Bioresource Technology 150 (2013) 287–297

Contents lists available at ScienceDirect

Bioresource Technology

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

Osmotic membrane bioreactor for wastewater treatment and the effect of salt accumulation on system performance and microbial community dynamics

Guanglei Qiu, Yen-Peng Ting *

Department of Chemical and Biomolecular Engineering, National University of Singapore, 4 Engineering Drive 4, Singapore 117576, Singapore

HIGHLIGHTS

- Salt accumulation caused significant succession of bacterial community.
- High rejection of the FO membrane resulted in significant pollutant accumulation.
- Significant succession occurred among species of *Nitromonas*.
- *Nitrospira* was not evidently affected while *Nitrobacter* was washed out.
- Denitrifying bacteria shifted from α- to γ-*Proteobacteria* members.

ARTICLE INFO

Article history:
Received 3 July 2013
Received in revised form 18 September 2013
Accepted 21 September 2013
Available online 7 October 2013

Keywords:
Osmotic membrane bioreactor (OMBR)
Salt accumulation
Bacterial community dynamics
Nitrification
Denitrification

ABSTRACT

An osmotic membrane bioreactor was developed for wastewater treatment. The effects of salt accumulation on system performance and microbial community dynamics were investigated. Evident deterioration of biological activity, especially nitrification, was observed, which resulted in significant accumulation of organic matter and NH_4^+–N within the bioreactor. Arising from the elevation of salinity, almost all the dominant species was taken over by high salt-tolerant species. Significant succession among different species of *Nitromonas* was observed for ammonia-oxidizing bacteria. For nitrite-oxidizing bacteria, *Nitrospira* was not evidently affected, whereas *Nitrobacter* was eliminated from the system. Salt accumulation also caused significant shifts in denitrifying bacterial community from α- to γ-*Proteobacteria* members. Overall, the microbial community adapted to the elevated salinity conditions and brought about a rapid recovery of the biological activity. Membrane fouling occurred but was insignificant. Biofouling and inorganic scaling coexisted, with magnesium/calcium phosphate/carbonate compounds identified as the inorganic foulants.

1. Introduction

Membrane bioreactor (MBR) technology, first reported in wastewater treatment application about 40 years ago, is now commonly employed in municipal and industrial wastewater treatment. Its popularity is due to several distinctive advantages such as allowing high sludge concentrations and low production of excess sludge, producing high quality effluent, and with reduced footprint (Meng et al., 2009). Unfortunately, the widespread commercialization of MBR is challenged by the higher operational and capital costs associated with membrane fouling (Drews, 2010), as well as its relatively high energy demand due to the hydraulic pressure applied for separation.

Recently, there has been increasing interest in a novel integration of forward osmosis (FO) and biological process for wastewater treatment, known as the osmotic membrane bioreactor (OMBR), which has the potential to overcome these limitations (Achilli et al., 2009; Chung et al., 2012; Su et al., 2012). In an OMBR system, a high rejection semipermeable forward osmosis (FO) membrane is used instead of a microporous membrane. Water is transported from the mixed liquor into a draw solution (DS) under a driving force of osmotic pressure. Compared to traditional MBR, OMBR offers some unprecedented advantages, such as potential low energy consumption and higher theoretical water flux, higher rejection of the FO membrane and resultant high quality produce water, as well as low fouling potential (Wang et al., 2010; Yap et al., 2012). For these reasons, OMBR is considered a promising alternative in wastewater treatment and reclamation, especially for the removal of emerging trace organic compounds (Alturki et al., 2012).

* Corresponding author. Tel./fax: +65 65162190.
E-mail address: chetyp@nus.edu.sg (Y.-P. Ting).

0960-8524/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2013.09.090

Despite the many advantages, the utilization of the high rejection FO membrane unfortunately introduces some unique new challenges. For instance, the high rejection of the FO membrane causes accumulation of dissolved salts within the bioreactor. To compound the problem, reverse salt diffusion from the DS further enhances salt accumulation in the bioreactor (Ge et al., 2012). This elevated salt concentration in the bioreactor significantly reduces water flux and causes membrane fouling. Additionally, the majority of microorganisms involved in conventional wastewater treatment are generally non-halophilic; these microorganisms do not possess the mechanisms to cope with the osmotic stress exerted by an elevated salt environment (Lay et al., 2010). In particular, some functional bacteria, i.e. ammonia-oxidizing bacteria (AOB), nitrite-oxidizing bacteria (NOB), and denitrifying bacteria are reportedly more sensitive to elevated salinity conditions (Moussa et al., 2006; Osaka et al., 2008; Wan et al., 2013). Hence, the elevated salinity is likely to impact biological activities as well as system performance. A previous study on the removal of trace organics in OMBR found some indirect evidence indicating the deterioration of biological activity (Alturki et al., 2012). Currently, knowledge on the effects of salt accumulation on the system performance of OMBR is inadequate to assess this technology. In addition, although characterization of microbial assemblages is essential for better understanding of biological wastewater treatment processes, the effects of salt accumulation on the structure of the bacterial community and its dynamics in OMBR is largely unknown.

In the present study, an OMBR system was developed using a flat sheet membrane module and $MgCl_2$ as the DS. The OMBR system was operated under continuous flow for 80 days. The aim of this study is to investigate the effect of salt accumulation on the system performance and the microbial community dynamics. Pollutant removal efficiency, flux stability and membrane fouling were examined under elevated salinity conditions caused by salt accumulation. The response of the total bacterial community and functional bacterial (AOB, NOB and nitrifying bacteria) communities to the elevation of salinity was also investigated.

