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Organic fouling characterization of a CTA-based spiral-wound forward osmosis (SWFO) membrane used in wastewater reuse and seawater desalination

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ABSTRACT

This research explores initial organic membrane fouling of element-scale spiral-wound forward osmosis (SWFO) operated at a wastewater plant using real secondary wastewater effluent (SWWE) as feed solution (FS) and synthetic seawater as draw solution (DS). The SWFO was operated long-term and the average water flux reduced from 6.0 to 3.2 L/m^2·h. After the operation, membrane samples were taken from three locations in the SWFO element (i.e., inlet, middle, and outlet) to study the structural effects of organic membrane fouling. The membrane foulants were extracted in sodium hydroxide and deionized water to characterize irreversible and reversible organic foulants, respectively. Organic matter (OM) contained in the FS was dominated by hydrophilic (HPI) aromatic proteins (molecular weights (MWs) of 30,000 Da) and soluble microbial byproducts (which are associated with humic substances and have MWs of 920–2000 Da). The highest organic content (2.67 mg-C/cm^2) was found in the inlet of the SWFO element and, interestingly, was mostly irreversible. In the inlet, humic- or fulvic-like organics and aromatic proteins were dominant, while higher protein-like organics were detected in the middle and the outlet of the element. The organic fouling behavior of the SWFO membrane can be explained as follows: HPI OM formed the initial, irreversible fouling on the membrane surface, after which the hydrophobic (HPO) OM, which is reversible, attached to the initially formed HPI fouling layer by electric interaction dominantly. Therefore, HPI organic foulants should be controlled to reduce irreversible fouling and subsequently guarantee the sustainable operation of SWFO in the SWWE treatment.

1. Introduction

Substantial effort has been expended in the exploration of advanced water treatment methods with better efficiency and reduced environmental impact [1–3]. Membrane processes such as ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) have been widely applied for water treatment, desalination, and water reuse due to their compactness, high contaminant removal efficiency, and relatively short treatment time compared to conventional water treatment processes such as sand filtration or reservoir sedimentation. However, membrane processes require high-pressure conditions and are plagued by membrane fouling [4–7]. Various integrated membrane processes (IMPs) have been suggested to address these problems, including the forward osmosis/reverse osmosis (FO-RO) hybrid system. Currently, the FO process is considered to be one of the most promising candidates for low-pressure, low-energy, and low-cost desalination [2,8–10]. The FO-RO hybrid system can be used for both wastewater reuse and desalination. In this process, the seawater used as the draw solution (DS) is diluted and transported to the main RO process and the wastewater used as the feed solution (FS) for FO is concentrated. Therefore, the FO-RO hybrid system simultaneously and cost-effectively treats wastewater and produces fresh water while utilizing various water resources [1,11–15]. However, the FO-RO system is still being used at testing scales as information crucial to scaling up the system is lacking.

The FO process is not free of membrane fouling, especially when treating wastewater containing high organic and nutrient concentrations. Hence, numerous researchers have conducted FO membrane fouling studies at the laboratory scale using flat sheet membrane coupons [16–20]. In addition, many researches related to membrane fouling have been conducted and they focused on the characterization of fouling by monitoring its formation and investigating its rejection mechanism, ultimately to control the membrane fouling (Table 1).

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Nomenclature

SW	spiral wound
FO	forward osmosis
SWWE	secondary wastewater effluent
FS	feed solution
DS	draw solution
OM	organic matter
HPI	hydrophilic
HPO	hydrophobic
TPI	transphilic
MWs	molecular weight
UF	ultrafiltration
NF	nanofiltration
RO	reverse osmosis
MF	microfiltration
IMPs	integrated membrane process
FO-RO	forward osmosis/reverse osmosis
CTA	cellulose triacetate
BOD	biological oxygen demand
COD	chemical oxygen demand
SS	suspended solid
TN	total nitrogen
TP	total phosphate
TOC	total organic carbon
DOC	dissolved organic carbon
UV_{254}	ultraviolet absorbance at 254 nm
SUVA	specific UV absorbance (L/mg·m)
FEEM	fluorescence excitation-emission matrix
IC	ion chromatograph
FE-SEM	field emission scanning electron microscope
EDX	energy dispersive X-ray
FTIR	Fourier transform infrared
HPSEC	high performance size exclusion chromatography
Ex	excitation
Em	emission
ZP	zeta potential
BNR	biological nutrient removal
I_{max}	intensity max
Jw	water flux ($L/m^2{\cdot}h$, LMH)
Tba	tank bottom area (m^2)
H	height of the FS (m)
A	membrane area (m^2)
t	operating time (h)

