



## Submerged Membrane Bioreactor and Fouling Problems

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### บทคัดย่อ

บทความนี้นำเสนอความรู้หลักที่เกี่ยวกับปัญหาการอุดตันในระบบถังปฏิกรณ์ชีวภาพเมมเบรน จมตัว ความหมายและประเภทของการอุดตันได้ถูกแนะนำไว้ในส่วนแรกของบทความ รายละเอียดและแผนภาพของการเกิดปรากฏการณ์อุดตันทั้งแบบภายในและภายนอกได้ถูกอธิบายไว้ในส่วนถัดมา รวมถึงแม่นยำของความสัมพันธ์ระหว่างปัญหาการอุดตันและปัจจัยที่มีผลยิ่งไปกว่านั้น เนื่องด้วยการประยุกต์ใช้ระบบถังปฏิกรณ์ชีวภาพเมมเบรนรวมตัวกับระบบบำบัดน้ำเสียแบบตากองน้อย จุลินทรีย์กำลังเป็นเทคโนโลยีใหม่ที่ได้รับความสนใจทั่วโลก บทความนี้จึงนำเสนอข้ออภิปรายและข้อถกเถียงเกี่ยวกับปัญหาการอุดตันและองค์ประกอบของตากองน้อยจุลินทรีย์ด้วย ได้แก่ ปัญหาการอุดตันจากความเข้มข้นของตากอง ความเข้มข้นของสารโพลีเมอร์ชีวภาพ และประเภทของตากอง เป็นต้น ในส่วนท้ายสุดบทความนี้ได้รับรวมแนวทางแก้ไขปัญหาการอุดตันด้วยวิธีการต่างๆ อันได้แก่ การฉีดอากาศภายในและภายนอกเมมเบรน การให้อากาศแบบไม่ต่อเนื่อง การกรองภายในได้ฟลักซ์วิกฤต การกรองแบบไม่ต่อเนื่อง และการล้างย้อน เป็นต้น กล่าวโดยสรุปคือบทความนี้จะหนักถึงความเชื่อมโยงระหว่างธรรมชาติของระบบถังปฏิกรณ์ชีวภาพเมมเบรน จมตัว สาเหตุของการอุดตัน และวิธีการตอบสนองที่เป็นไปได้ ซึ่งอาจเป็นประโยชน์ต่อผู้อ่านที่ข้องเกี่ยวกับการประยุกต์ใช้เมมเบรนต่อไป

**คำสำคัญ:** ถังปฏิกรณ์ชีวภาพเมมเบรนรวมตัว การอุดตัน การบำบัดน้ำเสีย

### Abstract

This paper delivers the principle knowledge about fouling problems in a submerged membrane bioreactor (SMBR) process. Firstly, the definition and classification of fouling found in the SMBR are introduced. Details and schematic diagram of fouling phenomena in the SMBR cross-flow filtration are depicted with a focus on both external and internal forms. Aspects of a correlation between SMBR fouling and their influencing factors are described. As the so-called SMBR process is still a hot topic in worldwide technology for sludge wastewater treatment, a relationship and a controversial discussion about SMBR fouling problems and sludge components are provided including fouling caused by MLSS, EPS, sludge fractions and sludge categories. Lastly, solutions against these fouling problems are gathered and presented specifically air scouring outside and inside the membrane module, intermittent aeration, sub-critical flux filtration, intermittent filtration and back washing. In sum, this paper, perhaps, makes developers more aware of the complicated links among

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the nature of SMBR process, causes of fouling and its reachable responses which might be beneficial to all involving membrane application.

