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## Exploring an innovative surfactant and phosphate-based draw solution for forward osmosis desalination



Hau Thi Nguyen<sup>a</sup>, Shiao-Shing Chen<sup>a,\*</sup>, Nguyen Cong Nguyen<sup>a</sup>, Huu Hao Ngo<sup>b</sup>,  
Wenshan Guo<sup>b</sup>, Chi-Wang Li<sup>c</sup>

<sup>a</sup> Institute of Environmental Engineering and Management, National Taipei University of Technology, No.1, Section 3, Chung-Hsiao E. Rd, Taipei 106, Taiwan, ROC

<sup>b</sup> Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology, Sydney, Broadway, NSW 2007, Australia

<sup>c</sup> Department of Water Resources and Environmental Engineering, TamKang University, 151 Yingzhuan Road, Tamsui District, New Taipei City 25137, Taiwan, ROC

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## ABSTRACT

The reverse salt flux phenomenon of forward osmosis affects the quality of the feed water, reduces water flux, and increases the cost for replenishing lost draw solute. In this study, a novel draw solution comprising a mixture of Triton X100 and  $\text{Na}_3\text{PO}_4$  for minimizing the reverse salt flux during forward osmosis (FO) was explored. The results indicated that the reverse salt flux caused by coupling 0.5 mM Triton X100 to 0.55 M  $\text{Na}_3\text{PO}_4$  draw solution was only 0.13 g/m<sup>2</sup> h, and the specific reverse salt flux was 0.03 g/L using DI water as the feed solution, which are the lowest recorded values among all forward osmosis studies. Hydrophobic attractive interactions between tail groups of Triton X100 with the FO membrane are believed to be the main mechanism for minimizing salt leakage. Results from desalination experiments demonstrated that using 0.55 M  $\text{Na}_3\text{PO}_4$  coupled with 0.5 mM Triton X100 as the draw solution and brackish water and seawater as the feed solution with total dissolved solids of 4090 and 36,800 ppm achieved water fluxes of 4.89 L/m<sup>2</sup> h and 1.15 L/m<sup>2</sup> h, respectively. Furthermore, using a two-stage ultrafiltration–nanofiltration system for the draw solution recovery enabled 98% recovery of solutes.

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### 1. Introduction

The increase in the world population accompanied by an increase in agricultural and industrial activities [1], has caused water scarcity to become a concern. Researchers have conducted numerous studies related to desalination of brackish water and seawater to produce potable water. Among the proposed desalination methods, such as thermal desalination, crystallization, ion exchange, and solvent extraction, reverse osmosis (RO) is one of the most promising potential types of technology for seawater desalination [2]. However, several drawbacks are associated with RO, including (1) high energy requirement; (2) low recovery rate; and (3) environmental impact caused by brine discharge [3–6]. To overcome these limitations, researchers in the scientific community must create a more effective desalination technology. Forward osmosis (FO) is a form of technology that has been developed in recent years. It can potentially be applied to seawater desalination

[7–10], the food industry [11,12], power generation [13–15], osmotic membrane bioreactors [16–18] and sludge dewatering [19–21].

FO uses natural osmosis as a driving force for separation, and therefore is expected to (1) possess low energy requirements for operation; (2) exhibit less fouling than pressure-driven membrane processes; and (3) achieve a high potential recovery rate. McGinnis et al. [22] demonstrated that energy savings of FO compared to current technologies for seawater desalination on an equivalent work basis are projected to range from 72% to 85%. Altaee et al. [23] found the recovery step in an FO–RO desalination system to use 96–98% of the total power consumption. However, the major challenge of creating marketable FO technology is the lack of an ideal draw solution that can achieve high water flux, low reverse salt flux, and coefficient recovery. Particularly, reverse diffusion of salt from the draw solution to the feed side not only affects the quality of the feed water, but causes water flux decline and increases the cost of replenishing the lost draw solute [24].

Numerous types of draw solutions for FO desalination have been explored in previous studies. For example, monovalent salts (NaCl, KCl, KBr, KNO<sub>3</sub>, NH<sub>4</sub>Cl, KHCO<sub>3</sub>, NaHCO<sub>3</sub>, NH<sub>4</sub>HCO<sub>3</sub>) with

\* Corresponding author. Tel.: +886 2 27712171 4142; fax: +886 2 27214142.  
E-mail address: [f10919@ntut.edu.tw](mailto:f10919@ntut.edu.tw) (S.-S. Chen).

favorable water solubility are frequently used, but the greatest disadvantage of using these salts as a draw solution for FO is the extremely high salt leakage (reverse salt flux reached 29.2 g/m<sup>2</sup> h when using 0.88 M KBr as a draw solution) [25–27]. To overcome this problem, divalent (CaSO<sub>4</sub>, MgSO<sub>4</sub>, CuSO<sub>4</sub>, MgCl<sub>2</sub>, CaCl<sub>2</sub>) and trivalent salts (Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, EDTA–2Na) were proposed as draw solutions [26,28–30]. Compared with monovalent salts, the reverse salt fluxes of divalent and trivalent salts were lower because of the larger hydrated radius and higher electrostatic repulsion. However, the reverse salts still reached 0.9 g/m<sup>2</sup> h for 0.62 M MgSO<sub>4</sub>, 9.5 g/m<sup>2</sup> h for 0.56 M CaCl<sub>2</sub>, 5.6 g/m<sup>2</sup> h for 0.50 M MgCl<sub>2</sub>, and 0.32 g/m<sup>2</sup> h for 0.50 M EDTA–2Na. Additionally, Warne and Chung were the first to successfully synthesize magnetic nanoparticles (MNPs) for use as innovative draw solutes for FO. This concept provided the ideal draw solution without salt leakage, but an agglomeration problem was observed for magnetic nanoparticles during the regeneration stage [31–34]. Recently, zwitterions, hexavalent phosphazene, switchable polarity solvents, 2-methylimidazole-based organic compounds, and ferric and cobaltous hydroacid complexes have also been investigated as potential draw solutes for FO [35–39]. Although these draw solutes created high osmotic pressure, synthesis of the solutes was costly and recovery of the diluted draw solution was complex.

