reverse solute flow, nontoxicity, and so on are all desirable characteristics of a perfect DS [4]. Traditional draw solutions based on inorganic salts like NaCl, $MgCl_2$, and NH_4HCO_3 can create a high water flow, but they also produce a large reserve flux of solute, compromising product quality and raising replenishment costs [5]. Furthermore, an efficient way for generating clean water from these draw solutions is lacking. To overcome the inherent drawbacks of inorganic solutes, several novel draw solutions have been developed recently, including synthetic organic solutes [6, 7], polyelectrolytes [8–11], magnetic nanoparticles [12], polymer hydrogels [13–16], switchable polarity solvents [17], and ionic liquids [18, 19]. The simplicity and effectiveness of any of these DS recovery and separation technologies will be critical elements in FO desalination for portable applications' future success. Thermal separation, membrane separation, chemical precipitation, and stimuli-responsive recovery (e.g. light, electricity, magnetic field, etc) [20] are some of the different draw solution recovery procedures. It is worth mentioning that despite the high potential that the FO process has, it has not yet been fully commercialized due to several challenges. one of these critical challenges is the high energy cost for the DS regeneration process as it has a great impact on the energy efficiency. Therefore, it is necessary to develop suitable DS to break through the bottleneck of FO's development toward the practical application. FO would have a substantial advantage over RO desalination technology if the diluted draw solution could be utilized directly without the requirement for DS separation and regeneration. These FO methods have recently been effectively utilized in arid regions for drinking [21], fertilization [22], irrigation, and soil prevention [23], where concentrated fertilizer solutions are used as DS, diluted, and then used for irrigation.

The major objective of this study is to assess the viability of using three different types of draw solutions namely L-ascorbic acid, L-aspartic acid, and thiourea.

To this end the major objective of this study is to assess the viability of using three different types of draw solutions namely L-ascorbic acid (vitamin C) and L - aspartic acid (an essential human body amino acid), and thiourea (plant growth improver). To the best of our knowledge no previous studies have examined vitamins as draw solution. It is attended in the present work that the diluted draw solution of both L-ascorbic acid (vitamin C), L - aspartic acid (an essential human body amino acid) would be used directly for drinking after dilution to the daily adult dosage of vitamin C and L-aspartic acid respectively. Whereas the diluted DS of thiourea would be used directly for irrigation.

The drinking water fortified with vitamin C would improve in general the immunity system of human body. Since vitamin C is essential for the synthesis of collagen, a protein important in the formation of connective tissue and in wound healing. It acts as an antioxidant, protecting against damage by reactive molecules called free radicals. The vitamin also helps in stimulating the immune system.

L - aspartic acid fortified drinking water would help fight against chronic fatigue and helps with improving metabolization, removing toxins, increasing building muscle mass. So far L - aspartic acid fortified drinking water is recommended for the athletes to provide them with essential amino acids. The performance of the suggested DS will be expressed in terms of water flux (LMH). The effect of different parameters will be examined such as the initial concentration of feed solution, initial concentration of the draw solution, and the membrane orientation.

2. Materials and methods

2.1. Materials

Table 1 lists the chemical and reagent specifications used in this study. The experiments were carried out using the FO lab unit depicted in Fig. 1. The FO lab unit consists mainly of a flow system and a membrane unit. The flow system includes two storage tanks, two liquid flow meters (Z-3000, China), in addition to two 1.25 LPM diaphragm pumps (DBP0202, Taiwan). One pump discharges the feed solution, while the other discharges the draw solution. A silicon piping system is connecting between the various parts of the flow system. A flat sheet of polyamide membrane (catalog no. TFC- 75F) provided by (Aqua Filter, USA) divides the membrane unit into two identical channels of dimensions $10 \times 8 \times 0.6$ cm^3. One channel is feed solution whereas the other is draw solution.

2.2. FO unit Performance Evaluations

In a one-liter measuring flask, different types of draw solutions of 1 M concentration were created by dissolving sufficient weight in distilled water. Whereas in the case of preparation of 1 M of Sodium L-aspartate, 133 g of L-aspartic acid was dissolved in a 2 M NaOH solution. Distilled water and simulated brackish water with different salinities were used as feed solutions. The two storage

Table 1. Specifications of the chemicals and reagents used in the present work.