2. Methods

2.1. Description of OMBR system

A schematic of the laboratory scale OMBR system is shown in Fig. 1. The bioreactor (200 mm length × 125 mm width × 250 mm height) had an effective volume of 4.85 L and housed a plate-and-frame module holding two pieces of 12 × 15 mm OsMem™ CTA-ES flat-sheet membrane (Hydration Technologies Inc., Albany, OR) with the active layer of the membrane facing the mixed liquor and an effective membrane area of $2 \times 0.018\ m^2$. The system was continuously aerated at 150 L/h to supply oxygen to the activated sludge as well as to create sufficient hydrodynamic shear force to minimize membrane fouling.

The bioreactor was operated with feed wastewater delivered from a feed tank placed on a digital scale (Kern, Balingen, Germany). The liquid level in the bioreactor was maintained using an overflow trough with its bottom connected to the bioreactor. Water flux was calculated from weight change of the influent recorded by the digital scale. Salt accumulation in the bioreactor was determined by monitoring the conductivity of the mixed liquor using a conductivity meter (Thermo, Pittsburgh, PA). A peristaltic pump (Cole-Parmer, Barrington, IL) was used to recirculate the DS at 0.2 L/min. Constant DS concentration was set and maintained by a conductivity controller linked to a concentrated DS reservoir. The DS was maintained at 23.2 ± 0.5 °C by a water bath (Polyscience, Niles, Illinois). Heat transfer took place through submerged stainless steel heat exchanger coils within the DS tank.

During the entire OMBR operation, the sludge retention time (SRT) was fixed at 50 days by daily discarding 96 ml of mixed liquor from the bioreactor through the sludge wastage outlet (Fig. 1). Additionally, to achieve a relatively stable final salt concentration within the bioreactor, 300 ml mixed liquor was withdrawn daily from the bioreactor and settled for 30 min, and 147 ml of the clarified supernatant (including the samples for analysis) discarded, and the rest of the mixed liquor returned to the bioreactor. The hydraulic retention time (HRT) of the OMBR was 15.4 h initially and eventually increased to 22.6 h due to permeate flux decline.

2.2. Feed and draw solution

Activated sludge collected from Ulu Pandan MBR plant in Singapore was used as the inoculum for the OMBR system. Before use, the activated sludge was cultivated for 1 month using synthetic wastewater (of composition 600 mg/L glucose, 151.4 mg/L NH_4Cl, 35.12 mg/L KH_2PO_4, 71 mg/L $MgSO_4{\cdot}7H_2O$, 19.3 mg/L $CaCl_2{\cdot}2H_2O$, 17.4 mg/L $FeSO_4{\cdot}7H_2O$, 0.07 mg/L $CuCl_2{\cdot}2H_2O$, 0.13 mg/L $MnCl_2{\cdot}4H_2O$, 0.13 mg/L $ZnSO_4{\cdot}7H_2O$, 0.03 mg/L $Na_2MoO_4{\cdot}2H_2O$, 0.025 mg/L H_3BO_3 and 0.033 mg/L), giving a COD, NH_4^+–N, and PO_4^{3-}-P value around 600 mg/L, 40.0 mg/L, and 8.0 mg/L, respectively. The same synthetic wastewater was also used as feed for the OMBR system. For start up, the cultivated activated sludge was added in the bioreactor to a final MLSS concentration of about 7.0 g/L, which was maintained during the operation of the OMBR.

The DS was prepared by dissolving 48.4 g $MgCl_2$ in 1 L deionized water (corresponding to an osmotic pressure of 4.0 MPa, at 23 °C) and filtered using a 0.45 μm cellulose acetate microfiltration membrane. The osmotic pressure of the DS as a function of solution concentrations were calculated using OLI Stream Analyzer™ software (OLI Systems, Inc., Morris Plains, NJ).

The OMBR system was operated under continuous flow for 80 days. In order to improve denitrification, a baffle was added in the bioreactor at the 60th day, which separated the bioreactor into an anoxic chamber (2.13 L) in the influent side and an aerobic chamber (2.72 L) which housed the membrane module. In the anoxic chamber, an overhead stirrer (IKA, Staufen, Germany) was installed and operated at 180 rpm to ensure the complete mixing of the mixed liquor. A peristaltic pump was used to transfer the mixed liquor from aerobic chamber back into the anoxic chamber at a constant flow rate of 150 ml/L for denitrification.

2.3. Analyses of wastewater quality

Grab samples were taken daily from the influent tank, the bioreactor and the DS tank, respectively. The dissolved organic carbon in the influent, the mixed liquor supernatant and DS was derived from the total organic carbon (TOC) determined using a TOC analyzer (Shimadzu, Kyoto, Japan) after filtration through a 0.45 μm membrane. The COD, NH_4^+–N, NO_2^-–N and NO_3^-–N concentrations were measured according to standard methods (APHA, 1999).

For SEM–EDX analysis, the entire membrane module was removed from the bioreactor on the 40th day and replaced with a new module. After rinsing with sterile deionized water, the module was disassembled, and a piece of fouled membrane (about 2.5 × 2.5 cm) was cut, fixed with 2.5% glutaraldehyde at 4.0 °C overnight, gradient dehydrated with 50–100% ethanol, dried at room temperature, platinum-coated, and observed using an SEM (JEOL JSM-5600, Tokyo, Japan) with EDX system (INCA x-act, Oxford, UK).