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Using adsorbent made from sewage sludge to enhance wastewater treatment and control fouling in a membrane bioreactor

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ABSTRACT

An adsorbent prepared from rich carbonaceous sewage sludge was added to membrane bioreactors (MBRs). The efficiency of wastewater treatment and membrane fouling were compared for a standard MBR, a reactor with additional sludge-based adsorbent (SBA)-MBR, and powdered activated carbon (PAC)-MBR. The removal efficiencies for dissolved organic carbon (DOC) and UV_{254}, the heavy metal contents of effluent, extracellular polymeric substances (EPS), soluble microbial products (SMP), the sludge particle size, and the trans-membrane pressure of the three reactors were monitored for more than 100 d. The wastewater treatment efficiency of SBA-MBR (UV_{254}: 58.5%; DOC: 88.8%) was similar to that of PAC-MBR (UV_{254}: 62.3%; DOC: 90.1%) and better than MBR (UV_{254}: 47.8%; DOC: 85.9%). Moreover, SBA-MBR showed least membrane fouling. The findings are explained as follows: In SBA-MBR, the contents of EPS and SMP, which led to membrane fouling, were relatively low; the sludge comprised dense flocs of relatively large size; higher Fe and Al contents in SBA preferentially absorbed the colloid substances and EPS, and limited the adhesion of contaminants to the membrane surface.

Keywords: Sludge-based adsorbent; Membrane bioreactor; Membrane fouling control; Extracellular polymeric substances; Soluble microbial products; Wastewater treatment

1. Introduction

Membrane bioreactors (MBRs), combining biologically activated sludge processing with solid–liquid separation by membrane filtration, are a popular technology for wastewater treatment to comply with increasingly stringent environmental regulations [1]. However, such MBRs can be susceptible to membrane fouling during filtration, which greatly decreases filtration flux and increases the frequency of membrane cleaning procedures [2,3]. Consequently, these shortcomings may lead to increased investment and operational costs, and ultimately constrain its application and commercialization.

Various methods have been tested to reduce membrane fouling in MBRs, such as coagulation/flocculation [4] and addition of powdered activated carbon (PAC) [5,6]. Previous studies reported that the addition of PAC could provide excellent removal of organic compounds, reduce the direct loading of dissolved organic contaminants onto the membrane, and mitigate membrane fouling [7].

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Although acceptable results have been obtained in laboratory- and pilot-scale tests, PAC addition in MBR has few practical applications because of its high maintenance costs and generally high PAC dosages [8].

Due to rapid urbanization and the implementation of stringent effluent standards for municipal wastewater treatment in recent decades, sewage sludge is increasingly being generated all over the world, thereby necessitating eco-friendly methods for its utilization. One approach involves using sludge to prepare adsorbent; this is subsequently reused in wastewater treatment for pollutant removal, as it is carbonaceous in nature and rich in organic materials. The material is not only much cheaper to produce than commercially available activated carbon, but also has wider applications, such as absorbing different dyes, organic compounds, and heavy metals, and exhibits excellent effectiveness [9]. The present authors previously studied sludge-based adsorbent (SBA) for wastewater treatment, and found that SBA had similar efficiency as PAC for removing organics from wastewater [10]. To the authors' knowledge, there are no published studies on the addition of SBA to a MBR for wastewater treatment.

The purpose of this project is to study the efficiency of inexpensive SBA material for removing pollutants from wastewater in a MBR, and to investigate the control of membrane fouling in a SBA-MBR.

2. Materials and methods

2.1. Sludge-based adsorbent

SBA was prepared from chemically enhanced primary treatment (CEPT) sludge, by chemical activating via zinc chloride. The CEPT sludge was dried at 103˚C to reduce water content until the level of less than 5%. The dried sludge was ground and sieved ($d < 0.1$ mm), and then impregnated in $ZnCl_2$ (3.0 M) with the mass ratio of 1:1. The sludge was kept in contact with the acid in air for 24 h, and then dried at 103˚C in air for another 24 h. Then, the sample was pyrolyzed in a muffle furnace in anaerobic condition, with the increase in temperature to 700˚C at a rate of 18˚C/min, and the final temperature of 700˚C maintained for 1 h. After being pyrolyzed, the product was ground and sieved to powder approximately 0.1 mm and washed with 3.0 M HCl to remove the inorganic impurities. Then, the sample was thoroughly washed with deionized water until the pH of rinsed water became constant. Finally, the sample was dried at 103˚C for 24 h.

2.1.1. Physical characterization

The surface area of SBA was analyzed with a surface area analyzer (ASAP 2020M, Micromeritics Instrument Co.) by using the adsorption isotherms of gas adsorption (N_2, 77 K). The specific surface area (S_{BET}) was calculated by Brunauer–Emmett–Teller (BET) equation [11]. Micropore volume (V_{mi}) was obtained by *t*-plot method [12]. Macropore and mesopore (17.00–3000.00 Å) volume (V_{me+ma}) was calculated by the BJH method [13].

2.1.2. Chemical characterization

The elemental compositions of aluminum and iron were measured by an Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES, Optima 5300DU, Perkin Elmer Inc). To determine the metal contents in SBA, a predigestion was employed to make the metals soluble by soaking 0.3 g of each adsorbent in 8-ml HF and 3-ml HNO_3 at 180˚C for 30 min in a microwave digestion device (Mars-5 CEM, USA). The C and H contents of SBA were measured by Element Analyzer (CHNS-Vario EL).

