A comparison study on membrane fouling in a sponge-submerged membrane bioreactor and a conventional membrane bioreactor

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Abstract

This study compared membrane fouling in a sponge-submerged membrane bioreactor (SSMBR) and a conventional membrane bioreactor (CMBR) based on sludge properties when treating synthetic domestic wastewater. In the CMBR, soluble microbial products membrane fouling in SSMBR were also attributed to larger particle size, higher zeta potential and relative hydrophobicity of sludge flocs.

Keywords: Submerged membrane bioreactor; Sponge; Attached growth; Membrane fouling; Cake layer

1. Introduction

membrane fouling after 70 days of operation as well as less backwash frequency. A chemical cleaning-in-place (CIP) was investigated by Wei et al. (2011) in a long-term operation of pilot-scale submerged MBR for municipal wastewater treatment. They reported that the chemical CIP, in both transmembrane pressure (TMP) controlling mode and time controlling mode, effectively removed the fouling in terms of membrane pore blockage and gel layer caused by colloids and soluble organic substances. Wu and He (2012) suggested that the low irreversible fouling was found in the cyclic aeration mode, which could be ascribed to the floc destruction and re-flocculation processes. During the short high aeration period, the preservation of the strong strength bonds within activated sludge flocs caused less release of soluble and colloidal material in the supernatant. The weak strength bonds damaged in the high aeration period could be recovered in the re-flocculation process in the low aeration period.

In addition, using biomass carriers (e.g. plastic media, powdered activated carbon (PAC), sponge) in MBR is an effective and promising method to control membrane fouling. Jin et al. (2013) suggested that biomass flocs were less easily broken up with addition of relatively light and large-sized suspended carriers (AnoxKaldnes, K1 carriers) in ceramic SMBR. Moreover, both extracellular polymer substances (EPS) and soluble microbial products (SMP) were lower in the SMBR with carriers than those in the SMBR without carriers. Ng et al. (2013) indicated that higher concentration of fresh PAC in the SMBR could provide better simultaneous adsorption, decomposition, and biodegradation effects for the reduction of fouling components in the supernatant of the mixed liquor such as EPS, fine colloids and planktonic cells. As an idea attached growth media, sponge has also exhibited excellent performance during biological treatment due to its advantages of high internal porosity and specific surface area, high stability to hydrolyses, light weight and low cost (Ngo et al., 2006). When employing in MBRs, it can act as a mobile carrier for active biomass, reduce cake layer formation on the membrane surface and retain microorganisms by incorporating both their attached growth and suspended growth (Ngo et al., 2008). Guo et al. (2008) investigated the effects of sponge addition on sustainable flux and membrane fouling. They found that compared to SMBR alone, the suspended sponge cubes in the sponge-submerged membrane bioreactor (SSMBR) with sponge volume fraction of 10% could significantly reduce the membrane fouling as well as improve sustainable flux by 2 times. Nguyen et al. (2012) also confirmed that SSMBR had lower TMP development than that of conventional SMBR during primary effluent treatment. Meanwhile, SSMBR could maintain good microbial activity and constant sludge volume index value.

The experiments were conducted using a synthetic wastewater to avoid any fluctuation in the feed concentration and provide a continuous source of biodegradable organic pollutants such as glucose, ammonium sulfate and potassium dihydrogen orthophosphate. It was used to simulate domestic wastewater just after primary treatment. The synthetic wastewater has dissolved organic carbon (DOC) of 100−130 mg/L, chemical oxygen demand (COD) of 330−360 mg/L, ammonium nitrogen (NH_4-N) of 12−15 mg/L and orthophosphate (PO_4-P) of 3.3−3.5 mg/L. $NaHCO_3$ or H_2SO_4 was used to adjust pH to 7.

2.2. Experimental setup and operating conditions

A SSMBR and a CMBR with the same effective working volume were operated in parallel to compare the performance and membrane fouling behavior. For each MBR, a polyvinylidene fluoride (PVDF) hollow fiber module with a pore size of 0.2 μm and surface area of 0.1 m^2 was used. Both MBRs were filled with sludge from a local Wastewater Treatment Plant and acclimatized to synthetic wastewater. They were started with identical seeding activated sludge with similar initial sludge concentration (7.03 g/L for SSMBR, 6.98 g/L for CMBR). No sludge was withdrawn from both MBRs. The reticulated porous polyester-polyurethane sponge (PUS) was used in using a feeding pump to control the feed rate while the effluent flow rate was controlled by a suction pump. A pressure gauge was used to measure the TMP and a soaker hose

images of sludge particles obtained by the Olympus System Microscope Model BX41

These results indicated that sponge addition could significantly mitigate membrane fouling, which is further discussed in details in Section 3.5.

