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A novel plate settler in immersed membrane bioreactor (iMBR) in reducing membrane fouling

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ABSTRACT

Membrane separation technology has been widely applied in water and wastewater treatments, especially in the water reclamation and recycling. However, the membrane fouling decreases the membrane efficiency and increases the cost of the process, thus limiting the membrane application. There are two types of membrane bioreactors (MBRs), immersed (iMBR) and side streamed. However, the membrane surfaces of these two types of MBR are always directly exposed to high concentration of suspended solids (SS) and easily get fouling. A novel MBR was designed to reduce membrane fouling. Incorporation of inclined plate in MBR can separate high SS from direct contact with the membrane surface and decreases membrane fouling. The iMBR used in this study consists of an aeration zone, a settling zone, and a filtration zone. The reactor operated under the upflow mode of operation with 0.06 μm membrane pore size and with and without membrane backwashing. The results showed that the novel iMBR can reduce the SS concentration in the filtration zone up to 97.3% and increase the permeate flux over 41.9% than that of normal iMBR.

Keywords: Membrane bioreactor; Inclined plate; Air scouring; Periodic backwash

1. Introduction

The membrane Bioreactor (MBR) is a combined system of biological and physical treatment processes. MBR technology offers many advantages over the conventional activated sludge process [1]. It has been considered as one of the most promising processes for wastewater treatment and reclamation in the past decades [2]. The advantages of MBRs are well known, e.g. a reduced footprint, improved effluent quality, high treatment efficiency, and higher retention of solids [3–5]. The two basic MBRs are side stream membrane bioreactor (sMBR) and immersed membrane bioreactor (iMBR), as shown in Fig. 1(a) and (b), respectively [6]. In sMBR, the mixed liquor is circulated outside the bioreactor to the membrane module, where the applied pressure leads to the separation of water from the sludge [7]. The iMBR is a bioreactor where the membrane module is immersed in the bioreactor (activated sludge) itself. A suction force is

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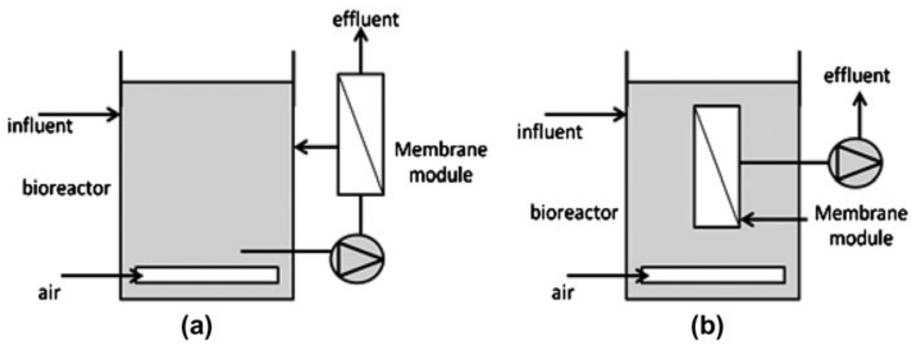

Fig. 1. Schematic diagrams of basic MBR configuration. (a) Side sMBR with membrane module and (b) iMBR with membrane module immersed in the bioreactor.

applied to draw the water through the membrane. The iMBR is more commonly used because of the less energy requirement [8]. The aeration can prevent the deposit formation on the membrane surface [7].

Nowadays, MBR has been gaining popularity in wastewater treatment worldwide. A membrane filtration step is used to replace the traditional sedimentation tank [9,10]. But the main obstacle for the application of MBRs is the rapid decline of the permeation flux due to membrane fouling. This is caused by the direct contact of the membrane with solid and biological matters in the bioreactor [11]. Membrane fouling not only decreases the permeate productivity but also increases the operating costs [12].

