Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.768403

51 (2013) 5121–5131
July

Taylor & Francis
Taylor & Francis Group

Recent advances in membrane fouling caused by extracellular polymeric substances: a mini-review

Zhiwei Wang*, Xiaomeng Han, Jinxing Ma, Pan Wang, Xiaojie Mei, Zhichao Wu

State Key Laboratory of Pollution Control and Resource Reuse, College of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
Tel./Fax: +86 21 65980400; email: zwwang@tongji.edu.cn

Received 4 June 2012; Accepted 11 September 2012

ABSTRACT

Membrane fouling caused by extracellular polymeric substances (EPS) is a complicated issue and a hot topic in membrane bioreactor (MBR) research. A large number of articles have been published recently. However, the results of them are sometimes different, controversial and even contrary, which is hindering our understanding on the role of EPS in membrane fouling. That is mainly attributed to the fact that most of the studies focus on one specific aspect of EPS while overlooking their overall behaviors. This review is designed to synthesize the knowledge of EPS and to eliminate confusions through analyzing their secretion, transformation, release, and adsorption based on the recent publications and our own research, which is expected to provide a sound understanding of membrane fouling caused by EPS in MBRs.

Keywords: Extracellular polymeric substances; Membrane bioreactor; Membrane fouling; Soluble microbial products; Wastewater treatment

1. Introduction

During the past decades, membrane bioreactors (MBRs) have been widely used in municipal and industrial wastewater treatment due to their advantages over conventional activated sludge process, such as reduced footprint, improved effluent quality, and decreased sludge production. Their widespread applications, however, are restricted by membrane fouling which results in flux reduction, and/or transmembrane pressure increase, and frequent membrane cleaning. Among various components contained in the activated sludge, extracellular polymeric substances (EPS) and soluble microbial products (SMP) are currently considered as the major foulants of membranes in MBRs [1–3]. The adhesion/deposition of EPS and SMP toward membranes can block membrane pores and/or form a fouling layer, leading to the increase in filtration resistance [4,5].

EPS are a matrix of large polymeric molecules containing variable proportions of proteins, polysaccharides, nucleic acids, humic-like substances, lipids, and heteropolymers such as glycoproteins, which are secreted by microorganisms and located at or outside microbial cell surfaces. EPS are mainly responsible for the structural and functional integrity of the aggregates and considered as the key to the physicochemical and biological properties [6,7]. To date, it has been well

*Corresponding author.

7th Aseanian Membrane Society Conference (AMS7), 4–7 July 2012, Busan, Korea

accepted that EPS can be classified into soluble EPS and bound EPS. According to the unified theory for EPS and SMP, soluble EPS are actually SMP [8,9], and the bound EPS can be further classified into loosely bound EPS (LB-EPS) and tightly bound EPS (TB-EPS). SMP are closely related to bound EPS, and the hydrolysis of bound EPS is the major origin of biomass-associated products (BAP) of SMP. Therefore, the understanding of bound EPS characteristics and behaviors may hold the key to clarify membrane fouling caused by those biopolymers in MBRs.

To date, a large number of peer-reviewed article have been published regarding the behaviours and role of bound EPS in MBRs. Part of the article focus on characterization of bound EPS characteristics [10,11], while other article deal with the variations of bound EPS under different operating conditions [12–14]. In addition, a large proportion of article pay more attention to the correlations of EPS with membrane fouling [3,5,15,16]. However, the results of bound EPS fouling are sometimes different, controversial and even contrary, which is hindering our understanding on the role of EPS in membrane fouling. This is partially because most of the studies merely concentrate one aspect while overlooking the overall behaviors of bound EPS. The whole process of bound EPS fouling should be comprised of four stages, that is EPS secretion, transformation, releasing, and adsorption onto membranes. Another reason is due to the fact that microinterfaces play a key role in the transformation, release, and fouling process. Currently, there is a lack of studies on the overall behaviors of EPS through microinterface perspective.

In this review, we propose a scenario, as illustrated in Fig. 1, to comprehensively understand and to review EPS behaviors and fouling process in MBRs, that is, EPS secretion, EPS transformation, EPS-releasing behaviors at bound EPS-solution interface, and adsorption behaviors at membrane-solution interface based on the recent related publications and our own research. The microinterface concept is emphasized and incorporated in this article to draw an overall picture of bound EPS in MBRs. It is expected to provide a sound understanding of membrane fouling caused by EPS in MBRs.