Fig. 1.

3.2. Mixed liquor suspended solids (MLSS) concentration and apparent viscosity

During the experimental period, sludge concentration kept increasing in both MBRs due to no sludge withdrawal. MLSS concentrations were 11.50 ± 4.52 g/L and 9.41 ± 2.38 g/L in the CMBR and SSMBR after 35 and 90 days of operation, respectively. The lower MLSS concentration in the SSMBR might be attributed to the fact that sponge addition could balance the microorganism growth in suspended activated sludge as well as on and inside the porous sponge cubes (Ngo et al., 2006). It was found that there is an exponential relationship between MLSS concentration and sludge viscosity (Reid et al., 2008). In this study, sludge viscosity was higher (3.30 ± 0.50 mPa·s) in the CMBR than that (2.60 ± 0.40 mPa·s) in the SSMBR, demonstrating that higher sludge viscosity was attributed to higher MLSS concentration. In addition, it has been reported that the sludge flocs with excess filamentous bacteria showed high viscosity due to presence of high EPS concentration (Meng et al., 2006a). Overgrowth of filamentous bacteria was found in the CMBR on day 14, whereas there were less filamentous bacteria in the SSMBR until 83 days, which revealed that higher sludge viscosity in the CMBR was also due to abundance of filamentous bacteria. Similar observations were also recorded by Meng et al. (2007) who suggested that sludge viscosity was influenced by MLSS concentration, EPS and filamentous bacteria.

3.3. Zeta potential, relative hydrophobicity (RH) and particle size distribution

It has been demonstrated that the flocculation ability of sludge flocs is affected by their hydrophobicity and surface charge, which positively influences the hydrophobic interaction and electrostatic repulsion, respectively (Liao et al., 2001; Mikkelsen and Keiding, 2002). In this study, activated sludge in the SSMBR had higher zeta potential (- 6.85 ± 3.65 mV) and higher RH (81.00 ± 7.80%) than those in the CMBR (zeta potential of -10.50 ± 4.50 mV, RH of 63.13 ± 13.60%). The results indicated that there might be a positive relationship between surface charge (zeta potential) and hydrophobicity of activated sludge. Additionally, Meng et al. (2006a) reported that excess filamentous bacteria could prevent the agglomeration of floc particles by producing a bridge lattice due to the generation of abundant filaments from the flocs similar bound EPS concentrations, slightly higher protein concentrations (EPS_P) but significantly lower polysaccharide concentrations (EPS_C) were obtained in the CMBR. After 7 days of operation, the SMP concentrations (including SMP_P and SMP_C) of both MBRs presented minor difference. On the other hand, bound EPS concentrations (12.3–24.6 mg/L) in the CMBR were higher than those in the SSMBR (12.2–17.3 mg/L), with lower protein concentrations (EPS_P) but significantly higher polysaccharide concentrations (EPS_C). In this study, increase of sludge concentration under infinite SRT condition induced the decrease in food to microorganism (F/M) ratio (0.1–0.2 d^{-1}). As a consequence, both MBRs were fed with limited available substrate, which could cause more cell lysis and cell hydrolysis, thereby releasing EPS and SMP in activated sludge (Yigit et al., 2008). Moreover, the excess growth of filamentous bacteria could produce more SMP, resulting in severe fouling (Pan et al., 2010). Therefore, the CMBR exhibited more serious fouling compared with the SSMBR. In the SSMBR, it was obvious that sponge addition could reduce SMP_C concentrations during the first 7-day run and EPS_C afterwards by the means of adsorption onto sponge as well as biodegradation by attached biomass of the sponge.