Chemical	Formula	Supplier	Purity
Ascorbic Acid	$C_3H_8O_6$	Alpha ChemicKa	99.8%
Sodium chloride	NaCl	ElNasr Chemicals	99.5%
L-Aspartic acid	$C_4H_7NO_4$	Caisson Labs	USP Grade
Sodium hydroxide	NaOH	AlAhram Chemicals	98%
Buffer solutions		Fisher Chemicals	pH = 10

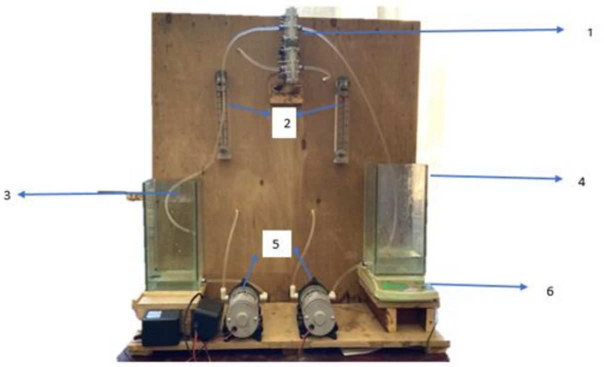

Fig. 1. FO lab unit set up 1) A membrane cell 2) Two flowmeters 3) Feed solution tank 4) Draw solution tank 5) Two Diaphragm pumps 6) Digital balance.

tanks were filled with half liters of feed and draw solutions, respectively, before each cycle. Both feed and draw solutions were circulated through the membrane unit in a co-current pattern at a constant flow rate of 1.25 LPM. All runs were conducted at a constant temperature of 25±2 ºC. The increase of the weight in DS was recorded using a digital balance (SF-400A, China) within intervals of 10 minutes during the run. The following equation was used to compute the water flux at any given time.

$$J_w = \frac{V_t - V_i}{A \times t} \tag{1}$$

Where J_w is the water flux in LMH, V_t is the volume of draw solution at time t in a liter, V_i is the initial volume of the draw solution in liter, A is the active membrane area in m^2 and t is the time in h. The water flux was estimated by monitoring the rise in the feed solution's conductivity over time in studies where the feed solution was simulated brackish water. The conductivity of FS can be expressed in terms of concentration according to the following equation:

$$\lambda = B \times C_t \tag{2}$$

Where λ is the conductivity of the FS (mSm), B is the slope of the calibration curve and Ct is the concentration of FS (ppm).

Fig. 2 shows a plot of conductivity versus concentration of sodium chloride solutions from which the value of B was determined. The following equation can be used to calculate the volume of feed water at any given time.

$$V_t = \frac{C_i \times V_i}{C_t} \tag{3}$$

Where C_i is initial FS concentration, V_i is the initial volume of FS, C_t is FS concentration at a certain time t and V_t is the volume at the same time. At 25±2 °C, the viscosity and density of the present draw solutions were determined using an Ostwald viscometer and a density bottle [24].

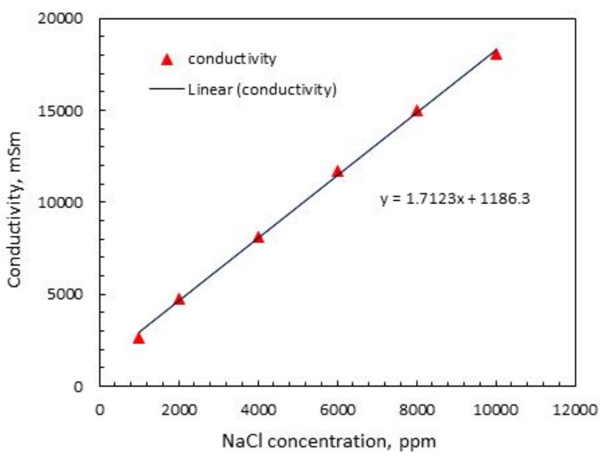

Fig. 2. Conductivity versus different standard NaCl concentrations.