Physical and chemical characterizations of the materials are shown in Tables 1 and 2. A commercial PAC (Jiangsu province, China; average particle size 0.1 mm) was used as a reference.

2.2. Experimental apparatus

The experimental system consisted of three sets of online, parallel, and bench-scale devices, each with a capacity of 3 L. Inflow to the reactors was controlled by a constant-level water tank. The overall system was controlled by a programmable logic controller (PLC) and a computer. A schematic diagram of the membrane reactors is shown in Fig. 1. The three reactors were, respectively: MBR (without any adsorbent), SBA-MBR (with SBA), and PAC-MBR (with commercial PAC). The ultrafiltration membrane modules (Litree, China) were made of polyvinylchloride (PVC), with a nominal pore size of 0.01 mm and a total membrane area of 0.05 m^2. Filtrate was pumped from the membrane modules through peristaltic pumps. Membrane flux was constant 10 L/(m^2 h) and the relevant hydraulic retention time was 6 h. Sludge retention time in the experiment was limited to 30 d. The operational mode of the three MBRs was to pump for 10 min followed by backwashing for 30 s. A pressure sensor was located between the membrane module and pump to monitor trans-membrane pressure (TMP). An aeration system located at the bottom of

Table 1
Surface and pore characteristics of the adsorbents

Adsorbent	S_{BET} (m^2/g)	Pore diameter (Å)	Micropores volumes (cm^3/g)	Meso(macro)pores volumes (cm^3/g)
SBA	363.0	46.9	0.122	0.269
PAC	1114.7	33.5	0.147	0.390

Table 2
Ultimate analysis and the metal contents of the adsorbents

	Ultimate analysis (%)			Contents of metals (mg/g)		
Adsorbent	C	H	N	Al	Fe	Zn
CEPT sludge	33.4	4.71	5.22	38.8	12.9	0.66
SBA	39.8	3.65	4.78	17.4	7.8	12.9
PAC	70.9	1.69	0.82	3.62	1.96	–

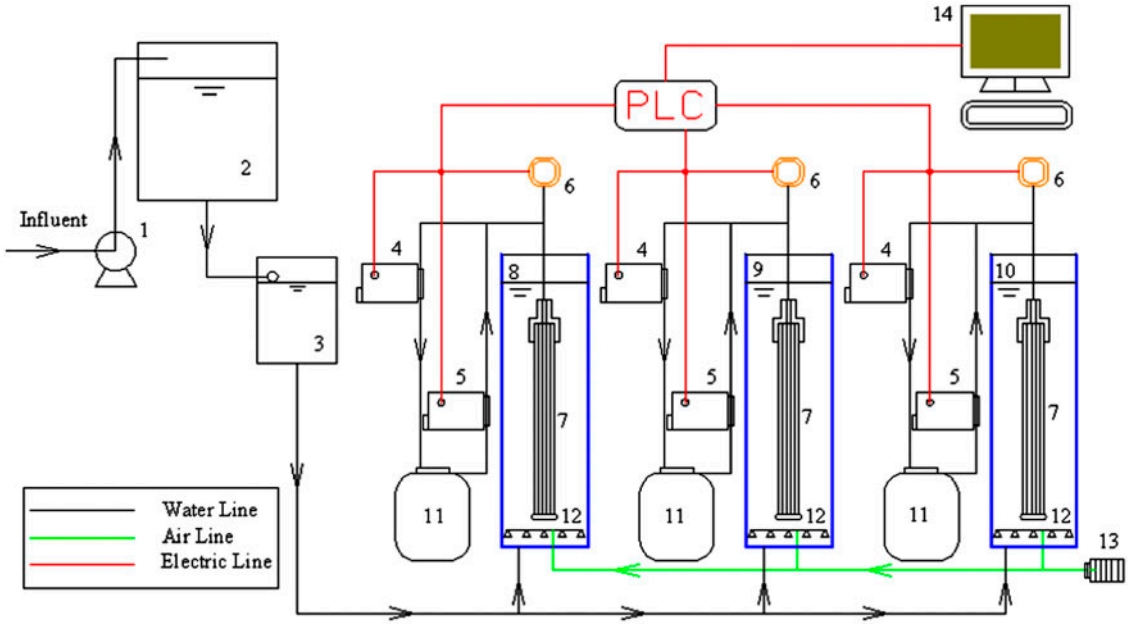
the reactor continually provided the activated sludge with adequate oxygen and strong turbulence to scour the membrane modules. The initial addition of SBA or commercial PAC was 2.0 g/L, and the concentration was maintained during operation of the reactor by timely replenishment of losses. The domestic wastewater (dissolved organic carbon [DOC]: 72.9 ± 6.0 mg/L; UV_{254}: 0.342 ± 0.024 cm^{-1}) under treatment was collected from a schoolyard sewer in a residential district.

The activated sludge was obtained from secondary biological tank of an urban wastewater treatment plant and acclimated in the schoolyard wastewater for one month before the experiments.

2.3. Analysis

2.3.1. Analysis of water samples

UV absorbance at 254 nm (UV_{254}) was determined via a spectrometer (UV754, CANY, China) after the water sample was filtered by 0.45-μm cellulose acetate



1. Feed pump; 2. High-level water tank; 3. Constant level water tank; 4. Suction pump; 5. Backwashing pump; 6. Pressure sensor; 7. Membrane module; 8. MBR; 9. SBA-MBR; 10. PAC-MBR; 11. Water tank; 12. Air diffuser; 13. Aerator; 14. Computer.

