Effect and mechanism of reduced membrane bioreactor fouling by powdered activated carbon

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ABSTRACT

Powered Activated Carbon – Membrane Bioreactors (PAC-MBRs) have been used with good results for slightly polluted water treatment. Our batch experiments showed that the transmembrane pressure of a PAC-MBR was 25% less than that of a MBR in one period of test, which indicated that PAC did help control the fouling in MBRs. Based on this observation, several mechanisms of membrane fouling of MBRs and PAC-MBRs were investigated to have some insight into how PAC brought a positive impact. The total resistances decreased by 60% and different resistances were redistributed after adding PAC. The dominant one changed from filtration resistance to cake resistance. These smaller cake resistances resulted from the PAC because, showing in the scanning electron microscopy pictures, it made the cake layer looser and rougher than that on a normal membrane. Meanwhile, the analysis of the membrane eluent showed that the addition of PAC changed the microbial species and its metabolites on the membrane and effectively reduced the adsorption of hydrophilic organic molecules on the membrane surface. Additionally, PAC prevented polypeptide compounds from being trapped inside the pores of membranes, so the cake on the PAC-MBR contaminated membrane surface was easier to scrape off. In the test of cleaning methods, alkaline cleaning removed the most organics from contaminated membranes to restore membrane performance.

Key words | membrane fouling, PAC-MBRs, slightly polluted source water, surface morphologies

HIGHLIGHTS

- Powered activated carbon (PAC) contributed to reducing the cake layer resistance of MBR membranes.
- The addition of PAC decreased the adsorption of hydrophilic organic molecules on the membrane surface.
- PAC changed the microbial species and its metabolites, which were responsible for membrane fouling.
- The PAC-MBR membrane cake layer was easier to remove and its membrane flux recovered faster.

INTRODUCTION

Membrane bioreactors (MBRs), incorporating both biodegradation and membrane interception, have been widely used and employed as an alternative to conventional wastewater treatment processes (Aslam et al. 2017). As for slightly polluted source water, concentrations of organic matter are very low compared to wastewater, which results in limited microbial degradation of soluble organic matter, especially those biodegradable materials having a small molecular weight (Dos Santos & Daniel 2020). Besides, the surface and pores of MBR membranes adsorb many...
suspended particles, colloids, organic matter, microorganisms, and cellular debris (Du et al. 2020). The various molecular weights of biopolymers lead to a combination of reversible and irreversible hydraulic membrane fouling, which can be classified into four categories: colloidal fouling, inorganic fouling, organic fouling, biofouling (Abuabdou et al. 2020). As another pain point of membrane technology, all these kinds of membrane fouling decrease membrane permeability and separation performance (Xia et al. 2015) and increase the pressure on the transmembrane; furthermore, they increase operating costs and instabilities of effluent quality (Shamsuddin et al. 2015). Therefore, it is necessary to study the mechanisms of membrane fouling to reduce its occurrence and mitigate its negative impact on operation.

Facing these two concerns, researchers proposed a combined system—PAC-MBR. Powdered activated carbon (PAC) has a large specific surface area for organic adsorption. In the submerged MBR and PAC hybrid system, physical adsorption, biodegradation of organic matter, membrane interception, and sludge accumulation can be performed in one reactor (Jiang et al. 2020). In recent years, PAC-MBR processes have been used with good results for slightly polluted water treatment (Ma et al. 2012; Nguyen et al. 2014; Alvarino et al. 2017). What’s more, the addition of PAC helps to control the membrane fouling in MBRs. Maxime Remy et al. (2010) reported that strong sludge flocs were formed with incorporated PAC. This strength was particularly important in the vicinity of the membrane surface, where the flocs were exposed to extra shear. It could therefore be expected that less gel-layer formation would occur, which could reduce MBR membrane fouling. In a pilot-scale PAC-MBR, Jiang et al. (2020) reported that PAC was favorable for pollutant removal; meanwhile, the small particles changed the cake layer formation. Similarly, Lei et al. (2019) found that a new gel-like cake layer was observed after the addition of PAC. Kaya et al. (2016) found that the root mean square (RMS) of the average height of membrane surface peaks in atomic form microscopy (AFM) images of a PAC-MBR membrane was close to that of a clean membrane. The highest RMS value was obtained from a fouled membrane without added PAC. In terms of membrane cleaning, many cleaning methods can be applied to remove fouling; for example, in-situ/ex-situ, physical/chemical, and biological/biochemical (Abuabdou et al. 2020). Physical and chemical cleaning was proved to effectively separate out the deposited PAC and fouling layers (Shao et al. 2017; Zhang et al. 2019). Among these related studies, the surface morphologies of contaminated membranes after the addition of PAC have not been well illustrated and the mechanism of how PAC reduces membrane fouling and influences the membrane cleaning are not deeply understood.