2. Biological secretion of bound EPS

The secretion of bound EPS is closely related to the biological kinetics, which is affected by the following factors, that is, the influent wastewater, operating conditions, and sludge properties. Fig. 2 schematically shows the correlations of bound EPS secretion with the above-mentioned factors. Bound EPS secretion is closely related to sludge physiochemical properties, which can be affected by influent wastewater and operating conditions.

2.1. *Influent wastewater*

Influent wastewater is one of important factors affecting bound EPS secretion in biological treatment processes. It has been reported that sludge fed with glucose contains more bound EPS than that fed with acetate due to the fact that glucose metabolism is more complex that likely involves more enzymes including extracellular enzymes in comparison with

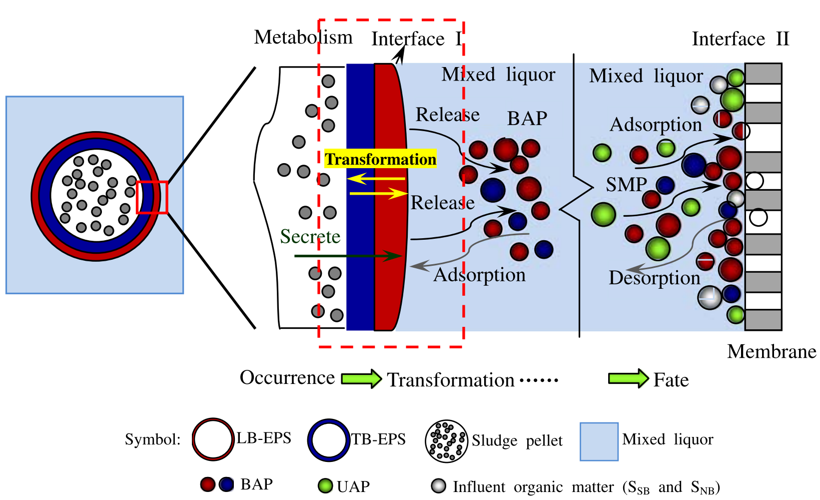

Fig. 1. Schematic of membrane fouling formation caused by EPS and SMP (BAP, UAP) through EPS secretion, LB-EPS and TB-EPS transformation, releasing behavior at interface I (bound EPS-solution interface), and adsorption at interface II (membrane-solution interface). S_{SB}: slowly biodegradable substances; S_{NB}: non-biodegradable substances.

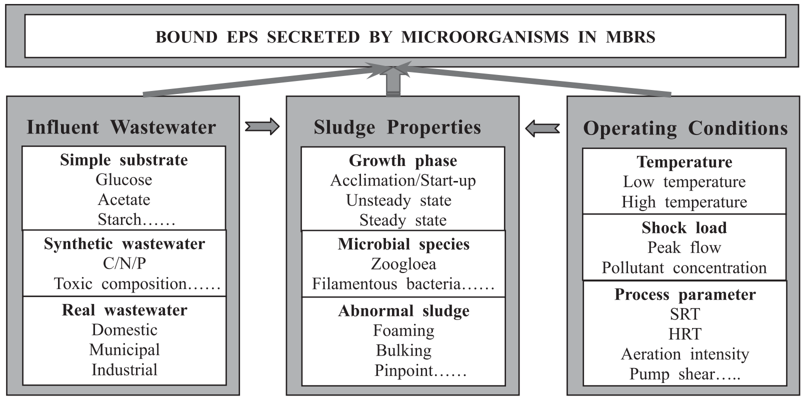

Fig. 2. Factors affecting the secretion of bound EPS.

acetate degradation [17]. In another study, Ye et al. [18] observed that sludge fed with acetate produces more LB-EPS than that fed with glucose and starch, while bound EPS is relatively at same level regardless of different substrates. The citric acid cycle plays an important role in the metabolism of organic compounds and the biosynthesis of microbial materials. Sodium acetate can enter the citric cycle directly, but glucose, starch, and other substrates have to be first degraded to pyruvate and then oxidized to form acetyl-CoA before it can enter the cycle [19]. Therefore, it is argued that the use of acetate as substrate can produce high LB-EPS, because EPS formation rate is proportional to substrate utilization [18]. This judgment is not consistent with the results of Li and Yang [17]. It illustrates that other factors may also influence bound EPS production even under same substrate utilization, such as microbial species [20]. Sheng et al. [21] compared the EPS production from a photosynthetic bacterial strain using various substrates, and the bacteria produced more EPS using benzoate as the substrate than using acetate, propionate, and butyrate.