Fig. 1. Schematic diagram of the experimental setups.

membrane. A total organic carbon (TOC) analyzer (TOC-VCPN, Shimadzu, Japan) was used to measure DOC. Following membrane filtration, the heavy metal contents of the effluent were measured by ICP-AES.

2.3.2. Characterization of sludge in the reactor

The particle size distribution of the sludge was determined by a laser particle size analyzer (Mastersizer, Malvern Instruments). Extracellular polymeric substances (EPS) and soluble microbial products (SMP) of sludge were extracted by high-speed centrifugation [14]: (1) prepared buffer solution (2-mmol/L Na_3PO_4, 4-mmol/L NaH_2PO_4, 9-mmol/L NaCl, and 1-mmol/L KCl; pH 7); (2) 50 mL of sludge mixed liquid was centrifuged for 10 min at 3,000 rpm; the supernatant was filtered by 0.45-μm Millipore membrane, to derive the filtrate including SMP; (3) buffer solution was added to the sludge mixed liquid to restore the original volume of 50 mL; (4) this liquid was centrifuged (Allegra 64R, Beckman, USA) for 30 min at 12,000 rpm and 4˚C; and (5) supernatant was filtered by 0.45-μm Millipore membrane to give the filtrate including EPS. Anthrone–H_2SO_4 colorimetry was used to determine the carbohydrate content of EPS and SMP [15]. The Folin–Lowry method was used to determine protein [16]. Mixed liquid suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), and sludge volume index (SVI) were measured according to standard methods [17]. The particle morphology of sludge in the mixed liquid was observed by fluorescence photographic microscope (FPM, BX511TF, Olympus Co.) [18].

2.3.3. Characterization of membrane fouling

The morphology of the surface and cross-section of the membrane were observed by scanning electron microscopy (SEM, Hitachi S4800 HSD, Japan) after specific pretreatment [19]. The sludge functional group of the membrane surface was analyzed by Fourier transform infrared spectroscopy (FTIR, PerkinElmer Spectrum One B) via the KBr method [20]. Membrane fouling was characterized by the change in TMP.

3. Results and discussion

3.1. Efficiencies of wastewater treatment

The efficiencies of organic matter removal achieved by mixed liquid sludge, membranes in the three MBRs, and the overall system of MBRs during the 100-d operational period are shown in Tables 3 and 4.

As shown in Table 3, the three MBRs showed similar membrane removal efficiencies (16.3, 17.1, and 20.4%, respectively) for UV_{254}, and the reactors with adsorbents were slightly higher (difference between 1 and 4%). On the other hand, the removal efficiency of mixed liquid in PAC-MBR achieved the highest removal rate (53.2%) for UV_{254}, followed by SBA-MBR (49.6%) and MBR (35.3%). Hence, it was inferred that the difference of total removal efficiencies among the reactors (47.8, 58.5, and 62.3%, respectively) were due to forming of a bio-adsorbent in SBA-MBR and PAC-MBR, which could remove UV_{254} comparatively well.

As shown in Table 4, the DOC removal efficiencies of the three MBRs were 74.6, 79.1, and 82.3%, respectively; whereas, the removal by the membranes were similar, with the efficiencies of 44.6, 45.3, and 42.5%, respectively. The results suggest that the differing removal efficiencies among the reactors mainly depended on the composition of the mixed liquid. The findings suggest that bio-SBA or bio-PAC was formed in SBA-MBR and PAC-MBR, leading to greater capacity for DOC removal.

SBA could absorb micro-organisms, enzymes, and organics in MBR, which intensified microbial metabolism and facilitated proliferation of micro-organisms on the surface of the SBA. Moreover, the organics on the surface of the SBA were able to be degraded by the micro-organisms [21]. Overall, the biological and absorption processes played synergistic roles in removing organic contaminants from wastewater [22]. The reason why the removal efficiency of SBA was lower than that of PAC during the wastewater treatment was that its specific surface area, pore volume, and carbon content were lower than those of PAC (from Tables 1 and 2).

Table 5 shows the heavy metals contents of effluent from SBA-MBR. SBA was chemically activated by $ZnCl_2$; therefore, the zinc content of SBA was very high (12.9 mg/g, as shown in Table 2). It made a concern that the SBA might release hazardous heavy metals during its use in the wastewater treatment. However, when the adsorbent was added to MBR, the Zn content of the effluent was very low, only at 0.31 mg/L. It is possible that the activated sludge absorbed the heavy metal that leached from the SBA in the reactor [23,24]. Other heavy metals were only detected at a lower concentration (see Table 5). The heavy metal concentrations of SBA-MBR effluent were lower than the World Health Organization standard for drinking water quality [25].

Table 3
Removal of UV_{254} by the three MBRs

Reactor	Influent $\times 10^{-2}$ (cm^{-1})	Mixed liquid $\times 10^{-2}$ (cm^{-1})	Removal efficiency by mixed liquid (%)[a]	Effluent $\times 10^{-2}$ (cm^{-1})	Removal efficiency by membrane (%)[b]	Total removal efficiency (%)[c]
MBR	34.2 ± 2.4	22.1 ± 3.1	35.3 ± 9.4	17.9 ± 1.8	16.3 ± 9.8	47.8 ± 4.8
SBA-MBR	34.2 ± 2.4	17.3 ± 4.4	49.6 ± 12.4	14.2 ± 3.2	17.1 ± 10.8	58.5 ± 9.2
PAC-MBR	34.2 ± 2.4	16.0 ± 4.1	53.2 ± 11.4	13.0 ± 2.8	20.4 ± 11.5	62.3 ± 7.6

[a]Difference between influent and mixed liquid/influent.
[b]Difference between mixed liquid and effluent/mixed liquid.
[c]Difference between influent and effluent/influent.

