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Fouling control in a forward osmosis process integrating seawater desalination and wastewater reclamation

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ABSTRACT

A hybrid system that combines forward osmosis with a reverse osmosis seawater desalination process could reduce both energy requirements and environmental impacts by osmotic dilution of the seawater and concentrated brine with an impaired low salinity stream, such as treated wastewater effluent. In this study, we investigate the membrane fouling behavior in forward osmosis under conditions simulating the osmotic dilution process and the use of hydrodynamic methods without the use of cleaning chemicals, to control membrane fouling. Fouling runs with seawater or SWRO brine draw solution and deionized (DI) water feed solution showed insignificant water flux decline, which implies negligible effect of particulate and organic matter in the seawater/brine on fouling of the FO membrane support layer. Fouling of the membrane active layer was evaluated by using an enriched synthetic wastewater effluent containing a mixture of inorganic and organic foulants, focusing on the impact of permeate drag force on fouling layer formation. Our results demonstrate that higher permeate water flux causes an increase in concentration build-up of foulants at the membrane surface, thereby forming a dense inorganic/organic combined fouling layer during FO fouling runs. We also examined three hydrodynamic methods for minimizing FO membrane fouling in the osmotic dilution process: (1) applying shear force on the membrane surface by increasing the cross-flow velocity, (2) using a feed-channel spacer to induce turbulence, and (3) employing pulsed flow to remove foulants from the membrane surface. Our results show that these hydrodynamic methods substantially reduce fouling and flux decline rate.

1. Introduction

Forward osmosis (FO), a recently resurgent membrane process, utilizes a draw solution that can generate high osmotic pressure as a driving force for separation [1–3]. FO has the potential to be integrated with conventional pressure-driven membrane processes to improve performance or to be a sustainable alternative to several conventional membrane-based separation processes [4–6]. However, one critical drawback that hampers its practical application is the lack of an ideal draw solution [7]. Although several attempts have been made to develop an ideal draw solution [8–11], draw solutions that are able to create high osmotic pressure and can be easily recovered and regenerated with low energy and cost have not yet been successfully identified [12].

However, FO does not always require draw solution regeneration [13]. In the "osmotic dilution" process proposed for integrating seawater desalination and wastewater reclamation, either seawater or brine from a seawater reverse osmosis (RO) desalination plant is utilized as a draw solution [14]. The seawater and/or brine are diluted with an impaired water source (e.g., treated wastewater effluent) and sent to the desalination RO stage or discharged to the ocean, respectively. Dilution of seawater reduces the required hydraulic pressure in the RO stage and hence, the energy demand for desalination, while dilution of brine lessens adverse impacts of desalination plants on marine environments [13,14]. Therefore, successful application of osmotic dilution processes could significantly improve the efficiency and sustainability of existing desalination and wastewater treatment processes [15].

For successful application of osmotic dilution, several important aspects of the process should be evaluated. One critical issue that demands considerable research efforts is FO membrane fouling [16–25]. Membrane fouling will require pretreatment of source water and membrane chemical cleaning, which incur additional cost and increase energy consumption [26]. Understanding the fouling behavior in the osmotic dilution process is particularly important because both sides of the FO membrane are in constant contact with impaired waters: the active layer with wastewater effluent and the support layer with seawater or brine. Therefore, there is a critical need for a systematic understanding of membrane fouling behavior and for the development of strategies for fouling mitigation.

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The objectives of this study are to better understand the fouling behavior of FO membranes in the osmotic dilution process and to evaluate the effectiveness of hydrodynamic control strategies to mitigate fouling. The fouling behavior of the FO membrane support and active layers was independently evaluated and the factors determining the extent of fouling and subsequent flux decline were investigated. Lastly, hydrodynamic conditions to lessen fouling potential are proposed and their effect on fouling mitigation is evaluated. Our results show that membrane fouling in the osmotic dilution process can be mitigated by employing relatively simple control strategies that involve hydrodynamic mixing.