Carbon-to-nitrogen ratio (C/N) and nutrient level of influent wastewater can affect the production of bound EPS. It was observed that LB-EPS composition was changed due to the difference of C/N ratio, while TB-EPS were not obviously influenced [22]. It has been reported that EPS production can be promoted if phosphorus is in short supply [23]. Bound EPS composition can be also changed if nutrient level is varied. Hoa et al. [24] found that carbohydrate content in EPS tended to increase when phosphorus content was low. Durmaz and Sanin [25] observed that EPS had high content of proteins and low content of carbohydrates at a C/N ratio five, while proteins decreased rapidly and carbohydrates increased when the C/N ratio increased to 40. Liu and Fang [26] reported that microorganisms in sludge tended to produce EPS with a high protein/carbohydrate ratio with influent wastewater of a low C/N ratio.

In the presence of toxic substances (e.g. heavy metal), microbes tend to produce more bound EPS to protect cells against toxic substances [27,28]. However, at a level below the minimum inhibitory concentration, some toxic substances, for example, bismuth dimercaptopropanol can inhibit the production of EPS, and it was found that carbohydrates and proteins in EPS decreased by about 95% during 5-day period after Brevundimonas diminuta was exposed to bismuth dimercaptopropanol at a level near the minimum inhibitory concentration [29]. It was also reported that bound EPS concentration increased from 54.2 to 99.5 mg/gVSS with the elevation of NaCl concentration from 0 to 10 g/L, among which LB-EPS changed more significantly than TB-EPS [30]. Similar results using potassium ferrate to stimulate LB-EPS production were reported by Ye et al. [31].

In MBRs for real wastewater treatment, the production of bound EPS is more complex than those MBRs fed with simple substrates or synthetic wastewater. Real wastewater contains readily biodegradable, slowly biodegradable, and refractory substances, and sometimes toxic substances are present. Sponza [32,33] investigated EPS production of sludge from continuous stirred tank reactors treating various types of wastewaters and observed that under steady-state conditions the protein content was higher in the EPS from the sludge treating winery and municipal wastewaters than that treating pulp-paper, textile, and petrochemical wastewaters.

2.2. Operating conditions

It has been well accepted that operating conditions are closely related to EPS production. Table 1 briefly summarizes bound EPS production under various

Table 1
EPS production under different operating conditions in MBRs

Operating conditions	EPS production	Explanation	Feeding water	Ref.
Temperature	Temperature↓→bound EPS↑	Bound EPS hydrolysis ability decrease	Municipal	[34]
	Temperature↓→EPS↑		Synthetic	[35]
Shock load	Organic shock load→bound EPS↑ then↓	Biomass enriching then granule disintegrating	Municipal	[12]
	Salinity shock load→soluble EPS↑, bound EPS irregular	Filamentous bacteria growing	Synthetic	[36]
Process parameter	SRT↑→bound EPS↑	/	Synthetic	[37]
	SRT↑→bound EPS↓	Low formation rate of microbial substances	Synthetic	[38,39]
	Shear stress↑→bound EPS↑	Floc breakage	Synthetic	[48,49]
	Shear stress↑→bound EPS↓	Erosion resistant at high shear stress	Synthetic	[50]
	HRT↓→bound EPS↑	Higher volumetric organic loading	Synthetic	[13,40]
	HRT↓→bound EPS↓	Biodegradation enhancement by increased biomass	Municipal	[41]
	HRT↓→bound EPS↓	shock load of toxic substances	Synthetic	[14]
	Aeration intensity↑→bound EPS↑	Floc breakage	Synthetic	[42,43]
	Aeration intensity↑→bound EPS↓	Shortage of DO	Synthetic	[44]
	DO↓→bound EPS↓	EPS hydrolysis	Municipal	[45]
	DO↑→bound EPS↑	The carbohydrates production in EPS increased	Synthetic	[46]
	F/M↑→bound EPS↑	More nutrients absorbed	Municipal	[47]