Table 4
Removal of DOC by the three MBRs[a]

Reactor	Influent (mg/L)	Mixed liquid (mg/L)	Removal efficiency by mixed liquid (%)	Effluent (mg/L)	Removal efficiency by membrane (%)	Total removal efficiency (%)
MBR	72.9 ± 6.0	18.6 ± 1.8	74.6 ± 3.2	10.2 ± 1.4	44.6 ± 8.8	85.9 ± 2.2
SBA-MBR	72.9 ± 6.0	15.2 ± 2.5	79.1 ± 3.7	8.19 ± 1.31	45.3 ± 7.5	88.8 ± 1.5
PAC-MBR	72.9 ± 6.0	13.0 ± 2.8	82.3 ± 4.0	7.25 ± 1.18	42.5 ± 8.9	90.1 ± 1.3

[a]The calculation as Table 3.

3.2. Characteristics of sludge in three MBRs

3.2.1. Mixed liquid suspended solids

The concentrations of MLSS in the three MBRs were shown in Fig. 2. It could be seen that the initial concentration of MLSS in three MBRs was 3 g/L, and then rose to a steady concentration of approximately 4 g/L after 25 d. MLSS of SBA-MBR and PAC-MBR were slightly higher than that of MBR, which was mainly contributed to more adsorption surface area for micro-organisms to grow after adding the adsorbents

3.2.2. Sludge volume index

Fig. 3 shows the change of SVI in the three MBRs during operation. The SVI of MBR was between 90 and 110 mL/g, whereas those of SBA-MBR and PAC-MBR were lower, at 50–60 mL/g and 60–70 mL/g, respectively. The reason for this might be that the activated sludge had better settling characteristics since less compressible flocs were formed in the reactor after the addition of SBA or PAC [26]. Some studies indicated that activated sludge settled better after the addition of commercial activated carbon [27,28]. Moreover, the SVI of SBA-MBR was lower than that of PAC-MBR, indicating greater sludge settlement and stronger dehydration ability in SBA-MBR. This might be attributed to that SBA contained more amount of iron and aluminum metal compounds; the metal

Table 5
Heavy metals contents of SBA-MBR effluent (mg/L)

Metal	As	Cd	Cr	Cu	Pb	Zn
Effluent	–	–	0.038	0.017	–	0.31

Note: "–" equals "had not been detected".

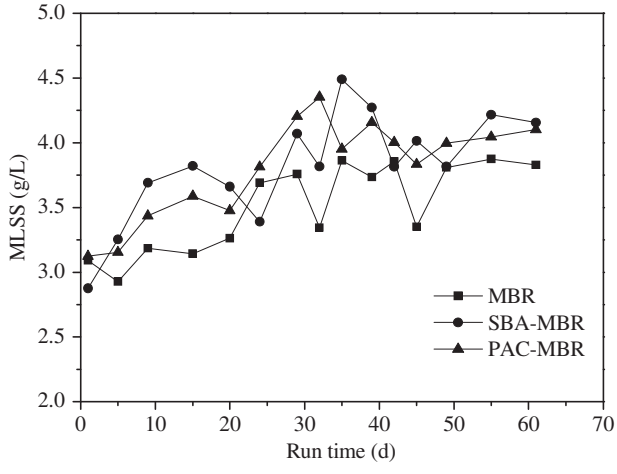


Fig. 2. MLSS in the three MBRs.

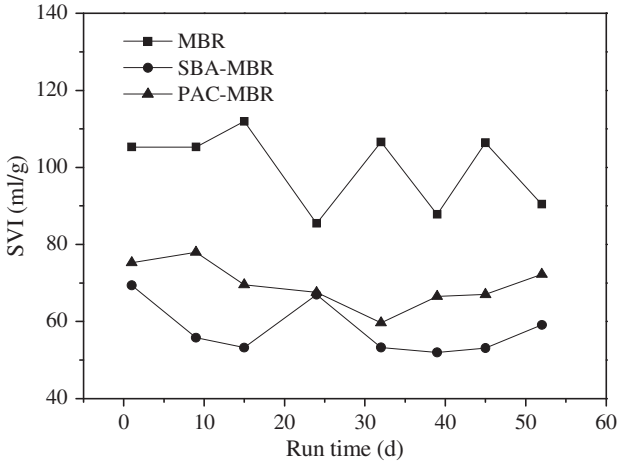


Fig. 3. SVI in the three MBRs.

compounds of SBA performed the function as coagulant, which enhanced microbes to flocculate around SBA as the central core, producing a denser floc structure and giving the sludge greater incompressibility and precipitation.

