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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.

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

Chinese NEPA standard methods (2002) and by a TOC analyzer (TOC-Vcsh, Shimadzu, Japan), respectively. The total dissolved solids (TDS), MLSS, MLVSS and the specific oxygen uptake rate (SOUR) of the mixed liquor in the OMBR were determined according to the Chinese NEPA standard methods (2002). Particle size distribution was analyzed by a BT-2003 Laser Particle Size Analyzer (Bettersize Instruments Ltd., Dan Dong, China).

The specific extraction of SMP and BEPS from activated sludge has been reported in previous literatures (Chen et al., 2011; Wang et al., 2012). Both the SMP and BEPS extractions were normalized as the sum of polysaccharide and protein. Polysaccharide was measured by the phenol sulfuric acid method with glucose as a standard (Dubois et al., 1956), while protein was determined by a modified Lowry method using Bovine serum albumin (BSA, Sigma fraction V, 96%) as protein standard (Lee et al., 2001). DHA was determined by the TTC-dehydrogenase activity determination methods (Zhang et al., 2011). All the above analyses were conducted at least 3 times, and their mean values ± standard deviations were reported. An analysis of variance (ANOVA) was used to test the significance of results, and $p < 0.05$ was considered to be statistically significant.

2.4. Methods for microbiological analysis

PCR-DGGE technology was applied for comparison and analysis of population structure of the bulk sludge in the OMBR. The sludge samples were collected from the OMBR at the beginning and the end of both SRTs. The detailed experiment steps of DNA extraction, amplification and DGGE gel analysis were according to the methods described by Duan et al. (2009). Cluster analysis was carried out by Quantity one V4.31 (BIO-RAD) to investigate the relationship between DGGE profiles.

3. Results and discussion

3.1. Process performance

Results for the water production (J_w) and the salinity in terms of conductivity are presented in Fig. 1. As shown in Fig. 1, the water flux quickly reduced from the initial value of about 9 LMH to the steady value of approximately 2 LMH during the operation of OMBR at both SRTs. The flux decline during the operation of OMBR has also been reported by other researchers (Lay et al., 2011; Yap et al., 2012). It could be attributed to several reasons such as ICP, salt accumulation and membrane fouling (McCutcheon and Elimelech, 2006; Achilli et al., 2009). Compared to the flux variation at SRT of 10 d, the longer SRT of 15 d had a quicker trend of flux reduction. In contrary to the variation of water flux, the salinity of the mixed liquor characterized by the conductivity significantly increased under both SRTs as shown in Fig. 1. In order to further investigate the origin of the salinity in the mixed liquor, the TDS was also determined. It could be seen from Fig. S2 of the Supporting information that the TDS had the similar variations and values as the conductivity at both SRTs, indicating that the salt accumulation in the OMBR was mainly due to the high retention of the solute. A steady-state reactor concentration was reached when the solute entering into the OMBR was balanced by the salt discharge in the continuous sludge wasting (Xiao et al., 2011). In the current study, the stable salinity at SRT of 15 d was about 65 ms/cm, while it was about 50 ms/cm at SRT of 10 d. The ANOVA indicated that the SRT had a significant impact on the stable salinity ($p < 0.05$), suggesting that the decrease of SRT might be helpful for alleviating the salt accumulation by increasing the discharge of waste activated sludge.

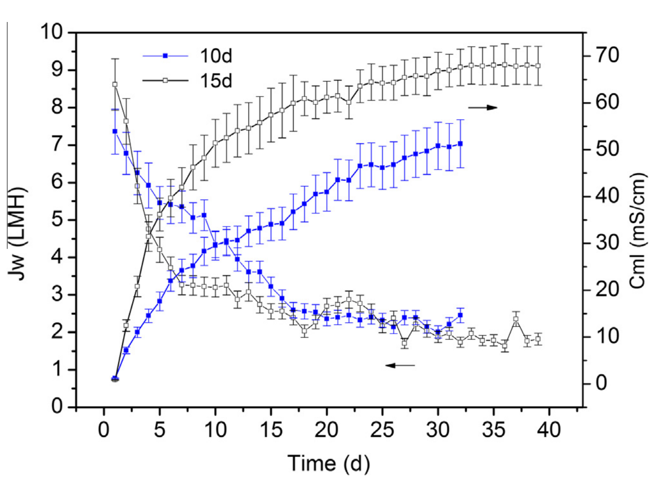

Fig. 1. Variations of water flux (J_w) and conductivity of the mixed liquor (C_{ml}) in the OMBR at both SRTs.