It has been reported that large quantity of EPS in activated sludge increased floc strength by polymer entanglement, thereby increasing the extent of sludge flocs agglomeration (Mikkelsen and Keiding, 2002). However, in this study, lower EPS concentration but larger particles were observed in the SSMBR, pointing out that the flocculation ability of sludge flocs may not only depend on EPS concentration. Lee et al. (2003) found that the ratio of proteins to polysaccharides (PN/PS ratio) in EPS was important in controlling the hydrophobicity and surface charge of sludge flocs. Table 3 shows that a significantly higher PN/PS ratio in bound EPS was found in the SSMBR after 7 days operation. Higher RH of activated sludge in the SSMBR proved that higher EPS_P concentration increased the hydrophobicity of sludge flocs by providing amino acids with more hydrophobic side groups, while lower EPS_C concentration contributed to less hydrophilic nature of sludge. Moreover, the amino groups in EPS_P containing positive charges neutralized some of negatively charged activated sludge, thereby inducing higher zeta potential of sludge flocs in the SSMBR (Lee et al., 2003; Liao et al., 2001). Thus, PN/PS ratio in bound EPS could positively influence hydrophobicity and zeta potential of activated sludge, thereby having an impact on the agglomeration ability of the flocs.

Table 2.

Table 3.

3.5. Membrane fouling behaviour

Results of fouling resistance showed that the CMBR had a higher total resistance (R_T) (5.47×10^{12} m^{-1}) than that of the SSMBR (2.56×10^{12} m^{-1}). The clean membrane resistance (R_M) were the same (1.71×10^{12} m^{-1}) for both MBRs. Higher cake layer resistance (R_C) was found for the CMBR than that for the SSMBR, corresponding to 3.04×10^{12} m^{-1} and 0.85×10^{12} m^{-1}, respectively. Moreover, pore blocking resistance (R_P) for the CMBR was notably higher. R_P of the CMBR accounted for about 20% of R_T, whereas there was no R_P in the SSMBR. These results suggested that cake layer formation was one of the main factors contributing to membrane fouling. Furthermore, sponge could alleviate membrane fouling not only by preventing pore blocking but also by reducing cake layer formation. Some researchers (Jamal Khan et al., 2012; Yang et al., 2006) have reported the similar findings that R_C was major fraction of R_T and sponge addition could reduce R_C.

As discussed in Section 3.2, activated sludge in both MBRs possessed different properties, which were correlated with membrane fouling potential as well as fouling resistance. Higher MLSS concentration could lead to formation of a sticky cake layer on membrane surface due to higher sludge viscosity (Itonaga et al., 2004). Additionally, the sludge flocs with abundance of filamentous bacteria would more easily deposit on membrane surface due to its high viscosity, causing the formation of a non-porous cake layer (Meng et al., 2006a). Therefore, it could be noted that higher MLSS concentration and overgrowth of filamentous bacteria contributed to formation of sticky and non-porous cake layer, giving rise to higher R_C in the CMBR. Being the major fraction of the total fouling resistance, the cake layer was analysed with respect to EPS and SMP (including polysaccharides and proteins). Fig. 2 shows the composition of EPS and SMP in the cake layer on membrane surface for both SSMBR and CMBR. Bound EPS concentrations were similar for the SSMBR (15.0 mg/(L·g cake layer)) and the CMBR (13.9 mg/(L·g cake layer)). However, higher concentrations of SMP_C and SMP_P (14.4 and 15.5 mg/(L·g cake layer), respectively) were obtained for the CMBR, while SMP_C and SMP_P of the cake layer were comparatively lower for the SSMBR (9.8 and 7.1 mg/(L·g cake layer), respectively). These results elucidated that higher R_C in the CMBR was mainly caused by SMP (including SMP_C and SMP_P) on membrane surface. At high TMP, more SMP_C and SMP_P could be adsorbed and/or attached onto membrane surface due to the high drag force provided by permeate pump. On contrary, sponge addition effectively reduced SMP_C and SMP_P in cake layer on membrane surface. Apart from adsorption of SMP_C and SMP_P on the sponge and biodegradation by attached microorganisms, reduction of cake layer could be also attributed to physical clearance mechanism of sponge, such as frictional force exerted by circulating media on submerged membrane, solute back-transport effect from the membrane surface to the bulk solution due to turbulence of suspended carriers, and membrane shaking by the impact of suspended carriers against them (Lee et al., 2006; Yang et al., 2006).

Fig. 2.