Table 1
Recent research trend of membrane fouling studies.

Process types	Feed water types	Objectives	References
MBR processes	Wastewater effluents and model foulants	Investigation of membrane fouling phenomenon according to the pre-filtration methods and fouling control using mechanical cleaning	[25–27]
MF and UF processes	Model foulants (protein, humic acid, BSA)	Membrane fouling control using membrane surface modification and chemical agent	[28–31]
Ceramic membrane and NF processes	Textile dye bath wastewater, glycerol and secondary effluent	Characterization of membrane foulants and identifying molecular properties of foulants	[32–36]
RO and FO processes	Textile secondary effluent, domestic wastewater, coal seam gas and NOM	Fouling monitoring and modeling for investigate fouling mechanism and scaling control	[37–42]
Hybrid processes	Distillery wastewater, protein solution, municipal wastewater, seawater and ground water	Identification of membrane foulants and investigation of rejection mechanism of foulants	[15,27,39,43–46]

However, few studies have explored element-scale module systems, which is an essential first step in designing a large-scale system. Recent element-scale FO researches have focused on the evaluation of element performance under various operation conditions, and applied fertilizer as DS and wastewater collected from different wastewater treatment plants [4,12,21–24]. Data obtained from laboratory-scale tests are difficult to employ directly in pilot-plant design because the operating conditions and membrane configurations differ. In addition, element-scale or pilot-scale experiments using real feed water are necessary for investigating fouling phenomena in practice.

To this end, our research team previously compared a laboratory-scale flat-sheet FO membrane and a spiral-wound FO (SWFO) element

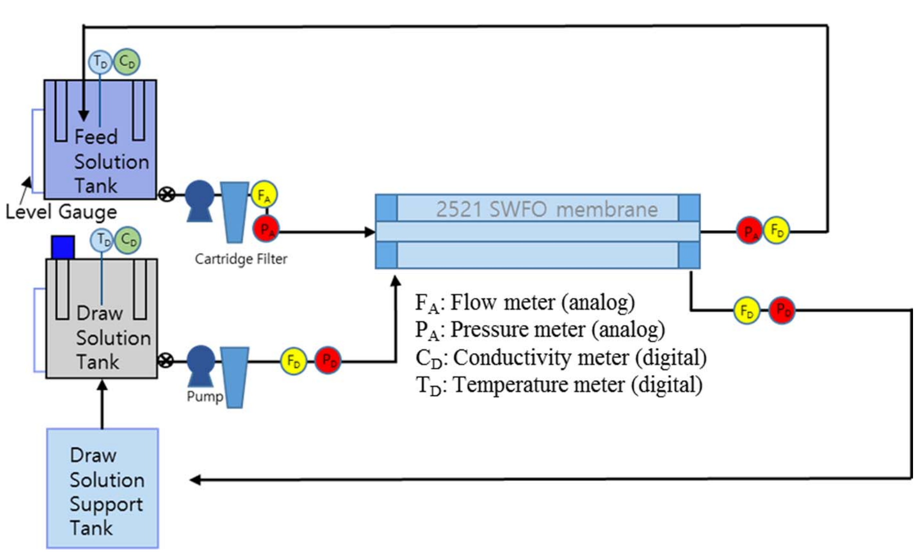

Fig. 1. A schematic diagram of the SWFO element test unit.