Desalination 363 (2015) 64–74

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Long-term pilot scale investigation of novel hybrid ultrafiltration-osmotic membrane bioreactors

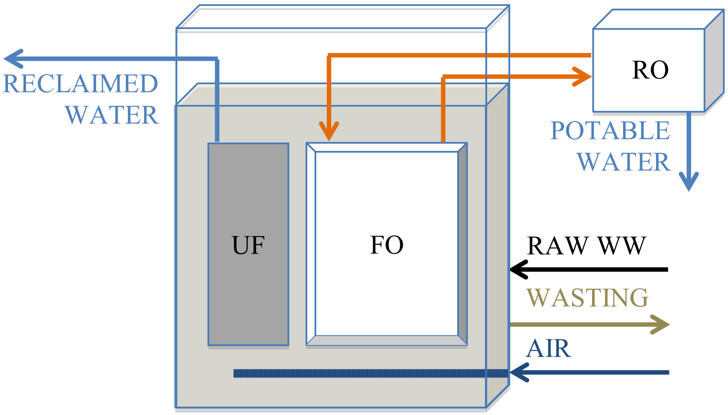
Ryan W. Holloway [a], Andrew S. Wait [a], Aline Fernandes da Silva [a], Jack Herron [b], Mark D. Schutter [b], Keith Lampi [b], Tzahi Y. Cath [a,*]

[a] Colorado School of Mines, Golden, CO, USA
[b] Hydration Technology Innovations, Albany, OR, USA

HIGHLIGHTS

- A hybrid ultrafiltration-osmotic membrane bioreactor was developed and tested.
- Potable water and reclaimed water for beneficial reuse were continuously produced.
- FO water flux was maintained constant for more than four months with the UFO-MBR.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 October 2013
Received in revised form 28 April 2014
Accepted 21 May 2014
Available online 18 June 2014

Keywords:
Membrane bioreactor
Forward osmosis
Osmotic MBR
Nutrient recovery
Salt rejection
Direct potable reuse

ABSTRACT

An osmotic membrane bioreactor (OMBR) and a novel hybrid ultrafiltration OMBR (UFO-MBR) were investigated for extended time. In OMBR, water is drawn by osmosis from activated sludge through a forward osmosis (FO) membrane into a draw solution. OMBRs provide superior rejection of dissolved constituents, including salts and nutrients, compared to conventional UF MBRs, and the FO membranes in OMBR have low fouling propensity. Yet, the high rejection of dissolved constituents in OMBR results in accumulation of salts and nutrients in the activated sludge, with potential detrimental effects on the biological processes. A new strategy for mitigating salt accumulation was investigated using a UF membrane in parallel to the FO membrane in the same bioreactor (UFO-MBR). Results from long-term OMBR and UFO-MBR investigations revealed that the overall removal of chemical oxygen demand, total nitrogen, and total phosphorus were greater than 96%, 82%, and 99%, respectively. We have demonstrated that low salinity in the activated sludge could be maintained, that phosphorus could be recovered through the UF permeate at concentrations greater than 50 mg L^{-1}, and that FO membrane fouling was substantially reduced. Additionally, the UFO-MBR was capable of simultaneously producing high quality RO permeate stream and nutrient-rich UF permeate stream from one integrated system.

---

* Corresponding author. Tel.: +1 303 273 3402; fax: +1 303 273 3413.
E-mail address: tcath@mines.edu (T.Y. Cath).

http://dx.doi.org/10.1016/j.desal.2014.05.040
0011-9164/© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Wastewater treatment facilities are increasingly being considered as resource recovery facilities where water, energy, nutrients, and other materials can be harvested for beneficial use/reuse. For example, reclaimed water has been identified as an essential resource that can be used to augment or substitute existing supplies through non-potable or indirect and direct potable reuse [1]; and nutrients (primarily nitrogen and phosphorus) have been successfully harvested from wastewater and used as plant fertilizers in-lieu of conventional chemical fertilizers [2,3]. Furthermore, municipal wastewater treatment facilities may become energy positive enterprises as most wastewater streams theoretically contain more potential energy in the organic fraction and thermal content than is required to treat the wastewater [4,5].

Non-potable reuse applications require consistent water quality, low in suspended solids and turbidity, to reduce the likelihood of bacterial contamination and to protect potential users and receiving environments. Membrane bioreactors (MBRs) operated with low-pressure microfiltration (MF) or ultrafiltration (UF) membranes are ideal technologies for most non-potable reuse applications because of the superior and consistent effluent quality that they produce compared to conventional clarification processes [6]. For the same reason, UF membranes provide an excellent pretreatment for reverse osmosis (RO) membranes by reducing colloidal, organic, and biological fouling on RO membranes [7,8]. Yet, the rejection of low molecular weight constituents, including trace organic compounds (TOrCs), ions, and viruses by UF membranes is limited [9]. This deficiency might restrict indirect or direct potable reuse applications that require a multiple barrier treatment approach to ensure that public health is not compromised [1].