Since particles could lead to severe membrane fouling by pore blocking and cake formation on the membrane (Lim and Bai, 2003), the CMBR contained smaller sludge flocs and induced higher TMP increment rate (Fig. 1), which illustrated that the presence of smaller sludge flocs contributed to higher R_C and R_P in the CMBR. As larger particles could not easily deposit on membrane surface due to higher shear induced diffusion and inertial lift force, SSMBR demonstrated significantly lower membrane fouling propensity (Pan et al., 2010).

In addition, as above-mentioned in Section 3.4, SMP in activated sludge appeared as a major contribution to initial membrane fouling. However, in later stage, membrane fouling development was mainly governed by bound EPS in activated sludge. It has been showed that SMP could increase fouling tendency due to the combined effects of pore clogging and adsorption on membrane walls and within membrane pores (Shen et al., 2012). Thus, higher SMP content of the CMBR cake layer led to higher R_P, which was well consistent with the results by Jamal Khan et al. (2012). Besides, higher concentration of bound EPS in activated sludge could also increase both R_C and R_P in the CMBR. Ng et al. (2006) observed a thick fouling layer on the membrane consisting of microbial cells covered with EPS, which blocked membrane pores. Similar results were also found by Meng et al. (2006b) that the total amount of EPS had a significant positive correlation with the fouling resistance caused by pore blocking and cake formation.

Previous studies have reported that PN/PS ratio in EPS or SMP had a significant impact on filtration resistance as well as fouling propensity (Lee et al., 2003; Tian et al., 2011; Yao et al., 2011). In this study, as both SMP and EPS (especially SMP_C and EPS_C) were responsible for membrane fouling in the CMBR, a new fouling indicator the CMBR governed membrane fouling in the initial stage and later stage, respectively. However, sponge addition could mitigate membrane fouling significantly by preventing pore blocking and reducing cake layer formation. In the SSMBR, lower R_C and R_P were ascribed to lower biomass growth, lower sludge viscosity, less filamentous bacteria, larger sludge flocs, as well as lower concentrations of SMP and bound EPS in activated sludge.

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References

1. APHA, AWWA, and WEF, 1998. Standard Methods for the Examination of Water and Wastewater, twentieth ed. American Public Health Association, Washington, DC.
2. Choo, K.H., Lee, C.H., 1996. Membrane fouling mechanisms in the membrane coupled anaerobic bioreactor. Water Research 30, 1771–1780.
3. Frølund, B., Palmgren, R., Keiding, K., Nielsen, P.H., 1996. Extraction of extracellular polymers from activated sludge using a cation exchange resin. Water Research 30, 1749–1758.

4. Guo, W.S., Ngo, H.H., Vigneswaran, S., Xing, W., Goteti, P., 2008. A novel sponge submerged membrane bioreactor (SSMBR) for wastewater treatment and reuse. Separation Science and Technology 43, 273–285.
5. Guo, W.S., Ngo, H.H., Palmer, C.G., Xing, W., Hu, A.Y.J., Listowski, A., 2009. Roles of sponge sizes and membrane types in a single stage sponge-submerged membrane bioreactor for improving nutrient removal from wastewater for reuse. Desalination 249, 672–676.
6. Guo, W.S., Ngo, H.H., Li, J.X., 2012. A mini-review on membrane fouling. Bioresource Technology 122, 27–34.
7. Itonaga, T., Kimura, K. Watanabe, Y., 2004. Influence of suspension viscosity and colloidal particles on permeability of membrane used in membrane bioreactor (MBR). Water Science and Technology 50, 301–309.
8. Jamal Khan, S., Zohaib-Ur-Rehman, Visvanathan, C., Jegatheesan, V., 2012. Influence of biofilm carriers on membrane fouling propensity in moving biofilm membrane bioreactor. Bioresource Technology 113, 161–164.
9. Ji, J., Qiu, J., Wai, N., Wong, F.S., Li, Y., 2010. Influence of organic and inorganic flocculants on physical-chemical properties of biomass and membrane-fouling rate. Water Research 44, 1627–1635.
10. Jin, L., Ong, S.L., Ng, H.Y., 2013. Fouling control mechanism by suspended biofilm carriers addition in submerged ceramic membrane bioreactors. Journal of Membrane Science 427, 250–258.
11. Kimura, K., Hane, Y., Watanabe, Y., Amy, G., Ohkuma, N., 2004. Irreversible membrane fouling during ultrafiltration of surface water. Water Research 38, 3431–3441.