According to the system mass balance, the variations of C_{ml} as a function of time and the steady-state salt concentration in the OMBR could be determined as follows (Xiao et al., 2011; Lay et al., 2012a):

$$\frac{C_{ml}(t)}{C_{in}} = e^{-\frac{t}{SRT}}\left[\frac{C_{ml}^{t=0}}{C_{in}} - \left(\frac{SRT}{HRT} + \left(\frac{SRT}{HRT} - 1\right)\left(\frac{J_s/J_w}{C_{in}}\right)\right)\right] + \left(\frac{SRT}{HRT} + \left(\frac{SRT}{HRT} - 1\right)\left(\frac{J_s/J_w}{C_{in}}\right)\right) \quad (1)$$

$$C_{ml}^{steady} = \frac{SRT}{HRT}C_{in} + \left(\frac{SRT}{HRT} - 1\right)\frac{B}{A\beta R_g T} \quad (2)$$

where t is the operating time, C_{in} the influent salt concentration, J_w the water flux, J_s the salt flux, A the overall water permeability, B the overall salt permeability, R_g the ideal gas constant, T the absolute temperature, and β the Van't Hoff coefficient.

According to Eq. (1), the significant difference in the conductivity of the mixed liquor after only 2 d of operation at both SRTs could be attributed to the fact that the used SRTs in this study were much longer than the time of operation. Based on the facts that the coefficients of β, R_g and T were constant at both SRTs due to the same operating conditions and the B/A ratio was associated with the used FO membrane, the stable salinity at SRT of 15 d should be larger than that at SRT of 10 d according to Eq. (2), which was consistent with the data obtained from Fig. 1. Therefore, the Eqs. of (1) and (2) could be perfectly used to interpret the variations of salinity in the OMBR at both SRTs.

TOC and NH_3-N concentrations in the influent, sludge supernatant and effluent of the OMBR system are demonstrated in Fig. 2. TOC and NH_3-N removals due to the activated sludge process and the total process in the OMBR could be obtained based on their concentration in the supernatant of mixed liquor and FO membrane effluent compared to that in the influent, respectively. Although the TOC removal in the bioreactor slightly decreased with increasing SRT, the total TOC removal efficiency in the OMBR could keep constant at over 90% under both SRTs. The difference in the TOC removal between the bioreactor and the total system indicated that most dissolved TOC components probably microbial metabolic matters could be expelled by the FO membrane. It is well known that membrane separation plays an important role in maintaining a high TOC removal (Lay et al., 2011). With respect to NH_3-N removal, no obvious difference between the bioreactor and the total system was observed at both SRTs, suggesting that the rejection of the FO membrane for NH_3-N was not as good as that for the TOC, which was consistent with the results reported in Yap et al. (2012). The reduction of TOC and NH_3-N removals in the bioreactor at both SRTs might be due to the inhibitory effect of salt accumu-