**Keywords:** Submerged Membrane Bioreactor, Fouling, Wastewater Treatment

## 1. Introduction

Over the last decades, a modification of the conventional activated sludge process using submerged membranes technology called submerged membrane bioreactor (SMBR) has been used to separate of the effluent, replacing sedimentation, which reduces the plant size due to the absence of settling tanks. Moreover, SMBR is capable to deal with high sludge concentration and gives constant and effective disinfection of treated water. The main applications of SMBR technology reported in industry are for treatments of heavily loaded wastewaters such as oily wastewaters, or discharges from landfill leachate, tanneries and textile industries. Although their several advantages are well recognized, the SMBR process also has its principal limitation on membrane fouling, which causes permeate flux decline and necessitates frequent cleaning and/or replacement of membranes. These disadvantages affect on high aeration cost. Therefore, this paper aims to broaden a better understanding of fouling problems in SMBR and its possible solutions for these problems.

## 2. Characterization of Membrane Fouling

Mass transfer in the SMBR process can lead to the attachment, accumulation or adsorption of material onto the membrane surface or within membrane pores causing an increase in hydraulic resistance over time [1]. This phenomenon is called membrane fouling.

Fouling can be classified as [2],[3].

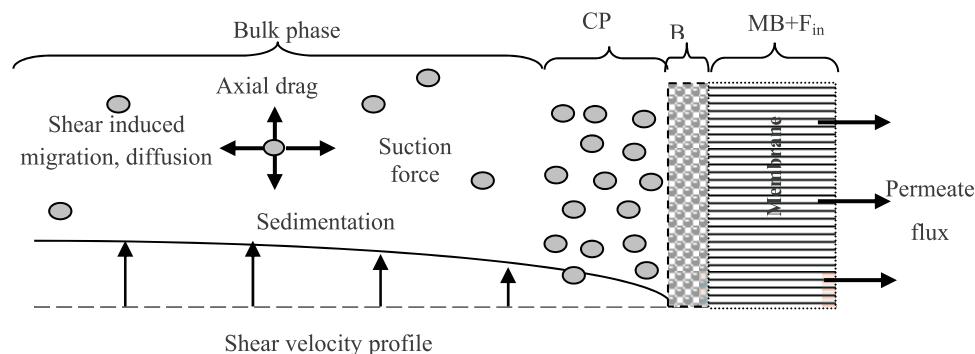
- Crystalline fouling (scaling): deposition of mineral due to the excess of soluted product
- Organic fouling: deposition of dissolved humic acids, oil, grease and lipids
- Particle and colloidal fouling: deposition of clay, particulate substances, debris and silica
- Biofouling: adhesion and accumulation of microorganism forming biofilms

The crystalline fouling mainly happens in membrane application for ground water treatment due to salt precipitation (eg. Calcium salts, Magnesium salts). The organic fouling and biofouling are commonly causes for membrane fouling in wastewater treatment, while particle and colloidal fouling are major fouling causes for membrane surface-water treatment.

Fouling is the key problem in all membrane applications. Fouling changes the pore size and pore size distribution either by deposition of a layer onto the membrane surface or by blockage or partial blockage of the pores.

## 3. Fouling Phenomena in SMBR Filtration

Transport phenomena of SMBR crossflow filtration are shown in Figure 1, which shows a particle under a number of influences for a vertical plane membrane surface. Particles flow toward the membrane surface by permeate-suction force, while the crossflow forces particles back transport into the bulk by shear-induced migration and diffusion mechanisms (to a lower concentration). If the suction force is higher than other forces, fouling, either gelatinous form or cake form (layer B in Figure 1), will occur on the membrane surface. In the ideal case, only the clean membrane resistance is involved, while,



**Figure 1** Schematic of submerged membrane filtration displays the effective force on suspended microorganism particle and fouling phenomena on membrane surface, where CP = concentration polarization, B = membrane biofouling (gel or cake formation), MB + F<sub>in</sub> = membrane layer and internal fouling.

\*Note: Shear velocity profile = a profile presenting velocity of shear aeration as a function of distance.

in the real condition, fouling causes by several factors such as concentration polarization, external fouling on the membrane surface, and fouling inside membrane layer by narrowing and plugging of the pores. Bulk phase is a phase of influent and considered to be less influence from suction force. Concentration Polarization (CP) is a layer of stagnant solution where the suspension concentration remains higher than the bulk stream concentration due to the balance between suction forces and migration/diffusion forces back to the bulk solution. When the diffusion force is a spontaneous passive transport (with non-energy requiring) of small molecules from the higher concentrated area to another area.