In the paper, scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), and AFM were used to investigate differences in membrane fouling between MBRs and PAC-MBRs. Three-dimensional fluorescence and ultraviolet absorbance of organic matter in membrane-side eluates were also analyzed. The data revealed the mechanism by which PAC improves membrane filtration and controls organic fouling. Finally, the effects of various chemical cleaning methods were compared. Overall, this work will provide the technical mechanism of how PAC helps MBRs to control the membrane fouling when treating slightly polluted source water, and will introduce suitable cleaning methods after membrane use.

**MATERIALS AND METHODS**

**Materials**

The raw water for the PAC-MBR was from an artificial lake at Tongji University. It was filled in a special tank once a day and used to dilute domestic sewage used as the feed water for PAC-MBR. This ensured organic matter and ammonia nitrogen content in the system. The domestic sewage to raw water was 1:10. The main water-quality parameters of the influent are listed in Table 1.

**Bench-scaled apparatus**

A schematic of the bench-scale apparatus is illustrated in Figure 1. A MBR was made of plexiglass, with a diameter of 0.08 metre, a height of 0.40 metre, and an effective
The membrane was a bundle of polyvinyl chloride hollow fibers, with a 0.01 μm pore size and a 0.1 m² filtration area. It was provided by Lisheng water purification technology industry Co., Ltd. in Hainan. The feed water entered the reactor through a constant water tank, and the effluent was pumped directly from the membrane module by a peristaltic pump. A vacuum gauge between the membrane module and the peristaltic pump monitored the transmembrane pressure (TMP) difference. At the bottom of the reactor, aerators provided continuous dissolved oxygen; the hydraulic erosion effect of aeration reduced deposition of pollutants on the membrane surface.

**Batch experiments**

During the 100-day test, a time relay was used to control the MBR operation, which had an 8-min intermittent mode of water discharge and 2 min of water stoppage. The controlled membrane filtration flux was 15 litre/m²·h, the finished water output was 1.5 litre/h, the hydraulic retention time was 1 h, and the temperature was 22–30 °C (the normal temperature was 22–26 °C, except on a few hot days). Continuous aeration provided greater than 6.0-mg/l dissolved oxygen in the MBR. During the start-up phase some activated sludge was injected into the reactors, along with spiked glucose, to accelerate the growth of microorganisms in the sludge mixture. PAC (3 g), as microbial carriers, was added into the reactors at one time. The PAC concentration in the reactor was maintained at 2 g/l, and sludge was not discharged. After reactor operation, the membrane modules were removed and soaked for 24 hours in a 300-ml sodium sulfate solution with an ionic strength of 0.1 M. They were then removed and the solution was filtered through a 0.45-μm membrane. The filtrate represented soluble substances on the contaminated membrane surface (Her et al. 2007).

**Chemical analysis**

Water quality analysis was conducted following American Public Health Association (APHA) standard methods (Clescerl et al. 1998). The permanganate index (CODMn) was analyzed via potassium permanganate oxidation. Ammonia nitrogen (NH₄N), nitrite nitrogen (NO₂-N), and UV₂₅₄ were determined by colorimetric methods using a spectrometer (DR5000, HACH, USA). The turbidity was measured with a turbidimeter (2100Q, HACH, USA), and the TOC was measured with a TOC meter (Liqui type II, Elementar, Germany).

The membrane resistance distribution and their relations can be expressed by Darcy’s law in Equations (1) and (2) (Lin et al. 2014):

\[ R = \frac{\text{TMP}}{\mu J} \]  
\[ R_t = R_m + R_p + R_c \]

where \( J \) is filtration flux, and \( \mu \) is dynamic viscosity of permeate.

The four types of resistance were tested as follows (Li et al. 2020): first, the clean membrane was filtered with ultra-pure water when TMP was measured at the same time, and with this value the resistance calculated through the Equation (1) was the membrane inherent resistance \( R_m \); then, the clean membrane was used to filter 200 mL raw water. Meanwhile, the flux was measured and the calculated resistance was the total resistance \( R_t \); after that, the adherent on the membrane surface was wiped off with skinned...
cotton, then the same membrane was used for pure water filtration, the flux was measured, and the calculated resistance value deducted from $R_m$ was the membrane pore blockage resistance $R_p$. Cake resistance $R_c$ was calculated by Equation (2).