The osmotic membrane bioreactor (OMBR) is an ideal multi-barrier technology that can be used for indirect and direct potable reuse applications [10–16]. OMBRs use forward osmosis (FO) membranes to extract water through a dense, semi-permeable membrane from a low-salinity waste stream into a high-salinity draw solution (DS). In some implementations an RO system is used to reconcentrate the diluted DS and simultaneously recover ultrapure water. Unlike the hydraulic pressure difference used in conventional UF or MF MBRs, the driving force for water flux in OMBRs is the difference in osmotic pressure between the feed stream, in this case activated sludge, and the DS, which can be a concentrated NaCl solution, seawater (with adequate pre-treatment), or other solutions having high osmotic pressure. The main advantages of FO over other membrane separation technologies for wastewater treatment are the potential low membrane fouling propensity and the excellent rejection of macromolecules, TOrCs, and ions [17–25].

Previous studies have highlighted the advantages and applications of OMBRs [10,15]; however, they have also identified the accumulation of total dissolved solids (TDS) and other dissolved constituents in the bioreactor as a major drawback of the OMBR process [10,15,16]. Accumulation of these dissolved constituents in the OMBR is due to the high rejection of feed stream TDS and nutrients by the FO membrane and due to the reverse diffusion of salts from the DS into the activated sludge. The increase in activated sludge TDS concentrations results in decreased osmotic pressure difference across the FO membrane (lower driving force and water flux) and can adversely affect microbial activity and functionality in the bioreactor [26,27].

Salt accumulation in OMBRs was modeled by Bowden et al. [28] and Xio et al. [29]. Although the complexity of these models differs, both studies concluded that the steady state salt concentration in the bioreactor is a function of the solids retention time (SRT). Ideally, an OMBR would be operated at a short SRT to reduce the concentration of TDS in the bioreactor; however, operating at a short SRT limits biological nitrogen removal [30] and reduce water recovery (more wasting from the bioreactor). An alternative strategy for minimizing TDS and nutrient concentrations in the bioreactor without changing the SRT would be to operate a UF membrane parallel to the FO membrane in the bioreactor. In this configuration, which is termed UFO-MBR, dissolved constituents are removed from the bioreactor with the UF permeate.

An additional benefit of the UFO-MBR is the enabling of nutrient recovery. Nitrogen and phosphorus that are rejected by the FO membrane and accumulated in the bioreactor can be removed and harvested from the system using the UF membrane [31,32]. Furthermore, the concentration of nitrogen and phosphorus in the bioreactor is predetermined by operating the UF membrane at different permeate rates — low concentrations recovered at high permeate flow rates and high concentrations recovered at low permeate flow rates. Thus, the UFO-MBR simultaneously produces high quality FO-RO permeate fit for potable reuse applications and a nutrient-rich UF permeate suitable for nitrogen and phosphorus recovery or for non-potable reuse applications. While adding a new process to the system might add capital and operating and maintenance costs (e.g., energy, chemicals, and membrane replacement), it is very likely that the benefits outweigh the shortcomings.

A novel pilot hybrid UFO-MBR system that employs a UF membrane and an FO membrane in the same bioreactor was constructed and operated for several months. The main objective of the study was to evaluate water flux and membrane fouling over time, and rejection of feed and DS solutes. Furthermore, the results from the UFO-MBR investigation were compared to results from an OMBR study conducted under similar test conditions to determine the benefits of using UFO-MBR compared to OMBR.

2. Materials and methods

An OMBR and a hybrid UFO-MBR were tested in two phases of the study for 124 days (January 2012 to May 2012) and 125 days (October 2012 to March 2013), respectively. The long-term OMBR and UFO-MBR pilot investigations were conducted with raw domestic wastewater at the Water Reclamation Research Facility of the Colorado School of Mines in Golden, Colorado.

2.1. The OMBR, UFO-MBR, and RO systems

Experiments were conducted using an automated pilot FO-RO system that extracts water from activated sludge into a concentrated NaCl DS of 32 g L^{-1} and 26 g L^{-1} for OMBR and UFO-MBR testing, respectively. The RO subsystem continuously re-concentrates the DS that becomes diluted by the submerged FO membranes, and produces the final reuse-quality RO product water. A UF membrane was submerged in the activated sludge bioreactor and operated when needed. Schematics of the OMBR and UFO-MBR systems are shown in Fig. 1.

Using a peristaltic pump (Cole-Parmer, Vernon Hills, IL), screened (2 mm) makeup raw wastewater was pumped into a 105 L anoxic tank whenever the level in the bioreactors declined below a preset elevation due to extraction of water through the FO and UF membranes. Activated sludge was continuously circulated between the anoxic tank and aerobic tank at a rate of 0.5 to 1.0 L min^{-1}. Sludge was wasted manually using a graduated cylinder from the aerobic tank at a rate of 4 L d^{-1} starting on day 55 of the OMBR operation, and the calculated SRT at this wasting rate is approximately 70 days. During UFO-MBR tests, sludge was wasted automatically using a programmable peristaltic pump (Cole-Parmer, Vernon Hills, IL) at a rate of 10 L d^{-1} (SRT of approximately 30 d) from the aerobic tank for the first 100 days of operation, and was reduced to 5 L d^{-1} (SRT of approximately 60 d) after day 100 for the remainder of the UFO-MBR testing.

The volume of the aerobic/OMBR tank was 170 L and the volume of the aerobic/UFO-MBR tank was 235 L. The FO plate-and-frame skid was submerged in the aerobic tank and was continuously aerated at a rate of 20–30 L min^{-1} (ActiveAqua™ 70, Portland, OR). The air was distributed under the FO membrane plates through an array of fine-bubble diffusers during the OMBR investigation and through a coarse bubble diffuser