operating conditions. It can be seen that temperature has negative correlations with bound EPS production, that is, low-temperature operation can stimulate bound EPS production [34,35]. Shock load, such as peak flow or pollutant concentration variations, can also induce the production of bound EPS [12,36]. Regarding the impacts of process parameters (e.g. SRT, HRT, and aeration intensity) on bound EPS production, there are still no consistent results. Some researchers found the EPS production increased with an increase in SRT while others have observed the opposite trend. Ng et al. [37] found a reduction in bound EPS at shorter SRT ranging from 0.25 to 5 d. However, Masse et al. [38] reported that the total bound EPS content decreased from 45–70 mg/g VSS to 20–40 mg/g VSS when SRT increased from 10 to 53 d. Ahmed et al. [39] found that the EPS content decreased by 15% as SRT increased from 20 to 100 d attributed to a lower production of microbial substances or an increase in their degradation rate.

There are also controversial conclusions about the influence of HRT on bound EPS production. Patsios and Karabelas [13] reported that bound EPS increased by 50% when HRT decreased from 10 to 5 h. It was explained that lower HRT resulted in higher volumetric organic load and the biomass has more substrate per unit volume and time, which could stimulate the production of bound EPS. Meng et al. [40] also found lower HRT caused more bound EPS releasing in the bulking sludge. It is not consistent with the results of Baek et al. [41]. It was found that bound EPS reduced from 42 to 22 mg/g VSS with the decrease in HRT. That mainly because the EPS was biodegraded by the increased biomass due to the high organic load. Moreover, the lower bound EPS and deflocculation of activated sludge is observed under low HRT in an MBR used for the treatment of wastewater containing styrene, which was ascribed to the shock load of styrene [14].

In a cross-flow MBR, aeration not only provides oxygen to the biomass, but also maintains the solids in suspension and scours the membrane surface by generating a shear stress. Some researchers have found that aeration intensity can alter EPS production rates in MBRs, but the results of these studies are divergent. In general, high aeration intensity induced more bound EPS secretion to adhere and resist the damage of suspended cells caused by environmental forces [42]. Meng et al. [43] studied the performance of three MBRs with different aeration intensity and found that the bound EPS production increased significantly with the increase in intensity from 150 to

800 L/h. It was explained that the higher aeration intensity generated a stronger shear stress and then resulted in a severe floc breakage which caused the release of more EPS. However, some other researchers [44] observed that bound EPS production decreased with the increase in aeration intensity from 40 to 120 L/h, in which they hypothesized that more EPS were produced under low DO concentration. DO concentration in mixed liquors may be another influential factor for EPS production. Nielsen et al. [45] reported that the bound EPS content would decrease under anaerobic conditions since activated sludge flocs tended to disintegrate due to the oxygen limitation. Shin et al. [46] found that bound EPS production increased as DO increase, and that more carbohydrates in EPS were generated at a high DO level.

The food-to-microorganism ratio (F/M) has an important effect on the bound EPS production. Jang et al. [47] reported that EPS content of the MBR sludge increased with the increase in F/M ratio. Moreover, both protein and carbohydrate concentrations in bound EPS increased with the increase in F/M ratio. That was mainly because the protein and carbohydrate from the influent could be absorbed by the EPS matrix under higher F/M ratio.

2.3. Microbial physiochemical properties

Influent wastewater and operating conditions finally result in different sludge properties that significantly correlate with bound EPS production. Different microbial species can have different bound EPS secretion properties [20,23]. Jia et al. [51] reported that the EPS content was related to the bacterial growth phase. They found that during the exponential growth phase, the EPS content increased with cultivation time, while it decreased with cultivation time during the stationary phase. However, it was also found that the EPS content from a photosynthetic bacterial strain decreased with cultivation time during the exponential growth phase and remained almost unchanged in the stationary phase [52–54]. The contradictory results of different microbial species again illustrate that microbial species have significant influences on bound EPS production.