Scanning Electron Microscopy (SEM) (TS5136MM, TESCAN, Czech Republic) was used to obtain high-resolution images of film surfaces and cross-sections. The surface morphology of clean and fouled membranes was also analyzed with an AFM (NanoNavi E-sweep, SII, Japan), equipped with a Ultrasharp probe in tapping mode. The scan size was $10 \mu m \times 10 \mu m$ at a 1.77 Hz scan rate.

The filtrate obtained at the end of batch experiments was characterized by three-dimensional fluorescence spectroscopy (Cary Eclipse, Varian, USA). The 200–400 nm excitation range was provided by a xenon lamp. The emission was scanned over 250–580 nm, with 5 nm excitation and emission slit widths. The scanning speed was 12,000 nm·min$^{-1}$.

The sludge sample on the surface of membranes was dried, ground into a powder, and uniformly mixed with powdered potassium bromide. It was then pressed into a pellet for Fourier transform infrared spectroscopy over the range 400–4,000 cm$^{-1}$ (Nicolet 5700, Thermo Nicolet Corporation, USA). The spectrometer was scanned 32 times with 4 cm$^{-1}$ detector resolution. Samples were directly cut from UF membranes in the MBRs and dried at low temperatures to prevent degradation of contaminants in the membrane pores. Infrared scanning was then performed on the samples and compared with spectra of new, clean membranes. The attributions of characteristic peaks from the samples were analyzed with Omnic 7.0.

**Cleaning test**

The cleaning device consisted of a membrane reactor, a vacuum gauge, and a peristaltic pump. The membrane module was immersed in the membrane reactor having a 1.5 l effective volume. The membrane flux during the cleaning test was 20 litre/(m$^2$·h). Before the membrane cleaning, fresh water was filtered with the membrane module to remove loose cake layers on the membrane surface. The cleaning test was as follows. (1) The membrane module that was cleaned with fresh water was subjected to constant flux filtration with deionized water for 30 minutes, and the pressure value was recorded to monitor membrane filtration resistance. At the end of the first stage, several membranes were cut off for characterization, and openings in the membrane module were sealed with AB glue. (2) The filtrate in the membrane pool was replaced with chemical cleaning solution and the membrane was cleaned for 1 h. Then, the membrane filtered deionized water again and the TMP was recorded. At the end of the cleaning stage, several membranes were cut off for characterization. (3) The resistance of the membrane after chemical cleaning was determined.

Two cleaning tests were performed and compared with distilled water. The chemical cleaning agents and cleaning sequences were:

1. Acid cleaning: 2% citric acid solution cycle-cleaning for 1 h, followed by deionized water backwashing for 30 min.
2. Alkaline cleaning: mixture of 1 mol/l NaOH solution and 0.05% NaClO solution cycle-cleaning for 1 h, followed by deionized water backwashing for 30 min.

**RESULTS AND DISCUSSION**

**Differences in TMP between MBR and PAC-MBR**

TMP is a key parameter for indicating membrane fouling. (Woo et al. 2016) The rate of fouling can be reflected by TMP variances during operation at a constant flux. The TMPs for both MBR and PAC-MBR membranes were recorded in a period of 100 days, plotted in Figure 2. The MBR TMP increased faster from 0.005 MPa to 0.048 MPa over 70 days of operation, while the PAC-MBR TMP increased only from 0.005 MPa to 0.038 MPa during the same period. At the end of the batch experiments, the TPM of membranes in the PAC-MBR was 25% less than that in the MBR. Similar fouling rate was also recorded in the publication (Zhang et al. 2015) when treating micro-polluted surface water. Thus, the MBR membrane fouled faster than the PAC-MBR.
relative to that in the PAC-MBR, indicating that PAC can mitigate membrane fouling, reduce the fouling rate and furthermore, the frequency of physical and chemical cleaning.

Membrane resistance distribution and SEM imaging of contaminated membrane surfaces

TMP is directly related to the total resistance ($R_t$) against membrane permeability, which can be classified as the sum of membrane filtration resistance ($R_m$), pore blocking resistance ($R_p$), and cake resistance ($R_c$).