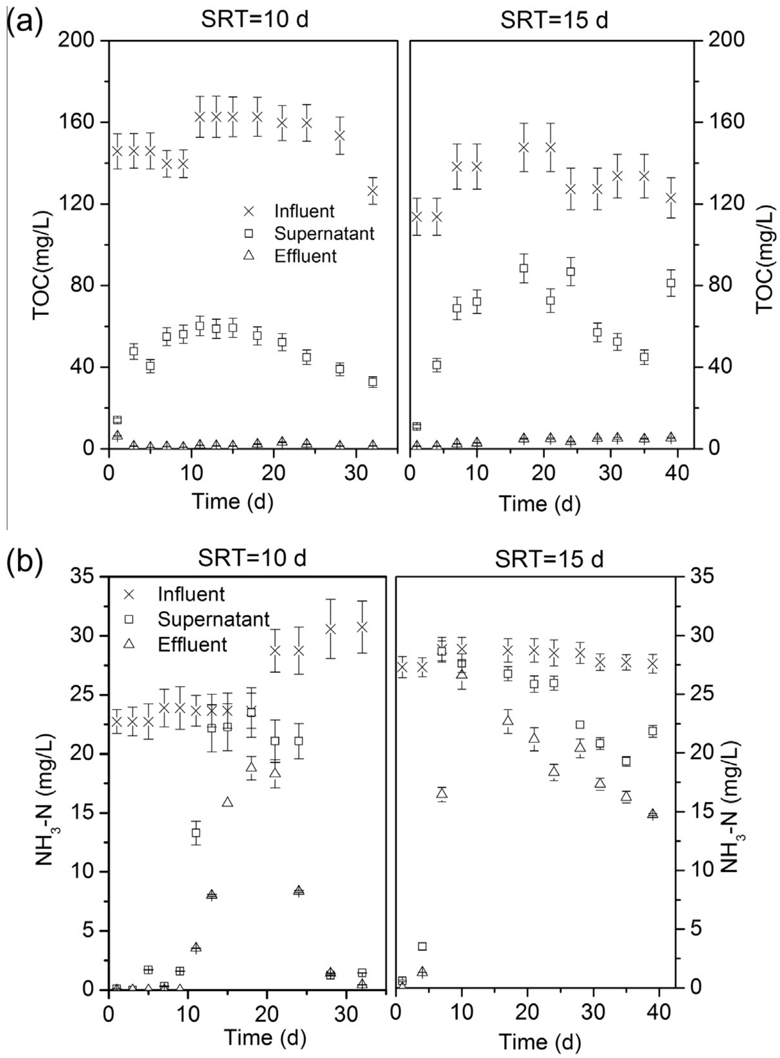

Fig. 2. Variations of TOC (a) and NH_3-N (b) concentrations in the influent, sludge supernatant and effluent of the OMBR system at both SRTs.

lation on the microorganisms. It has been reported that a higher salinity could result in the loss of metabolic activity and plasmolysis causing the release of intracellular constituents and soluble microbial products (Yogalakshmi and Joseph, 2010). Furthermore, other reports pointed out that the presence of high TDS interferes with the oxygen transfer and affects the biological metabolism thereby reducing the capacity of the reactor to sustain shock loads (Pophali et al., 2003). This would also be the possible reason in the current study for the decrease of TOC and NH_3-N removals.

3.2. Particle size distribution

The average volume size of sludge particles at both SRTs in the OMBR was determined at the first and final days. It all decreased over the whole experimental periods at both SRTs, i.e., from 136.64 to 116.85 μm at SRT of 10 d, and from 136.44 to 113.66 μm for SRT of 15 d. The ANOVA indicated that the variation of average particle size at steady state of the OMBR under both SRTs was not statistically significant ($p > 0.05$). In order to further investigate the variation of particle size with the operation time, the particle size of sludge granules at different operation time under SRT of 10 d was measured. As shown in Fig. S3 of the Supporting information, the sludge granules were collected from the OMBR on days 1, 15, 19 and 32, and their average volume sizes were 136.64, 137.57, 129.04 and 116.85 μm, respectively, indicating that the sludge granules were broken during the operation of the OMBR. It might be due to the increase of salinity based on the fact that the high salt concentration could make the microbial cell cytoplasm dehydration, leading to the loss of microbial activity and the reduction of the average volume size (Hu and Xia, 2012). Except for the reduction of the size of sludge particles, the high salinity environment in the OMBR also caused the decrease of MLSS and MLVSS/MLSS (see Table S1 of the Supporting information), because the microbial consortium was unable to withstand and adapt itself to the increasing sodium chloride concentration (Pophali et al., 2003; Yogalakshmi and Joseph, 2010).

3.3. EPS

EPS, consisting of a variety of organic substances such as polysaccharide, protein, lipids and nucleic acids, had significant impacts on the sludge properties and membrane fouling (Wang et al., 2009). It can be classified as BEPS and SMP based on the distribution feature of EPS on cell. BEPS is located at or outside the cell surface, while the SMP is in sludge supernatant. SMP and BEPS distributions in the mixed liquor at both SRTs are listed in Fig. 3. It could be observed that the SMP and BEPS at SRT of 10 d firstly increased then decreased at 20 d and then increased again at 30 d, while they firstly increased then decreased at 30 d until 40 d. As shown in Fig. 1, the OMBR reached a steady salinity at about 28