Generally, the suspended particles in MBR system are small enough to neglect both inertial (or axial drag) and gravitational forces. Only the shear migration force and suction force can be considered. As seen in Figure 1, SMBR crossflow filtration resistance can be divided into three categories;

1) The natural membrane resistance for pure water ( $R_m$ ), which depends on pore size, pore

density, pore depth, the material's wet-ability, and the hydrodynamic resistance of the device holding the membrane [4]-[6].

2) A resistance due to concentration polarization ( $R_{cp}$ ) is caused by convection through the membrane. The thickness of the CP layer depends upon the solution velocity created by the difference between suction force and shear force on the membrane surface. The higher the shear force compared with suction pressure, the thinner the CP layer. If the fluid flows through the membrane faster than the retained material can transport back into the bulk fluid, a dense particle layer forms in front of the membrane surface and creates a secondary dynamic membrane [4].

3) Resistance due to membrane fouling ( $R_f$ ) composed of cake resistance ( $R_c$ : shown as layer B in Figure 1) and internal plugging resistance ( $R_i$ : shown as layer F<sub>in</sub> in Figure 1). Many studies found that the filtration resistance due to the accumulated cake (or particles) on the membrane surface is dominant in the membrane process (>60%), compared to the resistance due to the micropore plugging or surface adsorption



which block and narrows the pores [4], [6],[7]. Most filtration resistance due to the micro-pore plugging or irreversible adherence to the membrane was caused by organic substances [7],[8].

For simplicity and for practical reasons, fouling is often separated into internal and external fouling, or cake fouling and internal fouling. This is because it is almost impossible to distinguish between the different types of fouling in practice. If the suspension has particulates with diameters larger than the membrane pores, the surface mechanism of sieving occurs.

A cake layer grows on the membrane surface based on the retained particles. The cake provides an additional resistance to filtration. For dead-end filtration, the cake continuously grows but in the crossflow operation, the tangential shear stress may arrest the cake growth and extended operation is possible [9]. Under the assumption of an incompressible cake, its porosity and resistance are independent of pressure [10]. Cake fouling resistance ( $R_c$ ) can be more easily removed by shear stress and/or chemicals than the internal fouling. Contrary to external fouling, internal fouling resistance ( $R_{in}$ ) is considered more severe. The internal fouling resistance normally happens below the surface level of the membrane, including adsorption and partial pore blocking. It is comparably harder to eliminate internal fouling because it is more difficult to reach micro-pores with back-flushing or even with a chemical cleaning agent. If some membrane pore areas cannot be accessed by the cleaning agent, a loss of total membrane capacity, which is expressed as decreasing initial flux, is the result. Thus, the treatment of internal fouling is essential lengthen membrane life expectancy and should be appropriately carried out.

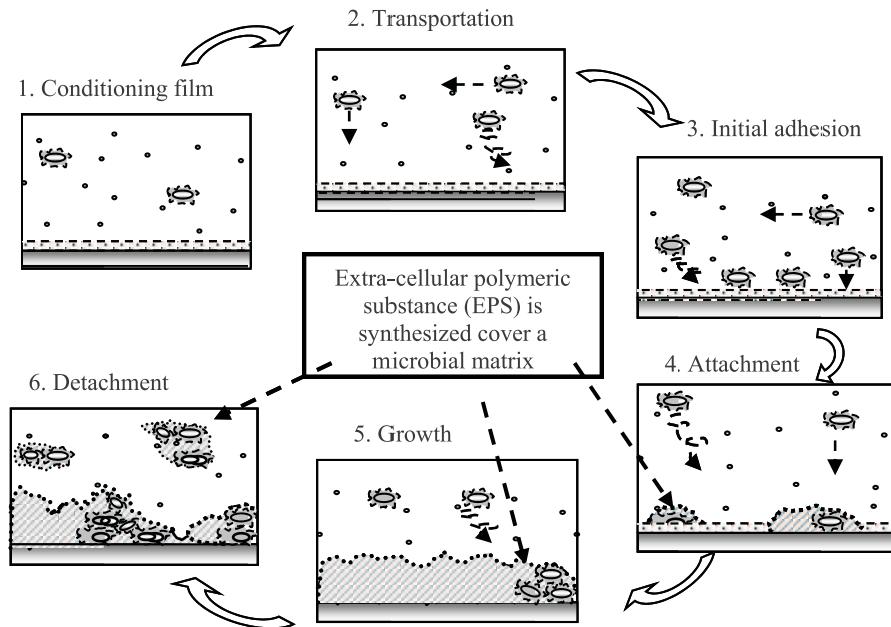
#### 4. SMBR Fouling and Influencing Factors