The membrane resistance distributions in two reactors were illustrated over the same operating time (Table 2) and under the same TMP condition (Table 3). In Table 2, $R_t$ in both reactors increased with time, and was always larger in the MBR than in the PAC-MBR. In Table 3, when the TMP was 45 kPa, $R_c$ and $R_p$ in the MBR reactor accounted for 58 and 17% of $R_t$, respectively. Thus, the decreased MBR membrane flux was mainly due to increased $R_c$. The addition of PAC significantly reduced $R_c$ by 22% and $R_p$ by 6%, which accounted for $R_m$ becoming the main component of membrane resistance. Adding PAC could significantly reduce $R_c$, thus greatly reducing the decline in membrane flux.

The fouling resistance increased with fouling layer compactness. Therefore, morphologies of the external foulants could explain the difference in external fouling resistance between the PAC-MBR and the MBR membranes (Shao et al. 2014). At the end of reactor operation, the nanoscale morphologies of two MBR membranes and one new membrane were imaged with a SEM, as illustrated in Figure 3. The surface of the new membrane was regular and smooth. In contrast, the two contaminated membrane surfaces had deposited microorganisms and EPS forming a rough and irregular cake layer. Furthermore, images of fracture surfaces indicated that a thicker cake layer was formed after the PAC was added. The investigation of Jiang et al. (2020) showed that one component of the cake layer was deposited PAC. In this case, it is worth using the PAC with large sizes to prevent this deposition.

AFM imaging of contaminated membrane surfaces

The fracture surface SEM images of the contaminated membranes (Figure 5) and the membrane resistance distributions (Table 3) in the two reactors revealed that the addition of PAC increased the cake layer thickness on the membrane surface. However, $R_c$ did not increase, but was greatly reduced instead. Hence, it had no direct proportional relationship with the thickness of the cake layer, and only correlated with aggregation of pollutants on the membrane surface. Therefore, to further understand the relationship between membrane filtration performance and cake layer thickness, three-dimensional imaging of the contaminated membrane surfaces from the two reactors was performed with AFM. This enabled analysis and characterization of the microscopic surface of the cake layer, as shown in Figure 4. The fracture shape of the cake layer in the MBR membrane was denser and the pores were smaller; that is the cake layer formed by the sludge in the MBR reactor was compacted. This was mainly because a large amount of EPS and microbial metabolites were deposited inside the cake layer, even though the 2,089 nm cake layer of PAC-MBR membrane was thicker than the 765 nm layer on the MBR membrane. These results were opposite to those of Yasemin Kaya (Kaya et al. 2016). But the PAC-MBR cake layer was loose, with large peak-to-peak intervals, and there were a large number of holes in the layer for better permeability. Thus, the addition of PAC changed the structure of the cake layer on the membrane surface. It improved permeability, slowed the fouling rate, and slowed the TMP increase under constant flux conditions.

Three-dimensional excitation and emission matrix fluorescence analysis and specific UV absorbance analysis of membrane eluent

Natural organic matter is generally considered as one of the most problematic membrane foulants because of its complex components such as humic substances, polysaccharides, proteins, and lipids (Xing et al. 2018). Three-dimensional

| Time(d) | Membrane total resistance $R_t$ during the operation period |
|---------|-------------------------------------------------------------|
| Time(d) | MBR | PAC-MBR |
| 63      | 4.20E + 11 | 3.50E + 11 |
| 84      | 5.50E + 11 | 3.80E + 11 |
| 96      | 6.00E + 11 | 4.50E + 11 |

| Reactors | $R_m$ | $R_c$ | $R_p$ | $R_t$ |
|----------|------|------|------|------|
| MBR      | 1.54E + 11 | 3.50E + 11 | 1.01E + 11 | 6.05E + 11 | 11(25%) | 11(58%) | 11(17%) | 11(100%) |
| PAC-MBR  | 1.20E + 11 | 0.80E + 11 | 0.26E + 11 | 2.30E + 11 | 11(53%) | 11(56%) | 11(11%) | 11(100%) |
fluorescence analysis was used to analyze the contaminated membrane eluent, as shown in Figure 5. The peak fluorescence position of the dissolved organic matter was similar for the two reactors. For further comparison, the spectroscopic parameters for the contaminants on two membranes are listed in Table 4, where there were four fluorescence regions for the eluents. The representative organic substances were aromatic proteins (region A), fulvic acid (region B), quasi-soluble microbial by-products (region C), and quasi-humic acids (region D) (Wang et al. 2009). The highest peak fluorescence mainly appeared in region A, while those of regions B and C were similar. In addition, the contaminated eluent fluorescence peak was blue-shifted relative to the influent fluorescence peak. The peak intensities of several substances in the PAC-MBR were slightly larger than those in the MBR. This indicated that the PAC changed the microbial species, and its metabolites, responsible for membrane fouling. This kind of