Abnormal sludges, such as bulking, foaming, and pinpoint sludges, can affect the production of bound EPS. The studies by Meng et al. and Choi et al. [55,56] showed that the bulking sludge had a higher bound EPS concentration than normal sludge due to the overgrowth of filamentous bacteria. However, other researchers found that there was no significant difference in the production of bound EPS between bulking and normal sludge, while much more SMP were produced in bulking sludge [57]. For foaming sludge, Al-Halbouni et al. [58] has reported that in a full-scale MBR the bound EPS concentrations and SVI are higher when the sludge foaming occurs. Moreover, the deflocculated sludge was found to have a higher bound EPS concentration than normal sludge but lower than bulking sludge [59].

3. Transformation of bound EPS

Prior to the release of bound EPS into solution at interface I (see Fig. 1), it is believed that the transformation of bound EPS composition (i.e. TB-EPS and LB-EPS) plays an important role. BAP and substrate *utilization-associated products* (UAP) are two components of SMP. BAP should be mainly originated from LB-EPS, and that is to say, TB-EPS first transform into LB-EPS and then LB-EPS hydrolyze/release into solution forming BAP [60]. Currently, it is thought that UAP is originated from substrate utilization, however, it is still not clear whether they are from bound EPS or other locations of microbial cells. We believe that the possibility of bound EPS pathway forming UAP may outweigh that of other cell locations. Anyway, TB-EPS and LB-EPS mutual transformation may be an important factor governing the release of bound EPS into mixed liquor.

Recently, Hwang et al. [61] has observed that the presence of ozone could destroy LB-EPS and enable them to transform into TB-EPS in a MBR combined with a turbulent jet flow ozone contactor. They found that with the decrease in LB-EPS, the floc size became larger and mixed liquor filterability was enhanced. It was also reported that LB-EPS can be detached from TB-EPS under the presence of alkali solution [62]. The study of Azami et al. [63] showed that floc size increased with the increase in TB-EPS to LB-EPS ratio, which could enhance membrane resistance. Although the above-mentioned studies are helpful for us to understand the double-layered structure of bound EPS and their possible transformation, a lot of future research efforts should be dedicated to this topic. An emerging technology, for example, quartz crystal microbalance with dissipation monitoring (QCM-D), which has been widely used in organic chemistry, can be a powerful tool to investigate the transformation of TB-EPS and LB-EPS by quantitatively monitoring viscoelastic properties of bound EPS [64–66]. TB-EPS adsorption layer and LB-EPS adsorption layer can be dynamically established on the microbalance, and their differences of viscoelastic properties can be obtained. Through adjusting the composition of TB-EPS and LB-EPS, the transformation mechanisms may be clarified through a viscoelastic perspective.

4. Bound EPS release

Interface I (see Fig. 1), that is, bound EPS-mixed liquor interface, is the location where the release of bound EPS into solution takes place. The release behaviors are closely related to the microinterface environment, for example, turbulence (shear), solution chemistry, and so on. The previous publications provide us some useful information on understanding bound EPS release behaviors. Wang et al. [16] studied the impacts of shear stresses on bound EPS release and found that the increase in shear stress or the prolongation of shear duration could elevate SMP concentration in mixed liquors, indicating that the release of bound EPS was stimulated. Similar results were reported by other researchers [67,68]. The correlations of solution chemistry with bound EPS release have been also studied. Feng et al. [69] found that excessive NH_4^+ in the supernatant could facilitate the role of NH_4^+ as a monovalent and the replacement of the polyvalent cation in bound EPS, resulting in the release of bound EPS and the formation of new SMP. pH may be another important factor depending on the physicochemical properties of bound EPS and thus release behaviors [65,70].

However, to date, the detailed release behaviors at microinterface scale have not been clearly elucidated. As mentioned in Section 3, QCM-D should be a powerful tool to investigate the behaviors at interfaces [64–66] and can be used to characterize the formation of thin films (nm scale). With QCM-D, the kinetics of both structural changed and mass changes are obtained simultaneously. It is very convenient for us to establish thin films of bound EPS on the senor plate, that is, a thin quartz disc sandwiched between a pair of electrodes, and to monitor their release by washing the sensor with different solutions. The molecular interactions with surfaces as well as interactions between molecules, viscoelastic, and conformational changes of deposited bound EPS layer can be characterized, which provides valuable insights into bound EPS behaviors. Other fingerprint measurements can be also incorporated into microinterface study. Through combining atomic force microscopy (AFM), Fourier transform infrared spectroscopy (FTIR), etc. the release behaviors of bound EPS layer established onto microbalance of QCM-D can be obtained through varying microinterface environment.