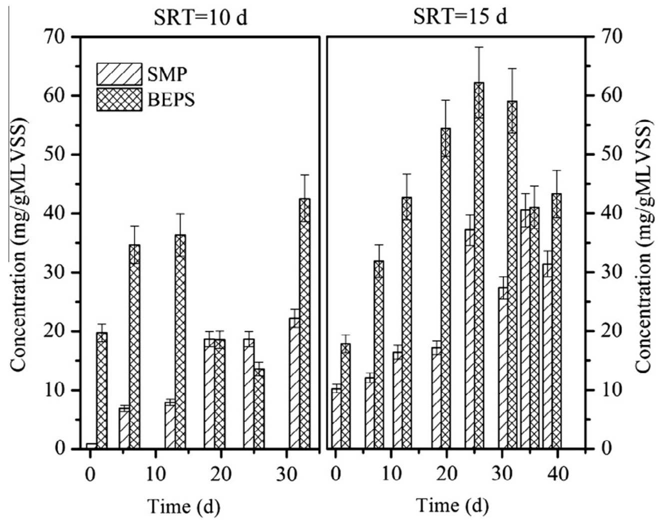

Fig. 3. Concentrations of SMP and BEPS in the OMBR at both SRTs.

and 35 d under SRTs of 10 and 15 d, respectively. Before the stable state of the OMBR, the salinity and sludge properties having a strong impact on the variations of EPS would change all the time. Therefore, the violent variations of EPS before 28 and 35 d for SRTs of 10 and 15 d could be attributed to the fact that the OMBR was not stable. In order to evaluate the impact of SRT on the EPS, the EPS values at the steady state under both SRTs were used. The ANOVA indicated that SRT had a significant impact on the SMP ($p < 0.05$) while it slightly influenced the BEPS ($p > 0.05$). The violent increase of SMP at steady state from SRT 10 to 15 d might be attributed to the fact that the higher salinity at SRT of 15 d had a severer inhibition on the growth of microorganisms, which resulted in the more release of SMP (Laspidou and Rittmann, 2002; Yogalakshmi and Joseph, 2010; Jang et al., 2013).

3.4. Microbial activity test

The enzymes in sludge play key biochemical functions in the overall process of material and energy conversions (Molina-Munoz et al., 2010). SOUR has been widely used to monitor the microbial activity of activated sludge in various aerobic processes (Choi et al., 2007). As shown in Fig. 4, SOUR steadily decreased over the whole experiment at both SRTs. However, the ANOVA indicated no statistical difference in the stable SOUR values at SRTs of 10 and 15 d ($p > 0.05$), which might be due to the lower MLSS at both SRTs (see Table S1). Considering the fact that the steady MLSS was less than 1 g/L at both SRTs, the SOUR was not suitable for evaluating the impacts of SRT on the microbial activity.

As one of the most important enzymes in activated sludge, DHA plays a significant role in the biological oxidation of organic matter by transferring hydrogen from organic substrates to inorganic acceptors (Molina-Munoz et al., 2010). Based on the fact that the calculation of DHA was not related to the MLSS, DHA was used to characterize the microbial activities of bulk sludge in the OMBR. As for the DHA, the initial seed sludge under both SRTs had the similar DHA at about 178.7 ± 4.7 mgTF/(L h); however, it dramatically reduced to 6.88 ± 0.4 and 1.57 ± 0.09 mgTF/(L h) at the end of SRTs of 10 and 15 d, respectively. Considering the facts that the synthetic waste water used as the influent of the OMBR did not contain the toxic species, the significant decrease of DHA at both SRTs might be due to the accumulation of salinity in the OMBR. The negative effect of high salinity on the microbial activity of activated sludge has been present in a previous study (Li et al., 2013). Furthermore, the ANOVA indicated that the SRT had a significant impact on the stable DHA at SRTs of 10 and 15 d ($p < 0.05$).

3.5. Microbial diversity analysis

PCR-DGGE, a well-established fingerprinting technique used to study microbial ecology, has got meaningful information on changes in microbial community composition although it has some limitations (Lay et al., 2012c). PCR-DGGE was used to reveal the bacterial communities of the OMBR sludge at both SRTs (as shown in Fig. 5). The initial seed sludge (S0) was also analyzed as a contrast. It could be observed that some bands (bands 3, 8, 10, and 14) seemed to be stable in the OMBR, while other bands (bands 2, 5, 7, 11, and 17) detected in S0 were less pronounced or disappeared at both SRTs. Compared with the bands in S0, some bands (bands 4, 6, 9, 15, and 16) at the end of both SRTs became more pronounced. Furthermore, cluster analysis was carried out to evaluate the similarities among these samples. As shown in Fig. 5, the