Figure 3 | SEM images of surfaces (a,b,c) and fracture surfaces (d,e,f) of new and contaminated membranes: (a,d) new membrane; (b,e) MBR membrane; (c,f) PAC-MBR membrane.
results matched those found by other researchers (Zhang et al. 2019; Asif et al. 2020), proving that PAC enriched the dominant bacteria responsible for pollutant removal and the growth of more than 20 genera for nitrifying and denitrifying.

The specific ultraviolet absorbance (SUVA) represents the UV absorbance of a unit organic matter, where SUVA = UV<sub>254</sub>/TOC. This can be used to characterize the hydrophilicity and hydrophobicity of organics in water samples. Previous work (Edzwald & Tobiason 1999) has suggested that when SUVA < 2 litre/(mg·m), the organic matter was mainly small hydrophilic molecules from non-humic substances. When SUVA was 2–4 litre/(mg·m), the organic matters was mainly hydrophobic and hydrophilic humic organics. When SUVA > 4 litre/(mg·m), the organic matter was mainly hydrophobic macromolecular humus. As presented in Table 4, the proportion of small hydrophilic molecules in feed water was relatively large, the eluent from the MBR membrane was mainly hydrophobic and hydrophilic humic substances, and that from the PAC-MBR membrane was mainly hydrophobic humus. This was because the PAC could remove hydrophilic organics in the feed water, resulting in increased hydrophobic organics in the sample.

Infrared analysis of contaminated membrane surface

Properties of contaminants on the membrane surface were identified using FT-IR, as shown in Figure 6. The characteristic functional groups of the contaminants in cake layers on the surface of the two contaminated membranes had similar infrared absorption characteristics, although different intensities. This suggested that the UF membranes in the two reactors exhibited relatively consistent material retention but had different amounts of trapped material. The presence of a broad absorption peak at 3,307 cm<sup>-1</sup> indicated the presence of ≡CH functional groups in the cake layer. The peak at 2,928 cm<sup>-1</sup> in the saturated region and the peak at
1,038 cm\(^{-1}\) in the fingerprint absorption band were C-H and C-O stretching vibrations, respectively (Alkim et al. 2017). These saturated structures were mostly in polysaccharides and amino sugars. In the cake layer of the PAC-MBR membrane, there were two peaks typical of protein secondary structures at 1,649 cm\(^{-1}\) (amide I band, C=O) and 1,550 cm\(^{-1}\) (amide II band, C-N+NH) (Kumar et al. 2006). In contrast, the protein peptide bond band in the MBR cake layer was weak. This was consistent with the fact that the DOC content and the UV\(_{254}\) from the surface of the PAC-MBR membrane was higher than that of the MBR membrane.

It was also found that the peak position of the cake layer was mainly concentrated below the saturated bond region at 3,000 cm\(^{-1}\) (Coates 2006). This indicated that the MBR had the best retention of polysaccharides and amino sugars, followed by protein and aliphatic organics. Combined with the three-dimensional fluorescence characteristics of the influent and eluent, the contents of aromatic groups and fulvic acids appeared high in the influent, while removal of proteins with aromatic groups and tryptophan was best. Therefore, the weaker peaks of protein peptide bonds in the cake layer scraped off the MBR membrane surface did not indicate that the MBR membranes were less contaminated. Instead, it suggested that polypeptide compounds may be more trapped inside the pores of the MBR membrane. Thus, proteins in the cake layer obtained by the physical scraping method were correspondingly weaker in the infrared spectrum. The cake on the PAC-MBR contaminated membrane surface was easier to scrape off because of its structure, resulting in a relatively strong infrared absorption peak. This was consistent with the conclusions in Sections 3 that the PAC-MBR membrane cake layer was easier to remove and its membrane flux recovered faster.

