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Evaluation of forward osmosis membrane performance and fouling during long-term osmotic membrane bioreactor study

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ABSTRACT

Forward osmosis membrane performance and fouling was studied during 100 days of continuous activated sludge treatment. The purpose of the study was to compare the performance and fouling of commercial cellulose triacetate and newly developed polyamide thin film composite membranes that treated high salinity and low salinity activated sludge from two membrane bioreactors. Water flux, reverse salt flux, and specific reverse salt flux were measured to evaluate the performance of virgin and fouled membranes. Membrane autopsy was used to investigate foulant composition and compare physicochemical membrane properties before and after fouling. The results indicated that both membrane types attained steady-state water flux over 100 days, characterized by an initial decline and subsequent steady-state period. Biofouling and organic fouling caused overall water flux decline, in which foulants were identical between membrane and activated sludge types. Water flux results were similar for the two activated sludge types and demonstrated that FO membrane performance and fouling was independent of total dissolved solids, calcium, and mixed liquor suspended solid concentrations. Lastly, virgin membrane properties (i.e., hydrophilicity and surface roughness) did not contribute substantially to membrane fouling. Cellulose triacetate membranes outperformed thin film composite membranes, with lower fouling propensity, higher water flux, lower reverse salt flux, and lower specific reverse salt flux.

1. Introduction

The osmotic membrane bioreactor (OMBR) is a novel advanced wastewater treatment system that uses highly selective forward osmosis (FO) membranes to allow water permeation from activated sludge feed solutions to saline draw solutions (DS) [1–5]. The process is driven by the osmotic pressure difference across an FO membrane, between a low-salinity activated sludge feed stream and high-salinity DS. The nonporous FO membranes used in OMBRs reliably reject pathogens [6], trace organic compounds [5,7–14], and ions [15,16], making the OMBR an attractive technology for water reuse. However, one of the main challenges associated with the operation of OMBR and conventional membrane separation processes is membrane fouling, which shortens the membrane life [17,18], decreases water production [18,19], and increases operating costs [19].

FO is commonly described as having a low fouling propensity compared to pressure driven membrane technologies such as reverse osmosis (RO) and nanofiltration (NF) [20–22]. Although FO membranes have a lower fouling propensity, FO membrane fouling still occurs and periodic membrane cleaning is required [1,3]. Furthermore, OMBR membrane cleaning is more difficult than cleaning microfiltration (MF) and ultrafiltration (UF) membranes used in membrane bioreactors (MBRs), which are commonly cleaned using hydraulic and chemical backwashing [18]. OMBR

Abbreviations: AFM, Atomic force microscopy; CA, Cellulose acetate; CECP, Cake enhanced concentration polarization; COD, Chemical oxygen demand; CTA, Cellulose triacetate; DOC, Dissolved organic carbon; DS, Draw solution; EDS, Energy dispersive spectroscopy; EPS, Extracellular polymeric substances; ESEM, Environmental scanning electron microscope; FO, Forward osmosis; FTIR, Fourier transform infrared spectroscopy; HRT, Hydraulic retention time; HS, High-salinity; HTI, Hydration technology innovations, LLC; IC, Ion chromatograph; ICP-AES, Inductively coupled plasma atomic emission spectroscopy; LS, Low-salinity; MBR, Membrane bioreactor; MF, Microfiltration; MLSS, Mixed liquor suspended solids; MLVSS, Mixed liquor volatile suspended solids; NF, Nanofiltration; OMBR, Osmotic membrane bioreactor; PA, Polyamide; RO, Reverse osmosis; RSF, Reverse salt flux; SB-MBR, Sequencing batch membrane bioreactor; SBR, Sequencing batch reactors; SMP, Soluble microbial products; SPE, Solid-phase extraction; SRSF, Specific reverse salt flux; SRT, Solids retention time; TDS, Total dissolved solids; TFC, Thin film composite; TOC, Total organic carbon; TN, Total nitrogen; TP, Total phosphorus; TSS, Total suspended solids; UF, Ultrafiltration; UFO-MBR, Ultrafiltration-osmotic membrane bioreactor

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membranes can be cleaned using osmotic backwashing, in which the concentrated DS is flushed from the DS side of the membrane and replaced with a very low-salinity cleaning solution (e.g., deionized water or de-chlorinated municipal water). Water from the low-salinity stream diffuses from the DS side of the membrane, through the membrane, to the feed stream; thereby, attached organic and inorganic particles are dislodged and dissolved from the membrane surface. Due to the complexity and time intensive nature of osmotic backwashing, it is important to mitigate FO membrane fouling to minimize the frequency of FO membrane cleaning in OMBR operations.

In general, membrane fouling is grouped into three categories: biofouling, organic fouling, and inorganic fouling (i.e., scaling) [23]. Biofouling is the result of biofilm formation through a series of fundamental steps, including reversible attachment of planktonic bacteria, irreversible attachment of more bacterial cells (e.g., through bacterial quorum-sensing), cell growth and extracellular polymeric substance (EPS) production, and ultimately the formation of a mature biofilm [24,25]. Organic fouling is the adsorption of organic compounds (e.g., EPS, soluble microbial products (SMPs), and humic substances) from the feed stream onto the membrane surface [18,23,25], and inorganic fouling is the chemical or biological precipitation of inorganic solids (e.g., struvite [26], $CaCO_3$ [27], and $CaSO_4$ [28]) onto the membrane surface.