##### 4.1 Biofouling Mechanism

Unwanted deposition and growth of biofilm are commonly embedded on a membrane surface in a matrix of microbial origin, consisting of extra-cellular polymeric substances (EPS) and microorganisms [11]. The formation of a biofilm in an aqueous environment generally proceeds in the following sequence [12]-[14] (Figure 2):

- 1) When organic matter is presented, a conditioning film of adsorbed components is formed on the membrane surface prior to the arrival of the first microorganisms.
- 2) Microorganisms are transported to the surface through diffusion, convection, sedimentation or active movement. This step is the initial step of membrane biofouling.
- 3) Initial microbial adhesion occurs when EPS is synthesized to protect and stabilize cell attachment from the outside environmental effects.
- 4) Attachment of adhering micro-organisms is strengthened through EPS production and unfolding of cell surface structures.
- 5) Growth and metabolism of the attached microorganisms and film develop, and continue secretion of exo-polymers or biopolymer.
- 6) Localized detachment of biofilm organisms caused by occasionally high fluid shear or other detachment forces operative starts after initial adhesion, although adhesion of individual microorganism is frequently considered irreversible (whether justified or not), and increase with time as it is related to the number of microorganisms present in the biofilm [11].

Detachment of parts of a biofilm can occur by cohesive failure inside the bulk of the biofilm



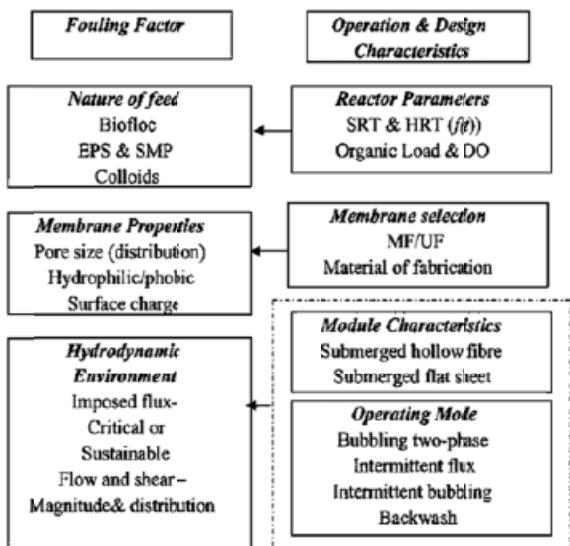
**Figure 2** Sequential steps in biofilm formation. (adapted from [13]).

involving interfacial rupture. Furthermore, as the number of biofilm organisms increases, growth rates will decrease due to nutrient and oxygen limitations and accumulation of organic acids, eventually leading to a stationary biofilm thickness, where adhesion and growth counterbalance detachment [13].

The attachment and accumulation of biofouling introduce to the maximum biofouling thickness which later sloughs off due to the shortage of substrate and oxygen for the layer cells next to the membrane. However, in crossflow membrane filtration, the density of the biofilm thickness increases with time until reaching the steady state owing to the effect of continuous shear migration force.