3.2.3. Morphology and size distribution of sludge particles

Fig. 4 shows FPM images of the sludge particles in each reactor. It can be seen that those in SBA-MBR and PAC-MBR are larger than that in MBR, which supports the findings of Kim and Lee [29] and Cao et al. [30]. For the sludge particles in SBA-MBR and PAC-MBR, it can clearly be observed that SBA or PAC particles were embedded to constitute the framework of the flocs. Table 6 shows the sludge particle size distribution in the mixed liquid of the three MBRs. SBA-MBR with addition of SBA had the largest particle size and the widest size distribution, followed by PAC-MBR and MBR.

As the result of the absorption of SBA or PAC as well as biological adhesion properties, these adsorbents, as a central core particle, were wrapped by free micro-organisms and some colloidal substances. Further biological reproduction increased the secretion of extracellular polymers. Since more extracellular polymers intertwined together irregularly, the flocs would coagulate and increase in size, with the SBA or PAC as the framework. The larger flocs containing SBA or PAC were able to withstand greater impacts during aeration, thereby avoiding the reduction of sludge particles size and the release of extracellular polymers [31].

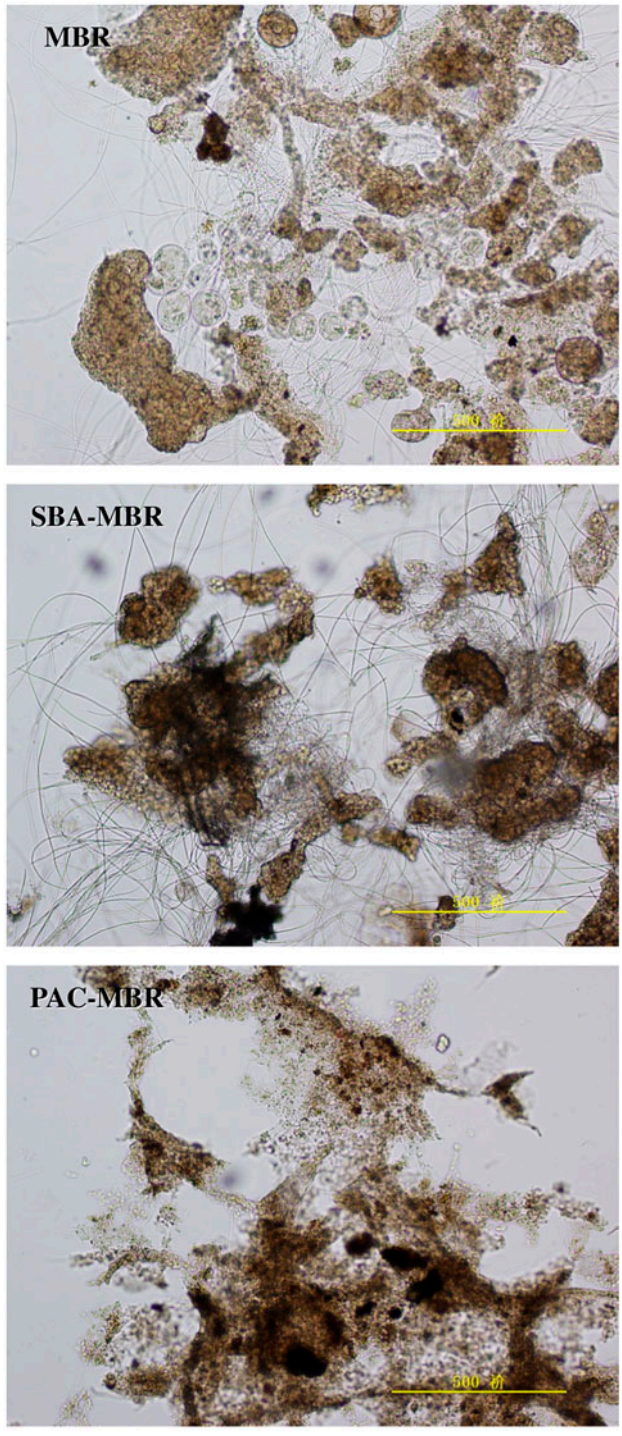


Fig. 4. Sludge particles observed under an optical microscope in the three MBRs.

3.2.4. The content of SMP and EPS

Tables 7 and 8 show the carbohydrate and protein contents of SMP and EPS in mixed liquids of the three MBRs. The carbohydrate contents in the SMP

Table 6
Analysis results of sludge particle size distributions in the three MBRs

Reactor	Particle size (μm)		Particle size distribution (%)				
	Average	Range	<10 μm	10–50 μm	50–100 μm	100–200 μm	>200 μm
MBR	89.5	0.91–477.0	4.52	35.00	38.60	13.80	8.01
SBA-MBR	151.7	0.91–555.7	2.18	12.80	27.60	27.80	29.60
PAC-MBR	127.8	0.91–477.0	2.04	9.73	27.10	33.80	27.40

Table 7
Composition of carbohydrate and protein of SMP in three MBRs

Reactor	Carbohydrate (mg/L)	Protein (mg/L)	Amount of SMP (mg/L)
MBR	37.0 ± 6.6	58.2 ± 9.8	95.2 ± 11.5
SBA-MBR	36.3 ± 6.9	48.7 ± 14.0	85.0 ± 19.6
PAC-MBR	34.0 ± 7.4	43.3 ± 10.9	77.4 ± 17.5

Table 8
Composition of carbohydrate and protein of EPS in three MBRs

Reactor	MBR	Carbohydrate (mg/g MLVSS)	Protein (mg/g MLVSS)	Amount of EPS (mg/g MLVSS)
MBR	MBR1	8.31 ± 3.41	18.7 ± 5.5	27.1 ± 8.2
SBA-MBR	MBR2	6.75 ± 0.82	15.9 ± 9.1	22.6 ± 9.6
PAC-MBR	MBR3	6.60 ± 0.78	17.0 ± 5.0	23.6 ± 5.2

of the three MBRs were similar (Table 7). However, the protein contents in SMP of SBA-MBR and PAC-MBR were lower than that of MBR. Table 8 shows that the carbohydrate content in MBR was higher than that of the other two reactors. The protein contents of EPS in the three MBRs were quite different, being highest in MBR and lowest in SBA-MBR (22.6 mg/g MLVSS).

