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Impacts of sludge retention time on sludge characteristics and membrane fouling in a submerged osmotic membrane bioreactor

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HIGHLIGHTS

- The lower SRT was helpful for alleviating the salt accumulation and flux decline.
- The main reason for flux decline was not membrane fouling but salt accumulation.
- SRT had a negative impact on the removal of NH_3-N.
- SRT had strong effects on SMP and microbial activity.
- High salinity in the OMBR significantly affected the microbial communities.

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ABSTRACT

Sludge retention time (SRT) is a feasible method to alleviate the salt accumulation in the osmotic membrane bioreactor (OMBR) by discharging the waste activated sludge. In this study, effects of SRT on sludge characteristics and membrane fouling were investigated using a submerged OMBR under two SRTs of 10 and 15 d. The results showed that the lower SRT was helpful for alleviating the salt accumulation and flux decline. Besides that, the removal of NH_3-N was significantly influenced by SRT. SRT also had a strong effect on soluble microbial products (SMP) and microbial activity due to the variation of salinity. Microbial diversity analysis indicated that the high salinity environment in the OMBR significantly affected the microbial communities. The flux decline in the OMBR was mainly attributed to the reduced driving force resulting from the salt accumulation, and the reversible fouling was the dominant forward osmosis (FO) membrane fouling in the OMBR.

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1. Introduction

As an emerging technology, forward osmosis (FO) has attracted growing interests due to a series of advantages such as good product water quality, low energy consumption, low fouling tendency, etc. (Cath et al., 2006; Lay et al., 2012b; Yap et al., 2012). Recently, a new concept of integrating FO within a membrane bioreactor (MBR) setup called osmotic membrane bioreactor (OMBR) has been proposed to reduce the relatively high energy consumption in the MBR (Cornelissen et al., 2008; Achilli et al., 2009). In the OMBR, the pure water is obtained by the feed water across a selectively permeable membrane under an osmotic driving force provided by a draw solution. Compared with the conventional MBR, the OMBR has a lower fouling propensity because it utilizes osmotic pressure instead of hydraulic pressure (Cornelissen et al., 2008, 2011; Achilli et al., 2009; Qin et al., 2010). Furthermore, higher quality water is produced from the OMBR due to the high retention of FO membrane (Cornelissen et al., 2008, 2011; Achilli et al., 2009; Qin et al., 2010).

Although the OMBR has many advantages over the conventional MBR, there are some drawbacks associated with the OMBR such as lower water flux and salt accumulation (Yap et al., 2012). Internal concentration polarization (ICP) has been recognized as a major drawback of FO membrane (Cath et al., 2006; McCutcheon and Elimelech, 2006; Tang et al., 2010; Zhang et al., 2012a). Severe ICP eventually leads to the reduction of water flux, e.g., water fluxes of less than 5 L/(m^2 h) (LMH) were observed due to the ICP in the early tests of thin film composite (TFC) reverse osmosis (RO) membranes operated in the FO mode (McCutcheon and Elimelech, 2008). Apart from ICP, the high retention property of the FO membrane results in the solute accumulation in the bioreactor. Additionally, the draw solution would transport into the bioreactor through the FO membrane (Alturki et al., 2012). This

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phenomenon called "reverse salt transport" is expected to occur due to the difference in solute concentration between the draw solution and the bioreactor solution (Hancock and Cath, 2009; Alturki et al., 2012). The accumulation of solute and the reverse salt transport jointly cause the elevated salinity condition in the OMBR, which not only leads to a reduced driving force, but also has inhibitory or toxic effects on the microbial activity and population structure in the bioreactor (Lay et al., 2011; Yap et al., 2012).

In order to overcome the salt accumulation in the OMBR, many efforts have been put into the selection of draw solutes and development of an ideal FO membrane (Yap et al., 2012). Besides that, sludge retention time (SRT) might be a feasible method to alleviate the salt accumulation in the OMBR. During the operation of OMBR, the accumulating salt could only be reduced through the daily sludge discharge. Considering that the discharge of waste activated sludge is controlled by SRT, the variation of SRT could cause the change of salinity in the OMBR. In fact, Achilli et al. (2009) also thought that the salinity in the bioreactor would reach a constant value depending on SRT. In addition, Xiao et al. (2011) developed a theoretical model to explain the salt accumulation behavior in the OMBR and revealed the critical importance of hydraulic retention time (HRT) and SRT for optimizing the OMBR operation. Thus, as an important operating fact, SRT should be extensively investigated in order to better understand the performance of OMBR. Recently, effects of SRT on salt accumulation and FO water flux in the OMBR have been studied, and the results indicated that the lower SRT is helpful for reducing the high salinity and increasing the water flux (Xiao et al., 2011; Lay et al., 2012a). However, to date, impacts of SRT on sludge characteristics and membrane fouling in the OMBR could hardly be found in the literatures.