**Effect of PAC on membrane chemical cleaning**

Excessive membrane fouling not only can increase the power required for membrane filtration, but also is one of the major contributors to the operating cost and maintenance of membranes (Abuabdou et al. 2018). Therefore, an

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**Table 4** | Fluorescence spectral and SUVA parameters of influent and membrane eluent in two reactors

| Sample   | Influent (mg/L) | MBR membrane eluent | PAC-MBR membrane eluent |
|----------|----------------|----------------------|-------------------------|
| DOC      | 4.37           | 3.63                 | 3.24                    |
| UV       | 0.077          | 0.137                | 0.305                   |
| SUVA     | 1.76           | 3.77                 | 9.41                    |
| Region A | Ex/Em          | 225/338              | 230/320                 | 230/336                 |
|          | Intensity      | ——                   | 43.2                    | 55.8                    |
| Region B | Ex/Em          | 235/382              | 220/410                 | 220/410                 |
|          | Intensity      | ——                   | 28.1                    | 29.1                    |
| Region C | Ex/Em          | 280/342              | 280/328                 | 280/338                 |
|          | Intensity      | ——                   | 32.2                    | 33.4                    |
| Region D | Ex/Em          | 330/432              | 330/416                 | 310/426                 |
|          | Intensity      | ——                   | 19.6                    | 20.1                    |

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**Figure 5** | Three-dimensional fluorescence spectra of MBR and PAC-MBR membrane eluents.

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effective method to remove membrane fouling needs to be developed. Here, the effects of different chemical agents on cleaning contaminated MBR and PAC-MBR membranes were investigated, and the effects of PAC on membrane chemical cleaning were explored.

When the membrane filtration resistance increased in the two reactors, the TMP grew to 60 kPa. At this point, the filtration was stopped and membrane cleaning was performed. Changes in the TMP of the two reactors were measured after cleaning, as shown in Figure 7. The TMPs of both reactors were reduced from 60 kPa to 50 kPa after deionized water washing, which indicated that physical rinsing improved membrane filtration. A slightly better TMP recovery was observed after acid cleaning, while alkaline cleaning was the most effective way to reduce resistance. Furthermore, adding PAC led to better cleaning in both chemical methods.

At the end of each cleaning stage, fractures of contaminated membranes were imaged by SEM, as shown in Figure 8.

In the six SEM images of Figure 8, there were no substantial contaminants on the membrane outer surfaces after washing with deionized water; however, a thick layer of particulate contaminants remained in the hollow-fiber pores. The layer was thicker in MBR membranes than that in the MBR-PAC membranes, which revealed that the deionized water backwash could not effectively remove pollutants from inside the membrane. After acid cleaning, the fouling inside the membrane pores decreased to a relatively large degree in both reactor membranes, which indicated that the citric acid solution cleaned the hollow fiber membrane pores. After alkaline cleaning, the membrane pores in the two reactors were clearly visible, especially in the PAC-MBR. It was concluded that alkaline cleaning removed membrane contaminants more effectively than did acid cleaning. The purpose of acid washing is to eliminate inorganic fouling (crystals) (Wang et al. 2014); while the reaction duration in our batch experiment was not long enough to form crystals, so the alkaline cleaning, which can remove organic foulants (Wang et al. 2014), was more suitable for our PAC-MBR. The interpretation might be that the protein peptide bond band in the PAC-MBR cake layer was evident, so these protein foulants reacted with alkaline solution and changed to negatively charged, while weakening the bonding force between fouling and membrane surface materials, thus promoting their solubility and molecular repulsion (Zheng et al. 2018).

CONCLUSION

The batch tests showed that the PAC did help to reduce the membrane fouling in MBRs. Even if the membrane resistance increased with time in both MBR and PAC-MBR
reactors, PAC decreased the rate of membrane fouling by greatly reduced $R_c$ and $R_p$. Based on the observation of change in the $R_c$, the microstructure characteristics of the cake layer on MBR and PAC-MBR membrane surfaces were compared. SEM and AFM images of the membranes revealed that both MBR and PAC-MBR membrane surfaces were rough and covered with a layer of sediment. The cake layer on the PAC-MBR membrane was looser with more...
roughness, which enabled better permeability and a slower fouling rate. Besides, the composition and characteristics of organic matter in the membrane eluent was characterized. Small-molecule particles in the mixed solution deposited on the MBR membrane surface and inside the pores indicated that PAC increased membrane flux by decreasing the adsorption of hydrophilic organic molecules on the membrane surface. In terms of the membrane cleaning, the addition of PAC helped the removal of contaminants cake layer on the MBR membrane, which was conducive to the recovery of the membrane. Alkaline cleaning was the best method in our test to remove organics from contaminated membranes and restore membrane performance.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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