These results might be due to the absorption effect of adsorbents as well as the degradation of the microorganisms. The adsorbents provide more absorption sites, which might facilitate microbial degradation of organics in wastewater. Subsequently, the degradation of the microbe could reproduce the absorption ability of the adsorbent. These two effects jointly resulted in lower SMP or EPS contents of the mixed liquid compared with the ordinary activated sludge.

3.3. Membrane fouling and contributory factors

3.3.1. Surface contamination of membrane

SEM images of a new membrane and the surfaces and cross-sections of the three MBRs are shown in Figs. 5 and 6. Fig. 5 shows that the new membrane surface was clean and smooth and still had some pores distributed on the surface. However, following operation, the surfaces of the membranes were covered by an uneven gel layer. This gel layer was usually composed of different materials, such as micro-organisms, its excrement and inorganic substances, etc. [32]. Fig. 6 clearly shows the channel structure of the supporting layers of the new membrane surface. However, the membrane surface was covered by a filter cake layer after operation, and the fouling of the internal structure of the membrane extended deeply into the support layer at the bottom of the filter layer. The channel structure of the support layer has become narrower and less apparent.

Fig. 7 shows the FTIR spectrum of the membrane fouling in the three MBRs. The FTIR absorption peaks indicate the presence of some surface functional groups on the membrane. One characteristic peak at 1,650 cm^{-1} was assigned to the stretching vibration of C=O and C–N amide I. Another peak at 1,519 cm^{-1} was assigned to N–H deformation and C=N stretching amide II [27]. The two peaks in the FTIR spectrum indicated the presence of protein in the membrane foulant. The two small peaks at approximately 1,400 cm^{-1} suggest the presence of a phenolic

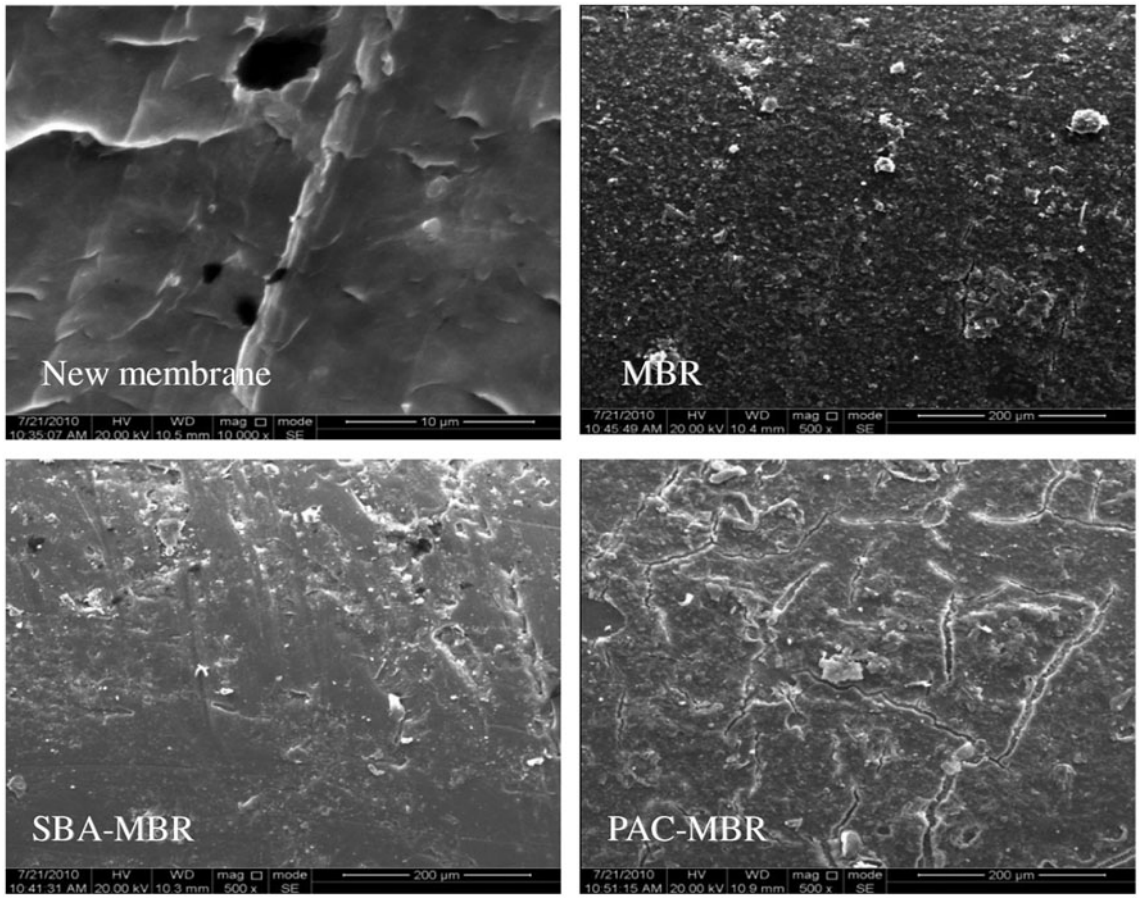


Fig. 5. SEM images of the membranes surface.

compound in the pollutants [33]. Another broader peak appearing at about 1,050 cm^{-1} corresponded to the C–O stretching peak of carbohydrates [34].