5. EPS membrane fouling

The release of bound EPS into mixed liquors can result in membrane fouling, which is related to the transformation behaviors in mixed liquors and adsorption behaviors into membrane pores or onto membrane surfaces. Released EPS are transformed in mixed liquors under the interactions between released EPS (UAP and BAP), other organic substances (influent organic matter), and inorganic substances (metal ions) (see Fig. 3). After the transformation, those substances, being colloidal and soluble states, may enter membrane pores or adhere to membrane surfaces to form membrane fouling under the interactions of foulant–membrane.

5.1. Transformation in mixed liquors

The transformation of released EPS in mixed liquors is an important process that is closely related to the consequent fouling behaviors. In mixed liquors, a series of organic and inorganic matters can be found, for example, the influent substances (slowly biodegradable and non-biodegradable substances), UAP, BAP, and inorganic metals. The released SMP can be transformed into macromolecular and colloidal states under the mutual interactions with other organic and inorganic substances. The major mechanisms may include polymeric interactions, adsorption, chelation, and cation-bridging effects. It has been reported that SMP can interact with soluble ions through complexation and chelation [71]. The detailed transformation process can be further clarified through using gel filtration chromatography, particle size distribution analyzer, and other direct observation technologies in MBRs. It has to be pointed out that the released SMP can be also biodegraded by

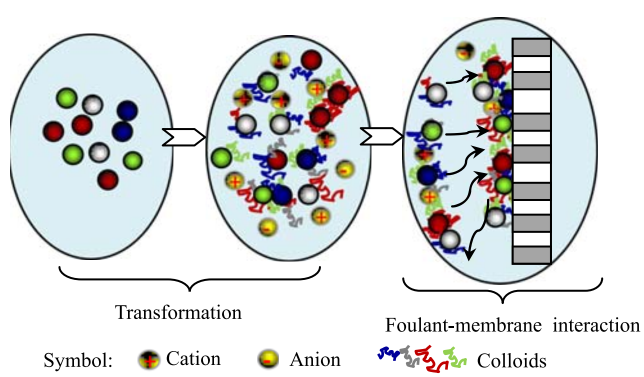

Fig. 3. Released bound EPS transformation in mixed liquor and their behaviors at foulant–membrane interface (except for the symbols listed in the figure, other symbols are same as those in Fig. 1).

microorganisms. They can absorb onto cells again to form bound EPS (see Fig. 1).

5.2. Adsorption at foulant–membrane interface

The role of EPS in foulant adhesion causing membrane fouling can be roughly classified into two aspects, that is, EPS-aided bacterium adhesion and released-EPS (SMP) adhesion. It has to be pointed out that the presence of EPS on cell surfaces could enhance cell deposition onto membrane surfaces. It was found that the carboxylate, phosphate, and amine functional groups contributed to the adhesion of bacteria to solid surface [72,73]. Park et al. [74] observed that the number of attached cells decreased if EPS were removed from sludge surfaces. Liu et al. [75] reported that EPS-rich strains had a much greater adhesion potential on porous media than EPS-deficient strains with a similar surface charge density. It was reported by Tsuneda et al. [76] that if the EPS amount was relatively low, cell adhesion onto solid surfaces was inhibited by the electrostatic interaction, while if it was high, cell adhesion was enhanced by the polymeric interactions and the suppression of electro-repulsive forces [77]. It is worth noting that solution chemistry can significantly influence the adhesion behaviors through changing physicochemical properties of EPS. It has been reported that EPS viscosity and elastic properties can be changed under different solution environment, which can subsequently impact the adhesion behaviors of EPS [64,65]. The contribution of EPS to bacterial adhesion can be roughly described by Derjaguin–Landau–Verwery–Overbeek (DLVO) theory or extended DLVO (XDLVO) theory. However, non-DLVO forces, such as polymeric interactions and ion bridging, should be taken into account [78].