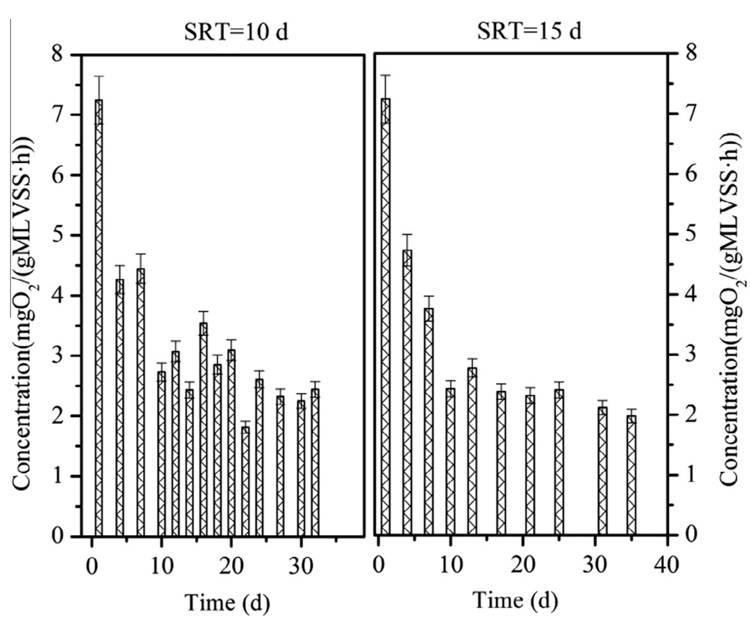

Fig. 4. SOUR variations in the OMBR at both SRTs.

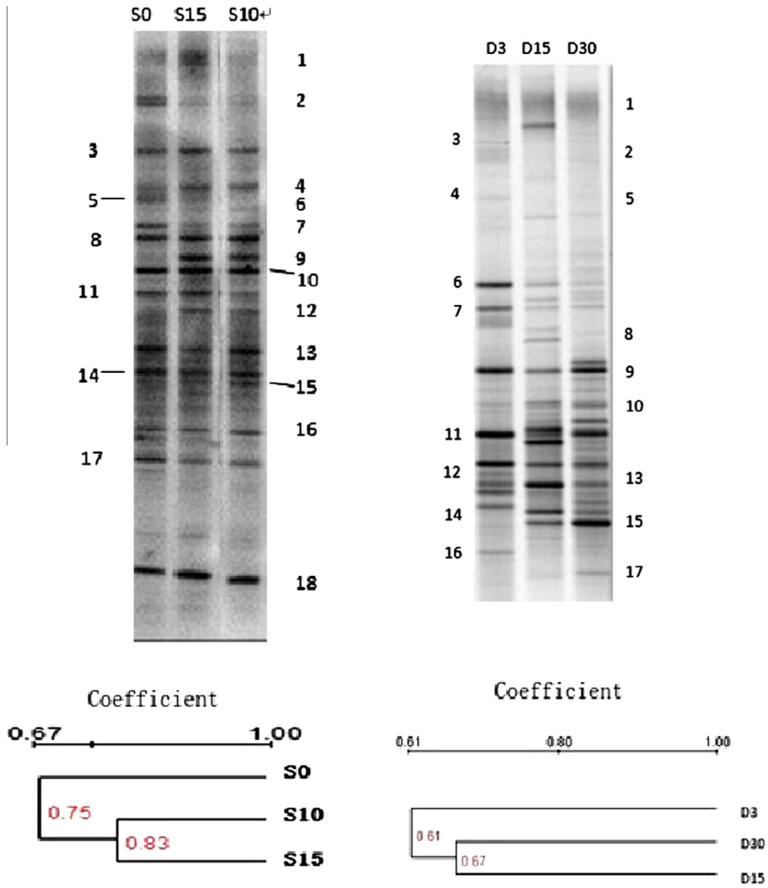

Fig. 5. DGGE profiles and cluster analyses of the initial sludge (S0) and the final sludge at SRTs of 15 d (S15) and 10 d (S10), and the activated sludge on different days at SRT of 15 d (D3, D15 and D30).

sludge at both SRTs had very similar microorganism populations compared with the initial sludge. This information implied that the microorganism communities had a significant variation after the long-term operation of OMBR. It might be due to the high salinity environment at the end of both SRTs based on the facts that the high salinity could influence the microorganism communities (Bassin et al., 2012).