3.3.2. Characterization of membrane fouling

The membrane fouling in the reactors was reflected by the changes in TMP, where higher TMP indicated more serious membrane fouling under the same conditions. Fig. 8 represents the changes in TMP throughout the operational period when the three MBRs operated at the same conditions. From Fig. 8, TMP in MBR increased slowly during the first 8 d, after which it increased very rapidly. From 9 to 12 d, TMP increased from −15 to −35 kPa, which was much faster than the first 8 d. Compared with MBR, the TMP of PAC-MBR increased more slowly. It showed a pronounced increase after 11-d operation, and took 15 d to reach −35 kPa, which was 4 d longer than MBR. The TMP of SBA-MBR with addition of SBA showed the slowest increase during operation. It increased relatively slow during the first 16 d and subsequently climbed much faster, displaying an obvious lag phase compared with MBR and PAC-MBR. The results suggest that absorption and flocculation could obviously reduce the direct pollution of the membrane, slow down the progression of membrane fouling, and prolong the membrane cleaning cycle with the addition of SBA.

3.3.3. Control of membrane fouling

3.3.3.1. EPS and SMP. Previous studies reported that EPS was the main cause of membrane fouling [35–37]. Lin et al. [38] considered that EPS was the key biological material to significantly contribute to membrane fouling in MBRs. A study by Nagaoka et al. [39] showed that there was a positive correlation between the content of EPS and the membrane resistance. Some previous investigations reported that SMP had important influence on membrane fouling. SMP readily blocked pores in the membrane and deposited a rigid

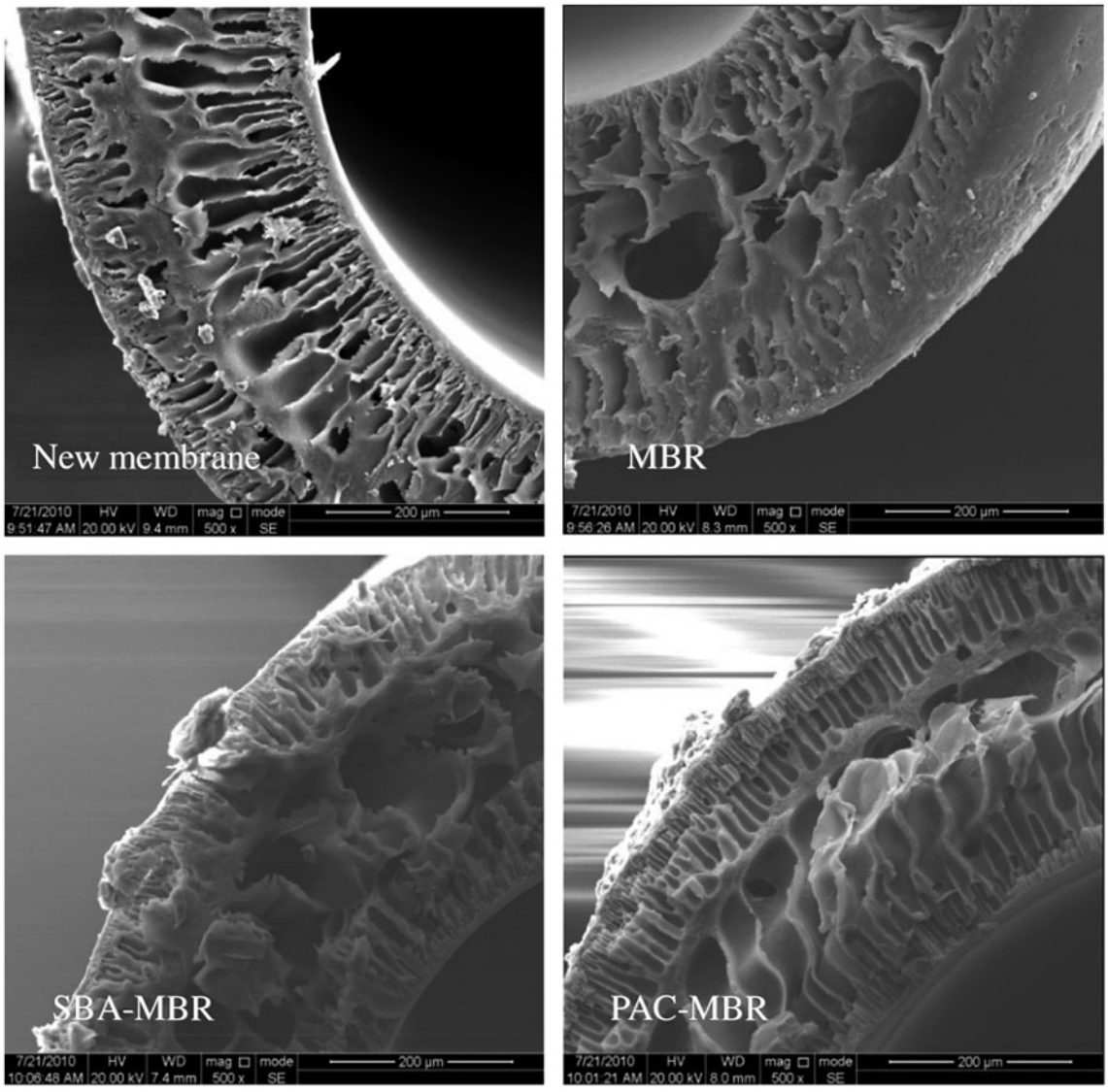


Fig. 6. SEM images of the membranes cross-section.