The adhesion of released EPS (i.e. SMP) is another important aspect causing membrane fouling. The interactions of SMP with membranes govern the adhesion behaviors. Currently, a number of publications have addressed the relations of SMP to membrane fouling [60]. However, the results are sometimes not consistent and even contrary due to various solution chemistry, different membranes, and diverse SMP properties (see Table 2). To date, different conclusions on membrane fouling caused by UAP and BAP have been also reported. Tian et al. [79] and Jiang et al. [80] found that UAP had higher membrane fouling potential, because UAP have higher percentage of low molecular weight molecules. To the contrary, Wu et al. [81] found BAP had higher potential to cause membrane fouling. It illustrates that SMP-related fouling is dependent not only on SMP concentration but also on SMP composition.

The use of XDLVO theory to analyze the comprehensive interactions between SMP and membranes may be a pathway to explain why the inconsistent results are sometimes obtained. XDLVO theory has been successfully used in the fouling of colloidal matters and natural organic matters to membranes [82,83]. Kim and Hoek [84] also used XDLVO theory to describe the biopolymer fouling of reverse osmosis membranes. It can be hypothesized that SMP-related fouling of membranes in MBRs can be also modeled by this theory if the following aspects can be addressed.

(1) Solution chemistry, such as ionic species, ionic strength, and pH, may play an important role in their fouling. The values of some factors in XDLVO equations should be modified according to specific solution chemistry. Cations,

Table 2
A summary of SMP related-fouling in MBRs

Fouling behaviors	References
Predation of aquatic earthworms under low aeration intensity→ SMP↑→fouling↑	[85]
Low-temperature→ SMP↑→fouling↑	[86]
Organic flocculants or inorganic flocculants →SMP↓→fouling↓	[87]
Filamentous bacteria→ SMP↑→fouling↑	[57]
SMP↑→fouling↑	[50,88,89]
SMP_p↑→fouling↑; SMP_c↑→fouling↑↑	[86,90]
SMP_c↑→fouling↗	[91]
Magnesium →SMP↓→fouling↓	[92]
Ferric chloride→MW > 10 kDa in the SMP↓→fouling↓	[93]
Influent protein/carbohydrate ratio↑→fouling↑	[94]
No clear relation between SMP and filtration characteristics could be found	[95–97]

especially multivalents, can bridge small-molecule SMP to form macromolecules.

(2) The slowly biodegradable and non-biodegradable substances existing in influent wastewaters should be taken into account, which may aid the fouling behaviors of SMP through mutual interactions.
(3) Membrane physico-chemical properties, such as Zeta potential, contact angle, roughness and so on, should be determined and incorporated into XDLVO theory to gain an overall picture of SMP fouling in MBRs.
(4) A series of SMP and membrane samples under diversified solution chemistry should be adopted to verify the XDLVO model, through which a general rule of SMP fouling may be obtained.

The EPS substances on membrane surfaces can be decomposed and detached by microbial activities. Nagaoka and Akoh [98] found that high molecular weight EPS (more than 1,000 kDa) accumulated on membrane surfaces could be decomposed to smaller molecular weight EPS and that filtration resistances of the membranes was finally mitigated. The detachment of EPS from membrane surfaces can be also affected by other factors such as shear stress along membrane surfaces and solution chemistry. Future investigations on EPS desorption can be helpful for membrane fouling control.

6. Concluding remarks

Membrane fouling caused by EPS includes several complex behaviors, that is, their secretion, transformation, release, and adsorption. Although numerous articles have been published regarding EPS membrane fouling, comprehensive studies on the overall fouling process are very limited. In particular, microinterface concept needs incorporating into the fouling investigation. A series of instruments (e.g. QCM-D, AFM, FT-IR, etc.) for microinterface investigations are very useful for future researches. By addressing the following problems, a general understanding of EPS membrane fouling might be obtained.

(1) *EPS secretion*: The influent wastewater, operating conditions, and microbial physiology may be the major factors governing EPS secretion.
(2) *LB-EPS and TB-EPS transformation*: Research on transformation at microinterface scale should be enhanced.
(3) *EPS release*: Solution chemistry and shear stress may be two important factors governing EPS release.
(4) *EPS membrane fouling*: XDLVO theory combined with interface-scale study may be an applicable way to study the fouling and to gain an overall understanding of EPS membrane fouling. In addition, EPS transformation in mixed liquors under complicated solution chemistry should be paid attention to.

Acknowledgments

This manuscript was financially supported by the National Natural Science Foundation of China (Grant No. 51008217) and the Sino-French Scientific and Technological Cooperation Project in the Domain of Water (2011DFA90400).

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