2. Materials and methods

2.1. Organic foulants

Dissolved organic matter in secondary wastewater effluent, commonly known as effluent organic matter (EfOM), can contribute to membrane fouling in the osmotic dilution process. EfOM mainly comprises polysaccharides, proteins, and natural organic matter (NOM) [27]. The model organic foulants chosen to represent polysaccharides, proteins, and NOM in wastewater EfOM were sodium alginate (Sigma-Aldrich, St. Louis, MO), bovine serum albumin (BSA) (Sigma-Aldrich, St. Louis, MO), and Suwannee River natural organic matter (SRNOM) (International Humic Substance Society, St. Paul, MN), respectively. Sodium alginate, BSA, and SRNOM were received in a powder form, and stock solutions (2 g/L) were prepared by dissolving each of the foulants in DI water. Mixing of the stock solution was performed for over 24 h to ensure complete dissolution of the foulants, followed by filtration with a 0.45-μm filter (Millipore, Billerica, CA). The filtered stock solutions were stored in sterilized glass bottles at 4 °C.

2.2. Synthetic wastewater

An enriched synthetic wastewater media was used for the accelerated fouling tests. The chemical composition of the synthetic wastewater was based on secondary effluent quality from selected wastewater treatment plants in California as summarized in Table 1 [28]. In order to accelerate fouling, the chemical composition shown in Table 1 was concentrated 3-fold. Specifically, to prepare an enriched synthetic wastewater, DI water was supplemented with 3.48 mM $Na_3C_6H_5O_7$, 2.82 mM NH_4Cl, 1.35 mM KH_2PO_4, 1.5 mM $CaCl_2 \cdot 2H_2O$, 1.5 mM $NaHCO_3$, 6.0 mM NaCl, and 1.8 mM $MgSO_4 \cdot 7H_2O$. The synthetic wastewater was supplemented with a mixture of the model organic foulants: alginate (75 mg/L), SRNOM (75 mg/L), and BSA (75 mg/L). The final pH was 7.2 and the calculated total ionic strength was 44.25 mM. All chemicals were ACS grade (Fisher Scientific, Pittsburgh, PA).

2.3. Characteristics of raw seawater and SWRO brine

Raw seawater and SWRO brine were collected from a SWRO pilot plant located in Gijang, Busan, Korea. Raw seawater was sampled from the intake line before the pretreatment stage, and brine was sampled from the bypass line after the RO membrane stage. The SWRO pilot plant was operating at 35% recovery when the samples were collected. Conductivity and TDS of sampled water were determined using a conductivity meter (Model 30, YSI Incorporated, Yellow Springs, OH). A total organic carbon (TOC) analyzer (TOC-V, Shimadzu Corp., Japan) was used to analyze the organic concentration in raw seawater and brine. Raw seawater filtered through a 0.45-μm filter was also prepared to verify the effect of particulate matter on fouling of the FO membrane support layer. The biological activity of the collected seawater and brine was minimized by storing the sample at 4 °C. Key properties of seawater and brine are shown in Table 2.

2.4. FO membrane

The FO membrane used in this study was provided by Hydration Technologies Innovation (Albany, OR). According to the manufacturer, the membrane consists of a dense asymmetric cellulose-based polymer layer with an embedded polyester mesh for mechanical support. The membrane samples were received as large flat sheets where glycerin was used to prevent the membrane from drying out. The membrane samples were rinsed with

Table 2
Characteristics of raw seawater and RO brine.

Type	pH	Conductivity (mS)	Turbidity (NTU)	TDS (g/L)	TOC (mg/L)
Raw seawater (not filtered)	8.24	44.25	2.50	32.2	2.09
Raw seawater (0.45-μm filter)	8.10	42.73	0.36	32.2	2.04
Brine	7.93	70.7	0.23	47.5	2.99

Table 1
Chemical composition of the enriched synthetic wastewater solution used for fouling tests. The ionic composition indicated in the table was concentrated 3-fold to induce accelerated fouling conditions.

	Constituent	Molecular weight (g/mol)	Concentration (mM)
Ionic composition	Sodium citrate	294.09	1.16
	Ammonium chloride	53.49	0.94
	Potassium phosphate	136.09	0.45
	Calcium chloride	147.01	0.5
	Sodium bicarbonate	84.01	0.5
	Sodium chloride	58.44	2.0
	Magnesium sulfate	246.47	0.6
	Constituent	**Molecular weight (kDa)**	**Concentration (mg/L)**
Organic matter	Alginate	12–80[a]	75
	SRNOM	1–5[b]	75
	BSA	60–70[c]	75

[a] Lee and Elimelech [45].
[b] Lee et al. [46].
[c] Ang and Elimelech [47].