3. Results and discussion

3.1. The performance of different types of draw solutions

Fig. 3 shows the water flux (LMH) of the present proposed draw solutions compared to water flux of 3.5% sodium chloride solution which is considered as a reference inorganic draw solution. It is obvious that the water flux of 1 M ascorbic acid is comparable with that of 3.5% sodium chloride solution, whereas the water flux of 1 M thiourea is about half that of 3.5% sodium chloride solution. The present results can be attributed to the difference of chemical structure of the suggested draw solution. Fig. 4 exhibits the chemical structure of the different type of draw solutions. The structure of ascorbic acid contains many hydroxyl groups, resulting in a high osmotic pressure when compared to other types of draw solutions. The water flux and reverse solute flux of several types of draw solutions are compared to current values in Table 2.

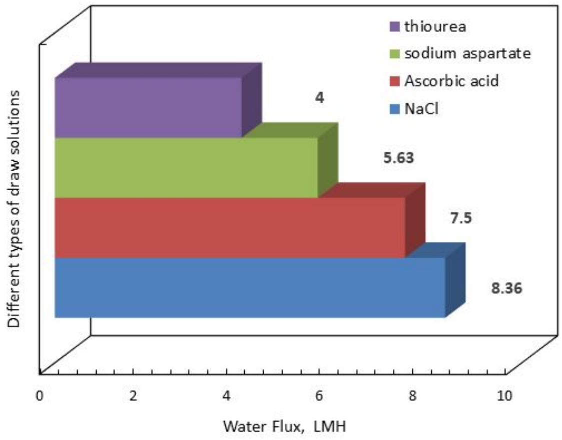

Fig. 3. Average water flux of various draw solutions (FS: distilled water, T = 25 ^{0}C, conc: 1M ascorbic acid, 1M sodium L-aspratate, 1M thiourea and 3.5% NaCl, FO mode).

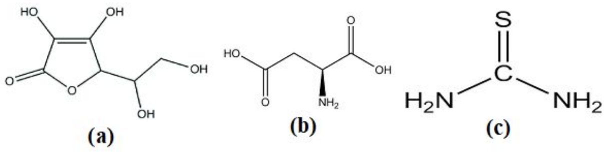

Fig. 4. The chemical structures of the present suggested draw solutions [(a) L-ascorbic acid; (b) L- aspartic acid; (c) Thiourea].

3.2. The influence of the concentration of the feed solution

At various initial feed concentrations, Fig. 5 depicts the average water flux of 1 M L-ascorbic acid and 1 M sodium L-aspartate. With increasing initial feed concentrations, the average water flux falls. The net osmotic pressure pushing force across the membrane diminishes as the initial feed concentration increases, and the average water flux falls as a result. It is obvious that water fluxes of ascorbic acid are higher than water fluxes of sodium L-aspartate at the same initial concentration.

The current trend can be described by explaining the draw solute's mass transfer resistance within the membrane porous support layer. Previous researches [30–35]

Table 2. The current and earlier investigated water flux, reverse solute flux, and regeneration approaches all draw solutions.

Draw Solution	Water Flux (J_w), LMH	Reverse Solute flux (J_s), gMH	Regeneration Method	Reference
NaCl	8.36	1.26	Present study	
L-Ascorbic acid (1M)	7.5	-	Direct use for drinking	Present study
Sodium L-Aspartate (1M)	5.63	-	Direct use for drinking	Present study
Thiourea (1M)	4	-	Direct use for Fertilization	Present study
EBs, GEBs and PEBs oligomers EBs, GEBs and PEBs oligomers	4.1-4.8 LMH at osmotic pressure of 28 bar	0.79-1.83 at osmotic pressure of 28 bar	At the same lower critical solution temperature	[25]
Highly dispersible sodium alginate sulfate coated- Fe_3O_4 nanoparticles (0.06 g/mL Fe_3O_4 @ SiO_2-SAS)	8.5 LMH	0.23	Magnetic field	[12]
5% Carbon Quantum Dots prepared by reflux method with 50% glycrol (TCQDs-G)	(a)10.6	0.03	-	[26]
Electro-responsive hydrogel made of 2-acrylamide-2 -methyl-1-propane sulphonic acid acrylamide with strong strong anionic comonomer P (AMPS-co-AM)	2.76 LMH	-	71% of adsorbed water can be recovered at 15 V in 40 minutes	[27]
Thermal-responding hydrogel produced in the presence of ionic polyglutamic acid (Ţ-PGA) and pore forming polyethylene glycol through polymerisation of N-isopropylacrylamide (NIPAM) (PEG)	1.99, 1.65, 1.31, 1.08.	-	At 35.2 °C	[13]
Ethanol	Very comparable to that of NH_4 HCO_3	Very high with TFC membrane.	8.8 kwh/m^3 by vacuum distillation.	[28]
Multi charged oxalic acid complexes	27.5 LMH	Negligible	Membrane distillation	[29]