In order to further evaluate the variation of microbial communities during the operation of OMBR, the sludge samples were collected from the OMBR at different days under SRT of 15 d and determined by PCR-DGGE. It could be seen from Fig. 5 that bacterial population shifted with operation time in different ways. At the third day of the experiment (D3), the microbial community was relatively diverse and evenly spread. However, it could be observed that the banding pattern on days 15 and 30 had a significant change, e.g., some bands (bands 3, 4, 6, 7, 11, 12 and 16) became less pronounced or disappeared, while some bands (bands 10 and 15) were more pronounced. Furthermore, the microbial community also had some differences between D15 and D30, for instance, some bands (bands 8 and 13) could be seen clearly in D15 while band 17 could only be observed in D30. The cluster analysis had similar results that the microbial communities would change during the operation of OMBR, suggesting that the variation of salinity in the OMBR had a significant impact on the microbial populations.

3.6. Membrane fouling assessment

After the continuous operation of the OMBR under both SRTs, no obvious foulants could be found on the membrane surface. The results of the batch flux test are summarized in Fig. 6. It could be observed that F_i of the FO membranes at both SRTs was in the range of 8–9 LMH. After the continuous experiments under both SRTs, F_f had a slight reduction from F_i, e.g., the water flux at SRT of 10 d decreased by approximately 29%. During the continuous operation of the OMBR under both SRTs (as shown in Fig. 1), the flux decline was much bigger, e.g., the water flux decline at the end of SRT 10 d was approximately 75%. Based on these facts, it

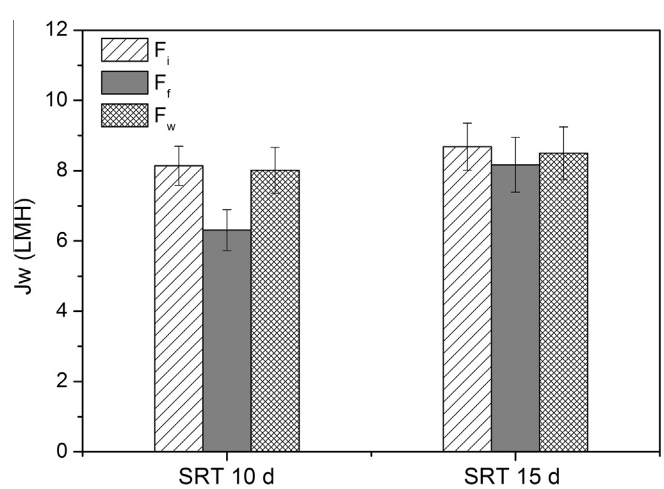

Fig. 6. Water fluxes of the virgin FO membranes (F_i) and fouled FO membranes before (F_f) and after (F_w) washing in batch tests at both SRTs.

Table 1
A short overview of research on the OMBR.

Configuration	Membrane	Active layer orientation	Draw solution	Temperature (°C)	SRT (d)	Operating time (d)	Stable salinity (g/L)	Steady flux (LMH)	References
Side-stream	CTA FO membrane	Feed solution	0.5 M NaCl	20 ± 2	–	0.33	–	5.1	Cornelissen et al. (2008)
Submerged	CTA FO membrane	Feed solution	50 g/L NaCl	23 ± 1	15	28	4	9[a]	Achilli et al. (2009)
Side-stream	CTA FO membrane	Feed solution	0.5 M NaCl	32 ± 2	–	6.25	–	7.2	Qin et al. (2010)
Side-stream	CTA FO membrane	Draw solution	0.5 M NaCl	20 ± 2	–	14	–	8.0	Cornelissen et al. (2011)
Submerged	CTA FO membrane	Feed solution	0.5 M NaCl	20–22	20	73	7.2–8.1	2.7	Lay et al. (2011)
Side-stream	CTA FO membrane	Draw solution	1.5 M NaCl	22.5 ± 0.1	–	7	4.13	3	Alturki et al. (2012)
Submerged	TFC FO membrane	Draw solution	0.5 M NaCl	20–22	20	35	7.9	4	Lay et al. (2012a–c)
Submerged	TFC FO membrane	Draw solution	0.5 M NaCl	23	10	55	6–7	3.9 ± 0.5	Zhang et al. (2012b)
Submerged	CTA FO membrane	Feed solution	1 M NaCl	25 ± 0.5	10	32	24–25	2.45	This study
Submerged	CTA FO membrane	Feed solution	1 M NaCl	25 ± 0.5	15	39	33–34	1.82	This study