The inclined plate settler has been used for the separation of suspended solids (SS) and was first described and quantified by Hazen 1904. The inclined plate settler consists of a series of closely spaced flat plates inclined at a horizontal angle of 45–60˚. The water with solids enters the plates and flows between the plate channels. As the water flows between the inclined plate channels, the heavy solids with a specific gravity higher than the water settle down on top the surface of the lower plate, and slide down the inclined plate surface to be collected in the sludge hopper. Thus, the inclined plates help in settling of SS more rapidly than conventional settlers due to their increased surface area and decreased settling distances [13]. The particles settle onto the upward-facing surface of each plate which is placed in the sloped position and slide down to the bottom of the settler where they are collected [14].

In this study, the novel iMBR is used to reduce the membrane fouling using an inclined plate settler in the conventional iMBR. This avoids the direct contact of solids from the membranes. The comparison between novel iMBR and conventional iMBR and the suitable operating conditions of this novel iMBR were investigated.

2. Material and method

2.1. Synthetic wastewater

Wastewater used in this study is a synthetic domestic wastewater. The characteristics are shown in Table 1. The sludge used in this experiment was collected from the settling tank of conventional activated sludge of Taiwan beverage manufacture wastewater treatment plant.

2.2. Membrane characteristics

The hollow fiber membrane made of polyvinylidene fluoride was used in this study, which was supplied by King Membrane Energy Technology Inc., Taiwan. The membrane diameter is 2 mm with 0.06 µm pore size. The total membrane area used was 640 cm^2.

2.3. Experimental setup and design

The novel design of iMBR used is shown in Fig. 2. The reactor consists of two compartments, inner and outer tanks, with a total volume of 60 L. It is divided into three zones, namely the aeration zone, the settling zone, and the filtration zone. The aeration zone (20 L) is the zone for organic biodegradation. The settling

Table 1
Ingredients of synthetic wastewater used in this study

Components	Concentration (g/L)
Glucose	1.0
NH_4Cl	0.1
KH_2PO_4	0.18
K_2HPO_4	0.29
$CaCl_2$	0.01
$MgSO_4·7H_2O$	0.1
$FeCl_3·6H_2O$	0.005
$CaCO_3$	0.1

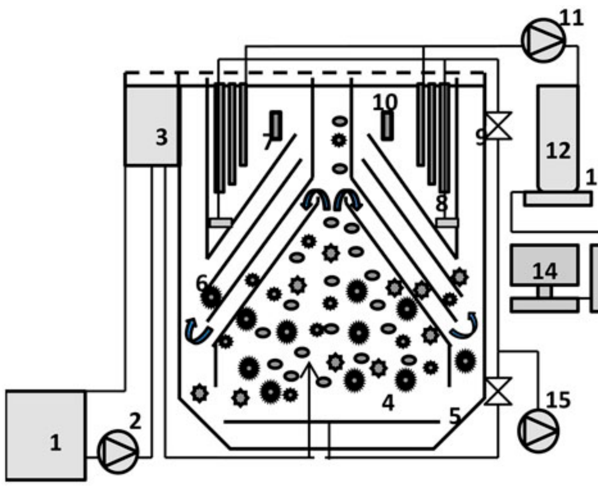

Fig. 2. MBR with inclined plate: (1) feed tank: (2) influent pump; (3) constant head tank; (4) aeration zone; (5) air diffuser; (6) settling zone; (7) filtration zone; (8) air diffuser; (9) membranes; (10) baffles; (11) effluent pump; (12) permeate tank; (13) balance scale; (14) data recorder; and (15) air pump.

zone (34 L) is used to settle down the SS coming from aeration zone. Finally, water overflows into the filtration zone (6 L) for membrane filtration.

The water level of this system is controlled by the constant head tank (3). Wastewater flows into the aeration zone (4) and gets mixed with the sludge inside the reactor. The mixed liquor flows through the inclined plate channel down to the inlet of the next two inclined plate channels and flows up upwards and then overflows into the filtration zone. The sludge settles down as the mixed liquor flows through the three inclined plate channels. This reduces the suspended solid concentration as it reduces the filtration zone. Sludge solids on the inclined plates will slide down to the bottom of tank then return back to the aeration zone.