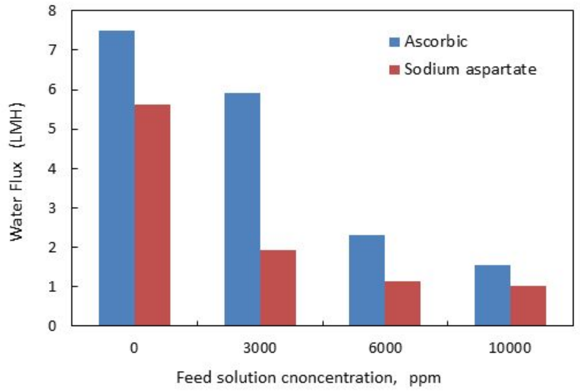

Fig. 5. Average water flux versus different feed solution concentrations (T= 25 ^{0}C, draw solution conc. 1M ascorbic acid, 1M sodium- aspartate, FO mode).

has used the K parameter to express the mass transfer resistance within the porous layer, which is defined as:

$$K = \frac{s}{D} \tag{4}$$

Where S stands for the membrane type-dependent structural parameter and D stands for the diffusion coefficient. D improves water flux by lowering mass transfer resistance. The measured viscosities of 1M L-ascorbic acid and 1M sodium-aspartate are 0.79 and 1.83 cP, respectively. As the viscosity increases the diffusion coefficient decreases at a constant temperature according to the Stokes-Einstein equation [36–39]:

$$\frac{D\mu}{T} = constant \tag{5}$$

It can be concluded that the diffusion coefficient of sodium L-aspartate is much lower than ascorbic acid which results in a high mass transfer resistance and high impact of internal concentration polarization and lower water flux. The net driving osmotic pressure force diminishes as the impact of ICP grows, and water flux decreases. The impact of dilutive internal concentration polarization (ICP) on the net driving osmotic pressure force is seen in Fig. 6.

3.3. The influence of draw solution concentration

The average water flux at various initial ascorbic acid draw solution concentrations is shown in Fig. 7. The average water flux decreases as the initial concentration of ascorbic acid rises, which is amazing. The presence of contact forces between the ascorbic acid molecules may explain why water flow decreases as draw solution concentration rises. This interaction force has the potential to reduce the osmotic pressure of the draw solution. Moreover, as the initial concentration of the DS increases its viscosity

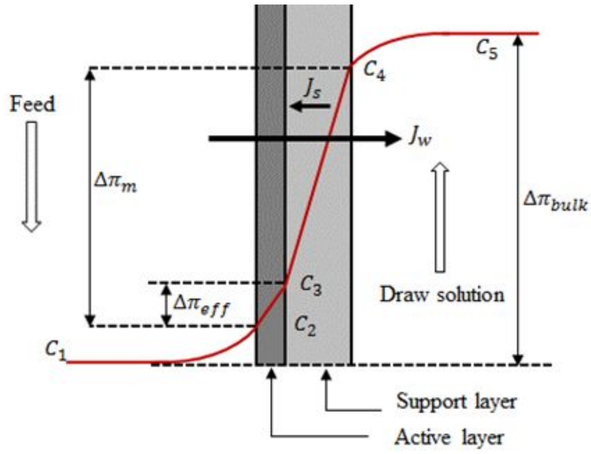

Fig. 6. The impact of dilutive ICP on the driving osmotic pressure force in FO mode.

increases as well. That increase in viscosity results in a decrease in ascorbic acid diffusivity. The lower the diffusivity, the greater the impact of the ICP and the greater the decrease in net osmotic pressure driving force. It has been reported that [40] at low DS concentrations, the dilutive internal concentration polarization (ICP) in FO mode was relatively minor, however, its impact was significant at high draw solution concentration and effective osmotic gradient dropped significantly.

