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Modeling full-scale osmotic membrane bioreactor systems with high sludge retention and low salt concentration factor for wastewater reclamation

Sung Hyuk Park [a], Beomseok Park [b], Ho Kyong Shon [c], Suhan Kim [b,*]

[a] Advanced Process and Materials R&BD Group, Korea Institute of Industrial Technology, 156 Gaetbeol-ro, Yeonsu-gu, Incheon, Republic of Korea
[b] Department of Civil Engineering, Pukyong National University, 45 Yongso-ro, Nam-gu, Busan 608-737, Republic of Korea
[c] School of Civil and Environmental Engineering, University of Technology, Sydney (UTS), Post Box 129, Broadway 2007, NSW, Australia

HIGHLIGHTS

- OMBR with sludge concentrator exhibits high retention and low concentration factor.
- The full-scale OMBR model simulates hollow-fiber and flat-sheet FO modules.
- The model helps to find optimal design parameters for OMBR–RO hybrid system.
- The appropriate water recovery ensures high flux and less adverse effect on microbes.
- FO cost decreases and RO cost increases at higher DS flow rates and concentrations.

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ABSTRACT

A full-scale model was developed to find optimal design parameters for osmotic membrane bioreactor (OMBR) and reverse osmosis (RO) hybrid system for wastewater reclamation. The model simulates salt accumulation, draw solution dilution and water flux in OMBR with sludge concentrator for high retention and low salt concentration factor. The full-scale OMBR simulation results reveal that flat-sheet module with spacers exhibits slightly higher flux than hollow-fiber; forward osmosis (FO) membrane with high water permeability, low salt permeability, and low resistance to salt diffusion shows high water flux; an optimal water recovery around 50% ensures high flux and no adverse effect on microbial activity; and FO membrane cost decreases and RO energy consumption and product water concentration increases at higher DS flow rates and concentrations. The simulated FO water flux and RO energy consumption ranges from 3.03 to 13.76 LMH and 0.35 to 1.39 kWh/m^3, respectively.

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1. Introduction

Membrane bioreactor (MBR) has several distinctive advantages over conventional activated sludge (CAS) processes: (1) complete solids removal without sludge bulking problem; (2) significant physical disinfection capability; (3) easiness for automation; (4) small footprints; and (5) less sludge discharge compared to CAS due to long solids (sludge) retention time (SRT) (Jang et al., 2006). Since being introduced by Achilli et al., 2009, osmotic membrane bioreactor (OMBR) has taken most advantages of MBR while it greatly enhances the pollutant selectivity by forward osmosis (FO) membranes (Lutchmiah et al., 2014; Qiu and Ting, 2014; Luo et al., 2015; Praveen et al., 2015). The excellent selectivity of FO membrane also brings accumulations of salts, nutrients, organic matters, and micropollutants in the bioreactor (Xiao et al., 2011; Lay et al., 2011; Johir et al., 2013; Qiu and Ting, 2013; Kim, 2014; Luo et al., 2015).

Salts are accumulated in OMBR because they are rejected by FO membrane and salts in draw solution (DS) diffuse to the bioreactor by the concentration difference between DS and feed, which is called reverse salt flux. The salt accumulation diversely affects water flux through FO membrane. The water flux decreases dramatically due to salt accumulation with long SRT (Lay et al., 2011; Xiao et al., 2011) and both DS dilution and salt accumulation in the full-scale OMBR induce a significant flux decline with a SRT of 5 days (Kim, 2014), which is because the salt concentration factor (CF) is proportional to SRT. However, OMBR as a biological

* Corresponding author. Tel.: +82 51 629 6065; fax: +82 51 629 6063.
E-mail address: suhankim@pknu.ac.kr (S. Kim).

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process needs a long SRT (*i.e.*, a high CF) for lower sludge production for disposal and the removal of slow-to-grade organic matters and persistent organic pollutants (Chen et al., 2012). Thus, this is an Achilles' hill of OMBR.

In addition, the salt accumulation diversely affects microbial bioactivity in the bioreactor. Evident deterioration of biological activity, especially nitrification, was observed due to significant accumulation of organic matters and NH_4^+-N and high salt-tolerant species become dominant in the bioreactor when a synthetic wastewater and $MgCl_2$ solution as DS were tested (Qiu and Ting, 2013). Fortunately, the microbial community adapted to the elevated salinity conditions and rapidly recovered the biological activity. When salt concentration was increased from 0 to 35 g/l NaCl in a lab-scale MBR system (Johir et al., 2013), the uptake rate of dissolved organic carbon (DOC) and ammonia (NH_4^+-N) decreased from 17.0 to 1.8 mg-DOC/g-MLVSS d and from 8.2 to 0 mg-NH_4^+-N/g-MLVSS d, respectively. Less significant drops in DOC and NH_4^+-N removals were observed when salt concentration was increased from 0 to 3.0 g/l NaCl in MBR. When the effect of salt accumulation on the fate of trace organic chemicals (TrOCs) were investigated (Luo et al., 2015), the removal of hydrophilic TrOCs by MBR decreased due to the salt accumulation and the removal of hydrophobic TrOCs was not significantly affected. In addition, the salinity stress enhanced the release of both soluble microbial products (SMP) and extracellular polymeric substances (EPS), leading to severe membrane fouling.