#### 4.2 Factors Affecting Fouling in SMBR

Degree of fouling in an MBR will be determined by three basic factors: 1) the nature of the feed; 2) the membrane properties; 3) the hydrodynamic



**Figure 3** MBR fouling factor roadmap [15]

environment experienced by the membrane [15]. The interactions between these parameters are complex and, not surprisingly, there are some contradictions in the literature that need to be resolved by further



analysis. Figure 3 (left-hand side) depicts the ‘fouling factors’ and illustrates the complex nature of the feed and the features of the hydrodynamic environment. On the right of Figure 3 are the ‘operation and design characteristics’ of the MBR that are believed to influence the fouling factors.

## 5. SMBR Fouling and Sludge Component

### 5.1 Fouling Caused by MLSS

The effects of mixed liquor suspended solids (MLSS) on membrane fouling are not yet fully understood and controversial reports about the effects of this parameter have been presented. Many studies reported that membrane fouling took place more rapidly at higher MLSS concentration [16]-[19], while some claimed that sludge concentration is not a main influencing factor or has little impact on membrane fouling [20]-[22]. Nevertheless, all these experiments were carried out on different scales, different operational conditions and different ranges of MLSS concentration. Therefore, influence and interaction of MLSS on membrane fouling should be simultaneously studied together with the changing of operating and sludge conditions.

### 5.2 Fouling Caused by EPS

Extra-cellular polymeric substances (EPS) are products of active secretion, cell surface material shedding, cell lysis and sorption from the environment [23] and EPS has been identified as the main foulant in MBR processes [24],[25]. The EPS matrix can be characterized by its relative levels of polysaccharides, proteins, and more rarely lipids and nucleic acids [26],[27]. EPS is produced by most bacteria and participates in the formation of microbial aggregates whether the bacteria grow in suspended culture or

in biofilms [28],[29]. Consequently, EPS plays an important role in the flocculation, settling and dewatering of activated sludge [30].

A positive relationship between the higher the suspended EPS concentration, the lower the filtration ability was showed in various researches [31],[32]. On the contrary, some research showed that the higher EPS caused a better filtration [33].

EPS can be classified as extracted EPS which are artificially produced from the biological cell flocs and the soluble EPS which are present in the activated sludge supernatant and are not associated with the cell (soluble microbial products) [34]. So far no standard method for EPS extraction exists, which causes difficulty in making a comparison between research groups.

### 5.3 Fouling Caused by Sludge Fractions

Activated sludge generally contains a range of metabolites produced during the biological reaction and the biomass itself in the form of flocs. Organic compounds from the suspension processes are usually divided into three fractions [35].

- Biomass: bacterial flocs which contain bacteria, attached EPS and some inorganic. Normally, the sizes of bacteria aggregates are bigger than 1  $\mu\text{m}$ .
- The colloidal fraction from 0.01 to 1  $\mu\text{m}$ .
- The soluble fraction: such as biopolymer and soluble EPS.

A number of researches have been focused on the contribution effects of suspended solids, colloids and soluble fraction to the fouling of the SMBR for activated sludge filtration [37]-[40]. The SMBR fouling affected by different fractions of activated sludge are variations and not easy to compare due to differences in operational conditions. Examples of sludge fraction influence are shown in table 1.

**Table 1** Fouling contribution of different activated sludge fractions [36]

Resource	Membrane	MLSS	Solute	Colloid	SS	Operational conditions
Wisniewski et al. [37]	0.1 $\mu\text{m}$ tubular di = 6.5 mm	10-15	52%	25%	23%	$u = 5 \text{ m/s}$ TMP = 100 kPa Back washing
Defrance et al. [38]	0.1 $\mu\text{m}$ tubular di = 6.5 mm	4.5	5%	30%	65%	$u = 3 \text{ m/s}$ TMP = 100 kPa SRT 60 days
Bouhabila et al. [39]	0.1 $\mu\text{m}$ hollow fibre	20.7	26%	50%	24%	Bubbling SRT 20 days
Lee et al. [40]	0.4 $\mu\text{m}$ hollow fibre	2.8	37%	63%	SRT 20 days	
		4.4	28 %	72%	SRT 40 days	
		5.5	29%	71%	SRT 60 days	

Note: MLSS unit is g/L.