12. Lee, W., Kang, S., Shin, H., 2003. Sludge characteristics and their contribution to microfiltration in submerged membrane bioreactors. Journal of Membrane Science 216, 217–227.
13. Lee, W.N., Kang, I.J., Lee, C.H., 2006. Factors affecting filtration characteristics in membrane-coupled moving bed biofilm reactor. Water Research 40, 1827–1835.
14. Liao, B.Q., Allen, D.G., Droppo, I.G., Leppard, G.G., Liss, S.N., 2001. Surface properties of sludge and their role in bioflocculation and settleability. Water Research 35, 339–350.
15. Lim, A.L., Bai, R., 2003. Membrane fouling and cleaning in microfiltration of activated sludge wastewater. Journal of Membrane Science 216, 279–290.
16. Meng, F., Zhang, H., Yang, F., Li, Y., Xiao, J., Zhang, X., 2006a. Effect of filamentous bacteria on membrane fouling in submerged membrane bioreactor. Journal of Membrane Science 272, 161–168.
17. Meng, F., Zhang, H., Yang, F., Zhang, S., Li, Y., Zhang, X., 2006b. Identification of activated sludge properties affecting membrane fouling in submerged membrane bioreactors. Separation and Purification Technology 51, 95–103.
18. Meng, F., Shi, B., Yang, F., Zhang, H., 2007. Effect of hydraulic retention time on membrane fouling and biomass characteristics in submerged membrane bioreactors. Bioprocess and Biosystems Engineering 30, 359–367.
19. Meng, F., Drews, A., Mehrez, R., Iversen, V., Ernst, M., Yang, F., Jekel, M., Kraume, M., 2009. Occurrence, source, and fate of dissolved organic matter (DOM) in a pilot-scale membrane bioreactor. Environmental Science and Technology 43, 8821–8826.

20. Mikkelsen, L.H., Keiding, K., 2002. Physico-chemical characteristics of full scale sewage sludges with implications to dewatering. Water Research 36, 2451–2462.
21. Ng, H.Y., Tan, T.W., Ong, S.L., 2006. Membrane fouling of submerged membrane bioreactors: impact of mean cell residence time and the contributing factors. Environmental Science and Technology 40, 2706–2713.
22. Ng, C.A., Sun, D., Bashir, M.J.K., Wai, S.H., Wong, L.Y., Nisar, H., Wu, B., Fane, A.G., 2013. Optimization of membrane bioreactors by the addition of powdered activated carbon. Bioresource Technology 138, 38–47.
23. Ngo, H.H., Nguyen, M.C., Sangvikar, N.G., Hoang, T.T.L., Guo, W.S., 2006. Simple approaches towards the design of an attached-growth sponge bioreactor (AGSB) for wastewater treatment and reuse. Water Science and Technology 54, 191–197.
24. Ngo, H.H., Guo, W.S., Xing, W., 2008. Evaluation of a novel sponge-submerged membrane bioreactor (SSMBR) for sustainable water reclamation. Bioresource Technology 99, 2429–2435.
25. Ngo, H.H., Guo, W.S., 2009. Membrane fouling control and enhanced phosphorus removal in an aerated submerged membrane bioreactor using modified green bioflocculant. Bioresource Technology 100, 4289–4291.
26. Nguyen, T.T., Ngo, H.H., Guo, W.S., Li, J.X., Listowski, A., 2012. Effects of sludge concentrations and different sponge configurations on the performance of a sponge-submerged membrane bioreactor. Applied Biochemistry and Biotechnology 167, 1678–1687.