Recently, a brilliant idea to mitigate the salt accumulation in OMBR with long SRT was reported (Wang et al., 2014; Holloway et al., 2014). Microfiltration (MF) or ultrafiltration (UF) membranes were submerged in the bioreactor to reject suspended solids (*i.e.*, to increase SRT) and the soluble matters such as salts, nutrients, and organic matters can pass through the MF or UF membranes to decrease salinity build-up in the bioreactor. The addition of MF membrane in the OMBR could increase TOC and NH_3-N removals due to the activated sludge by improving the microbial activity (Wang et al., 2014). For more than 120 days of operation of the UF-OMBR hybrid system with SRT longer than 30 days (Holloway et al., 2014), the overall removal of chemical oxygen demand, total nitrogen, and total phosphorus were greater than 96%, 82%, and 99%, respectively and the water flux was maintained at much higher and more stable values than those in the conventional OMBR process.

Despite of the great advantages mentioned above, there would be two challenges associated with applying the MF/UF-OMBR hybrid system: (1) MF/UF effluent water quality may exceed the wastewater treatment plant (WWTP) effluent standards due to accumulated organic matters and nutrients in the bioreactor by FO membrane; and (2) the fouling mitigation approaches for MF/UF and FO membranes in the same bioreactor may be different. The first challenge may be solved by selecting an appropriate CF by controlling FO permeate flow rate. The CF should be limited to prevent the MF/UF effluent water quality from exceeding the WWTP effluent standards. The second challenge may be solved by adopting a separate sludge concentrator to return sludge to increase SRT without concentrating salts. The type of sludge concentrator could be sedimentation basin or backwashable filter (including MF/UF). The schematic diagrams of OMBR systems with submerged MF/UF membrane or sludge concentrator are provided in Fig. 1. The mass balance in these systems will be discussed in Section 2.1.

The OMBR system with submerged MF/UF membrane or sludge concentrator exhibits high sludge retention and low salt concentration factor, and it should be very useful for wastewater reclamation. In this system, wastewater feed is divided into two separate streams, WWTP effluent stream through MF/UF or sludge concentrator and product water stream through FO and RO membrane. The product water should have excellent quality because it has passed through double barriers and no need to worry about the RO concentrate disposal, which is one of critical issues in wastewater reclamation system using RO (Bagastyo et al., 2011; Sun et al., 2014).

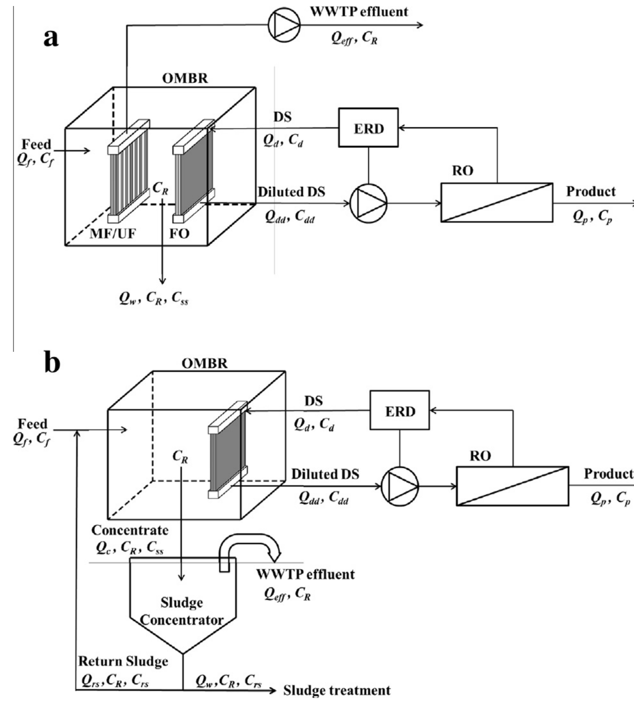

Fig. 1. Schematic diagrams of OMBR–RO hybrid systems for wastewater reclamation. (a) OMBR with submerged MF/UF and FO membranes in the bioreactor; (b) OMBR with a separate sludge concentrator.

The objective of this study is to introduce the methodology finding optimal design parameters (*e.g.*, FO membrane and module type, water recovery, DS flow rate, and DS concentration) of OMBR–RO hybrid system with high sludge retention and low salt concentration factor for wastewater reclamation. Fouling phenomenon and biological activities are not considered in this work. A full-scale OMBR model will be used to predict water flux and FO membrane area by simulating feed salt accumulation, DS dilution, and local variations in osmotic pressures in the DS channel. To the best knowledge of the authors, this is the first approach to systematically investigate the OMBR–RO wastewater reclamation system using a full-scale model and to find optimal design parameters. The full-scale OMBR model using hollow-fiber FO module was developed in a previous work (Kim, 2014) and it was modified to model flat-sheet FO module in full-scale OMBR in this study. The modified model was verified by lab-scale experimental data from literatures (Xiao et al., 2011; Wang et al., 2010; Tiraferri et al., 2011; Wang and Xu, 2015). RO system for DS recovery and water production was simulated by a commercial RO design program to predict RO energy consumption and product water quality. The strategies to select the design parameters for the OMBR–RO hybrid system to minimize FO membrane cost, RO energy consumptions, and product water concentration will be discussed using the full-scale OMBR and RO simulation results.

2. Methods

2.1. Conceptual design of full-scale OMBR–RO wastewater reclamation systems

The OMBR–RO hybrid system consists of OMBR as a biological and physical wastewater treatment and RO for DS recovery and

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