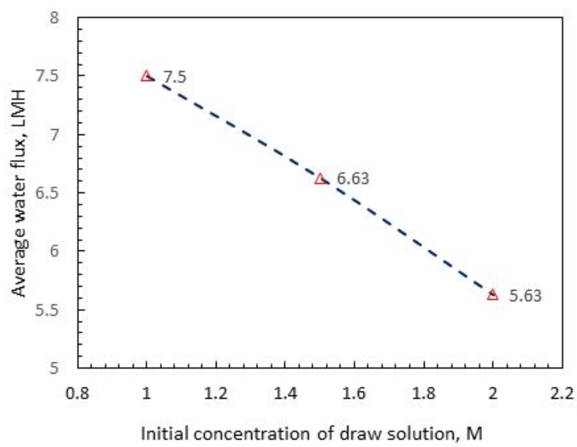

Fig. 7. Average water flux versus different initial draw solution concentrations (T= 25 ^{0}C, feed solution: distilled water, draw solution: ascorbic acid, FO mode).

3.4. The influence of membrane orientation

In both FO (active layer of the feed solution) and PRO (active layer facing the draw solution) modes, membranes were examined Fig. 8 shows a comparison between average water flux against distilled water feed solution at different membrane orientations, namely FO and PRO. It is well noted that the water flux obtained in FO mode is higher than that obtained in PRO mode. The current trend contradicts previous research [23–33]. The present behavior may be attributed to the interaction between the ascorbic acid molecules with the active polyamide membrane layer. That interaction could interfere with water permeation across the membrane and results in water flux reduction.

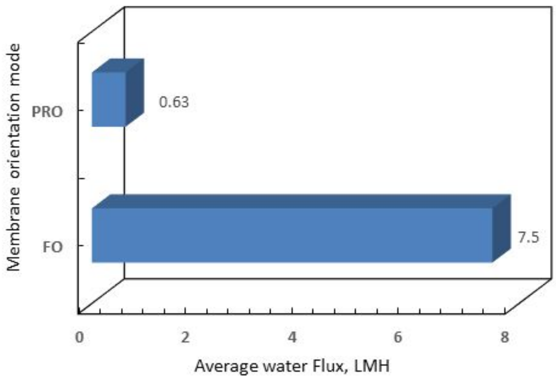

Fig. 8. Average water flux at different membrane orientation mode (T= 25 ^{0}C, feed solution: distilled water, draw solution: 1 M ascorbic acid).

4. Potential future applications

From the previous results and discussions, it can be concluded that Ascorbic acid or Vitamin C is a viable draw solution in FO desalination. The proposed draw solution is highly water-soluble, has high osmotic pressure, and has a large water flux with a low reverse solute flux. Vitamin C is also one of the safest and most effective supplements available to humans. Immune system inadequacies, cardiovascular illness, maternal health difficulties, eye disease, and even skin wrinkling may be protected by vitamin C [41]. The use of Vitamin C as a draw solution in the FO process has the potential to treat the feed stream's surface or brackish seawater. The diluted draw solution in this case is vitamin C enriched drinking water for long and healthy life.

Given that the water flux of brackish water FO is a strong function of its osmotic pressure, calculating the osmotic pressure of all dissolved salts is necessary before we can assess how well an actual brackish water feed solution performs. The same water flux should result if the overall osmotic pressure is similar to synthetic brackish water with, for example, 4000 ppm NaCl, assuming that the brackish water has no tendency to foul. Pretreatment or the application of an antiscalant is necessary in such cases where brackish water has a tendency to foul.

5. Conclusions

Different types of draw solutions were used in the FO process in this study. The impact of operational conditions on FO performance was looked into. Ascorbic acid, or vitamin C, was shown to be a promising draw solution for brackish water desalination. The intrinsic benefit of employing vitamin C as a draw solution is that it eliminates the requirement for recuperation because the diluted draw solution may be used as vitamin C enriched drinking water right away. It has been discovered that as feed and draw solution concentrations rise, water flux decreases. In addition, the FO mode has a larger water flux than the PRO mode. Although further research is needed before vitamin C can be used in the industry, this study has shown that it can be used to desalinate brackish water using the FO method.

Conflict of interest

None of the authors of the manuscript has declared any conflict of interest.

Nomenclature

Acronyms

λ	The conductivity of the FS
A	Active membrane area
B	Constant
C_i	Initial FS concentration
D	Diffusion coefficient
K	Solute resistance to diffusion in the support layer
S	Structure parameter of the membrane
T	Temperature
t	Time
V_i	Initial volume
V_t	Volume at time

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