27. Pan, J.R., Su, Y.C., Huang, C., Lee, H.C., 2010. Effect of sludge characteristics on membrane fouling in membrane bioreactors. Journal of Membrane Science 349, 287–294.
28. Reid, E., Liu, X., Judd, S.J., 2008. Sludge characteristics and membrane fouling in full-scale submerged membrane bioreactors. Desalination 219, 240–249.
29. Shen, Y.X., Xiao, K., Liang, P., Sun, J.Y., Sai, S.J., Huang, X., 2012. Characterization of soluble microbial products in 10 large-scale membrane bioreactors for municipal wastewater treatment in China. Journal of Membrane Science 415–416, 336–345.
30. Tian, Y., Chen, L., Zhang, S., Cao, C., Zhang, S., 2011. Correlating membrane fouling with sludge characteristics in membrane bioreactors: An especial interest in EPS and sludge morphology analysis. Bioresource Technology 102, 8820–8827.
31. Wei, C.H., Huang, X., Aim, R.B., Yamamoto, K., Amy, G., 2011. Critical flux and chemical cleaning-in-place during the long-term operation of a pilot-scale submerged membrane bioreactor for municipal wastewater treatment. Water Research 45, 863–871.
32. Wu, J., He, C., 2012. Effect of cyclic aeration on fouling in submerged membrane bioreactor for wastewater treatment. Water Research 46, 3507–3515.
33. Yang, Q.Y., Chen, J.H., Zhang, F., 2006. Membrane fouling control in a submerged membrane bioreactor with porous, flexible suspended carriers. Desalination 189, 292–302.
34. Yao, M., Ladewig, B., Zhang, K., 2011. Identification of the change of soluble microbial products on membrane fouling in membrane bioreactor (MBR). Desalination 278, 126–131.

35. Yigit, N.O., Harman, I., Civelekoglu, G., Koseoglu, H., Cicek, N., Kitis, M., 2008. Membrane fouling in a pilot-scale submerged membrane bioreactor operated under various conditions. Desalination 231, 124–132.

Table Titles

Table 1 Removal efficiency of DOC, COD, PO_4-P, NH_4-N and TN in SSMBR and CMBR during the operation period.

Table 2 SMP compositions and total SMP concentrations of mixed liquor in SSMBR and CMBR at two different stages (within and after 7 days of operation) during the operation period.

Table 3 Bound EPS compositions and total bound EPS concentrations of mixed liquor in SSMBR and CMBR at two different stages (within and after 7 days of operation) during the operation period.

Table 1
Removal efficiency of DOC, COD, PO_4-P, NH_4-N and TN in SSMBR and CMBR during the operation period.

Reactors	DOC (%)	COD (%)	PO_4-P (%)	NH_4-N (%)	TN (%)
SSMBR	94.74 ± 5.49	93.53 ± 4.46	63.57 ± 5.32	74.35 ± 3.22	53.28 ± 2.16
CMBR	94.17 ± 7.32	91.95 ± 6.53	27.22 ± 6.18	58.14 ± 6.13	37.20 ± 4.58

Table 2
SMP compositions and total SMP concentrations of mixed liquor in SSMBR and CMBR at two different stages (within and after 7 days of operation) during the operation period.

Day	Reactor	SMP			
		PN[a] (mg/L)	PS[b] (mg/L)	PN/PS ratio	SMP (mg/L)
Stage I (Day 1-7)	SSMBR	9.9-10.2	7.2-9.4	1.1-1.4	7.4-17.4
	CMBR	10.6-10.8	13.5-14.4	0.7-0.8	24.1-25.2
Stage II (After day 7)	SSMBR	1.0-4.4	1.0-6.9	0.3-2.3	1.5-9.2
	CMBR	0.4-5.7	1.0-5.8	0.1-3.2	1.1-9.8

[a] PN, proteins; [b] PS, polysaccharides

Table 3
Bound EPS compositions and total bound EPS concentrations of mixed liquor in SSMBR and CMBR at two different stages (within and after 7 days of operation) during the operation period.

Day	Reactor	Bound EPS			
		PN[a] (mg/L)	PS[b] (mg/L)	PN/PS ratio	Total EPS (mg/L)
Stage I (Day 1-7)	SSMBR	7.4-9.9	9.4-11.8	0.6-1.1	19.2-19.3
	CMBR	9.3-9.9	1.0-9.4	4.7-9.3	10.3-19.3
Stage II (After Day 7)	SSMBR	9.8-10.6	1.6-7.5	1.3-6.6	12.2-17.3
	CMBR	6.5-10.1	5.8-14.5	0.7-1.4	12.3-24.6