2.4. Chemical analysis

The chemical oxygen demand (COD) and Total organic carbon (TOC) of the influent and effluent were measured. The SS in all three zones of aeration, settling, and filtration were also measured. The measurement method follows APHA standard method.

2.5. Experimental condition

The experiments were conducted in different conditions after the acclimatization period of 7 d in order to make a comparison between novel iMBR (run No. 1 and run No. 2) and conventional iMBR (run No. 3). The operating conditions are presented in Table 2. The operating pressure was from −0.5 to −1.0 kg/cm^2 (suction). The membrane cleaning was offline by deionized water. The effect of air backwash was also studied, where backwashing was performed for a duration of 15 s every 60 min of membrane operation.

3. Results and discussion

3.1. SS removal efficiency

The mixed liquor SS concentration was measured in aeration, settling, and filtration zones. The results showed that the novel iMBR helped to lower the SS concentration in the filtration zone (Fig. 3), where membranes were in contact with water (Fig. 3). The SS in the filtration zone was less than 100–300 mg/L which corresponds to a removal efficiency of up to 98.3%.

As shown in Table 3, SS concentration was much lower near to the membranes when inclined plates were included (run No. 1 and 2 as compared to 3). The solids concentration at the settling zone was slightly higher for run No. 2 due to air scouring of membrane used in the filtration zone. This created turbulence at the top part of filtration zone which can be eliminated by introducing a baffle in the upper part of filtration zone near by the weir to eliminate the air bubbles escaping out of the filtration zone. However, even when the SS concentration in the filtration zone is low, the membrane fouling still occurred. This could be due to the deposition of mixed liquor particles (those are in suspension) on to membrane surface and sludge build-up in between the fibers in the membrane module. In addition, the accumulation of organic matters on and within the membrane material causes membrane fouling [15,16]. The organic matters those that are responsible for membrane fouling are mainly composed of proteins and polysaccharides, nucleic acids, lipids, and other polymeric compounds and are considered to be the most important irreversible membrane foulants. Furthermore, a thin biological deposition formed on the membrane surface is also responsible for membrane fouling due to biological activities [17]. However, the air scouring in the filtration zone is important to minimize membrane fouling.

3.2. Effect of permeate flux

3.2.1. Permeate flux between novel iMBR and conventional iMBR

Fig. 4 shows the permeate flux profile for each operational condition. The experimental period was 120 h. The permeate flux profile in a novel iMBR

Table 2
Experimental conditions

Factor	Operating conditions for different run numbers		
	No. 1	No. 2	No. 3
Membrane area (cm^2)	640	640	640
Air scouring in filtration zone	None	Yes	Yes
Inclined plates included	Yes	Yes	None
MLSS (mg/L)	5,500	6,000	5,530

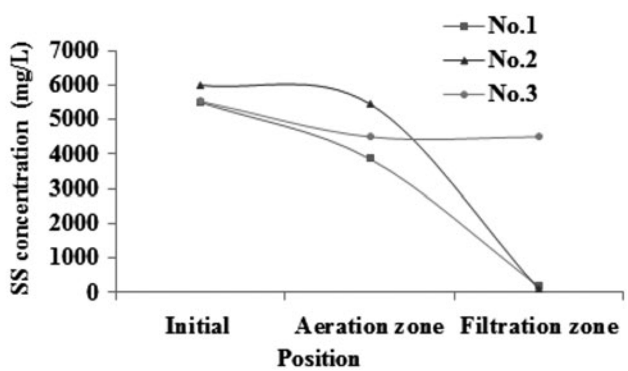

Fig. 3. The average SS concentration for different runs and zones.