The extent of membrane fouling due to biofouling, organic fouling, and inorganic fouling depends on a number of factors, including physicochemical membrane properties and wastewater composition [25,29]. Hydrophilic membranes with relatively low roughness and neutral charge are generally considered to be the most resistant to fouling [25,30–32]. Although these physicochemical properties have been used to explain differences in membrane fouling propensity, the effect of physicochemical membrane properties on fouling is uncertain. For example, Wang et al. [33] and Maximous et al. [34] concluded that hydrophilicity only deters initial colloidal fouling (e.g., bacterial attachment) and enhances membrane cleaning efficacy, while long-term fouling is dominated by foulant-foulant interactions. In terms of surface morphology, several studies have shown that smoother membranes may facilitate more effective membrane cleaning but no clear correlation between fouling and membrane roughness could be established [34,35]. Most studies still propose that hydrophilic and smooth membranes should be used to minimize fouling, but these studies also suggest that further work is needed to understand membrane properties and their effects on long-term fouling [36–39].

The composition of the wastewater is also critical to FO membrane fouling [25]. The organic and inorganic composition of the activated sludge in OMBRs is very different compared to more traditional activated sludge processes because the OMBR is often operated at high solids retention times (SRT) and elevated salt concentrations. The salt concentration of the activated sludge is higher in OMBRs because salts contained in the influent are retained in the bioreactors by the FO membranes and salts diffuse across the FO membrane from the DS to the feed. Salt accumulation in the OMBR has been shown to inhibit microbial activity [1,40,41], reduce the osmotic driving force for water flux (difference in salt concentration between the feed and DS) [1,42] and lead to higher divalent ion concentrations in the bioreactors (e.g., Ca^{2+} and Mg^{2+}) [1,36,43,44]. Divalent ions are considered to be major contributors to fouling due to bridging between the divalent ions and organic matter, resulting in more severe membrane fouling [20,36,37]. Salt accumulation also increases the ionic strength of the wastewater, which may increase bacterial adhesion to the membrane [45] and change the membrane surface charge (zeta potential) [46]. Coday et al. [46] demonstrated that increasing ionic strength reduced the negative charge of FO membranes, which can potentially affect membrane fouling propensity and the bidirectional diffusion of ionic constituents across the membrane [46–48].

The majority of studies exploring FO membrane fouling mechanisms have used synthetic feed solutions [3,20,22,29,36–38,49–58]; however, relatively few studies have examined OMBR membrane fouling using real wastewaters [1,2,43,59,60]. This is a major shortcoming in the literature because the use of synthetic or real wastewater can substantially influence the extent and characteristics of the fouling layer and membrane integrity [61]. Additionally, limited data is available on fouling and performance of different FO membrane materials and only few studies have compared the fouling and performance of commercially available FO membranes [36,62].

Thus, the main objective of the current study was to investigate and compare the performance and fouling of commercial cellulose triacetate (CTA) and polyamide thin film composite (TFC) FO membranes treating water from two different continuously operated activated sludge treatment systems: a low-salinity MBR and a high-salinity OMBR. The objectives of the study were to (1) evaluate and compare CTA and TFC membrane performance over 100-days of biological wastewater treatment, (2) examine physiochemical membrane property changes, and (3) investigate the effects of feed stream salinity on FO membrane fouling and performance.

2. Materials and methods

FO membrane performance (water flux and reverse salt flux (RSF)) and fouling were studied with CTA and TFC membranes using a field-operated membrane fouling system treating high-salinity activated sludge from a hybrid ultrafiltration OMBR (UFO-MBR) and low-salinity activated sludge from a sequencing batch MBR (SB-MBR) over 100-days. The UFO-MBR and SB-MBR were continuously fed with municipal wastewater and were located at the Water Reclamation Research Facility of the Colorado School of Mines in Golden, Colorado. Additional laboratory bench-scale experiments were conducted and several membrane characterization techniques were used to study the performance and physiochemical characteristics of the FO membranes before and after long-term fouling tests.

2.1. Pilot-scale test systems

2.1.1. UFO-MBR

High-salinity activated sludge feed was provided by a continuously operated UFO-MBR described in a previous publication [1]. The UFO-MBR system consists of an anoxic tank to remove nitrate, a UF unit to extract nutrients and ions, an aerobic tank to oxidize ammonia, a submerged FO membrane cassette, and an RO system for high-quality water production and DS reconcentration. The total dissolved solids (TDS) concentration of the activated sludge in the anoxic and aerobic tanks was maintained at approximately 4200 mg/L by adjusting the UF permeate flowrate. The ion concentrations in the UFO-MBR process tanks are summarized in Table 1.

2.1.2. SB-MBR

Activated sludge from the SB-MBR was used to supply low-salinity feed to the FO membrane fouling system. The SB-MBR is composed of two sequencing batch reactors (SBR) and two membrane tanks, described in detail elsewhere [63]. Carbon, phosphorus, and nitrogen are removed in the SBR by aeration cycles that control aerobic and anoxic conditions in the bioreactors. Wastewater treated in the SBR is recirculated from the