filter cake layer on the membrane surface [40,41]. Huang et al. [42] studied the accumulation of SMP during a long-term MBR operation. It was found that SMP could not only inhibit microbial metabolism, but also cause organic contaminant to reduce the membrane's filterability. Wisniewski and Grasmick [43] reported that SMP released from the sludge flocs would greatly increase membrane resistance and result in a serious pollution. As shown in Tables 7 and 8, SBA-MBR had relatively low SMP and EPS contents. Therefore, the membrane was subject to relatively little pollution and TMP increased slower, enabling the long-term function of MBR.

3.3.3.2. Sludge particle size. The studies show that the size of sludge particles was closely related to the increase of TMP [44–46]. Smaller particle size was associated with more serious membrane fouling. Sludge particles which were smaller than 50 μm in the MLSS had greater influence on membrane fouling. From Table 6, MBR had the largest fraction of particles smaller than 50 μm (approximately 39.5%) among the three MBRs, whereas the proportions in SBA-MBR (14.0%) and PAC-MBR (11.8%) were much smaller. The results were in accordance with the TMP increase, which increased fastest in MBR, followed by PAC-MBR and SBA-MBR.

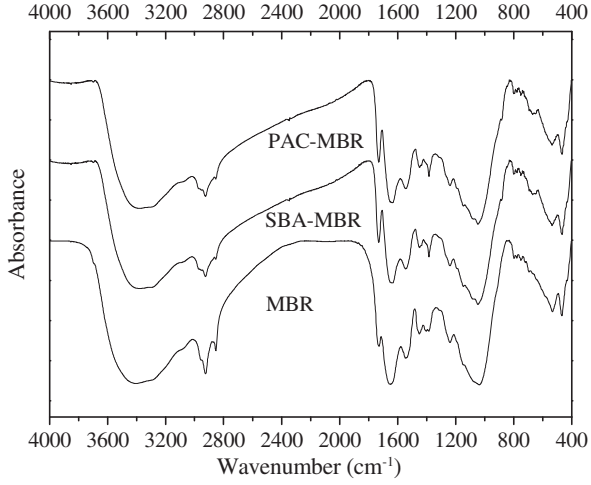


Fig. 7. FTIR spectra of the membranes foulants.

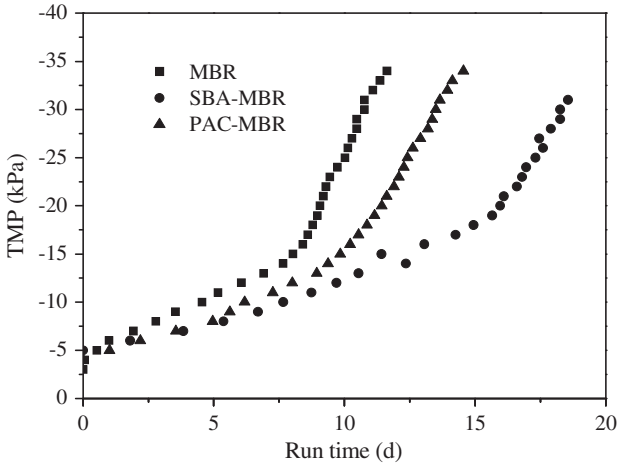


Fig. 8. Variation of TMP in the three MBRs.

3.3.3.3. Iron and aluminum contents. The findings suggest that colloids were the main cause of membrane fouling among the pollutants with different molecular weights, which could directly reduce membrane flux [47–50]. As seen in Table 2, SBA derived from chemical sludge had high contents of iron and aluminum. Previous studies [10] found that SBA with high concentrations of iron and aluminum was highly effective in absorbing suspensions, colloids, dissolved organic substances, etc. The biological SBA absorbed to the colloid substances and EPS in wastewater, which decreased the direct loading of organic contaminant attaching to the membrane surface and reduced the membrane fouling. Furthermore, the bioflocculate with adsorbent (high contents of iron and aluminum) as the central core would become denser, thereby limiting physical breakdown of the flocs structure during aeration. Therefore, membrane pollution in SBA-MBR tended to rise slower than the other two reactors, with the result that SBA-MBR remained longer operational period.

4. Conclusion

SBA-MBR achieved removal efficiencies of 58.5 and 88.8% for UV_{254} and DOC, respectively, which was similar to PAC-MBR and higher than MBR.

The results indicate that absorption and flocculation of the adsorbents could decrease direct pollution to the membrane, slow down the development of membrane fouling, and extend the cleaning circle of the membrane. SBA-MBR was effective in controlling membrane fouling: one was that the sludge had more pronounced sedimentation and could form larger and denser sludge flocs. Another was the lower contents of EPS and SMP. Furthermore, SBA contained high levels of iron and aluminum.

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