Table 3
Flow rate and fouling of iMBR in the experiments

Flow rate (mL/min)	No. 1	No. 2	No. 3
Initial	17.0	17.0	17.0
Average	10.1	13.3	11.4
Percentage of fouling	44.6	21.8	32.8

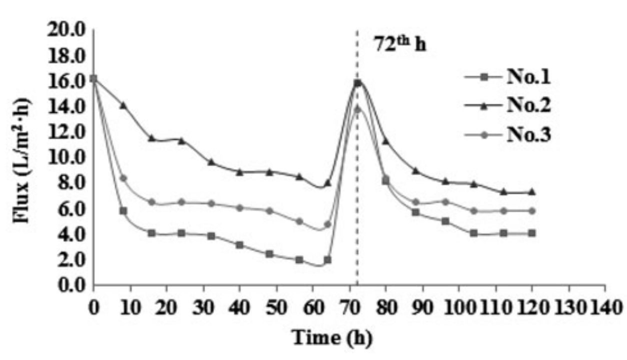

Fig. 4. The permeate flux variation for different runs.

(run No. 1 and 2) was compared with the conventional iMBR (run No. 3). The increase in flux at the 72 h was due to the membrane offline cleansing by deionized water. The novel iMBR resulted in higher flux than a conventional iMBR. There was a 41.9% increase due to lower SS contact with membrane (as shown in Table 3). Thus the placement of inclined plate in the iMBR is important. The flux of novel iMBR (No. 2) declined slowly when compared to No. 1 due to the air scouring adopted. The air scouring reduced the fouling on membrane surface. An introduction of air scouring, however, will increase the operating cost. An optimization of baffle dimension will reduce the aeration requirement which is the major operating cost.

In addition, the off line membrane cleaning (after 72 h of operation) helped to recover membrane flux (almost 100%) (run No. 1 and 2). This shows that the fouling was irreversible and mainly due to particle deposition on the membrane surface and inside the membrane bundles. A previous study showed that particle deposition on the membrane surface and inside the membrane bundles contributes to 40% of membrane fouling [18]. The novel iMBR with inclined plate settler helps to reduce the particle deposition due to the prior removal of SS by the incorporation of inclined plate.

3.2.2. Permeate flux with and without air scouring

An experimental run of 120 h was done to study the effect of air scouring in the filtration zone in the novel iMBR. Run No. 1 and No. 2 were conducted with and without air scouring, respectively. The average permeate flux increased from 5.4 to 10.5 $L/m^2 h$ when air scouring was provided at the filtration zone as shown as Fig. 5(a). The permeate flux increased with air scouring, because the air bubbles produced a shear force to the membrane surface which reduced membrane fouling. Furthermore, air scouring results in turbulence in the filtration zone. This turbulence can provide a shear force on the membrane surface to prevent membrane fouling by reducing the SS accumulation on the membrane surface and inside the membrane bundles. Thus, the air scouring is still needed in this novel iMBR although the water