#### 5.4 Fouling Caused by Sludge Categories

Some studies reported that different types of sludge (such as normal sludge, bulking sludge and de-flocculated sludge) could cause different degree of fouling. The bulking sludge could cause severe cake fouling due to the deposition of irregular shaped sludge flocs [41]. Comparatively, the normal sludge had a slight membrane fouling tendency. The bulking sludge had a higher bound EPS, however, the deflocculated sludge had a higher free EPS concentration, and the increase of free EPS concentration would do great harm to membrane bioreactor. Confocal laser scanning microscopy (CLSM) analysis also showed that the bulking sludge and deflocculated sludge could form a dense cake layer as compared with normal sludge [41].

### 6. Measures Against Fouling in SMBR

#### 6.1 Air Scouring Outside the Membrane Module

A number of researchers have found that the air scouring method could be achieved to improve MBR performance by removing cake fouling on membrane

surface. The effect of aeration increase can remove cake fouling on the membrane surface up to some certain limitation [42],[43], which means aeration has a significant impact on fouling improvement.

#### 6.2 Air Sparging Inside the Membrane Module

Air injection inside a membrane module was introduced to be applied in tubular and hollow fibre membranes. The flux enhancement after using gas-liquid two phase flow in the tubular ultra-filtration membrane was mentioned due to internal fouling reduction [44],[45]. The same benefits of bubbling injection inside membrane modules for bentonite filtration despite the difference hydrodynamics between tubular and hollow fibre membranes were found [46].

#### 6.3 Aeration Mode

Several studies have found that an implementation of intermittent aeration and fluctuation of the aeration intensity could offer better filtration performance than that with continuous aeration. This technique can mitigate cake fouling. The higher permeate flux can be obtained by increasing the bubble frequency and various the bubble size [47]. An intermittent aeration is even able to enhance the de-nitrification process [48],[49]. Moreover, fouling propensity is different after using air injection between different locations which can generate adequate turbulence to minimize the fouling formation.

#### 6.4 Sub-critical Flux Filtration

The sub-critical flux operation may be a desirable operational target for a clean MBR plant requirement due to delay of cake and pore fouling. Many researches are focused upon developing its enhancement to avoid



severe fouling. By correctly selecting the initial flux or TMP, the rate of membrane fouling can be greatly reduced. Some works described that it was impossible to maintain the initial flux which is above the critical flux [50]. Besides, the critical value of this flux (or TMP) is very much system specific.

### 6.5 Intermittent Filtration

It is reported that the intermittent suction mode was better for long term operation of the membrane system compared to continuous suction mode [51],[52]. The effect of intermittent filtration mode on the improvement of membrane fouling can be explained by the enhanced foulant back transport under filtration relaxation.

### 6.6 Backwashing

Backwashing or back flushing is a cyclic reversal of the gas or liquid (or some cleaning agents) back into the feed path. This technique has been commonly practiced in industry for many years and is a fairly simple effective way to fight internal fouling [9]. Unlike other methods, the backwashing technique is able to dislodge both foulants inside membrane pores and on membrane surface. However, the back flushing strategy is normally applied for submerged hollow fibre membrane systems, not for the submerged flat sheet membrane process due to different back pressure tolerances.

## 7. Conclusions

The SMBR technology has been widely used, especially in wastewater treatment due to its several advantages. However, this SMBR process still faced with main problem called fouling which can be occurred in both external and internal forms. These

fouling were influenced by biofouling mechanism and other factors such as MLSS concentration, EPS concentration, sludge fraction and sludge categories. To solve or reduce this SMBR fouling problems, some measurement against fouling were recommended in variety of ways namely: air scouring (outside and inside membrane module), intermittent aeration, sub-critical flux filtration, intermittent filtration and backwashing techniques. In summary, this paper, perhaps, makes us become more aware on the complicated links among nature of SMBR process, causes of fouling and its reachable responses which might be more useful to all readers who involving in membrane application.

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