Therefore, the objectives of this study are to investigate effects of SRT on sludge characteristics and membrane fouling in the OMBR using a laboratory-scale submerged OMBR treating synthetic wastewater under two SRTs of 10 and 15 d. The conductivity in the bioreactor, and sludge properties such as mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), bound extracellular polymeric substances (BEPS), soluble microbial products (SMP) and particle size distribution were determined. Furthermore, the microbial activity such as dehydrogenase activity (DHA) and microbial community were analyzed.

2. Methods

2.1. Experimental setup and operating conditions

The FO membrane used in this study is the cartridge type provided by Hydration Technology Innovations (HTI). It is woven and made of cellulose triacetate (CTA) with an embedded polyester screen mesh. Compared to the conventional RO membrane, this type of FO membrane is relatively smooth and hydrophilic (Tang et al., 2010). Thus, it has been used in a number of studies, and is currently viewed as one of the best available membranes for FO applications (McCutcheon et al., 2008; Yap et al., 2012). Based on the fact that the membrane orientation plays a significant role in FO applications, the orientation of "active layer facing feed" was adopted in order to avoid aggravated fouling especially pore-clogging in the support layer (Lay et al., 2011).

As shown in Fig. S1 of the Supporting information, the laboratory-scale submerged OMBR with an effective volume of 7.56 L was used in this study. In this apparatus, a unique plate-and-frame FO membrane module with an effective membrane area of 0.056 m^2 was immersed in the bioreactor with the activated sludge. The influent water was continuously pumped into the OMBR, and a one-way valve and an overflow tube were used for maintaining a constant water level in the reactor. Aeration with the intensity of 0.5 m^3/h was provided through an axial perforated tube below the membrane modules in order to supply oxygen for microorganisms and induce a cross-flow velocity for membrane fouling reduction. Analytical grade sodium chloride (NaCl) with the concentration of 1 M was used as the draw solution. Draw solution was circulated at the flow rate of 0.5 L/min from a 2 L glass reservoir through the FO membrane module and back to the reservoir. A conductivity control system was used to control the draw solution at constant concentration of 1 M. It included a conductivity probe in draw solution reservoir, a control device and a concentrated salt adding system. When the NaCl concentration in the draw solution reservoir was less than 1 M, the probe would give a signal to the control device, and then a peristaltic pump was started to transfer the concentrated draw solution of 5 M NaCl to the reservoir until the draw solution recovered its initial concentration.

The OMBR was put in a temperature-controlled room to maintain the temperature in the range of 25 ± 0.5 °C. The influent water of the OMBR was synthetic wastewater, whose concentrations of chemical oxygen demand (COD), ammonium nitrogen (NH_3-N), total nitrogen (TN) and total phosphorus (TP) were 373.3 ± 18.5, 33.1 ± 1.5, 46.8 ± 3.8 and 3.18 ± 0.25 mg/L, respectively. Activated sludge used in the OMBR was obtained from a laboratory-scale submerged membrane bioreactor (SMBR) continuously treating the same synthetic wastewater for about 6 months. The information on the SMBR and the composition of synthetic wastewater could be found in previous publications (Chen et al., 2011; Wang et al., 2012). Two commonly used SRTs of 10 and 15 d were adopted to investigate impacts of SRT on sludge characteristics and membrane fouling in the OMBR. A certain volume of excess sludge calculated from a SRT was extracted from the bioreactor zone once a day. The operating conditions were same for both SRTs.

2.2. Batch flux test

In order to evaluate the effect of membrane fouling on the flux decline of the FO membrane during the continuous operation of OMBR, a batch flux test for FO membrane was applied. In the batch test, the used reactor and operating conditions were same as the OMBR except for the feed solution. As for the test, the influent water was deionized water, and the FO membrane was also immersed in the deionized water. The duration of the test was approximately 8 h in order to obtain the constant flux. Before the operation of OMBR, the FO membrane was firstly placed in the batch apparatus to obtain the initial water flux (F_i). After the continuous operation of OMBR, the fouled FO membrane was immediately removed from the OMBR and placed in the batch apparatus to quantify the water flux (F_f). Based on the facts that the deionized water was used as the feed solution and the duration was only 8 h, the reverse salt transport in the batch test did not result in substantial salt accumulation in the bioreactor. Therefore, the difference between the F_i and F_f was the flux decline due to the membrane fouling only. Furthermore, the fouled membrane after washing by the deionized water was also tested the water flux (F_w) in order to verify the membrane fouling. The difference between F_i and F_w was the flux decline due to the irreversible membrane fouling, while the difference between F_w and F_f was the flux decline due to the reversible membrane fouling.

2.3. Analytical methods

Water flux through the FO membrane was calculated based on the weight change of the feed solution. The conductivity of the mixed liquor (C_{ml}) was monitored and recorded by a conductivity device (OKD-650, Shenzhen OK Instrument Technology Co., Ltd., Shen Zhen, China) in order to characterize the variation of salinity in the OMBR. NH_3-N and TOC in the influent, sludge supernatant and FO membrane effluents were conducted according to the

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