[a] The average water flux was used because the steady flux could not be obtained.

could be indicated that the membrane fouling was not the main reason for the flux decline in the OMBR. Thus, the flux decline during the operation of OMBR was mainly attributed to the reduced driving force resulting from the salt accumulation. Furthermore, it could be found that the water flux almost recovered after physical washing, suggesting that the membrane fouling of FO membrane was mainly due to the reversible fouling. The results of the slight FO membrane fouling in this study are consistent with the previous publications (Cornelissen et al., 2008; Achilli et al., 2009). Compared with the F_f and F_w at SRT of 10 d, they were bigger at SRT of 15 d, implying that the membrane fouling especially reversible fouling at SRT of 15 d was less. However, as shown in Fig. 1, the flux decline at SRT of 15 d was severer compared with that at SRT of 10 d. It might be due to the higher salinity at SRT of 15 d, which was consistent with the conclusion drawn from the difference of flux decline between the continuous operation and batch test.

4. Discussion

A short overview of research on the OMBR was summarized in order to compare the results obtained in this study with other researches on the performance of OMBR. It could be observed from Table 1 that there was a significant difference in the steady salinity and water flux of the OMBR among these publications, which might be attributed to the different membrane properties and operating conditions based on the fact that the water permeability, salt permeability, membrane orientation, concentration of draw solution, SRT and HRT significantly affected the salinity and water flux of OMBR (Xiao et al., 2011). Thus, it is difficult to compare the performance of OMBR in different studies with different membrane properties and operating conditions. As for the current study, the comparative study of salinity and water flux could be conducted because the same FO membrane and operating conditions were adopted at the two SRTs of 10 and 15 d. As shown in Table 1, the lower SRT was good for the alleviation of high salinity and flux decline, which was in accordance with the publications (Xiao et al., 2011; Lay et al., 2012a).

The significant impact of SRT on the sludge characteristics such as SMP in the current study was attributed to the variations of salinity depending on SRT. As for the OMBR at longer SRT, the salinity correspondingly increased. The elevated salinity had an adverse influence on the microbial activity and diversity, because microorganisms require sufficient energy produced by biological reactions for their survival in the elevated salt environment as a higher energetic cost is needed for osmotic adaptation (Yap et al., 2012). With regard to the biological treatment of wastewater, it relies comprehensively on microbial activity and the presence of functional species. Thus, when the microbial activity and diversity changed, the sludge characteristics would vary accordingly. Furthermore, the adverse effect of salinity on sludge characteristics resulted in the serious reversible membrane fouling.

According to the results obtained in this study and other researches, SRT could control the variations of salinity in the OMBR. In other words, an ideal salinity that had no adverse effect on the microorganisms could be achieved by decreasing the SRT. However, the lower SRT was not helpful for the microbial respiration in the OMBR. With regard to the ammonia removal via biological treatment in the OMBR, if the SRT of the OMBR was lower than 10 d, the nitrification microorganisms would decrease duo to their relative long generation time, and then the nitrification was inhibited in the OMBR. In this case, the concentration of ammonia would accumulate in the mixed liquor because the FO membrane only had a rejection of about 80% for ammonia (Yap et al., 2012). The relatively high ammonia concentration imposed the toxicity effect on microorganisms in the OMBR. Moreover, diffusion of high concentration ammonia across the FO membrane eventually led to the deterioration of permeates' quality (Yap et al., 2012). Thus, as for a long-term operation of the OMBR, the SRT should be controlled not less than 10 d. However, even if the OMBR was operated at SRT of 10 d, it could be found in the current study that the stable salinity was still high and had adverse impacts on the performance of OMBR. Therefore, it is necessary to search for other novel methods to control the salinity in the OMBR on the basis of ensuring the microbial activity. For instance, the microfiltration (MF) membrane might be a good choice because it could let the solute pass through but retard the activated sludge.

5. Conclusions

The findings of this study demonstrated that the lower SRT was helpful for alleviating the salt accumulation and flux decline. SRT had a negative impact on the removal of NH_3-N due to the salt accumulation, while it only had a slight influence on the TOC removal in the OMBR. It further indicated that the high salinity at longer SRT had a negative effect on sludge properties such as SMP and DHA, and the high salinity environment significantly influenced the microbial communities. Furthermore, the adverse effect of salinity on sludge characteristics resulted in the serious reversible membrane fouling.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2014.03.058.

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