[a] PN, proteins; [b] PS, polysaccharides

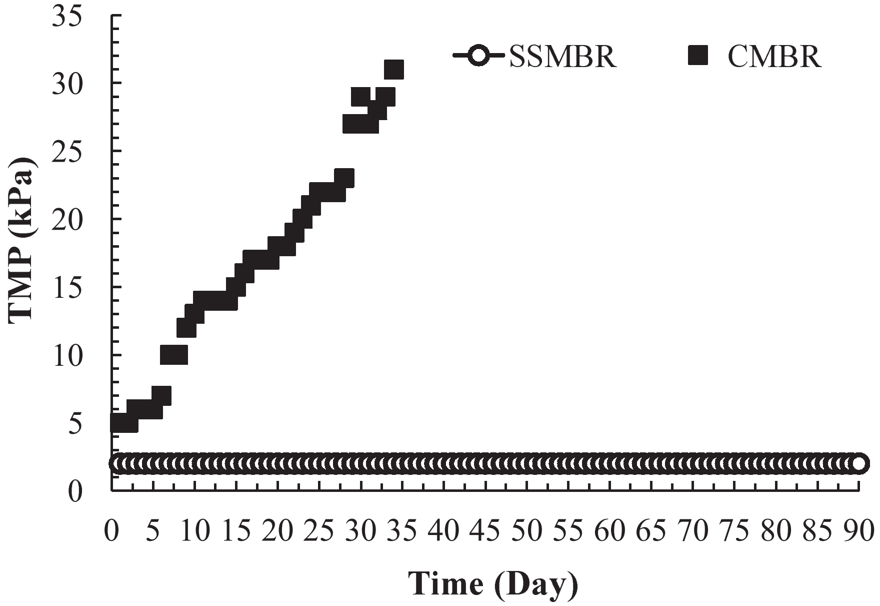
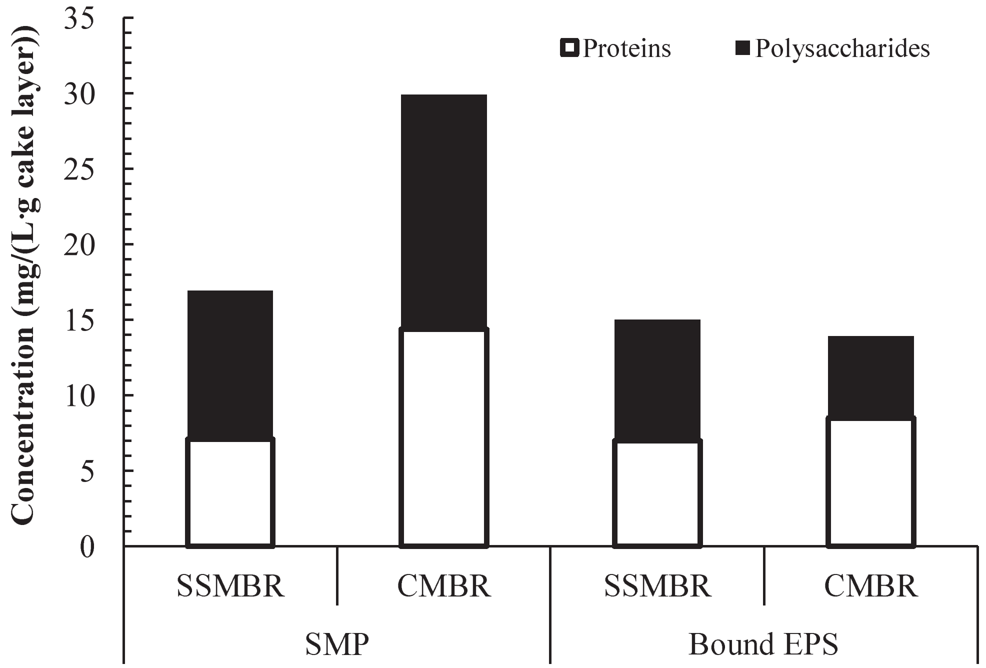

TMP (kPa)
35
30
25
20
15
10
5
0
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
Time (Day)
SSMBR
CMBR

Fig. 1.



Concentration (mg/(L·g cake layer))
35
30
25
20
15
10
5
0
Proteins
Polysaccharides
SSMBR
CMBR
SSMBR
CMBR
SMP
Bound EPS

Fig. 2.

Highlights

- Less SMP and bound EPS in activated sludge in the SSMBR induced lower R_C and R_P.
- Lower biomass growth and sludge viscosity contributed to lower R_C in the SSMBR.
- Larger sludge flocs, higher zeta potential and RH led to lower R_T in the SSMBR.
- Sponge could prevent pore blocking and cake layer formation.
- Sponge addition could reduce SMP_C and EPS_C through adsorption and biodegradation.