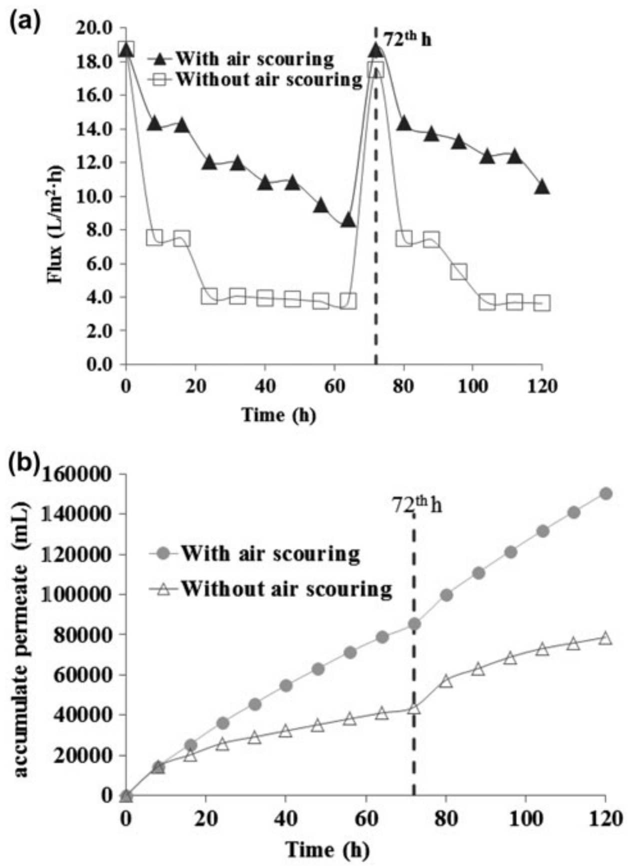

Fig. 5. Effect of air scouring of membrane on the (a) permeate flux and (b) cumulative permeate volume.

contacted with membrane is with very low SS concentration. An optimization of aeration is necessary to minimize the suspended solid deposition and to reduce the aeration rate.

The effect of air scouring on permeate-accumulated volume is presented in Fig. 5(b). The membrane filtration with air scouring can increase the permeate volume by more than 50% (i.e. it can be operated almost two times longer than that without aeration). In addition, this reactor has a baffle setting in the filtration zone. This baffle can prevent the turbulence caused by the bubbles coming out from the membrane air scouring of filtration zone.

3.2.3. Effect of backwash

Experiments were also conducted to study the effect of backwash on membrane fouling in the novel iMBR. Fig. 6 shows the results with and without air backwash. The off line cleaning of membranes after 72 h of membrane operation led to almost 100% recovery of flux with a periodic air backwash. On the other hand, offline cleaning without the periodic air backwash resulted in the membrane flux recovery of 93.1% of initial flux. Also, flux decline after 60 h of operation was 43.7% with periodic backwash when compared to 49.2% without the air backwash. This shows that air backwash was not efficient as that of air scouring.

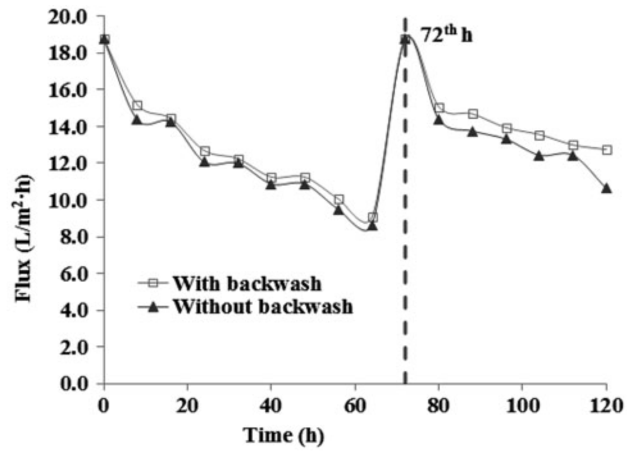

Fig. 6. Effect of backwash on the permeate flux.

3.2.4. Effect of flow rate

The initial and average permeate flow rates and membrane fouling rate are shown in Table 3. The membrane fouling rate is calculated using the following formula:

$$\text{Membrane fouling rate } (\%) = 100 \times \frac{\text{Initial flow rate} - \text{Average flow rate}}{\text{Initial flow rate}} \quad (1)$$

The results showed that the fouling percentage of conventional iMBR was 32.8%. The percentage of membrane fouling for run No. 1, 2, and 3 were 44.6, 21.8, and 32.8%, respectively. Here, run No. 1 and run No. 2 are with novel iMBR and run No. 3 is with conventional iMBR. Thus, the results showed that novel iMBR used in this study is better in terms of fouling reduction. Furthermore, it can be seen that the combined incorporation of inclined plate and aeration led to a better fouling reduction than inclined plate or aeration separately.