In this study, a novel draw solution for minimizing the reverse flux of ions during FO desalination by coupling nonionic surfactant (Polyethyleneglycol tert-octylphenyl ether, Triton X100) to a Na<sub>3</sub>PO<sub>4</sub> draw solution was explored. It is hypothesized that the hydrophobic interactions between tail groups of Triton X100 with membrane would form an additional layer on the membrane surface, preventing ions from escaping through membrane pores, thus reducing reverse salt flux. The reasons of using Triton X100 instead of other non-ionic surfactants are due to lower critical micelle concentrations (CMC) of 0.4 mM but larger molecule of Triton X100. Moreover, above the CMC, Triton X100 solution aggregates to form micelles that can couple with the trivalent phosphate to enlarge the molecular size of the draw solute, resulting in enhanced draw solute recovery using a two-stage ultrafiltration–nanofiltration (UF–NF) system. In addition, as compared with RO, UF–NF has been considered as a more energy efficient draw regeneration process using highly charged salts as draw solutions [26,40]. Therefore, the objectives of this study were to systematically investigate the effects of coupling Triton X100 to a Na<sub>3</sub>PO<sub>4</sub> draw solution on reverse salt flux and water flux for FO following: (1) effects of various concentrations of Triton X100; (2) effects of various concentrations of Na<sub>3</sub>PO<sub>4</sub>; (3) evaluation of desalination efficiency of the proposed draw solution and (4) recovery of the diluted draw solution.

**Table 1**  
Characteristics of ultrafiltration and nanofiltration membranes.

Membrane name	Manufacture	Material	Molecular weight cut-off (MWCO)	25 °C pH range
UF-GE	GE osmonics	TF (Thin Film)	1000	1–11
NF-TS80	TriSep	Polyamide	150	2–11

**Table 2**  
Synthetic brackish water and seawater as feed solutions at various TDS concentrations.

Feed solution	Brackish water 1 (BW1)	Brackish water 2 (BW2)	Brackish water 3 (BW3)	Brackish water 4 (BW4)	Brackish water 5 (BW5)	Seawater
TDS, ppm	4090	5020	6450	12,270	22,900	36,800
Osmotic pressure, bar	2.43	3.10	4.06	7.85	15.34	26.61

## 2. Materials and methods

### 2.1. FO membranes

The flat-sheet cellulose triacetate (CTA) FO membranes used in this study were supplied by Hydration Technology Innovations (HTIs OsMem™ CTA Membrane 130806, Albany, OR, USA) with size of 15 × 22 cm<sup>2</sup> for each piece. The FO membrane possessed a water permeation coefficient of 3.07 × 10<sup>−12</sup> m s<sup>−1</sup> Pa<sup>−1</sup> and salt rejection of approximately 95–99% [8,40]. The overall thickness of the membrane was approximately 50 μm, and the FO membrane was negatively charged at pH > 4.5 [41]. The contact angle of the CTA FO membrane was determined to be 60–80°, indicating that the membrane was also moderately hydrophobic [42,43]. Table 1 shows the characteristics of the UF and NF membranes used for draw solution recovery.

### 2.2. Feed solution and draw solution

In FO experiments, deionized (DI) water, synthetic brackish water, and seawater were used as feed solutions. The synthetic brackish water and seawater were prepared with total dissolved solid (TDS) from 4900 to 36,800 ppm by adding NaCl salt to DI water as shown in Table 2. The draw solution was prepared using laboratory-grade Na<sub>3</sub>PO<sub>4</sub> · 12H<sub>2</sub>O (Merck Co., Ltd., Germany) mixed with Triton X100 (Sigma-Aldrich, USA) as shown in Table 3 at mole ratios of 1000:1, 500:1, 200:1, 100:1, and 20:1 at room temperature for 60 min. These mixtures of phosphate sodium and Triton X100 were then maintained at pH 8 by adding phosphoric acid (H<sub>3</sub>PO<sub>4</sub>, Merck, 85% purity) and were continually stirred for 24 h before performing FO tests.

### 2.3. Experimental setup and product water recovery

FO experiments were conducted using a dual-channel cross-flow FO membrane cell, as shown in Fig. 1. The FO test cell (FO Sterlitech, USA) was designed with symmetric channels on both sides for the feed and draw solutions, and each channel was 4.5 cm in width, 9.2 cm in length, and 0.2 cm in height. The total effective FO membrane area for mass transfer was 41.40 cm<sup>2</sup>. Two peristaltic pumps (Masterflex L S Drive, Model 7518–00) with a flow rate of 500 mL/min were used to circulate the feed and draw solutions on both sides of the FO membrane. The temperature during experiments was maintained at 25 ± 0.5 °C using two water baths. Conductivity and pH sensors were installed in the containers for the feed solution and the draw solution to monitor any changes. The volume of the draw solution was 4 L; the feed solution tank (2 L) was placed on a digital weighing scale (BW12KH, Shimadzu, Japan) connected to a computer data logging system to monitor the weight and volume changes at specified time intervals. All data were obtained from three repeated tests. The experimental water flux ( $J_w$ , L/m<sup>2</sup> h) was calculated by measuring the volume change in the feed container based on time as follows:

$$J_w = \frac{\Delta V}{A \Delta t} \quad (1)$$

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