3.3. TOC and COD removal

Table 4 shows the TOC and COD removal in a novel iMBR. It was compared with the conventional iMBR. The TOC and COD in influent varied between

Table 4
Results of efficiency removal and permeate flux

Removal efficiency (%)	Experiments run number		
	No. 1	No. 2	No. 3
COD	81.4	96.9	92.1
TOC	79.0	96.8	86.3
SS*	95.4	98.3	–**
Average flux ($L/m^2 h$)	5.8	10.5	7.4

*The SS in filtration zone before membrane filtration. The COD and TOC were measured in the filter effluent.
**In the conventional iMBR, the membrane comes into contact directly with wastewater and sludge where there was no SS removal before membrane filtration. Here there was no inclined plate.

360 and 400 mg/L and 1,350 and 1,500 mg/L, respectively. The TOC and COD in the effluent were high during the startup period and improved during the experiment period. The removal efficiencies of TOC and COD were as high as 96.8 and 96.9%, respectively, during run No. 2. As shown in Table 3, the removal efficiency of run No. 2 is better than that of run No. 3. The reason might be the existence of sludge in the settling zone and also in the channel of the inclined plate settlers. TOC and COD removal in each operating condition are slightly different because of the difference in initial mixed liquor SS and the hydraulic conditions used. The different design of the reactor may also have influence on the position of sludge accumulation. The sludge accumulation will have influence on the biodegradation of wastewater.

3.4. DO concentration in the reactor

DO concentration in different positions was measured to study the hydraulic and sludge returning conditions of the novel reactors. Fig. 7 shows the average DO concentrations at different positions of run No 2. Here, the results of DO are only presented for run No. 2, as run No. 2 resulted in better performance than run No. 1 and 3 in terms of flux decline as well as organic removal. It can be seen that DO concentration in different zones of the reactor have a specific trend. DO in the filtration zone was the highest due to membrane air scouring and low organics and sludge concentrations. It was low in the settling and sludge accumulation zones due to high concentration of sludge which was still capable of consuming the oxygen for the degradation of the organics. All three types of reactors had DO lower than 1 mg/L in the sludge accumulation zone. DO in type 1 was almost 0 mg/L. This implies that DO almost used up and barely had a flow substitution (i.e. presence of dead zone).

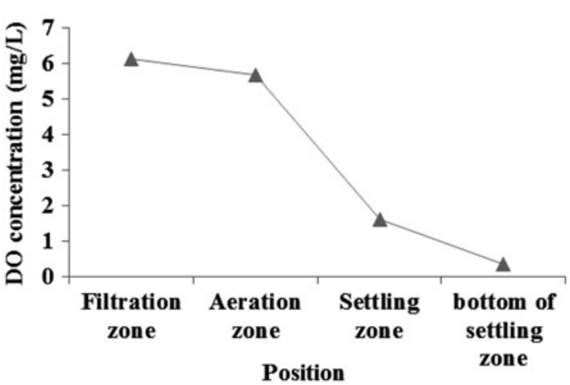

Fig. 7. DO concentration at different zones of the reactor.

4. Conclusions

This paper investigated COD, TOC, and SS removal in a novel iMBR with inclined plate settler. The results showed that the COD, TOC, and SS removal efficiencies were as high as 96.9, 96.8, and 97.3%, respectively. The permeate flux of a novel iMBR increased by 41.9% when compared to that of the conventional iMBR. The inclined plate settler introduced in the novel iMBR resulted in less SS in the filtration zone which lead to less membrane fouling.

However, the novel iMBR has some shortcomings such as (1) the incomplete return of sludge back into the aeration zone, which may result in the anoxic or anaerobic conditions in settling zone; and (2) the turbulence caused by air bubbles may interfere with the falling of solids in inclined plate channel which may in turn reduce the SS removal efficiency.

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